

Reducing Light Duty Vehicle Fuel Consumption and Greenhouse Gas Emissions: The Combined Potential of Hybrid Technology and Behavioral Adaptation

Danilo Santini and Andrew Burnham
Argonne National Laboratory

ABSTRACT

When comparing the potential of advanced versus conventional powertrains, a traditional approach is to hold glider design constant and simulate “comparable performance” to a conventional vehicle (CV). However, manufacturers have developed hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and all-electric vehicle (EV) powertrains in gliders designed to synergistically enhance fuel saving benefits of such powertrains by further reducing road load and engine output power (or continuous power for the EV) where no conventional powertrain option is provided. In the U.S. marketplace, there are now several examples of both hybrid and plug-in hybrid electric vehicles using gliders common to top selling CVs and a few using low load gliders to further reduce fuel consumption. We use fuel consumption estimates from FuelEconomy.gov for a number of plausible CV versus HEV, PHEV, and EV comparisons to estimate the potential additional annual fuel savings and greenhouse gas (GHG) emission benefits, using Argonne National Laboratory's GREET model, obtainable when consumers make the behavioral choice to purchase various electrified powertrains in low road load gliders. When electric generation comes from natural gas, PHEVs and EVs in low load gliders can provide about the same GHG benefits as low load HEVs, with less gasoline use. If renewables are used in conjunction with natural gas, the GHG benefits increase. In comparison to HEVs in standard gliders, there will be even greater benefits.

CITATION: Santini, D. and Burnham, A., "Reducing Light Duty Vehicle Fuel Consumption and Greenhouse Gas Emissions: The Combined Potential of Hybrid Technology and Behavioral Adaptation," *SAE Int. J. Alt. Power.* 2(2):2013, doi:10.4271/2013-01-1282.

INTRODUCTION

A common strategy for engineering evaluations of advanced versus conventional powertrains is to hold the glider design constant, impose performance requirements (e.g. acceleration rate and maximum speed) applicable to conventional vehicles (CVs), and simulate “comparable performance” powertrain capability [1].

However, manufacturers of hybrid electric vehicles (HEVs) and now plug-in hybrid electric vehicles (PHEVs) and all-electric vehicles (EVs) have adopted two alternative design strategies: (1) HEV, PHEV, and EV options within a vehicle glider previously designed primarily for conventional powertrains and (2) HEV, PHEV, and EV powertrains in vehicle gliders designed to synergistically enhance fuel saving benefits of the advanced powertrains, primarily by more sharply reducing road load and engine output power (or continuous power in the case of the EV) than in case 1. In the latter case, no conventional powertrain options are provided. When consumers choose the latter option, they choose a

technology that visibly indicates a conscious choice to prioritize fuel efficiency. Further, relative to the alternative vehicle they consider, they may sacrifice (1) top speed, (2) acceleration (3) grade climbing capability (4) luggage space and/or (5) towing capability. Thus, it can be said that a consumer choice of the latter case option often implies a willingness to modify vehicle owning and utilization behavior. The question in this paper is whether comparisons such as that shown in [Fig. 1](#) should also include examples of what could happen in the event of changes of consumer behavior in the selection of powertrain and vehicle body systems.

The usual approach by the defenders of a technology is to think of its competitor as inferior if it does not provide the same capabilities as their technology. Failure to defend the market status of the dominant technology occurs when the presumably less proficient alternative technology obtains a small anchor market niche and improves over time, capturing share from the dominant technology, and often eventually displacing it [2]. This process can take decades. Among

automotive powertrains, the adoption of front wheel drive in unibody gliders, with transversely mounted, reduced displacement engines was, and still is, criticized on the basis of poor driving dynamics and lack of towing capability. Yet, due to two widely separated oil price spikes and an ability to hold market share in between, this technology has increasingly taken share from the longitudinally mounted engine, rear wheel drive body-on-frame gliders [3].

