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 onsideration 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) less issues with range anxiety since the vehicle will 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 the powertrain architecture and the all-electric driving range. PHEVs real-world performance can also be a strong function of the owner' usage in terms of charging frequency, driving distances and style [6].

"Driving in charging mode" is a rather unique mode of driving in PHEVs. It is somewhat similar to charge sustaining mode (in that the engine is on and utilizing fuel), but the operation of the engine is kept at a level the provides more power than needed for moving the vehicle plus auxiliary demands, resulting in increasing the battery SOC over time. Driving in charging mode increases fuel consumption (compared to charge sustaining mode) while SOC is increasing, but it enables a subsequent electric drive during-which no additional GHG is created. However, some concerns were raised in [7] about driving in charging mode resulting in "significant" increase in GHG emissions, on the order of 50% more. And though at present day, charging mode isn't frequently engaged by most PHEV owners, but with several urban centers around the world planning for geo-fenced electric-driving only areas, charging mode may see more usage by PHEV drivers on their way towards such geo-fenced areas. To further investigate this issue, this paper conducts both on-road testing as well as fuel economy simulations for a model of a Prius Prime PHEV. Though several fuel economy simulation software tools exist, the one chosen in this paper is FASTSim [8], which is one of the software tools endorsed by US DOE [9] and is free open source to the public.

This paper starts with a brief overview and motivation for the research, followed by a brief summary of related work. The rest of the manuscript is organized as follows: next section presents a summary of real-world testing of a Prius-Prime vehicle under (as

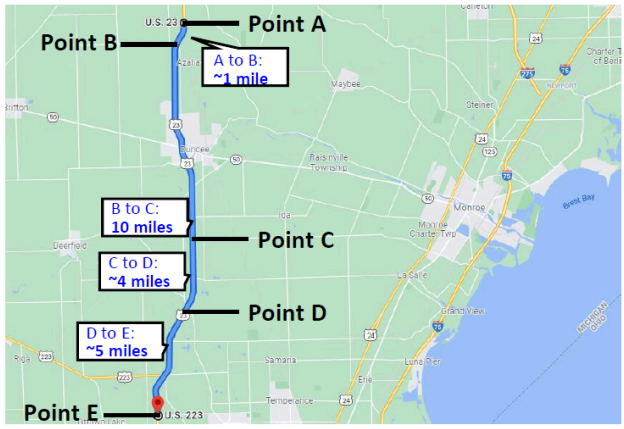
much as possible) controlled conditions for driving while charging and charge sustaining modes. The section that follows presents FASTSim simulations of a PHEV driving towards a virtual geo-fenced area, where electric-only drive is mandated. Discussion of simulation results follows before the manuscript concludes with a summary and future work.

Real-World Testing of Charge Mode

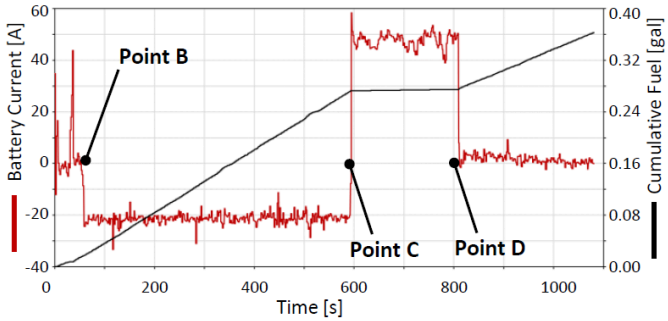
One Prius Prime vehicle was instrumented with an OBD logging device type OBDLink MX+ [10] that was Bluetooth-paired with a smart phone for recording various data channels of interest, including: GPS coordinates and altitude, vehicle speed, battery voltage and current, engine rpm, mass air flow rate and fuel trim, which are automatically processed by the device software to estimate fuel consumption. Data logging occurred at relatively high frequency but at a variable rate averaging about 4Hz (i.e. 4-5 data points per second). All test drives were conducted on a relatively flat (only 20ft difference in altitude between start and end points) ~20-mile stretch of highway US-23 in Michigan, as shown in Fig. 1.a. Two types of driving tests were conducted (in both of which the test begins with a depleted battery, i.e., charge sustaining mode), described as follows:

