California's Advanced Clean Cars Midterm Review

Appendix H:
Plug-in Hybrid Electric Vehicle Emissions Testing

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California Environmental Protection Agency
Air Resources Board

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I. Introduction

The California Air Resources Board (ARB or the Board) directed staff to study in-use data for plug-in hybrid electric vehicles (PHEV), including how these vehicles are driven, charged and their criteria pollutant emission impacts. This appendix will focus on the PHEV testing conducted at ARB to help quantify criteria pollutant emissions under real world driving conditions.

There is a distinct difference among PHEVs in the market today. Most PHEVs are “blended”, the engine can start to help power the vehicle before the battery is fully depleted. These vehicles can have an initial internal combustion engine (ICE) start under high-power demands even when the battery state of charge (SOC) is high. This occurs in cases where, even though the battery has sufficient charge, the electric portion of the drivetrain is not sufficient to meet the desired vehicle torque and the ICE must be started to help meet that immediate torque demand. The other type of PHEV is commonly referred to as “non-blended”, “US06 capable”, or “extended range electric vehicle (EREV)”. This vehicle depletes the battery first, and only when the battery is depleted, turns the ICE on to power the vehicle. The Chevrolet Volt, Toyota Prius Prime, and BMW i3 REX[1] are non-blended PHEVs available today.

PHEVs generally have their operation classified in one of two ways. While the vehicle is operating on electric only power, supplied by the grid, it is considered to be ‘charge depleting’ (CD) operation. When the vehicle is operating on ICE power (gasoline engine), it is considered to be ‘charge sustaining’ (CS) operation. For non-blended PHEVs, the vehicle would normally operate in CD mode until the grid energy is used up/battery depleted and then the vehicle would transition to CS mode. For blended PHEVs, the categorization is more complicated as both grid energy and the ICE can be used simultaneously, during CD operation, to power the vehicle. As noted above, generally this occurs when the vehicle power demand is higher than what the electric only propulsion system can provide and the vehicle starts the engine to combine the electric and ICE power to meet the vehicle demand. As a result, blended PHEV CD operation introduces a unique driving condition where the initial engine start of a trip occurs at a time where there is an immediate need for the engine to provide significant power and torque to help propel the vehicle. Such starts, referred to here as “high-power” cold-starts, can have different emission characteristics relative to the initial engine start of a conventional vehicle which typically occurs with the vehicle stopped, in park/neutral, and with a very low immediate torque demand. Given the unique start-up conditions that blended PHEVs can encounter, staff developed a test program to determine if real world high-power cold-starts may yield higher exhaust emissions than those observed during the regulated emission test cycles which are conducted for vehicle exhaust emission certification.

For this testing, staff evaluated the cold start emissions of several blended PHEVs believed to be representative of currently available PHEVs. The vehicles tested include the 2013 Ford

[1] For purposes of the zero emission vehicle (ZEV) regulation, the BMW i3 REX is categorized as a range extended battery electric vehicle, or BEVx, and earns additional credits relative to the other PHEVs. However, in operation, the vehicle behaves like a non-blended PHEV and will not turn on the ICE until the battery is depleted.

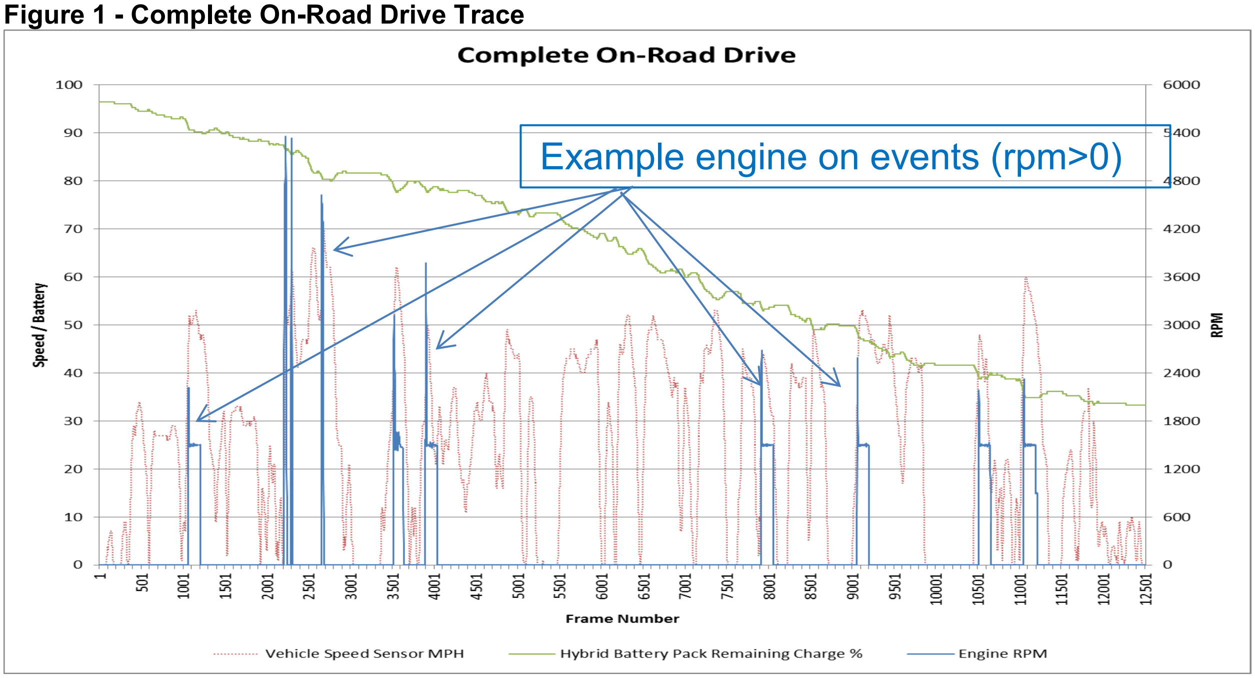
Fusion Energi PHEV, 2013 Toyota Prius PHEV, and a 2016 Hyundai Sonata PHEV. The results of the testing are summarized in this appendix.