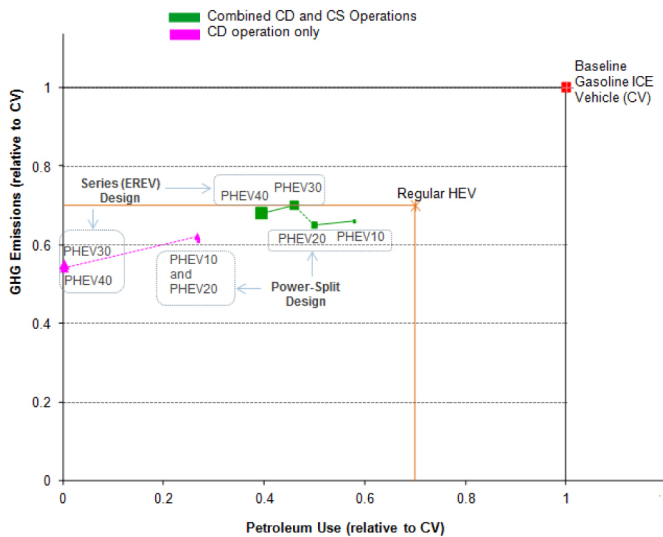


Figure 1. Well-to-wheel petroleum use and GHG emissions for gasoline PHEVs recharging in the western U.S. relative to baseline gasoline CVs [1]

There are now several examples of both hybrid and plug-in hybrid electric vehicles in category 1 and 2, as well as an indication from the marketplace that category 2 HEV designs (e.g. Toyota Prius) will sell better than the category 1 HEV options in CVs (e.g. Toyota Camry Hybrid). This paper uses FuelEconomy.gov fuel consumption estimates for a number of plausible CV versus HEV, PHEV, and EV comparisons to estimate the potential additional annual fuel savings and greenhouse gas (GHG) emission benefits obtainable when consumers make the behavioral choice to purchase category 2 designs rather than category 1. We make use of Argonne National Laboratory's Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model to assess the GHG effects of alternative electricity generation options for the plug-in electric drive segment of PHEV operation (as well as for EV operation). Alternative ways of converting natural gas and wind to kilometers of transportation services are examined. For CVs, use of Fischer-Tropsch diesel (FTD) via shale gas is contrasted with PHEVs and EVs using electricity via the shale-gas-to-combined-cycle-natural-gas pathway.

When electric generation comes from natural gas, PHEVs and EVs in low load gliders can provide about the same GHG benefits as low load HEVs with less gasoline use. If renewables can be used in conjunction with natural gas, the

GHG benefits increase. In comparison to HEVs in standard gliders, there will be even greater benefits.

Evolution of Methodology

This paper is a re-examination of relationships originally estimated in 2008, in anticipation that plug-in hybrid electric vehicles might soon be introduced into the market by original equipment automotive manufacturers (OEMs) [4]. That paper used simulation to estimate the fuel savings benefits of charge depleting (CD) operation of PHEVs, since no OEM PHEVs were available. At the time, it had been observed that, when averages over all daily travel in the National Household Transportation Survey (NHTS) were examined, the early part of daily travel had slower average driving speed than the latter portions [5]. Testing and simulation of vehicles at the time relied on the urban dynamometer driving schedule (UDDS), averaging 31.3 km/h and the highway fuel economy driving schedule (HWY), averaging 77.2 km/h. Charge depletion was anticipated to occur during the early portion of the average daily travel, which was slower, so the slower UDDS was used to characterize the CD mode operation of the PHEVs and comparison of presumed all-electric vs. gasoline operation were made based on simulation results for this cycle.