- Test drive including a sub-section driving with charge mode, which, going forward, we simply refer to as "*Charge Mode Test*". This test drive starts the OBD recording at point A in Fig. 1.a with the vehicle in charge sustaining mode. After approx. 1 mile (point B in Fig. 1.a) manually requests battery charging by holding down a specific button on the vehicle's dashboard. The driver confirms the vehicle is in charge mode by observing a specific dashboard indicator. (Charge Mode is also evident in the OBD recording.) This Charge Mode Test continues for the next 10 miles (until point C in Fig. 1.a), at which point the driver manually disables charge mode. The vehicle automatically switches to charge depletion mode (electric drive) until the charge accumulated between points B and C runs out. This happens at approx. point D in Fig. 1.a, where the vehicle automatically switches back to charge sustaining mode. The data logging then stops at point E in Fig. 1.a, which is at 20 miles since trip start. Thus, for 50% of the test, the vehicle is driving in charge mode. This test sequence also may start at the southern-most point, driving north, in which the same ordered sequence of driving is maintained (1 mile charge sustaining, 10 miles driving in charge mode, ~4 miles charge depletion, ~5 miles charge sustaining).
- Test drive performed entirely (from start to finish) with the vehicle in charge sustaining mode, which we refer to as "*Charge Sustaining Test*"

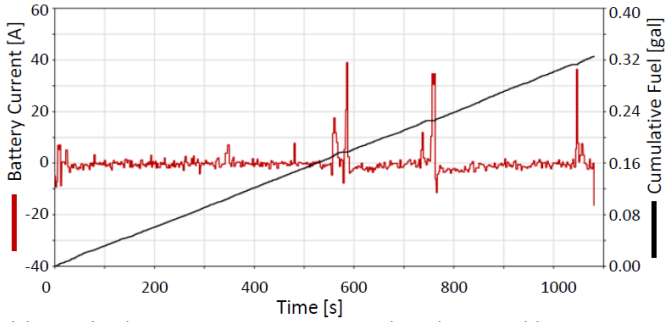
For the most part of every conducted test drive, the vehicle was travelling at a steady speed between 65 to 67 mph, with cruise control engaged. Example logs of the battery current (negative value implies charging) and fuel amount during one sample trip for Charge Mode Test and one sample trip for Charge Sustaining Test are shown in Fig. 1.b and Fig. 1.c, respectively. Each day of testing included a pair of test drives, one from North to South (N-S), followed immediately by a test drive from South to North (S-N). In half of the testing days, the first (N-S) trip would be a "Charge Mode Test", followed by (S-N) trip performing the "Charge Sustaining Test". On the other half of testing days, the first (N-S) trip would be a "Charge Sustaining Test", followed by a (S-N) "Charge Mode Test". This pattern attempts to mitigate some of the uncontrollable environmental factors between the two tests conducted each testing day, and we achieved a balanced number (N-S) and (S-N) test drives. The recorded amounts of fuel consumption for each test are listed in Table 1.



(a) Route Location and Sub-Sections (North to South)



(b) Sample Charge Mode Test Drive (North to South)



(c) Sample Charge Sustaining Test Drive (South to North)

Figure 1. Testing route and sample test drives.

Table 1. Real-world fuel consumption by test vehicle for conducted tests

Day #	Charge Sustaining Test (N-S)	Charge Sustaining Test (S-N)	Charge Mode Test (N-S)	Charge Mode Test (S-N)
1	0.346			0.303
2		0.326	0.363	
3		0.319	0.357	
4	0.331			0.317

Average Trip Fuel [gal]	**0.330**	**0.335**
Difference [%]		**+1.35%**

From a conceptual standpoint, it may be understandable that engaging charge mode could increase the overall fuel consumption. This is because the additional power demand in the section between points B and C could restrict the engine control logic from being able to operate the engine at its most efficient point. However, the average difference from the results in Table 1 appears to be only 1.35%, though this result is yet to be further affirmed via conducting more test drives in future work. Despite the small sample size, it is apparent that whether charge mode was engaged is not the only factor affecting fuel consumption. For example, (N-S) drive seems to consistently have higher fuel consumption than (S-N). In order to assess the effect of charge mode on PHEV driving to a geo-fence area (where electric-only drive is mandated), the next section resorts to more ideally controlled conditions via simulations.