II. Developing the Test Cycles

In a conventional vehicle, the cold start emissions are captured in emission certification test cycles. While manufacturers must meet numerous applicable standards over various cycles, only the Federal Test Procedure (FTP) captures cold-start emissions during the test. Other test cycles, like the US06 portion of the supplemental FTP (SFTP) either have the engine already running when the test starts or have the vehicle fully warmed up in advance so the initial engine start is a 'hot' start. The FTP test cycle is designed to represent urban driving and captures a cold start at the beginning of the test cycle. The US06 test cycle captures so-called "off-cycle" emissions resulting from more aggressive driving (from higher speeds and accelerations). Requiring manufacturers to meet standards for both moderate and more aggressive driving conditions helps ensure emissions are well controlled in the full spectrum of driving encountered in the real world. Blended PHEVs, however, provide for a unique condition not fully represented by either the FTP or US06 in cases where the initial engine start occurs while the vehicle is already in motion and in need of a more immediate delivery of power and torque from the engine.

To capture these high-power cold-starts, staff needed to develop unique test cycles. To re-create real world high-power cold-start exhaust emissions in a controlled laboratory environment, staff procured a 2013 Ford Fusion Energi, a blended PHEV, to conduct an on-road drive in El Monte, CA. During the on-road drive, an on-board diagnostics (OBD) scan-tool and laptop was used to record data of different types of driver/vehicle actions that caused the ICE to start during CD operation. The drive trace of the on-road driving is provided in Figure 1 below.

Figure 1 - Complete On-Road Drive Trace



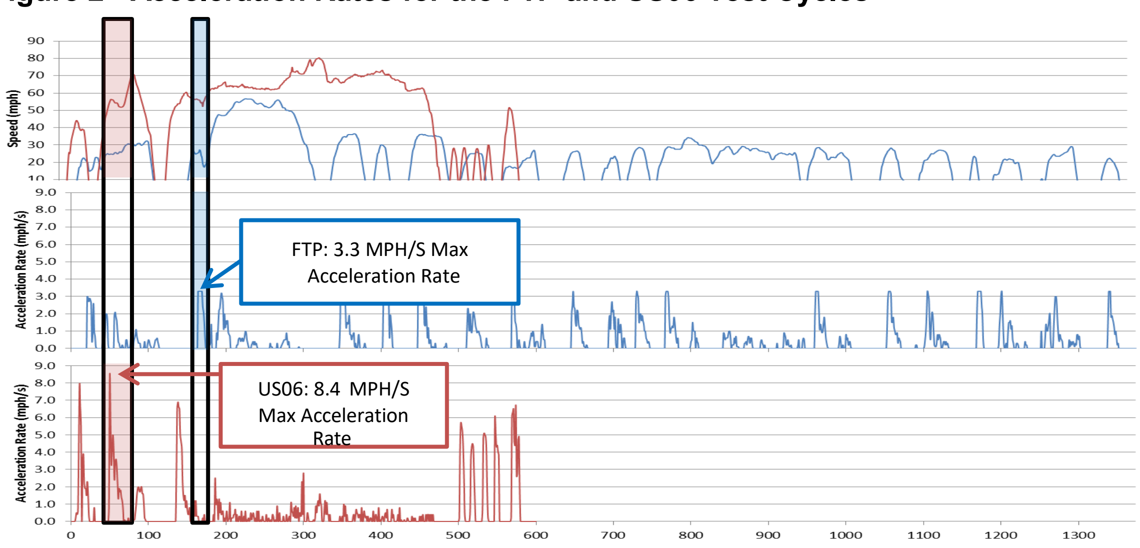
As seen from the trace above, a blended PHEV uses the ICE to supplement battery/electric motor power during CD operation. The blue in Figure 1 is the engine speed (rpm) and each spike in the graph represents an engine start event. The green line is the decreasing SOC of the battery indicating the depletion of grid energy during the drive. After the battery is depleted (not shown in Figure 1), the blended PHEV switches to CS operation where battery SOC is maintained at a certain level while the vehicle is driven and the vehicle behaves like a conventional hybrid with limited electric drive capability. From the trace above, staff developed six acceleration cycles and took the vehicle on the dynamometer to measure emissions. These acceleration cycles are described in Table 1 below:

Table 1 - Acceleration cycles developed for the dynamometer

Acceleration 1	Short freeway on-ramp acceleration.
Acceleration 2	Short freeway on-ramp acceleration combined with a merge and change lanes passing maneuver.
Acceleration 3	Short freeway on-ramp acceleration, brief cruise in slow lane, and then a change lanes passing maneuver.
Acceleration 4	Gradual demand freeway on-ramp acceleration with a merge into traffic.
Acceleration 5	City road (~40mph speed limit) passing maneuver.
Acceleration 6	Right-hand turn, merge into traffic on city road (~45mph speed limit).

