

An Energy Reallocation Model for Estimation of Equivalent Greenhouse Gas Emissions of Various Charging Behaviors of Plugin Hybrid Electric Vehicles

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ABSTRACT

This work presents a modeling approach for estimation of the equivalent greenhouse gas (GHG) emissions of plugin hybrid electric vehicles (PHEVs) for real driving patterns and charging behaviors. In general, modeling of the equivalent GHG for a trip made by a PHEV not only depends on the trip trace in question, but also on the electric range of the vehicle and energy consumption in previous trips since the last charging event. This can significantly increase the necessary computational burden of estimating the GHG emissions using numerical simulation tools, which are already computationally-expensive. The proposed approach allows a trip numerical simulation starting with a fully charged battery to be re-used for GHG estimation of a trip that starts with any initial state of charge by re-allocating the appropriate amount electric energy to an equivalent gas consumption. Thus, the proposed approach allows modeling of many charging behaviors with minimal additional computational effort beyond one numerical simulation for each drive trace. Validation of the proposed approach is established through comparative simulations using 1012 trip traces, where the error in estimated fuel consumption was less than 3% in most simulations. The full set of trip traces in California Household Travel Survey (CHTS) were then analyzed for the two PHEV models (with short and long electric range), for different charging behaviors and grid conditions.

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INTRODUCTION

Electrified powertrain vehicles have a key role to play in the reduction of global greenhouse gas (GHG) emissions according to several studies that follow and their market predict penetration [1,2,3]. These powertrains include plugin hybrid vehicles (PHEVs) which have an internal combustion engine (ICE), a battery and an electric drive, as well as battery-electric vehicles (BEVs), which have no ICE. A distinction is made between regular hybrids (HEVs) which have a relatively small battery and no electrical charging outlet, and plugin hybrids (PHEVs) have a charging outlet and a larger battery that can be electrically charged to propel the vehicle for a certain range with no/minimal reliance on the ICE. Electrified powertrains have two main advantages that allow for reduction of GHG emissions compared to conventional vehicles (CVs) that only have an ICE: i) energy consumption in the electric drive being fairly resilient to stop-and-go driving, and ii) consumption of electric energy that comes from the grid (PHEVs and BEVs), which can have cleaner sources than gasoline as the electric grid gets greener. With the initial cost of PHEVs being higher than CVs and HEVs and their lifecycle returns in terms of fuel savings somewhat uncertain to owners, economic incentives [4,5,6,7] have been in place to encourage their adoption. However, analysis of the societal benefits of PHEV incentives in terms of reducing GHG emissions (measured in kilograms of CO₂-equivalent) can be a complex task.

A number of numerical simulation tools (both proprietary and public-domain) are available, which have the capability to provide reasonable estimates of the energy consumption of various vehicle models for arbitrary speed traces, e.g. obtained from onboard devices in real vehicles monitored during travel surveys. However, such simulations are often computationally expensive. In order to gain insight to the GHG reduction benefit from HEVs, PHEVs, and BEVs as compared to a CV, it is possible to run the numerical simulation models for a sufficiently large/representative sample of trip speed traces collected in travel surveys, but such a simulation task requires large-scale computational capability, even for "single-mode" powertrains (CVs, HEVs and BEVs), which utilize a single "fueling" system (gas *or* electricity). Modeling of the equivalent GHG for PHEVs is even more challenging because of the "dual-mode" of operation depending on the initial state of charge (SoC) of the vehicle battery. In charge-depletion mode, the PHEV relies primarily on battery-stored electric energy (which came from the grid). On the other hand, in charge-sustaining mode, the vehicle relies on gasoline (or any other fossil fuel). Thus, in order to properly simulate the equivalent GHG of a trip made by a PHEV, one must also keep track of energy consumption by the vehicle in previous trips since the last charging event [8]. Complicating the simulation of PHEVs further is the fact that different charging behavior (e.g. overnight only, before every trip, etc.) also impacts the balance of charge-depletion and charge-sustaining modes, a topic this paper directly addresses. Moreover, as the grid gets greener (less equivalent CO₂ per kWh), the electric GHG emissions of the PHEV are reduced, but its gas

emissions remain largely unchanged. Thus, the grid effect not only shifts the average GHG per mile change, but also morphs the overall vehicle profile of the GHG emissions.