Virtual Geo-Fence Simulation

Drive Cycles Synthesis

In past work by the authors [5, 11], the advantages of utilizing real-world driving patterns (as opposed to standard dynamometer drive cycles) for fuel economy simulations of various powertrains have been emphasized. In this paper, we employ a similar approach via utilizing real-world trips from CHTS dataset [12] to construct a synthetic drive cycles for "drive into geo-fence" and "drive in and out of geo-fence" datasets as follows:

1. All trips in CHTS dataset with travel distance between 50 and 80 miles (perceived to include exurban-like driving) are extracted and set as the beginning part of a drive towards a geo-fence area
2. All trips in CHTS dataset with travel distance less than 5 miles (perceived to be mostly urban-like driving) are extracted
3. Starting from the first trip in the set of short trips of step 2, trips are stitched together in groups to create composite trips, with the composite trip lengths between 20 to 25 miles
4. Each exurban trip from step 1 is amended with one composite trip from step 3 – this completes a "drive into geo-fence" synthetic drive cycle
5. For "drive in and out of geo-fence" synthetic drive cycles, the composite trip from step 4 is amended with another copy of the exurban trip from step 1, emulating a drive to return home

A total of 774 synthetic drive cycles were created via this procedure for each of the two intended datasets. To allow replication of further results in this paper, copies of both datasets have been placed in a publicly accessible shared storage [13].

Sample Single-Trip Simulations

The public version of CHTS dataset does not include road slope information. As such, we utilize a FASTSim vehicle model for Prius Prime that has been calibrated to provide realistic energy/fuel consumption without road slope information. Details about the calibration may be found in [14], and a listing of the FASTSim model parameters is available on a publicly accessible shared storage in [15]. The version of FASTSim utilized in current simulations is based on the Java implementation [16], which follows the code flow in the Excel and python versions maintained by NREL [17], but applies a fork to the main code [16] that implements more options for the hybrid drive control logic. The updated code for hybrid control logic allows for setting a target for the battery state of charge (SOC) as function of the vehicle position (in miles since trip start), thereby enabling, among other things, the modeling of charge mode. In this sub-section, we show an example set of simulations (Fig. 2) for the first trip in the "drive into geo-fence" dataset.

Fig. 2.a shows the vehicle speed (in miles per hour) versus trip time, while Fig. 2.b shows the ensuing distance travelled (in miles) since start of the trip. Total time of the trip is about 7800 seconds (which is almost two hours and ten minutes). For convenience, the horizontal axis at the bottom of Fig. 2 has been labelled in seconds and hours, as well as miles since start of the trip. We note that the exurban-like part of the trip (from the start of the trip until approx. 4000s) occurs at much higher average speed than the remaining urban-like part of the trip. For this trip, we consider four simulation scenarios:

- The first scenario considered is one where the PHEV starts the trip with a "near-full" battery and the electric-drive geo-fence does not exist. In this scenario, the PHEV will start in charge depletion mode (electric drive) until the battery runs out, then it automatically switches to charge sustaining mode (consumes gasoline) until the end of the trip. For short notation, we refer to this as "*Normal Mode*". The battery SOC for this scenario is shown as a green colored curve in Fig. 2.c. As a note, what Fig. 2.c shows is the "relative" SOC between the minimum and maximum of the usable battery limits (which is different/less than rated battery capacity). Thus, a value of 0% implies the lower SOC limit, while 100% implies the maximum SOC limit. In this example, relative SOC of 96% is considered "near-full" while relative SOC of 3% is considered "near-empty".
- In the second scenario, the PHEV starts with a near-full battery but plans ahead for the geo-fence area, by going into charge sustaining mode at the start of the trip (as shown in the lighter blue curve in Fig. 2.c) until just before the geo-fence area, where it switches to charge depletion mode for electric-only drive. In this example, the switching happens at the last 24 miles of the trip (shorter distance than the rated range of Prius Prime, which is 25 miles). As a notation, we refer to this scenario as "*Hold Mode*".
- In the third scenario, we consider if the PHEV had started the trip with a near-empty battery and the geo-fence didn't exist. As such the PHEV goes through the whole trip while it is in charge sustaining mode (shown in an orange colored curve in Fig. 2.c). As a notation, we refer to this scenario as "*Hybrid Mode*" since it resembles how HV would have done the trip.
- In the fourth scenario, we consider the PHEV starting the trip with near-empty battery but plans for the geo-fence area. This is done by aiming to reach near-full battery (and then hold the SOC level) two miles before beginning of the electric-only drive. Charging of the battery happens via charge mode while driving throughout 40 miles of the exurban part of the trip. Though this scenario involves multiple modes of driving (charge sustaining at low SOC, charge mode, charge sustaining at high SOC, then charge depletion), for short notation, we simply refer to it as "*Charge Mode*", as shown in the dark blue color curve in Fig. 2.c.