The maximum acceleration rates of these six acceleration cycles were compared to the maximum rates during the FTP and US06 test cycles to provide perspective on the aggressiveness of the driving condition. Figure 2 below compares the maximum FTP acceleration rate, 3.3 miles per hour, per second (mph/s) with the maximum acceleration rate of the US06, 8.4 mph/s.

Figure 2 - Acceleration Rates for the FTP and US06 Test Cycles



For the six acceleration cycles developed by staff, the maximum acceleration rates range from 4 mph/s to 7 mph/s. Thus, the acceleration cycles fall in-between the FTP and US06 cycles in terms of acceleration rates. For emission testing purposes, each of the individual acceleration cycles was used as a separate emission test cycle to measure high-power cold-start emissions on a dynamometer with exhaust emission analyzers.

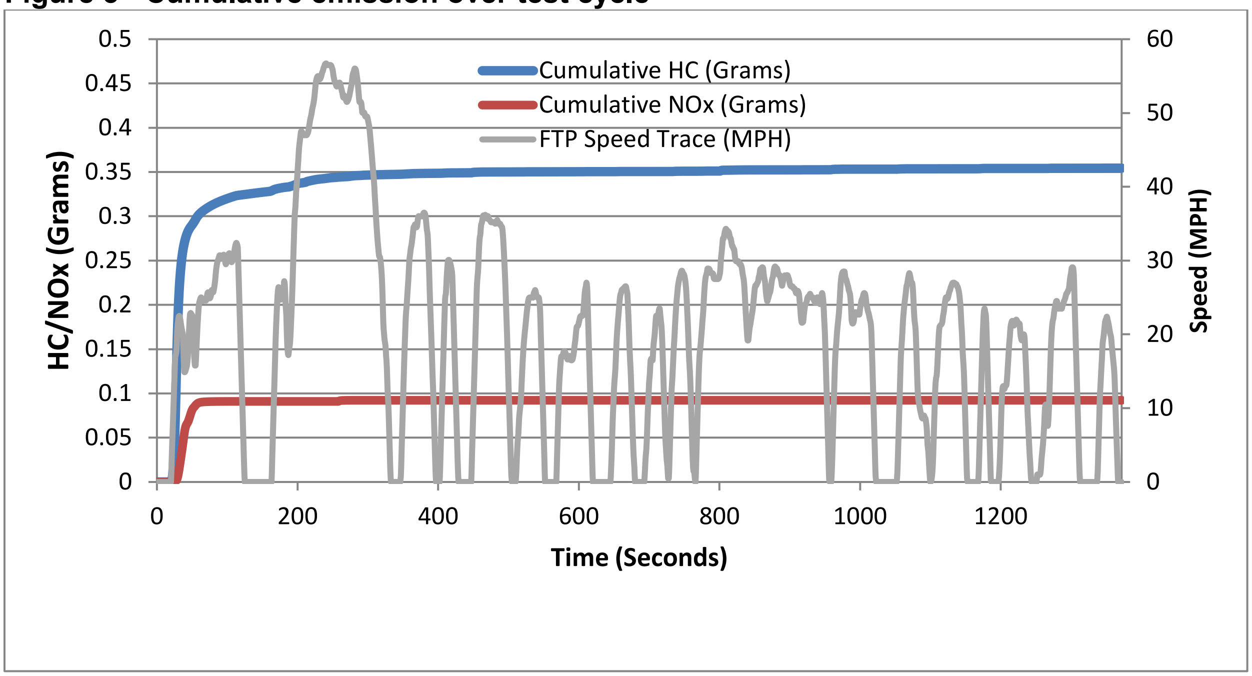
III. Finding a Method to Compare Test Cycle Emissions

The next step was to develop a method to compare real world high-power cold-start emissions to the emission levels required by the emission standards. Staff used the following assumptions:

- All the vehicles tested are certified to the super-ultra-low-emission vehicle (SULEV) emission standard on the FTP.

- The FTP consists of a cold start (bag 1) and transient (bag 2). Repeat testing in the laboratory shows that hydrocarbon (HC) and oxides of nitrogen (NOx) emissions are dominated by the initial engine start. As shown in Figure 3 below for a typical SULEV vehicle, 65-80% of the total HC and NOx emissions for an FTP emission test are emitted in the first 40 seconds of the test. By 120 seconds into the test, over 90-98% of the total emissions are emitted.

Figure 3 - Cumulative emission over test cycle



Using the composite gaseous mass-weighted equation from the official emission test procedures,[2] a theoretical maximum emission level from the cold start of the FTP test was calculated.

