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Plug-in Hybrid Electric Vehicle and Hybrid Electric Vehicle Emissions under FTP and US06 Cycles at High, Ambient, and Low Temperatures

Matthew R. Seidman and Tony Markel

ABSTRACT

The concept of a Plug-in Hybrid Electric Vehicle (PHEV) is to displace consumption of gasoline by using electricity from the vehicle's large battery pack to power the vehicle as much as possible with minimal engine operation. This paper assesses the PHEV emissions and operation. Currently, testing of vehicle emissions is done using the federal standard FTP4 cycle on a dynamometer at ambient (75°F) temperatures. Research was also completed using the US06 cycle. Furthermore, research was completed at high (95°F) and low (20°F) temperatures. Initial dynamometer testing was performed on a stock Toyota Prius under the standard FTP4 cycle, and the more demanding US06 cycle. Each cycle was run at 95°F, 75°F, and 20°F. The testing was repeated with the same Prius retrofitted with an EnergyCS Plug-in Hybrid Electric system. The results of the testing confirm that the stock Prius meets Super-Ultra Low Emission Vehicle requirements under current testing procedures, while the PHEV Prius under current testing procedures were greater than Super-Ultra Low Emission Vehicle requirements, but still met Ultra Low Emission Vehicle requirements. Research points to the catalyst temperature being a critical factor in meeting emission requirements. Initial engine emissions pass through with minimal conversion until the catalyst is heated to typical operating temperatures of 300–400°C. PHEVs also have trouble maintaining the minimum catalyst temperature throughout the entire test because the engine is turned off when the battery can support the load. It has been observed in both HEVs and PHEVs that the catalyst is intermittently unable to reduce nitrogen oxide emissions, which causes further emission releases. Research needs to be done to combat the initial emission spikes caused by a cold catalyst. Research also needs to be done to improve the reduction of nitrogen oxides by the catalyst system.

Introduction

The development of hybrid electric vehicles (HEV) reduces the use of gasoline and its associated side-effects. While still completely powered by gasoline, the HEV uses an optimized power train system of an IC engine, a battery pack, and an electric motor. A HEV is able to reduce fuel consumption by using regenerative braking to recover energy from braking and running the engine at its highest level of performance, to charge the vehicle's battery or directly power the wheels.

A plug-in hybrid electric vehicle (PHEV) goes one step further in conserving gasoline. The vehicle stores electricity from the grid in its battery pack. A PHEV still has an IC engine and is capable of operating like an HEV when necessary, but is programmed to use as much of the stored electric energy as possible. Using more battery and less fuel further reduces gasoline consumption and green house gas emissions, assuming the electricity from the grid comes from a renewable source. HEVs and PHEVs are bridging the gap between internal combustion engine vehicles and alternative energy vehicles.

Currently there are no PHEVs in production by any of the major automotive companies. As a result, not much is known about the emission characteristics of PHEVs. Initial studies have been done by Argonne National Laboratory using a dynamometer running Federal Test Procedure (FTP) cycles at ambient (75°F) temperatures [2]. The purpose of this research is to expand on Argonne National Laboratory's research by 1) presenting emission data on PHEVs under the FTP cycle and the more demanding US06 cycles, 2) presenting emissions data on PHEVs at high (95°F), ambient (75°F), and low (20°F) temperatures of operation for both cycles, 3) finding out if the Toyota Prius HEV and PHEV meet the Super-Ultra Low Emission Vehicle standards at all three temperatures mentioned above during a FTP cycle, and 4) looking at the emission trends for both systems under these real world operating conditions.

The Toyota Prius hybrid electric vehicle utilizes a hybrid transmission with a power-splitting device using a planetary gear system [3]. The engine drive shaft is connected to the planetary gear carrier, which allows power to be simultaneously supplied through the outer ring gear to the wheels and through the sun gear to the generator [3]. The electricity produced by the generator can then be directed to the electric motor to increase the power available to drive the car or through the inverter to be converted into direct current to charge the battery [3]. The standard Prius has a 6-Ah 1.3-kWh battery pack. The EnergyCS PHEV modification replaces the smaller battery pack with a 9-kWh battery pack and performance software. The larger battery pack allows the Prius to travel close to 50 miles on one charge in charge depletion mode.

