

1. Hello. My name is Ken Laberteaux. I will present our study, titled A Study on the Impact of Driving in Charge Mode on Well-to-Wheels GHG of Plug-in Hybrid Electric Vehicles. My co-authors are Karim Hamza and Jean Chu. Our employer, Toyota, provided the funding for this research, and has approved its publication. However, no one should misconstrue the following as an official position of our employer.
2. In this presentation, we will be describing both on-road driving tests, as well as simulations, of Plug-in Hybrid Electric Vehicles, or PHEVs. Our agenda is shown here.
3. Let us first review what we mean by a PHEV. PHEVs combine powertrain elements from both a Battery Electric Vehicle, or BEV, as well as a Hybrid Electric Vehicle, or HEV.
4. For most PHEVs, most driving is done in one of two modes. The first mode to discuss is “EV Mode”. In this mode, the engine is off. Driving power is supplied by the electric motor, which converts the energy in the battery into kinetic energy. This kinetic energy is then transferred to the wheels to propel the vehicle. It is also possible for the power flow to be reversed, when the wheels deliver power back to the battery, for example, by using regenerative braking. Thus, the power-flow arrows here are bi-directional. However, as the arrows suggest, energy from the battery to wheel is much greater than the reverse flow. Note that, in EV mode, the gas engine is not running.
5. The second mode that dominates PHEV driving is Hybrid Mode. Generally, this occurs once the State of Charge reaches some lower bound, as decided by the vehicle manufacturer. The engine turns on and begins converting fuel into kinetic energy to propel the vehicle. However, the battery/motor system remains active, performing similar functions to the battery/motor system of Hybrid Electric Vehicles. That can include providing power assist, regenerative braking, and low-speed stop-and-go driving. While some will describe this mode of PHEV driving as “Gas Mode”, or “Engine Mode”, the vast majority of PHEVs have HEV-like operation in this mode, and achieve HEV-levels of fuel efficiency. As such, we believe “HEV mode” is a more accurate description for this PHEV mode of operation. Additionally, the energy efficiency PHEVs is often between that of a BEV and HEV, assuming all have similar size and power.
6. While BEV Mode and HEV Modes are the dominant driving modes, this study focusses on a third mode of PHEVs, which we call “Driving in Charging Mode”. We use this clunky name to emphasize that this is NOT the much more common charging the vehicle from the grid while parked. Instead, this is charging the battery WHILE driving. In this mode, the engine creates even more power than it would in HEV Mode, and that power is split between moving the vehicle AND charging the battery. In all the PHEVs we are aware of, this mode must be explicitly chosen by the driver. In my own personal vehicle, this is done by pressing and holding a button marked “EV/HV”, a process I only discovered by consulting the vehicle manual.

We expect that most PHEV drivers rarely, if ever, do this. But there are some scenarios where it might make sense. For example, consider a driver that wished to drive in a no-engine area later in her trip, even though her car does not have sufficient battery energy to complete the driving in the no-engine area. In such a circumstance, the driver may wish to increase the PHEV’s State-of-Charge before entering the no-engine area.

Obviously, the PHEV will consume more fuel if it is in Driving in Charging Mode instead of HEV Mode. But how much more? And how is this balanced by the subsequent EV Mode driving enabled by Driving in Charging Mode? Answers to these questions are not widely understood.

7. For example, there was a widely-discussed 2020 report by Transport and Environment, titled *Plug-in hybrids: Is Europe heading for a new dieselgate?* It included such quotes as “Plug-in hybrids in new emissions scandal as tests show higher pollution than claimed.”

The report describes testing three PHEVs in on-road conditions, summarized in this figure. This report makes several problematic claims.

For example, in this figure, the report shows the CO₂ generated in on-road driving, showing the PHEV in BEV Mode (in bright blue), HEV Mode (in gray), and Driving in Charging Mode (in dark blue). However, this dark blue line describes only the CO₂ generated when the engine is simultaneously driving the wheels and charging the battery. It does not consider that Driving in Charging Mode enables future BEV Mode driving, where zero-additional CO₂ is emitted.