[2] Section G.5.5.2.2 (Equation 1) California Exhaust Emission Standards and Test Procedures for 2018 and Subsequent Model Zero-Emission Vehicles and Hybrid Electric Vehicles, (Amended: September 3, 2015).

Equation 1 - Composite Gaseous Mass-Weighted Equation

$$E_{[emission]\_FTPcomp} = 0.43(\frac{M_c}{D_c}) + 0.57(\frac{M_h}{D_h})$$

where:

M_c = mass of emissions from cold test (bag 1)
D_c = distance traveled in cold test (bag 1)
M_h = mass of emissions from hot test (bag 2)
D_h = distance traveled in hot test (bag 2)

To determine the maximum cold-start exhaust emissions that are allowed during a FTP, staff solved for the mass emissions from a cold-start exhaust test, M_c (Equation 2 below) assuming standard distances for the test cycle and the Low Emission Vehicle (LEV) III SULEV standard for the emission level.

Equation 2 – Solve for Mc

$$\frac{E_{[emission]\_FTPcomp} - 0.57(\frac{M_h}{D_h})}{0.43}(D_c) = M_c$$

$E_{[emission]\_FTPcomp}$ = 0.030 grams/mile (LEV III SULEV30 standard)
D_c = 7.45 miles
M_h = 0 grams (assuming there are no emissions from hot test)

Solving for M_c yields 0.520 grams which represents the maximum NMOG+NOx exhaust emissions that are allowed during a FTP cold-start exhaust test (Equation 3).

Equation 3 – Determining maximum NMOG+NOx exhaust emissions

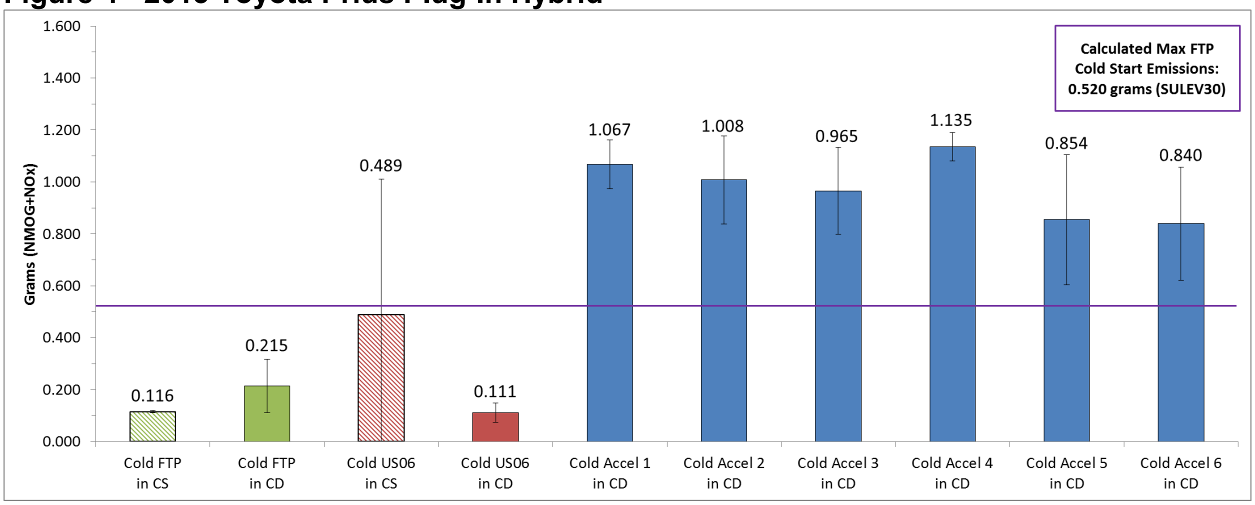
$$\frac{0.030 - 0}{0.43}(7.45) = M_c = 0.520 \text{ grams}$$

By calculating this in a total grams unit, instead of grams/mile like the emission standards, the emissions from the acceleration cycles can then be compared to the 0.520 grams maximum limit from Equation 3 to get a relative sense of the emissions from high-power starts.