The stock Prius operates in a charge-sustaining (CS) mode that constantly maintains the battery state of charge (SOC) by running the engine intermittently. The EnergyCS modified Prius, at full charge, will run in charge-depletion (CD) mode using as much battery as possible and will not enter CS mode until a low SOC is reached. In both modes the engine will turn on only when needed for speeds above 34 mph or on steep sections of road, when more power is needed. If the battery is able to supply all the power to drive the vehicle, the possibility for large gaps between engine uses may cause the catalytic converter to cool, resulting in higher levels of emissions during operation.

The environmental protection agency (EPA), up to the year 2003, used an emissions standard for all new vehicles called Tier I. The EPA is currently phasing in their new emission standard called Tier II. The California Air Resource Board (CARB) is also phasing in their new, more stringent emission standards as well. The three CARB emission standards applied to the Toyota Prius HEV and PHEV are the minimum low emission vehicle (LEV), the 50 percent cleaner than LEV ultra low emission vehicle (ULEV), and the 90 percent cleaner than LEV super low emission vehicle (SULEV). The emission values for all three CARB standards are displayed in Table 1. All emission testing is performed using the FTP cycle at ambient temperatures.

	LEV (grams/mile)	ULEV (grams/mile)	SULEV (grams/mile)
HC	0.09	0.055	0.01
CO	4.2	2.1	1.0
NO_x	0.07	0.07	0.02

Table 1. CARB emission standards.

The current Toyota Prius HEV has been certified to meet the new Super Ultra-Low Emission Vehicle (SULEV) standard set by CARB. This standard reduces most emissions by 70 to 97 percent from the current federal Tier 1 standards [1]. Under SULEV standards, vehicles must emit less than 0.01 grams/mile of hydrocarbons (HC), 0.02 grams/mile of nitrous oxides (NO_x), and 1.0 grams/mile of carbon monoxide (CO) [1]. Hydrocarbons are volatile organic compounds that cause smog and are toxic and carcinogenic [1]. Carbon monoxide is a poisonous gas that impairs the flow of oxygen to the brain and other parts of the body [1]. Nitrogen oxides aggravate respiratory problems, both directly and indirectly, by forming PM and smog; NO_x also causes acid rain and damages aquatic environments [1].

In standard vehicles, emissions are controlled by a catalytic converter that uses the heat from the engine's exhaust to activate the catalyst. The minimum catalyst operating temperature is 300°C and maximum operating efficiency is achieved at 400°C. The exhaust gases must alternate rapidly between high CO content, to reduce NO_x emissions, and high oxygen content, to oxidize the HC and CO emissions [5]. A rich air-to-fuel ratio (A/F ratio) will produce more CO while a lean A/F ratio will produce more oxygen.

Materials and Methods

The emission testing was performed using a dynamometer and emission testing systems at Environmental Testing Corporation in Aurora, Colorado. The vehicle was fitted with emissions sensors at the engine, the catalyst outlet, and the tailpipe. All the exhaust is collected in emission bags that can be analyzed for specific emissions and fuel economy. The facility was also capable of producing high, low, and ambient temperatures around the vehicle during testing.

An initial analysis called a coast down was performed to determine the rolling resistance of the vehicle. The dynamometer is capable of reproducing specific drive cycles using the vehicle's rolling resistance, the road's percent grade, and the vehicles aerodynamic drag at any speed. The operator must then reproduce the specific cycle by accelerating or braking the vehicle.

The (FTP) cycle is used for emission certification of passenger vehicles. This cycle has three separate phases: a cold-start (505-second) phase known as bag 1, a hot-transient (870-second) phase known as bag 2, and a hot-start (505-second) phase known as bag 3 [4]. These three test phases are referred to as bag 1, bag 2, and bag 3 because exhaust samples are collected in separate bags during each phase [4]. During a 10-minute cool-down between the second and third phase, the engine is turned off [4]. The 505-second driving trace for the first and third phases is identical. The 870-second driving trace for the second and fourth phases is identical. The fourth phase is not performed during the test because it is assumed that phase two and four begin at the same operating conditions where phase one and phase three do not because of cold and hot start conditions. The top speed for the cycle is 56.7 mph and the average speed is 21.4 mph. The distance traveled is approximately 15 miles [4].