As a note, the rate of charging the battery during charge mode can have implications on how efficient the engine is able to operate. The

charge rate considered in this simulation (40 miles to charge up for 24 electric miles) is somewhat more aggressive than one observed during the on-road tests of the Prius Prime (Fig. 1 indicates it took approx. 2.5 times the electric drive distance in charge mode to accumulate enough charge), but this is intended for illustration only. In the next subsection, we match the charging rate to the one observed in the real-world.

Fig. 2.d shows the simulated engine output power (in kilowatts) for the four scenarios. In the scenario for Normal Mode (green curve in Fig. 2.d), the engine does not turn on until the battery is near-empty, and then it follows a nearly identical trajectory as that of Hold Mode scenario (lighter blue curve in Fig. 2.d) for the exurban part of the trip. Both Normal Mode and Hybrid mode (orange curve in Fig. 2.d) scenarios continue to operate the engine as needed within the urban part of the trip (since they did not consider the existence of the geo-fence), and finish the trip with relative SOC at 3%. On the other hand, both Hold Mode and Charge Mode (dark blue curve in Fig. 2.d) scenarios successfully complete the last 24 miles of the trip in electric-only drive (with the engine completely off), and finish the trip relative SOC at 19%. The ensuing fuel consumption for each of the considered scenarios are shown in Fig. 2.e. Conforming with the engine power plots, fuel consumption does not begin in the Normal Mode scenario (green curve in Fig. 2.e) until the battery is depleted. Fuel consumption in all the other scenarios in Fig. 2.e follows along the same trajectory until about 2000s into the trip (all three scenarios are operating in charge sustaining mode within this section of the trip, despite there being differences in the SOC level between Charge Hold mode and the two other scenarios). When charge mode is engaged for the Charge Mode scenario (dark blue curve in Fig. 2.e) at approx. 2000s into the trip, there is a noticeable increase in the rate of fuel consumption until the battery SOC reached the target charge level. Upon reaching the electric drive section at approx. 4230s from start of the trip, Hold Mode and Charge Mode scenarios no longer consume fuel in Fig. 2.e, consistent with the engine being turned off in Fig. 2.d. At the end of the trip, the total amount of fuel consumption in Charge Mode scenario is slightly more than Hybrid Mode scenario (1.93 gal compared to 1.75 gal), while the total amount of fuel consumption in Hold Mode scenario is about the same as Normal Mode scenario (1.40 gal compared to 1.36 gal).

One notable observation from Fig. 2, is how different driving patterns affect electric energy and fuel consumption within different parts of the trip. The higher speed of driving in the exurban part of the trip depletes the battery rather quickly from 96% relative SOC to engine-on within only 21.7 miles (as opposed to nominal electric range of 25 miles) in the Normal Mode scenario, while the Hold Mode and Charge Mode scenarios are able to complete 24 miles of lower-speed urban-like driving with the battery relative SOC going from 96% to 19% (i.e. there was spare electric range in this sample simulation).

When attempting to study the effect of geo-fence areas on the overall GHG emissions, there are a number of issues to consider. The first of which, is setting a reference performance for the comparison. In the authors' option, the Normal Mode scenario is a reasonable reference for Hold Mode scenario (since both scenarios start with a near-full