IV. Summary of the Results

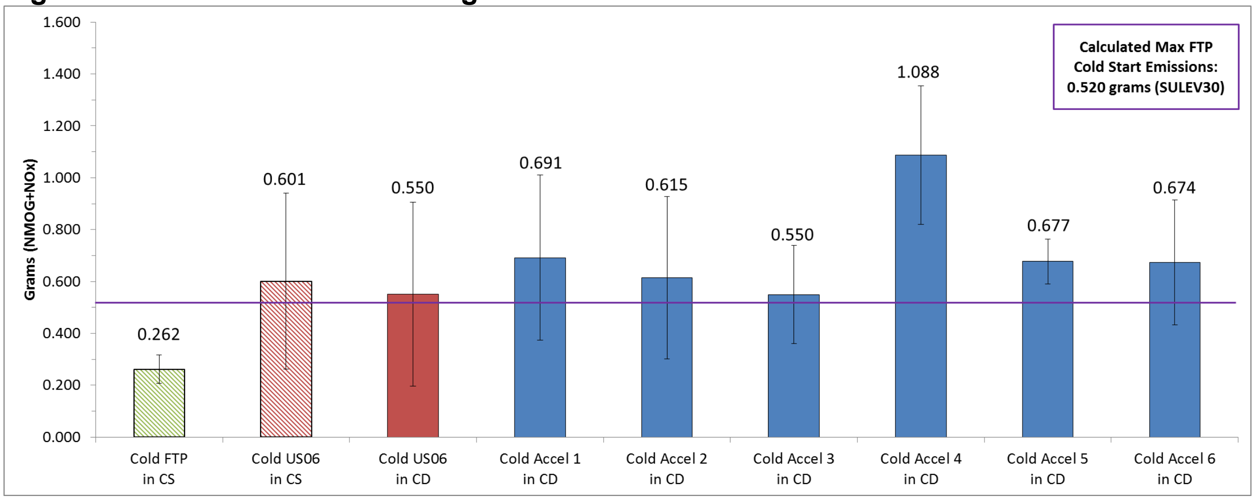
For the laboratory testing portion of the study, in total, three blended PHEVs (2013 Ford Fusion Energi PHEV, 2013 Toyota Prius PHEV, and 2016 Hyundai Sonata PHEV) were procured for testing. Dynamometer derivations for each blended PHEV were performed according to the provisions from each manufacturer. California Phase 3 fuel was used for this study. Each set of test cycles received a minimum of 1 overnight soak and 1 minimum 4-hour soak/forced cool-down with vehicle fan. To provide a relative comparison to the six acceleration cycles, exhaust emission modal analysis and bag analysis were performed on the FTP cycle, US06 cycle, and the acceleration cycles. The acceleration cycles were performed in CD operation to investigate high-powered cold-starts. The FTP cycle and US06 cycle were performed in CS operation and CD operation, time permitting. Of note, while the official test procedures for the US06 include a warmed up engine (hot start), for this testing, the test procedure was modified to include a cold start on the US06 to provide further comparison for the emissions from a more aggressive driving schedule where a high-power cold start could occur. As such, the emission results for the US06 cycles provided in the figures below cannot be compared to the applicable US06 standard. The test results of the 2013 Toyota Prius PHEV, 2013 Ford Fusion Energi, and 2016 Hyundai Sonata PHEV are shown in the following figures.

Figure 4 - 2013 Toyota Prius Plug-In Hybrid



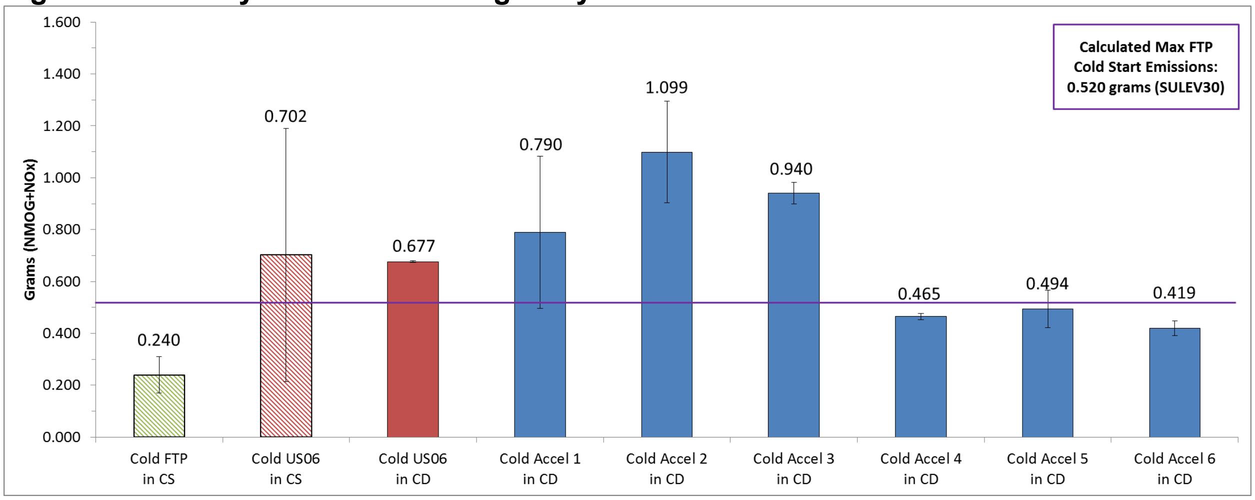
When comparing the 2013 Toyota Prius PHEV (see Figure 4) cold-start exhaust emissions to the 0.520 grams NMOG+NOx maximum limit from Equation 3, the FTP results are significantly below the limit. The cold-start US06 results, while more variable, are also fairly close to the FTP test levels. However, all of the acceleration tests were significantly higher and averaged around 5 to 8 times higher than the FTP test levels. When examining individual NOx and NMOG emission levels instead of the combined result, NOx emissions were roughly 10 to 18 times higher than the FTP NOx emission levels, and NMOG emissions were about 5 to 8 times higher than the FTP NMOG emission levels.