Notable work in the literature on the modeling of electrified powertrain vehicles include the work of Lee et al. [9] which focused on modeling of the electrified power train. Later studies in [10,11,12] introduced simplified models for prediction of lifecycle cost and environmental impact. Optimization of usage, charging patterns and infrastructure layout were examined in [13,14,15,16,17]. Because the driving conditions can have significant effect on lifecycle economics and GHG emissions, detailed models of GHG performance were considered for different standard drive cycles [18,19,20]. Previous work by the authors [21] included large-scale simulations to estimate the energy consumption for various single-energy-input vehicle models (i.e CVs, HEVs, and BEVs) for real driving patterns encompassing all the speed traces of recorded vehicle trips in the California Household Travel Survey (CHTS) data set [22]. However, the simulations for PHEV models were not included, since examining the equivalent GHG for different charging patterns and grid greenness would require multiple repetitions of the large-scale simulations, which the authors deemed prohibitively expensive from a computational resources standpoint. The later sections of this paper propose and validate an “Energy reallocation model”, which provides a much-reduced computational cost in simulating PHEVs under various charging behaviors. Specifically our proposed method requires only a single GHG simulation for any given PHEV model and speed trace, using a fully charged battery at the beginning of each trip. Then, if a different charging behavior needs to be modeled, our method calculates an equivalent amount of gas consumption based on the history of previous trips since the last charging event. This in turn allows for the goal of the work to be realized; simulation of multiple charging behaviors and levels of grid greenness, for different PHEV models.

This paper started with a motivation and brief review of relevant work in the literature. The rest of the manuscript is organized as follows: Next section presents an overview of the proposed energy reallocation model for estimation of equivalent GHG of PHEVs. Models for commonly-expected charging behaviors are presented next, which is followed by a verification study of the proposed model. Lastly, the GHG footprint of different range PHEVs for different charging behaviors and levels of grid greenness is briefly examined.

PHEV EQUIVALENT GHG EMISSIONS MODEL

Large-scale simulations of 18 different vehicle models were conducted by the authors in previous work [21] using the publicly available software: Future Automotive Systems Technology Simulator (FASTSim), which is developed and maintained by NREL [23]. The simulations included all of the available vehicle trip traces in CHTS data set (65,652 trips by 2910 vehicles), and were conducted on a Windows Azure Platform [24]. Computational resources utilized were approx. 5400 CPU-hours (fifteen parallel processes running for approx. two weeks). Additional models are

now considered for PHEVs (as pre-modeled in FASTSim) with nominal all-electric range of 10 and 40 miles, which will be termed PHEV10 and PHEV40 respectively.

Our simulations show that—at levels of GHG-equivalent per kWh corresponding to US national grid average or lower— a PHEV that starts each trip with a fully-charged battery obtains its lower bound for the minimum attainable GHG for that trip. However, experience and intuition suggest that a full charge before every trip is not typical for many PHEV drivers. Without our proposed energy reallocation model, in order to obtain more realistic estimates of the GHG emissions, FASTSim simulations would need to be repeated at different states of the battery at the beginning of each trip depending on the battery state in the previous trip, and whether or not the vehicle performed any charging in between the trips. Computational resources required to examine multiple driving and charging patterns using such an approach can be very large. Instead, a simplified model is proposed by the authors. This model, which is validated in a later section of the paper, leverages the fact that, whether delivered by an electric or gas powertrain, the energy delivered to the wheels of the vehicle for a specific portion of a trip is nearly the same. As such, we present a vehicle-specific process whereby the electric energy consumed for a given portion of a trip is converted into consumed gasoline. The amount converted depends on the amount of starting battery state-of-charge, based on a considered charging pattern and the preceding trips.

Our energy reallocation model is now explained in detail. For any given vehicle i and trip j , FASTSim calculates and outputs estimates of the amounts of gas (G_{ij} , gal) and electric energy (E_{ij} , kWh) that were consumed during the trip. Thus, the equivalent GHG emissions (measured in kg-CO₂ equivalent) for the trip (Γ_{ij}) is calculated as:

$$\Gamma_{ij} = \alpha_G G_{ij} + \alpha_E E_{ij} \quad (1)$$

And equivalent GHG per mile (γ_{ij}) is then calculated by dividing by the trip length:

$$\gamma_{ij} = \frac{\Gamma_{ij}}{d_j} \quad (2)$$

where:

α_G is the well-to-tank equivalent GHG for extraction, refinement and delivery, plus the GHG released during combustion per gallon of gas

α_E is the equivalent GHG per kWh of electric energy (including battery charging efficiency)

d_j is the trip length

It should be noted that the GHG equivalent per gallon of gas generally doesn't change much; for the US a value α_G of 11.893 kg-CO₂/gal is used, which corresponds to the sum of US average well to tank [25], plus carbon content of typical gasoline (8.89

kg-CO₂/gal), as per [26]. On the other hand, equivalent GHG emissions created to produce a kWh of electric energy can vary quite a bit depending on location and time of the day.