8. To clarify the actual impact of Driving a PHEV in Charging Mode, we construct the following, two-scenario experiment. In both, the battery starts with a SoC low enough to trigger Charge Sustaining mode. We then measure and compare fuel consumption for driving the next A plus B miles. In Scenario One, the first A miles are Driven in Charging Mode. After A miles, the vehicle is driven in BEV mode until the added electric range generated by the first A miles is exhausted, which marks the end of the B miles. We expect the amount of fuel consumed during the B miles is zero, but we measure it to be certain.

In Scenario Two, we redrive the same trip, but this time the A plus B miles are driven in the default HEV mode.

Our hypothesis is that the fuel consumed for the A plus B miles is roughly the same in both Scenarios.

If our hypothesis is true, we could say that Driving in Charging Mode essentially consumes the fuel needed to drive the B miles earlier than needed, but does NOT increase the amount of fuel needed to drive the final B miles.

Of course, to be completely true, the energy created for the B miles would have to have zero energy lost during its round-trip through the battery, which is impossible. However, as we will see, the loss is small.

9. In our paper, we explore our hypothesis with both on-road driving and simulation studies. Let's first describe the On-Road Driving tests. We use a Model Year 2020 Toyota Prius Prime to drive an approximately 20 mile stretch of highway in Southeast Michigan, as shown by this map. The car is pre-conditioned to start these tests in Charge Sustaining mode.

In all of the following on-road driving tests, the driver uses the cruise control to maintain a speed of 70 miles per hour. While trying to maintain this constant speed, safety requires some speed deviations. However, tests take place in non-peak traffic conditions, and interventions are infrequent.

We start Scenario 1 tests at Point A, driving South in HEV Mode. After a mile of driving, the driver manually starts Driving in Charging Mode at Point B. The vehicle Drives in Charging Mode for 10 miles. Then, at Point C, the driver manually disengages Driving in Charging Mode. The vehicle, now that it has charge in its battery, automatically switches to BEV mode. After approximately 4 miles of electric driving, at Point D, the battery is again exhausted, and the vehicle automatically switches to HEV mode. The driving test ends approximately 5 miles later, at Point E, which is 20 miles away from the starting point A. As measured at the OBD2 port, the fuel consumed between Point A and Point E is recorded.

Scenario 1 tests are also conducted while driving South to North, again starting in HEV Mode, and Driving in Charging Mode triggered by the driver approximately one mile into the test, and

manually turned off after 10 miles in that mode.

As such, we note that in Scenario 1 driving tests, the PHEV spends 50% of its distance Driving in Charging Mode.

10. For Scenario Two tests, the same roadway is used. Again, the vehicle is preconditioned to be in Charge Sustaining mode and drives with the cruise control set at 70 miles per hour, as safety allows. Again, driving speed interventions are few. This test requires no changes in mode, that is, it drives the whole 20 miles in HEV mode. Again, consumed fuel for the 20 mile trip is measured and recorded.

On each testing day, both scenarios are tested, back-to-back. The scenario assigned to the first of the day's two drives is chosen at random, and the return trip tests the other scenario. The first North to South trip is quickly followed by a South to North trip. The same driver drives both ways. The goal of this pattern is to minimize uncontrollable factors, such as the temperature. The only other expected change in vehicle's weight and condition during the two trips is due to changes in fuel levels caused by the test driving.