Figure 5 - 2013 Ford Fusion Energi



When comparing the 2013 Ford Fusion Energi (see Figure 5) cold-start exhaust emissions to the limit from Equation 3, the FTP emissions were also below the theoretical limit as expected. For the cold-start US06, emission levels were 2 to 3 times higher than the FTP emissions. With respect to the acceleration cycles, the emissions varied considerably from levels similar to the US06 or higher but were typically near the theoretical limit and approximately 2.5 to 3 times the FTP emission levels. When examining individual NOx and NMOG emission levels, NOx emissions were about 2 to 4 times higher than the FTP NOx emission levels, and NMOG emissions were about 2 times higher than the FTP NMOG emission levels.

Figure 6 - 2016 Hyundai Sonata Plug-In Hybrid

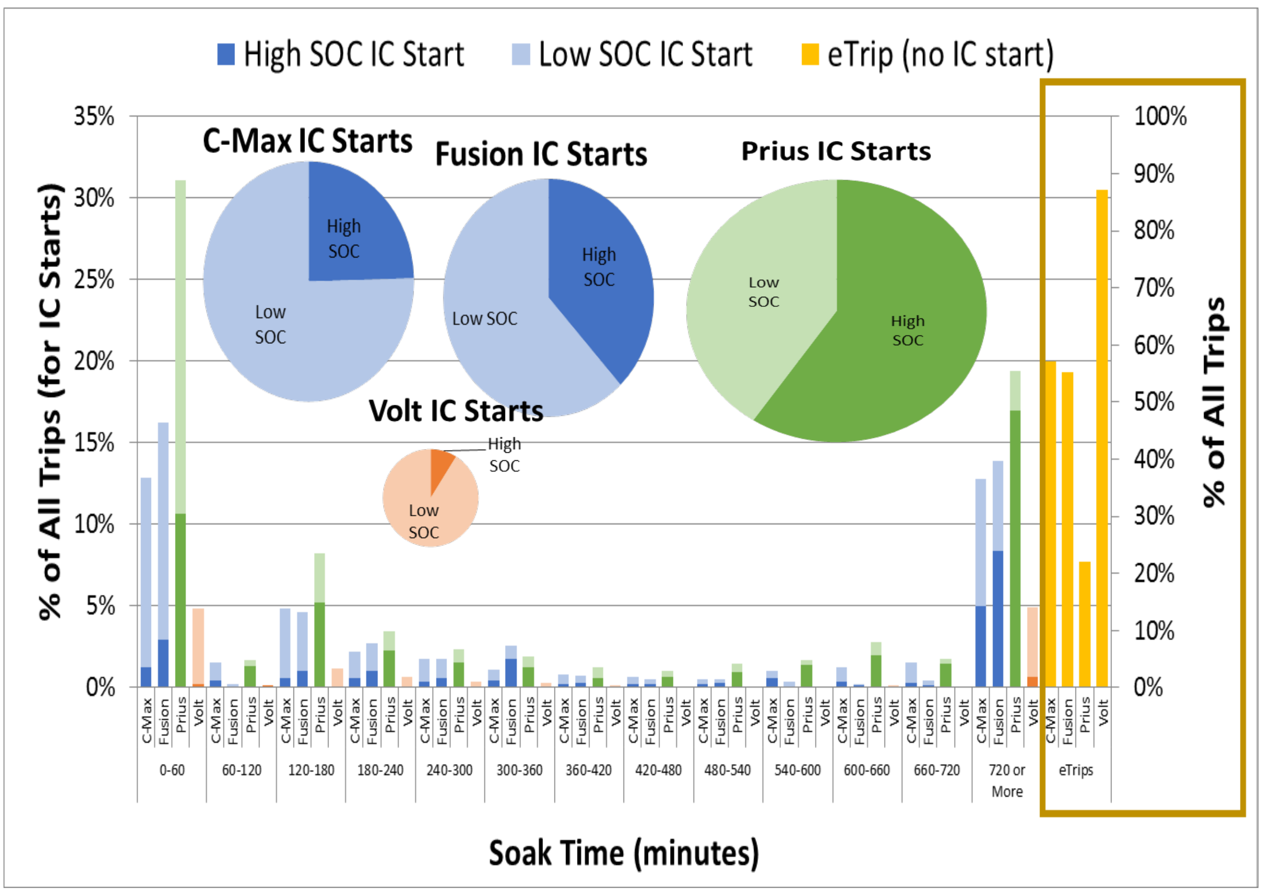


For the 2016 Hyundai Sonata PHEV (see Figure 6), the FTP emissions were below the limit from Equation 3. Cold-start US06 emissions were higher than the limit and approximately 3 times FTP levels. The acceleration cycle emissions varied significantly from levels around 2 times the FTP levels and just below the calculated limit to levels around 5 times higher than the FTP test levels. When examining individual NOx and NMOG emission levels, NOx emissions were about 3 to 6 times higher than the FTP NOx emission levels, and NMOG emissions were about 3 times higher than the FTP NMOG emission levels.

V. Relative Impact of High-Power Starts

While the testing focused on quantifying emissions from high-power starts, not all blended PHEV initial engine starts would be considered such starts. From previous testing used to develop modified certification test procedures for PHEVs and to study PHEVs for other purposes, staff found that PHEVs are generally capable of robustly controlling initial engine start emissions under non-high power start conditions such as when the vehicle is operated in CS mode or when the vehicle transitions from CD to CS mode when the battery is nearly depleted. As such, staff is also working with other data sets to understand how often high-power start conditions occur for blended PHEVs to understand the cumulative emission impacts. One data source of note is a household study being conducted for ARB by UC Davis that is collecting second by second data of PHEVs. Preliminary analysis for this study was presented at ARB's Advanced Clean Cars Symposium in September 2016[3] (shown in Figure 7) and found 25-59% of initial engine starts on the Ford and Toyota PHEVs could be high-power engine starts.