At about the same time, the U.S. Environmental Protection Agency was developing a new set of fuel economy estimation methods, in order to better inform consumers of the on-road fuel economy that they should expect [6]. The new system requires testing vehicles in cold and hot temperatures, at faster speeds, and for driving with higher rates of acceleration and deceleration than in the UDDS and HWY cycles. Two segments of the US06 driving cycle that had originally been developed for emissions verification purposes were separated out for on-road fuel economy estimation. The US06 city bag segment (tests are conducted by filling bags) averages 34.7 km/h requiring almost four times the average power of the UDDS. The US06 highway bag segment averages 98.5 km/h, requiring about 2 times the average power of the HWY cycle [6]. We have estimated the new "city" cycle average speed, which is a composite of five different combinations of temperature and driving pattern - called the "5-cycle" test. The 5-cycle city test includes only a 9% weighting for the US06 city bag [7]. Taking into account the weights of the different tests for the new city and highway ratings, the average speeds for the city cycle is almost unchanged. However, the new window label highway cycle average is raised to 92.7 km/h, since the US06 highway cycle test carries a 79% weight. In light of the increased average speed of the new consumer highway rating, aerodynamic drag carries an increasing importance in fuel consumption estimates. The window label values that consumers see include a separate city and highway value, and a composite value that places a 55% weight (in terms of share of distance driven) on the city results, 45% on the highway. The 55/45 split is unchanged from the prior weighting; however, EPA uses a 43% city and 57% highway weighting for model year

2005 vehicles and older in examining fuel economy trends [8]. Ironically, even though the average commuting speed of urban areas across the U.S. was consistently declining from 1990 through 2009 [9], the creation of the new 5-cycle window label fuel economy estimate implicitly increased average speed for the reference driving case that consumers see.

Establishing a target market and average speeds for that market

Early studies of PHEVs made the assumption that PHEVs would compete for the same market segment as EVs and used what is called the "Utility Factor" to estimate how many kilometers EVs could substitute for CVs [10]. Although the Utility Factor concept continues to be applied today, it has been challenged. For PHEVs, engineering based deductive logic has been used to show that PHEVs could electrify far more kilometers than EVs [11], since they could more readily be used to meet all consumer needs (i.e. both everyday driving and occasional long distance travel). However, this analysis did not consider cost of the HEV and PHEV architecture. Considering cost and requiring financial viability removes many vehicles that are driven relatively few kilometers per year from consideration, which is opposite to the implications drawn when using the Utility Factor [12]. Since battery packs and electric drive are relatively expensive, to be cost effective HEVs, PHEVs and EVs must be used intensively. As it turns out, consumers who drive their vehicles higher kilometers per day also spend more time in their vehicles, even though they drive at higher average speeds [13].

In addition to a need to regularly drive a distance long enough to deplete the battery pack when driven, cost effective operation of PHEVs requires very frequent overnight charging. Relative to a CV, the PHEV also has to benefit from charge sustaining (CS) operation, with both CD and CS contributing to paying off the incremental cost of the powertrain in comparison to a conventional vehicle. So, regular daily operation of a PHEV for daily distances well in excess of the CD distance is needed. The PHEV pack must not be too large, since it can reduce the CS operations efficiency by increasing vehicle mass.

Isolating this desired pattern of vehicle use, the average speed of the two most cost effective distance brackets examined in [12] is 50.3 km/h for those vehicles driven from 80 to 160 km/day, and 59.2 km/h for those vehicles driven 160 to 320 km/day. For vehicles driven house-to-house, the estimated share of total national kilometers in the fleet for the former distance category was estimated to be about 25%, for the latter 21%. These share estimates include kilometers driven by vehicles that do not return to the house or are not there in the morning. Due to their more intensive daily driving, the share of *vehicles* that would have to be operated to accomplish these national kilometer shares, however, is smaller, about 16% and 7% respectively.