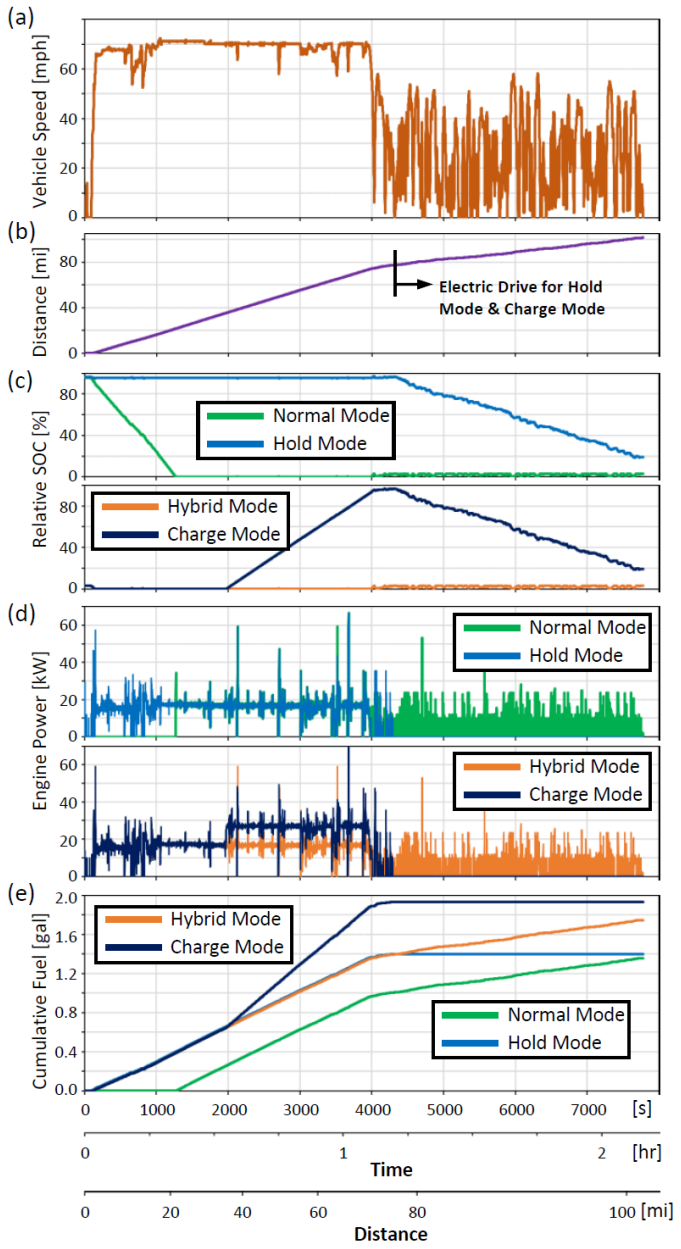


Figure 2. Simulation results for sample synthetic drive cycle.

battery), while the reasonable reference for Charge Mode scenario is the Hybrid Mode scenario (since both scenarios start with near-empty battery). One may consider an alternative scenario where the PHEV starts with a near-full battery, drives in charge depletion mode until near-empty battery then engages charge mode to re-charge the battery before a geo-fence area. However, such a scenario would be inferior to Hold Mode for no other reason aside from inappropriate planning, and thus was not considered in this paper.

Another issue when considering overall GHG emissions, is accounting for the equivalent GHG emissions for charging the vehicle from the grid. While the electric grid in many locations around the world have high fraction of renewables/low-carbon sources, none have reached zero GHG yet. Thus, when studying Hold Mode (with Normal Mode as the reference), it is important to conduct

a sensitivity/parametric study with various electric grid GHG intensities. However, since the focus of this paper is on Charge Mode (with Hybrid Mode as the reference), the amount of GHG emissions will be proportional to the amount of fuel (since neither Charge Mode nor Hybrid Mode are utilizing electricity from the grid) *provided* SOC at the end of the trip is similar. Thus, in the aggregate analysis of next sub-section, we utilize the "drive in and out of geo-fence" dataset, where the vehicle finishes the trip in charge sustaining in all four scenarios (SOC returns to low end during the return home trip after the geo-fence for both Charge Hold and Charge Mode scenarios).

Aggregate Simulation Results

In this sub-section, we repeat the FASTSim simulations for each of the four considered scenarios (Normal Mode, Hybrid Mode, Hold Mode and Charge Mode) for all 774 synthetic drive cycles in the "drive in and out of geo-fence" dataset, and the results are examined in aggregate. In these simulations, the Charge Mode scenario is modified such that the electric drive section (representing driving in geo-fence area) is only the last 15 miles of the urban section, and the 40 miles with driving in charging mode only bring up the battery SOC to a level capable of 16 electric miles (emulating the 2.5 ratio between miles in charging mode to miles in charge depletion mode observed in the real-world testing). As a first sanity check for these simulations, we examine the statistical distribution for SOC s at the point of exiting the geo-fence area, for the four considered scenarios, as shown in Fig. 3. The line plot in Fig. 3 shows the scaled (relative to maximum value) probability density mass (PDM), with boxplots on top marking some notable statistical quantities. Left and right limits of the box respectively mark the 25th and 75th percentile values, while the vertical line inside the box marks the median value, while the extension lines mark the 5th and 95th percentiles. The colored diamond shape marks the "non-outlier" average, which is the average value for observations between the 5th and 95th percentiles.