Figure 7 - Frequency of High Power Starts



[3] Nicholas, 2016. Michael Nicholas, Gil Tal. University of California Davis, Plug-in Hybrid and Electric vehicle research Center. Advanced Clean Car 2016 Symposium Presentation "Advanced Plug-in Electric Vehicle Driving and Charging Behavior" September 27, 2016. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/pev_data_from_uc_davis_household_study_first_year_michael_nicholas.pdf

To provide further perspective on the impact of these high power starts, a preliminary analysis was done to estimate the daily HC and NOx emissions from these PHEVs relative to a conventional vehicle certified to the LEV II SULEV emission standards. The Hyundai Sonata PHEV was not included in this analysis because activity data was not available to estimate the frequency of high-power starts for the vehicle. For the conventional vehicle, FTP emission data submitted to ARB for the in-use verification program of nearly 1,000 vehicles certified as partial zero emission vehicles was used to estimate typical daily emissions of non-PHEV, gasoline SULEV certified vehicles. Average bag 1 emissions were assumed to be all cold start emissions, average bag 2 emissions were assumed to be all running emissions, and average bag 3 emissions were assumed to be all hot start emissions.

For simplification, soak times were consolidated into three categories of hot starts (less than 60 minutes), intermediate starts (60 minutes to 720 minutes), and cold starts (greater than 720 minutes). Data from the 2013 California Household Travel Study[4] was used to determine the distribution of the soak times and average starts per day for the conventional vehicle as described in Appendix G. For the conventional vehicle, the hot and cold start emissions were used to estimate an intermediate start emission rate of approximately half of the cold start rate.

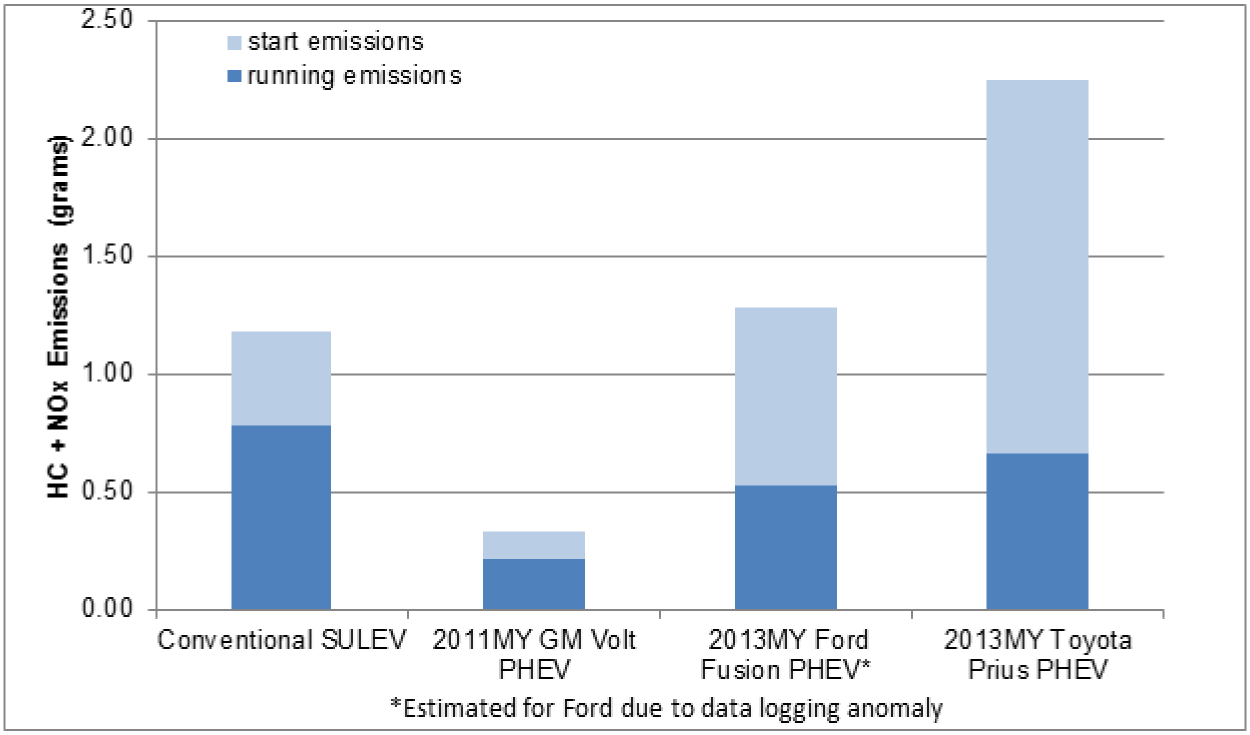
For the PHEVs, emission rates were estimated for hot starts, intermediate starts, and cold starts in both normal and high power start conditions. For all normal starts, high power hot starts, and running emission rates, similar values to the conventional vehicle were used. For the high power cold and intermediate starts, the results from ARB's testing were used for the cold starts and scaled down and used for the intermediate starts. The emission rates were then combined with the additional activity data for the PHEVs from section VI of Appendix G to determine starts per day and distribution of soak time conditions. And, for comparison purposes, all of the activity data (VMT, eVMT, and starts/day) for the PHEVs was scaled to match the 15,000 annual miles used for conventional vehicles.