When FTP testing HEVs and PHEVs, it is necessary to perform and record phase four during testing. The reason for the fourth phase is that the engine in HEVs and PHEVs does not operate the entire time like a standard vehicle. Based on the hybrids SOC and mode of operation, CD or CS, the emissions will vary between phase two and phase four negating the previous assumption that phase two and four are identical.

The US06 cycle is more representative of aggressive, rapid speed fluctuation, high speed, and high acceleration driving. The cycle is an eight mile drive with an average speed of 48.4 miles per hour and a maximum speed of 80.3 miles per hour over 596 seconds using one bag.

After collecting all the data, Microsoft Excel was used to graph the total emissions of hydrocarbon and nitrogen oxide for the HEV and PHEV under the FTP and US06 cycles. The resulting graphs showed emissions greater then SULEV, ULEV and even LEV standards at times. To further explore where the emissions were occurring cumulative emissions graphs were generated over the distances traveled in each cycle. These graphs revealed the common theme of emission spikes within the first few minutes of operation. To better understand these emission spikes a final set of graphs were constructed. These graphs looked at the speed trace, fuel consumption, SOC, engine exhaust temperature (CAT IN), first catalyst exhaust temperature (CAT MID), tailpipe exhaust temperature (CAT OUT), first catalyst's operating temperature (CAT 1), cumulative hydrocarbon emissions and the cumulative nitrogen oxide emissions over the first 600 seconds of testing.

Results

Bar graphs were generated based on the HEV and PHEV total bag calculated emissions in grams per mile for each cycle. The green line represents SULEV, the blue line represents ULEV, and the pink line represents LEV. Figures 1 and 2 show the hydrocarbon emissions for the HEV and PHEV respectively, under the FTP cycle. Figure 1 illustrates that the HEV meets the SULEV standard except during the cold run. Figure 2 shows that the PHEV fails the SULEV standard in CD mode and fails the ULEV standard in the cold run. The figure also shows that the PHEV meets the SULEV standard in CS mode but fails to meet SULEV during the cold run. Figures 3 and 4 present the nitrogen oxide emissions for the HEV and PHEV respectively, under the FTP cycle. Figure 3 illustrates that the HEV meets the SULEV standard during hot and ambient runs, but just misses the standard during the cold run. Figure 4 exhibits that the PHEV fails the SULEV standard, but meets the ULEV standard on all but one instance.

Figures 5 and 6 display the hydrocarbon emissions for the HEV and PHEV respectively, under the US06 cycle. Figure 5 demonstrates mild HC emissions for hot and ambient temperatures with large emissions for the cold temperature. This correlates with Figure 1, where the cold emissions are higher than the others. Figure 6 shows that HC emissions are higher when the PHEV is in CD mode. This figure also reveals that as the temperature decreases the emissions increase. Figures 7 and 8 represent the nitrogen oxide emissions for

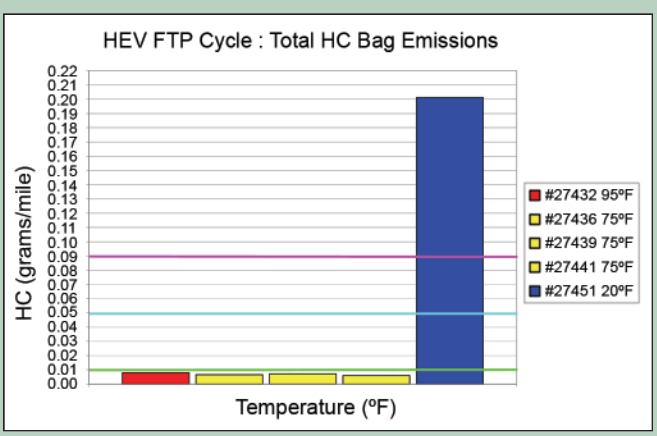

Figure 1. Hybrid electric vehicle-federal test procedure hydrocarbon emissions.