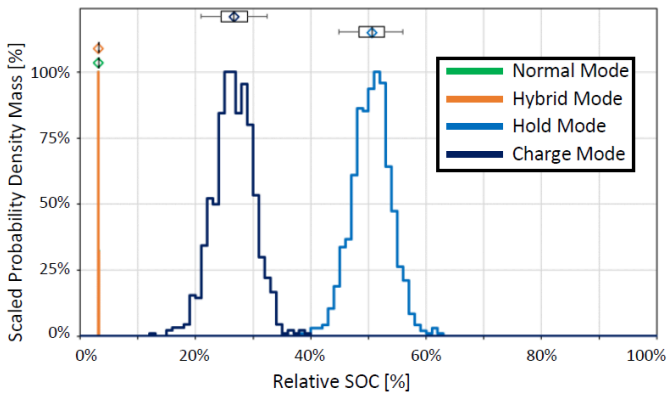


Figure 3. Statistical distributions of relative SOC at the point of exiting the geo-fence.

Some notable observations about Fig. 3 include:

- Normal Mode (green plot in Fig. 3) and Hybrid Mode (orange plot in Fig. 3) scenarios, which were not considering the existence of the geo-fence and were operating in charge sustaining mode throughout it, have very narrow band distribution (visually overlapping) around relative SOC value of 3.1%
- Hold Mode scenario (light blue plot in Fig. 3) has a wider band distribution, centered around 50% value for relative SOC, implying plenty of available battery at the point of exiting the geo-fence. This is understandably because Hold Mode scenario had a near-full battery (with nominal range 25 miles) at the beginning of 15-mile drive in electric mode. With electric urban driving being less energy intense than highway driving, the average remaining relative SOC came to about 50%, as opposed to an expected nominal value of 40% (15 electric miles ought to have consumed 60% of the battery)
- Charge Mode scenario (dark blue plot in Fig. 3) has a similarly wide band distribution as Hold Mode scenario. And while the expectation ought to have been close to empty (since it charged to SOC corresponding to a nominal remaining range of 16 miles prior to 15 miles in charge depletion), the lowest relative SOC observation for this scenario was at about 12%, indicating successful completion of the geo-fence in electric mode for all 774 synthetic drive cycles.

Next, we consider the relative SOC at the end of the trip (after the return home exurban section of the trip), which as shown in Fig. 4 (all four scenarios closely distributed around 3.1%), which in turn serves the purpose of confirming that all four scenarios ended the synthetic drive cycle in charge sustaining mode.

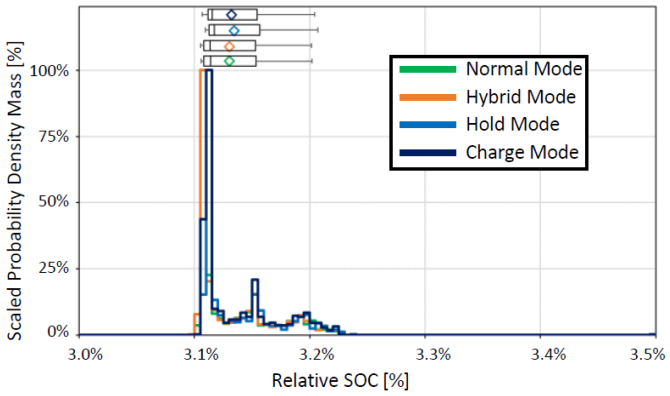


Figure 4. Statistical distributions of relative SOC at end of the trip

With trip ending SOC at charge sustaining mode for all simulated trips in all four scenarios, we then consider the "relative fuel consumption" (ψ), defined as:

$$\psi_i = \frac{gal_{\text{Test Scenario, } i} - gal_{\text{Reference Scenario, } i}}{gal_{\text{Reference Scenario, } i}} \quad (1)$$

