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A Study on the Impact of Driving in Charge Mode on Well-to-Wheels Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles

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Abstract

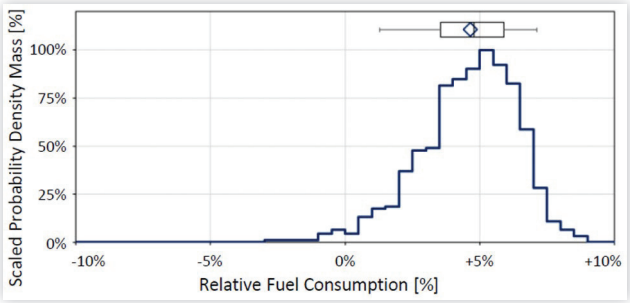
Plug-in hybrid electric vehicles (PHEVs) combine some of the attractive traits of both fully electric vehicles (EVs) and non-plug-in hybrid vehicles (HVs). EV traits shared by PHEVs include the capability to charge the battery via electricity from the grid while the vehicle is parked and the ability to drive an appreciable distance without having to turn the engine on, in what is known as charge depletion mode. HV traits shared by PHEVs include the ability to use the engine to maintain the state of charge (SOC) of the batteries within certain limits, in what is known as charge sustaining mode. Charge sustaining mode allows a PHEV to drive long distances without requiring stops for electrical charging (unlike EVs) but comes at the trade-off that fuel needs to be used. A mode of driving that is unique to PHEVs (though not seeing much real-world use at present day), referred to as "Charge Mode is when the engine is operated at a higher power output than the average vehicle power demand, thereby increasing the SOC of the battery (to allow for electric drive in a subsequent trip section) at the expense of more gas usage while increasing the SOC. This study utilizes an open-source fuel economy simulation software along with a model of Prius Prime (25-mile electric range PHEV) that has been calibrated via on-road testing data to examine the effect of engaging charging mode on the fuel consumption within virtual trips towards a geo-fenced area. Simulation results are in general agreement with on-road testing that the average net impact on fuel consumption is less than 5%.

Introduction

Electric drive vehicles have undergone many improvements since their first introduction nearly two decades ago. Loosely defined as a vehicle whose powertrain includes an electric motor capable of supplying a significant portion of the propulsion power, US Department of Energy (DOE) originally recognized electric drive vehicles in [1] as including hybrid vehicles (HVs), plug-in electric hybrid vehicles (PHEVs) and electric (only) vehicles (EVs). HVs include an internal combustion engine (ICE), similar to conventional vehicles, but also a (relatively small) battery and one or more electric motors that can supplement the engine power and/or recapture energy via regenerative braking. For the most part, aside from being currently somewhat more expensive in initial cost and less expensive in running cost, HVs usability is similar to conventional vehicles, which may have contributed to relatively fast pickup by the market; reaching sales volume more than 300 thousand units per year in the US between 2000 and 2007 according to [2]. EVs on the other hand, represent the other end of the spectrum in terms of a different ownership and usability experience. Not only do EV owners need to charge their vehicles (usually at home overnight), but also they need to plan their routes carefully when undergoing long-distance travel, since stops for recharging take a significantly longer time (even with fast chargers) than gasoline refueling. Further, fast charging infrastructure is currently less abundant than gas stations. Another consideration by EV drivers is making allowance for variations in expected achievable driving range, a behavior known as "range anxiety" [3, 4]. Though challenges exist for EV adoption, when the electricity source is low carbon (such as an electric grid with high fraction of renewable sources), EVs have the capability for large reduction in greenhouse gas (GHG) emissions during the use phase of the vehicle (also known as "Well-to-Wheels" GHG).

PHEVs combine some of the attractive traits of both EVs and HVs, most prominent of which are: i) the capability for charging the battery from the grid and driving a significant portion of total distance on electric energy, in what is known as "Charge Depletion Mode", and ii) fewer issues with range anxiety since the vehicle can continue driving if the battery runs out, and iii) capability for long distance travel without requiring stops for electrical charging, via switching to "Charge Sustaining Mode", during-which fuel is utilized to maintain the battery state of charge (SOC), similar to how HV would drive. Given a very low-carbon content electric grid, PHEVs GHG reduction ought to fall somewhere between that of HVs and BEVs [5] but is also dependent on other details of

FIGURE 6 Statistical distributions of relative fuel consumption in subsections of the trip corresponding to charging while driving sub-section, plus charge depletion sub-section.



For this purpose, we extract the fuel consumption information from the simulations of all 774 synthetic drive cycles, at point of starting the driving in charge mode until end of the electric drive (analogous to driving between point B to point D in Fig. 1a) for Charge Mode scenario, and we compare the fuel consumption between the same points in the trips for Hybrid Mode scenario. The resulting distribution for relative fuel consumption is shown in Fig. 6, which has a non-outlier average value of +4.7%. While this value may be somewhat higher than the on-road test, possible reason for the difference is that for repeatability reasons, the on-road tests were conducted with the vehicle moving at near-steady speed (with cruise control engaged), where as the synthetic drive cycles included variations of real-world driving (including acceleration and deceleration) within the exurban part of the trip while driving in charge mode is engaged.

Conclusion & Future Work

This work presented a summary of on-road testing as well as a simulation-based study that aims to gauge the effect of engaging charge mode of PHEVs due to driving towards a geo-fenced area with enforced electric-only driving. Results of the simulation study and the on-road testing appear to have good agreement that charge-mode increases fuel consumption (and/or GHG emissions) by less than 5% compared to hybrid drive mode. Future extensions of this work may include additional on-road testing to further increase reliability of the results, as well as simulation studies that utilize models of longer-range PHEVs.

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