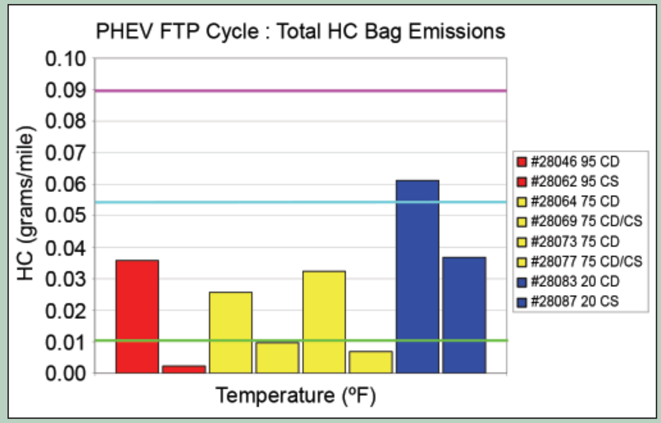

Figure 2. Plug-in hybrid electric vehicle-federal test procedure hydrocarbon emissions.

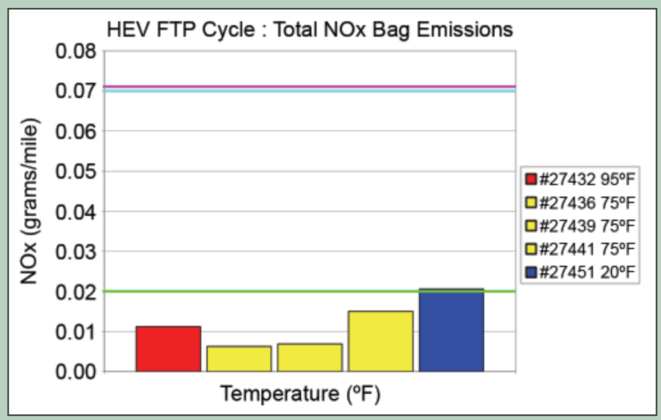

Figure 3. Hybrid electric vehicle-federal test procedure nitrogen oxide emissions.

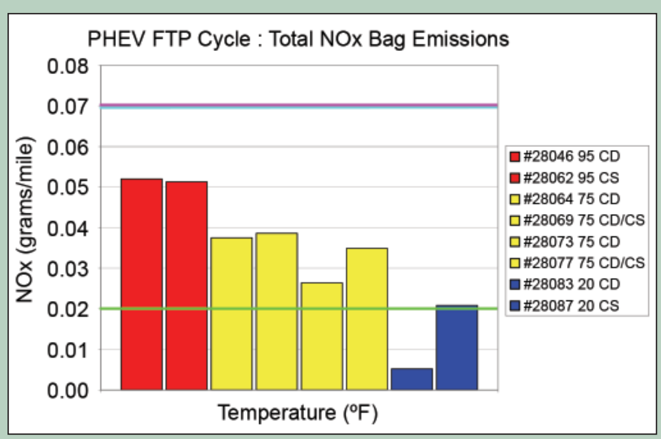

Figure 4. Plug-in hybrid electric vehicle-federal test procedure nitrogen oxide emissions.

the HEV and PHEV respectively, under the US06 cycle. Figure 7 illustrates consistent NO_x emissions except at the lower temperature. Figure 8 depicts higher NO_x emissions at high and low temperatures with a decrease in emissions at ambient temperature.

Figures 9 and 10 represent the HEV and PHEV cumulative hydrocarbon emissions respectively, under the FTP cycle. Figure 9 shows a sharp spike in emissions, then a leveling out during the first mile. After the 10 minute cool-down at mile 7 another emissions spike occurs, then a leveling out during the first half-mile. Figure 10 reveals that the CD mode emissions have a sharp spike in the first mile, but never level off as much as the CS mode. After the 10-minute cool-down the emissions spike again, but never level off like in the CS mode. Figures 11 and 12 impart the HEV and PHEV cumulative nitrogen oxide emissions respectively, under the FTP cycle. Figure 11 illustrates a stair-step function with a small slope, while Figure 12 reveals a stair-step function with a larger slope. Figure 12 also shows a large spike, which flat-lines in the first mile for the two cold runs.