For vehicles with a standard glider, prior fuel economy estimates for the old highway cycle for model year 2008 indicated that diesel vehicles generally have better fuel economy than available category 1 HEV powertrains [5]. Since average speed rises as average daily distance driven rises, this tends to make diesel vehicles increasingly competitive with HEVs as average speed increases. Though cost effectiveness analysis remains to be completed, Santini et al. [5] predicted that PHEVs and HEVs would not be cost competitive against diesels as average speed increases. In terms of share of kilometers in the fleet that are driven house-to-house, Santini et al. [12] estimated that 12% of the national total are driven more than 320 km/day, while 30% of kilometers are due to vehicles driven house-to-house less than 80 km/day. In terms of shares of vehicles driven, the > 320 km case represents a small market - about 2% of vehicles. Those two categories - highest and lowest daily use - were neglected because they were estimated to be non-competitive for PHEVs. However, the > 320 km daily use segment may deserve a second look, in light of the low load (LL) glider PHEV design, as we see in this paper.

To the extent that it means that the vehicle is not located at the house, the use of vehicles in long distance travel tends to diminish the odds that the plug in feature at the house can be effectively utilized. The ideal EV use pattern is driving every day from the overnight charge point (house/garage/carport) after an overnight charge, with no long distance travel. While the PHEV can use gasoline for long distance trips, time needed to refuel EVs driven hundreds of kilometers a day on interstate highways makes this use of EVs very unlikely. Accordingly, to best understand the marketability of plug-in electric vehicles, the difference from everyday house-to-house use and long distance high-speed vacation and/or business travel needs to be understood.

In a companion paper, this is investigated [14]. Long distance trips of 240 km or more were separated out of the 2009 NHTS, on the assumption that such distances must normally include a significant amount of travel on limited access highways. This proved to be correct, as the average speed for this subset of trips was estimated to be 99 km/h, almost identical to the speed of the US06 highway bag segment. The analysis found that 8.5% of the total kilometers of NHTS respondents were on trips of 240 km or more. Since the survey did not cover kilometers that vehicles were driven on days when there was neither an arrival at, nor departure from the residence, other sources were investigated as well. An upper bound of 19.5% was used for sensitivity analysis [14]. In this paper we assume that 12% of total annual kilometers are in trips of > 240 km. Absent estimates of the US06 cycle fuel consumption, we use the window label highway fuel economy estimate for this fraction of annual kilometers.

For house-to-house trips, we have two average speeds for two target market distance groups. Fig. 2 presents a plot of the share of distance vs. time in city and highway driving, for our estimates of the 5-cycle average speeds of 32 km/h city

and 93 km/h highway. Using these results, for the 50.3 km/h of the 80-160 km per day distance group, the city/highway distance split is 45/55, rather than 55/45, and the time split is 70/30. For the 160-320 km distance group, at 59 km/h, the city/highway distance split is 30/70, and the time split is 56/44. Thus, the implied house-to-house target market speeds can only be attained if a higher highway distance share is assumed than is presently used in the reference case for the composite fuel economy rating.

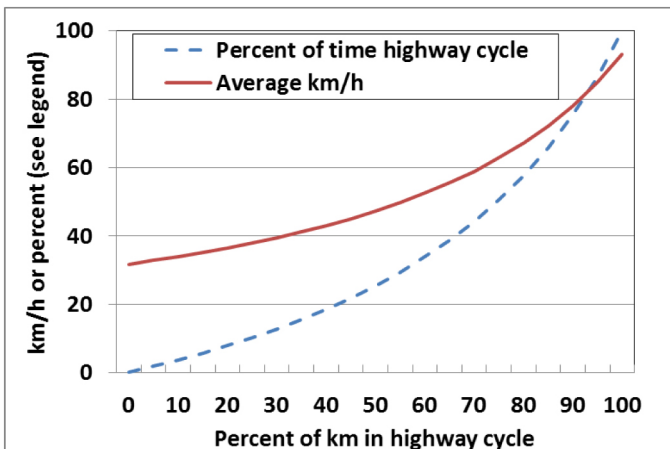


Figure 2. Share of distance vs. time in city and highway driving, using 32 km/h for city, 93 km/h for highway