where i in Eqn. (1) is an index for the simulated trip (among the 774 synthetic drive cycles) and *gal* is the total amount of fuel for the trip simulation (which FASTSim reports in gallons). As argued in the previous sub-section, we consider Normal Mode as the reference for Hold scenario, while Hybrid Mode is the reference for Charge Mode scenario. Statistical distributions of the relative fuel consumption are shown in Fig. 5. One notable observation about the simulations for Hold Mode scenario (Fig. 5.a), is that it seems to be beneficial compared to Normal Mode scenario in terms of reducing the overall amount of fuel consumption. In other words, as long as one expects to end a trip in charging sustaining model, conserving the battery for

the urban part of the trip (where it is most efficiently used) is a beneficial strategy compared to draining it in highway-like driving. To translate this result for Hold Mode scenario into GHG analysis however, one must also consider the carbon intensity of the electric grid (since both Normal Mode and Hold Mode scenarios start with full battery, equivalent to about ~6.2kWh of grid electricity), which is beyond the scope of current work.

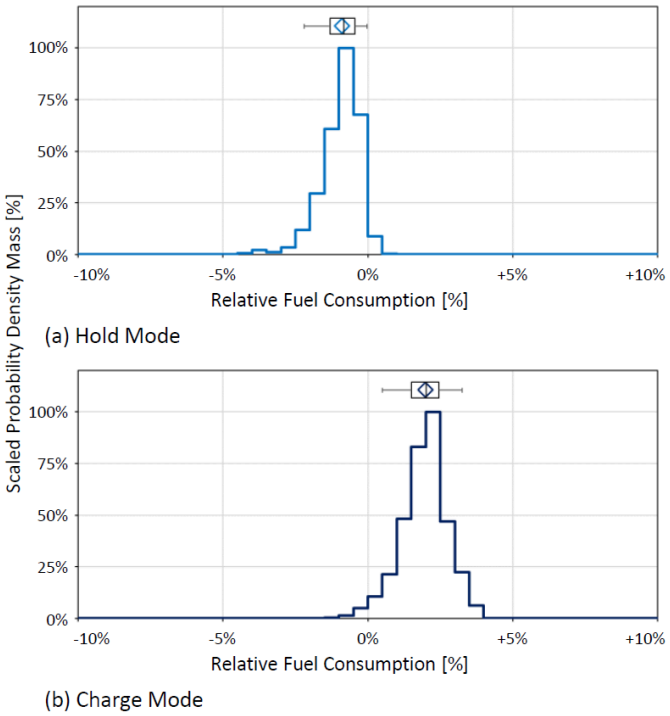


Figure 5. Statistical distributions of relative fuel consumption.

Relative fuel consumption for Charge Mode scenario (Fig. 5.b) shows only a very mild increase in total fuel consumption (compared to Hybrid Mode scenario), with a non-outlier average value of +2%, which at a glance might seem very close to the ~+1.4% value from on-road tests in Table 1. However, we note a difference of "dilution" effect where the on-road tests included a driving in charge mode section for 10 miles out of a total 20-mile trip (50% of the trip in driving while charging mode), while the simulations in this section include driving in charge mode in trips of varying total length between 125 to 185 miles (only 22% to 32% of the trip driving in charge mode). And while it may be arguable that driving in and out of a geo-fence area cannot occur in *only* driving in charge mode, it is still desirable to attempt to isolate a comparison between:

- Driving in charging mode for x miles, followed by charge depletion for y miles (analogous to driving between point B to point D in Fig. 1.a)
- Driving $x + y$ miles in charge sustaining mode

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. 1.a) 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.

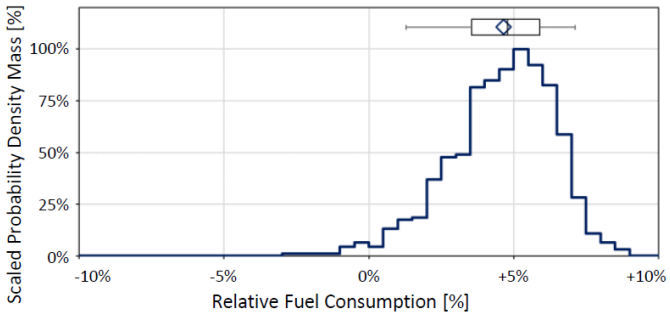


Figure 6. Statistical distributions of relative fuel consumption in subsections of the trip corresponding to charging while driving sub-section, plus charge depletion sub-section.

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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