Figures 13 and 14 represent the HEV and PHEV cumulative hydrocarbon emissions respectively, under the US06 cycle. Figure 13 displays various sizes of emission spikes within the first mile with a leveling off for the rest of the cycle. Figure 14 also displays various sizes of emissions spikes, but the slope after the emissions level off is greater than Figure 13. Figures 15 and 16 divulge the HEV and PHEV cumulative nitrogen oxide emissions respectively, under the US06 cycle. Figures 15 and 16 both exhibit stair-step function emissions curves.

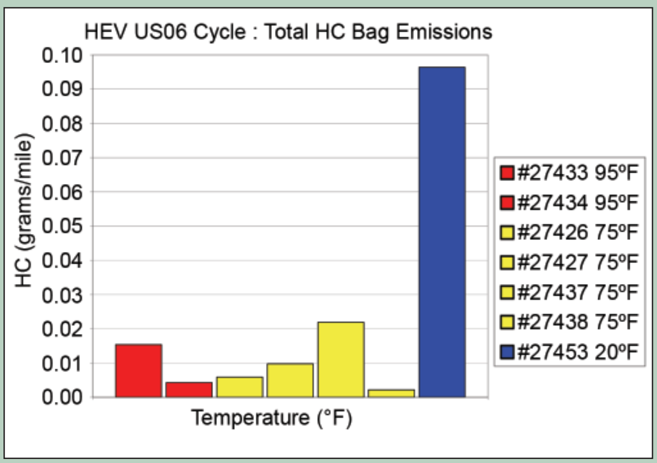

Figure 5. Hybrid electric vehicle-US06 hydrocarbon emissions.

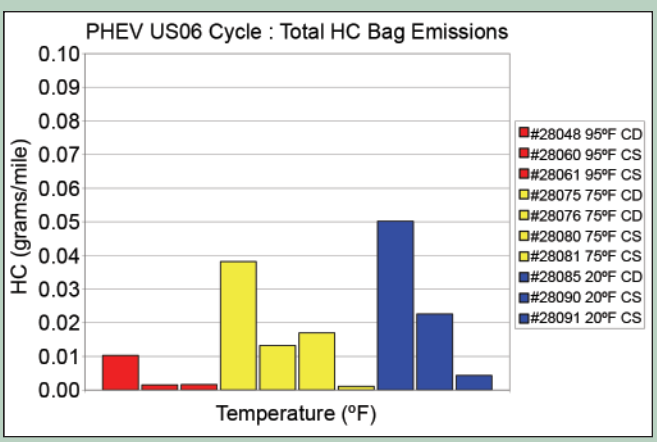

Figure 6. Plug-in hybrid electric vehicle-US06 hydrocarbon emissions.

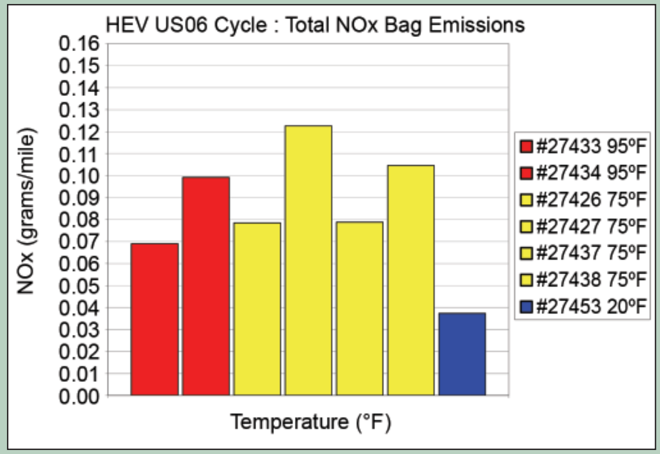

Figure 7. Hybrid electric vehicle-US06 nitrogen oxide emissions.