With subscript i (representing a given vehicle) not shown in order to reduce clutter, the calculation is performed as:

$$S_{o,j} = f_c(T_{f,j-1}, T_{o,j}, S_{f,j-1}) \quad (3)$$

$$E_{c,j} = \max(0, E_j - S_{o,j} C_{\max}) \quad (4)$$

$$\tilde{E}_j = E_j - E_{c,j} \quad (5)$$

$$\tilde{G}_j = G_j + \beta E_{c,j} \quad (6)$$

$$\tilde{\Gamma}_{ij} = \alpha_G \tilde{G}_{ij} + \alpha_E \tilde{E}_{ij} \quad (7)$$

$$S_{f,j} = \frac{S_{o,j} C_{\max} - \tilde{E}_j}{C_{\max}} \quad (8)$$

where:

$S_{f,j-1}$, $S_{o,j}$, $S_{f,j}$ are respectively the battery state of charge at the end of the previous trip ($j-1$), beginning of current trip (j), and end of the current trip. The state of charge can take any value between 0 and 1, with 1 implying that the battery is charged to its maximum charging limit, and 0 implies that the battery is at the charge sustain level

f_c is a functional representation of the charging model.

$T_{f,j-1}$, $T_{o,j}$ are the date/time at the end of the previous trip and beginning of current trip, respectively

$C_{\max}$ is the battery charging capacity between maximum charging limit and charge sustaining level

$E_{c,j}$ is the amount of electric energy (kWh) that would be re-allocated to an equivalent amount of gas

E_j , G_j are respectively the amounts of electric energy (kWh) and gas (gal) used in the trip if it had been started with the battery at maximum state of charge

$\tilde{E}_j$, $\tilde{G}_j$ are respectively the corrected amounts of electric energy (kWh) and gas (gal) used in the trip

$\tilde{\Gamma}_{ij}$ is the corrected estimate of GHG (kg-CO₂) for the trip

β is the conversion constant from electrical energy that would have been used by the vehicle (if its trip had started with battery at maximum state of charge) to equivalent gas

Equation 3 determines the initial state of charge of the battery at the beginning of the trip j , which is a function of the charging behavior, and will be discussed in more detail in the next section. Eqn. 4 then checks if the amount of electric energy consumed in the trip (simulated starting at maximum charge) exceeds the amount available (considering the correct state of charge at the beginning of the trip), then determines (if any) the amount that should be re-allocated to an equivalent amount of gas. Eqns. 5, 6, 7 then respectively calculate the corrected amounts of electric energy, gas and GHG emissions. Lastly, Eqn. 8 calculates the battery state of charge at the end of the trip (so it can be used in estimating the starting state of charge for next trip).

It should be noted that primary assumptions to enable the calculation of equivalent amount of gas via the simple formula in Eqn. 6 are: i) The power management of the PHEV attempts to keep both the internal combustion engine and/or electric motor running at as close as possible to their maximum efficiency operational point (torque and rotational speed), and ii) efficiency of the electric motor does not change much over a relatively broad range of operation. If the assumptions hold true then electrical energy can be converted to equivalent gas consumption (or vice versa) with reasonable approximation accuracy, irrespective of the speed profile of the vehicle trip. Validity of these assumptions will be examined for the considered PHEV10 and PHEV40 models, after the next section introduces some charging behavior models.

CHARGING BEHAVIOR MODELS

Charging behaviors can vary significantly between different owners of vehicles. Unfortunately, to the best of the authors' knowledge, neither CHTS nor any other publicly-available data set has detailed information of charging events by PHEVs. Thus it is important to consider multiple charging scenario models. This section presents models for calculating $S_{o,j}$ in Eqn. 3 for extreme max/min scenarios, as well as some intermediate ones.

Fully Charged before Every Trip

In this scenario, it is assumed that the PHEV battery is always charged to its maximum charge limit before every trip. Though this scenario is largely unrealistic, it represents a lower bound (when the grid is sufficiently green) for minimum attainable GHG footprint of the vehicle. For this scenario, Eqn. 3 becomes:

$$S_{o,j} = 1 \quad (9)$$

Never Charge

In this scenario, as the name implies, the PHEV is being used as if it was a regular gas hybrid. Though the scenario also appears unrealistic for most owners who likely paid more to purchase the vehicle (compared to a regular hybrid) then not use its plug-in capability, some reports [27] indicate that few owners choose to do so.