Perception from a fleet manager's perspective

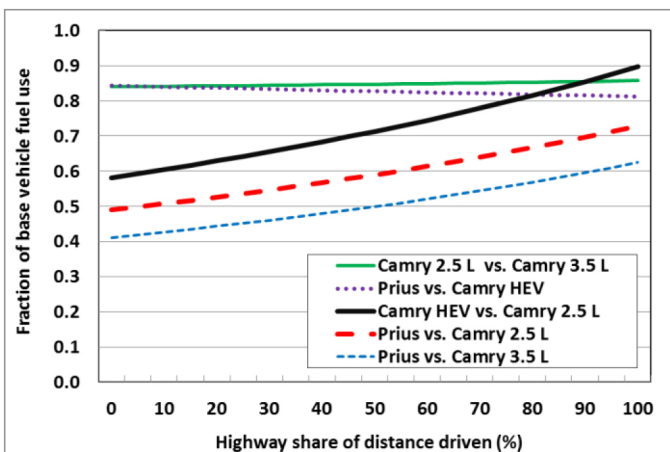


Figure 3. Fraction of base vehicle fuel use vs. highway share via a powertrain and/or glider switch - Toyota options

Most automotive engineers and researchers are likely well aware of the bias created by presenting fuel economy in terms of km/liter (mpg) instead of liters per 100 km. The window label now presents values from both perspectives. Less obvious is the possibility that for financial analysis, thinking of fuel consumption in terms of distance may be misleading compared to thinking in terms of fuel use per hour,

particularly savings per hour of operation when considering substituting one vehicle for another. Most fleet managers, who must pay drivers on a per hour basis, primarily track fuel use per hour of operation rather than fuel use per distance driven. Undoubtedly, they calculate fuel consumption per unit distance as well, but when overall costs per month, quarter, or year are estimated, fuel costs per hour of operation are probably relatively standard. Apart from an initial illustration (Fig. 3), our computations for this paper are developed, and comparisons plotted, on the basis of fuel savings per hour of vehicle operation.

Examples from the marketplace

The two companies producing HEV and PHEV powertrains in the U.S. in unique gliders are Toyota and Ford. Toyota has long had a family of HEVs in both categories, the Prius being the obvious illustration of the low load glider, while the Camry represents the standard glider. Both the Prius and Camry are rated as mid-size vehicles, though the Prius has less passenger volume. The Camry is available in both 3.5 liter and 2.5 liter engines, allowing a contrast between engine downsizing and hybridization. The Ford Fusion, which is a mid-size vehicle, is available in both turbocharged direct injection (TDI) and HEV versions. Ford has just introduced the C-Max HEV, which is classified as a large car. It is comparable in dimensions to the Ford Escape SUV, with about the same passenger volume but has smaller cargo volume. In addition, the Hyundai Sonata is a large car using a standard glider that has both turbocharged direct injection (TDI) and parallel HEV versions. Both the Prius and C-Max come in PHEV versions, so we can compare their operation. The Nissan Leaf is the highest selling all-electric vehicle. The only available compressed natural gas vehicle (CNGV) is a Honda Civic, which is rated as a compact vehicle. A clean diesel Volkswagen Passat is a mid-size vehicle. The Honda FCX Clarity hydrogen vehicle is a mid-size vehicle. These are the examples drawn from the marketplace that are used in this paper. Automatic transmissions are used for the CVs.

RESULTS

Fractional reductions

Fractional reductions, comparable to Fig. 1, are presented for five mid-size vehicle options from Toyota, with the fraction estimated to vary as a function of share of highway kilometers driven. Engine downsizing from a 3.5 to 2.5 liter engine in a CV Camry has about the same magnitude effect (15% reduction) on the city and highway, having the lowest fractional reductions estimated. Should one want to continue to use a Camry, the Camry HEV offers a widely varying fractional reduction, with over 40% reduction for city driving relative to the Camry 2.5 L vs. only 10% on the highway. Switching to the Prius HEV instead of the Camry HEV further increases fractional reduction and flattens out the variation a bit. For the 45/55 city/highway split, the reduction