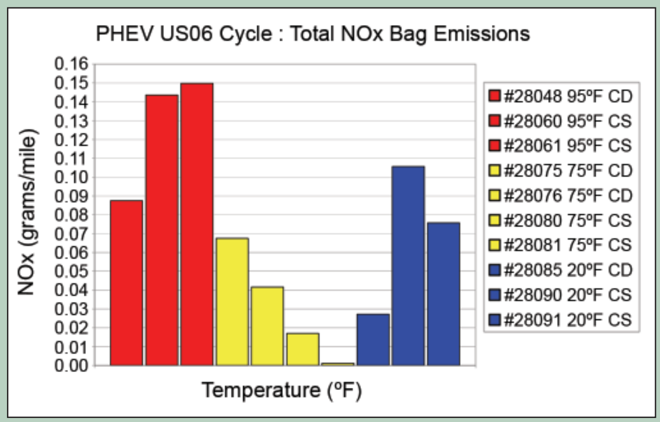

Figure 8. Plug-in hybrid electric vehicle-US06 nitrogen oxide emissions.

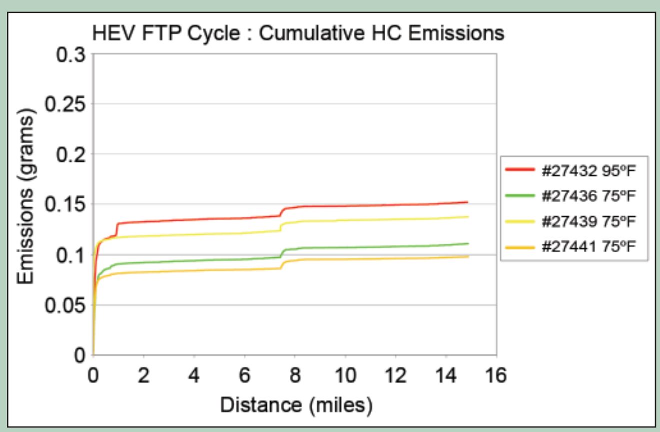

Figure 9. Hybrid electric vehicle-FTP cumulative hydrocarbon emissions.

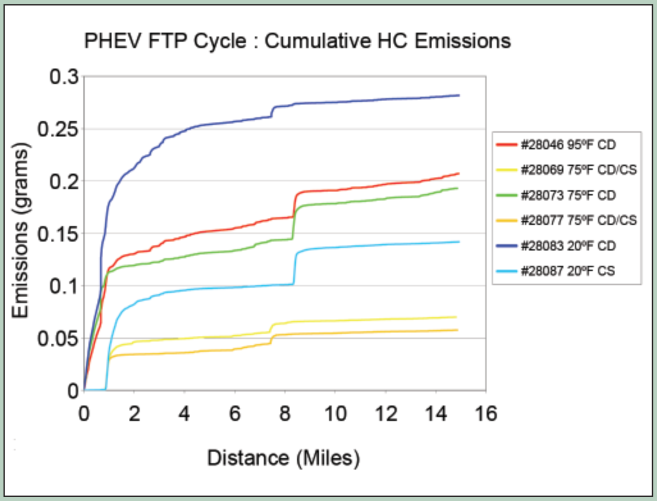

Figure 10. Plug-in hybrid electric vehicle-FTP cumulative hydrocarbon emissions.

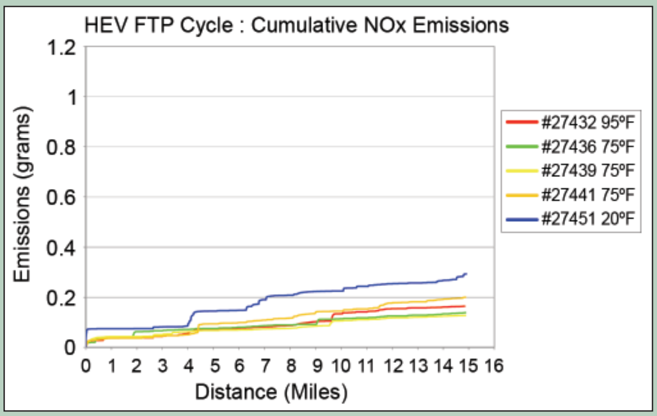

Figure 11. Hybrid electric vehicle-FTP cumulative nitrogen oxide emissions.