11. These graphs provide an example of a day's testing. The red line shows the amount of current leaving the traction battery, with negative values associated with battery charging. Charge sustaining driving shows a nominal amperage of zero, with occasional positive peaks primarily attributable to the electric powertrain providing power assist, and negative peaks with regenerative braking. Driving in Charging Mode displays an average negative current, while BEV driving mode displays an average positive current. The black line displays the amount of fuel consumed during the test, and changes as expected.
12. A total of four test days' data was analyzed, with half of the days starting in Scenario 1 for the first North to South driving test. We note some day-to-day variation occurred. Further, each day showed a larger fuel consumption driving North to South than the corresponding return trip, potentially due to a net-elevation difference between the North and South starting points. Having said all of that, the average fuel consumed for both Scenarios One and Two is nearly the same, with the Driving in Charging mode using 1.35 percent more fuel. Meaning that, as we earlier hypothesized, On-road testing finds that Scenarios One and Two consume nearly the same amount of fuel.
13. Now, let's test our hypothesis using simulations. We rely on the open-source fuel-economy simulator from NREL, named FASTSim. We added functionality to FASTSim which allows explicit switching the powertrain within a trip, between BEV mode, HEV mode, and Driving in Charging Mode. This functionality is available in the most-recent versions of FASTSim Java.
14. No longer constrained to our real-world 20 mile loop, we use trips from the California Household Travel Survey for longer-trip simulations. We use the term "Geo-Fenced" to describe an urban portion of a trip that encourages no-engine driving. Several short, mostly urban, stop-and-go CHTS trips are concatenated to create the Geo-Fenced portion of the trip. Preceding the Geo-fenced portion, a single 50-80 mile trip from CHTS is chosen. This same 50-80 mile trip is repeated after the Geo-fenced portion. Using this pattern, we generate 774 synthetic drive cycles.
15. All the simulated tests use the same PHEV vehicle model. Each synthetic drive cycle was simulated four times. For Scenario #1, driving in charging mode is utilized during the first part of the trip. When the Geo-Fenced part of the trip begins, the vehicle switches to BEV mode, and continues until the battery runs out. After that, the vehicle returns to HEV mode for the rest of the trip. We manually confirm that the battery is not exhausted before the Geo-Fenced portion

of the trip is completed. For Scenario #2, the second test with the drive cycle, no powertrain mode switches occur, that is, the whole trip is driven in HEV mode. The estimated fuel consumed for the two tests is then collected and compared. Comparing Scenarios One and Two allows us to test our hypothesis about Driving in Charging Mode.

16. But, we are also interested in another powertrain control strategy, where Driving in Charging Mode is not used. Unlike the first two strategies, we consider a case when the battery is full AND that the driver manually switches the car to HEV mode at the start of the trip. The driver saves the battery until just before he reaches the Geo-Fenced portion of the trip. To contrast with Scenario 3, we have Scenario 4. Scenario 4 is actually how a lot of PHEVs operate today. When they have remaining charge, they use it up immediately, and just drive the rest of the trip in HEV mode. So, comparing Scenarios 3 and 4 will give us some sense of whether the default Scenario 4 is always the best strategy.
17. Here we compare Strategies 1 and 2. The result is very much aligned with our on-road driving tests. We see that, on average, there is an efficiency penalty to charging the battery while driving, but the penalty is small, only 2%.
18. However, if we wish to zoom in, so that we only consider the periods of Driving while Charging Mode, followed by the enabled BEV driving, the penalty is a bit larger. We believe that the extra driving between points A to x, and especially z to D, dilutes the penalty. Still, with an average of less than 5%, we would characterize this penalty acceptable, especially when weighed against the time penalty of stopping to charge before entering the Geo-Fenced part of the trip.
19. Here is our last technical slide. As hinted at before, we see that the decision to hold the battery charge until the Geo-Fenced part of the trip results in a fuel savings. The intuition here is that, in Scenario 3, the driver is holding onto his battery charge until it can make a bigger difference. In this case, the battery is kept for the more urban, stop-and-go driving expected in the Geo-Fenced part of the trip.
20. OK, here are the conclusions. This work focused on a mode of PHEV driving known as Driving in Charging Mode. In this mode of operation, the engine consumes fuel at a higher rate than is necessary to propel the vehicle. This extra energy is stored into the traction battery, thereby increasing the State of Charge. This has the potential to allow the PHEV to return to all-electric driving, even after the battery's range at the start of the trip is exhausted.
We explored Driving in Charging Mode for the Prius Prime, both with on-road measurements and simulations. The former showed less than a 2% increase in fuel consumption. The more expansive simulation study suggests that a 2-5% increase in fuel consumption can be expected. This suggests that Driving in Charging Mode can be viewed as pre-consuming fuel for subsequent driving, and then performing that subsequent driving in all-electric mode, with no additional green house gas released. This operation only-slightly increases overall fuel consumption by a few percent. It further raises interesting possibilities of PHEVs potential operation through multiple no-engine driving zones, pushing the noise and air-quality concerns of fuel consumption away from population centers and other sensitive areas.
We also briefly explored the strategy of waiting to use a PHEV's all-electric driving capability until later into a trip, where the benefits of such no-engine driving within a longer trip can be maximized.
21. Thank you for your interest and attention for our work. Please reach out to us with questions and comments.