Figure 10 below shows the estimated HC plus NOx tailpipe emissions. The figure separately shows start emissions (cumulative from all start conditions) and running emissions (cumulative from all operation with the engine on after the initial start). For perspective in comparing the daily tailpipe emission estimates, the bar on the figure labeled as "Conventional SULEV" represents the typical emission levels estimated from FTP testing of non-PHEV vehicles certified to the LEV II SULEV standard as described above. For the GM Volt, no high power starts were assumed given the design of the vehicle which effectively precludes such operation. As seen in the figures, estimated daily emissions from the GM Volt are approximately 25% of those from a conventional vehicle due largely to the significantly fewer trips per day where the engine starts. For the Ford and Toyota blended PHEVs, the distribution of high power starts in each soak region was estimated from Figure 7 above. The figures show reduced running emissions due to the portion of miles driven electrically on these PHEVs. However, the increase in start emissions from high power starts results in total daily emissions that can be

[4] Caltrans 2013. California Department of Transportation. California Household Travel Survey. June 2013 http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_travel_analysis/chts.html

equal to or even higher than conventional vehicles. For the Ford PHEV, it should also be noted that additional estimates had to be made to adjust the number of starts per day and distribution of soak times given a data logging anomaly that caused very short trips to not be logged. Further details of this anomaly are provided in Appendix G.

Figure 8 - Estimated Daily Tailpipe HC+NOx Emissions



However, significant further analysis needs to be done to validate these estimates. An update of emission factors is underway which will be incorporated into a future version of ARB's EMFAC vehicle emission inventory model. More data is needed to determine the distribution between hot and cold starts and the relative emission levels as the higher emissions from high-power starts appears to be most prominent on cold starts. Further, this data represents first generation blended PHEVs that may not be representative of future PHEVs in terms of starts per day, distribution of soak times, or frequency of high power starts. As more capable PHEVs with longer electric range and higher electric only power capabilities are introduced, fewer overall engine starts would be expected and, as the GM Volt analysis shows, this can result in much lower criteria pollutant emissions. On the other hand, the introduction of PHEV architectures on larger and heavier vehicle platforms could, directionally, reduce the electric range and power levels that can be met without the engine resulting in a significant number of engine starts still occurring each day.

Staff has also begun discussions with the vehicle manufacturers to discuss emission control strategies and alternatives that may provide for more robust emission control in these conditions. At a minimum, additional effort by manufacturers could be used to ensure start-up strategies used to accelerate catalyst light-off are enabled under as broad of starting conditions as possible to mitigate the initial burst of emissions before the catalyst achieves light-off temperature. Additional control measures could include design considerations for sizing and location of close-coupled catalysts, or the use of additional aftertreatment controls such as hydrocarbon adsorbers, or electrically-heated catalysts to further reduce initial engine start emissions. Engine start strategy modifications might also be used to start the engine slightly earlier to provide additional time for the catalyst to warm-up before high power or torque demand in a high power start condition. Staff plans to continue to study this area and work with vehicle manufacturers to ensure any adverse impacts are eliminated or minimized on future vehicles.

VI. Summary

The testing confirms that cold-start emissions can be significantly higher under high-power demand conditions relative to more traditional engine start conditions however the cumulative impact on emissions from this fraction of starts has not yet been determined. Staff will continue to bring additional vehicles into the lab to conduct further testing and, as noted earlier, has begun discussions with the vehicle manufacturers to discuss emission control strategies and alternatives that may provide for more robust emission control in these conditions. It is also important to note that all of the vehicles tested are first generation PHEVs and most manufacturers are expected to introduce more capable second generation PHEVs. To the extent future blended PHEVs have stronger electric propulsion systems and longer range, they should be able to reduce the frequency of trips with an engine start including those with a high-power engine start. As one example, the Toyota Prius Prime is Toyota’s second generation PHEV and is designed to primarily operate as a non-blended PHEV, thereby eliminating all high-power engine starts. However, as more manufacturers enter the PHEV market and PHEVs are introduced on larger and heavier vehicle platforms, blended PHEVs will likely continue to play a significant role and warrant continued evaluation to ensure in-use start emissions are controlled as robustly as possible.

VII. References

Caltrans 2013. California Department of Transportation. California Household Travel Survey. June 2013 http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_travel_analysis/chts.html

Nicholas, 2016. Michael Nicholas, Gil Tal. University of California Davis, Plug-in Hybrid and Electric vehicle research Center. Advanced Clean Car 2016 Symposium Presentation "Advanced Plug-in Electric Vehicle Driving and Charging Behavior" September 27, 2016. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/pev_data_from_uc_davis_household_study_first_year_michael_nicholas.pdf