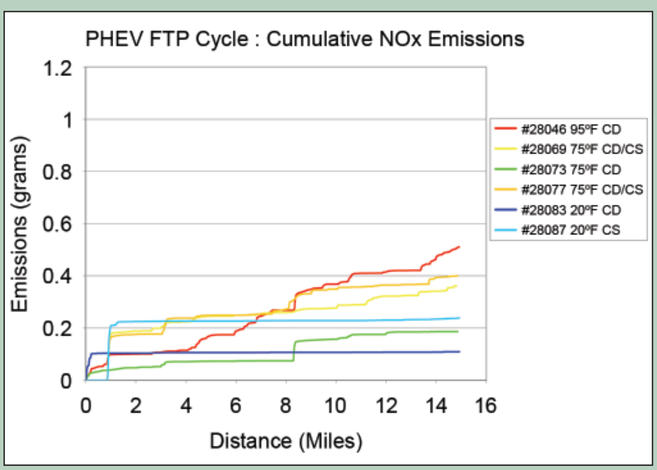

Figure 12. Plug-in hybrid electric vehicle-FTP cumulative nitrogen oxide emissions.

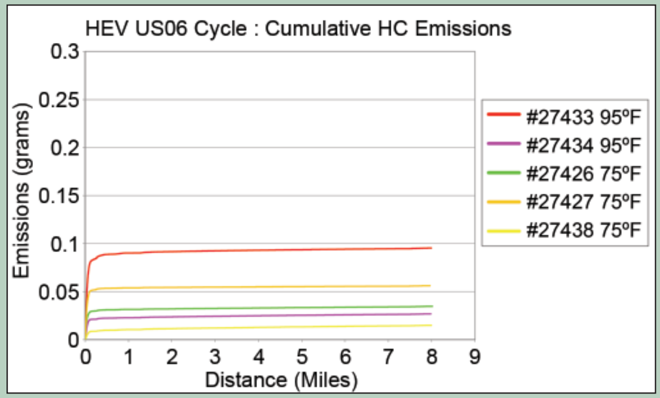

Figure 13. Hybrid electric vehicle-US06 hydrocarbon emissions.

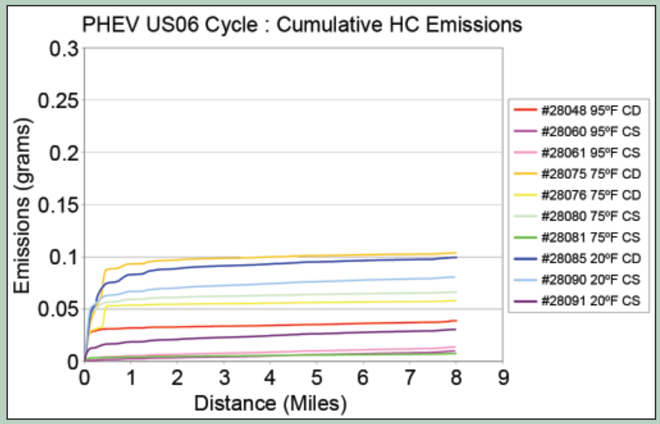

Figure 14. Plug-in hybrid electric vehicle-US06 hydrocarbon emissions.

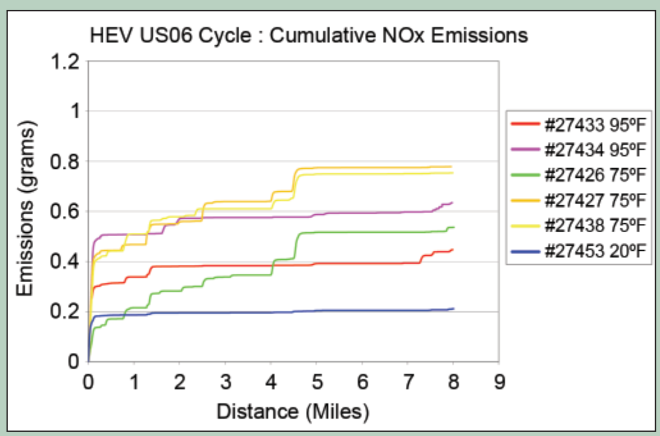

Figure 15. Hybrid electric vehicle-US06 nitrogen oxide emissions.

Figures 17 and 18 both depict the HEV operating under a FTP cycle at 75°F. The two graphs have a good correlation between exhaust and CAT 1 temperatures, fuel consumption, and HC emissions. The NO_x emissions vary in size and location of emission spike occurrences. Figures 19 and 20 illustrate the PHEV operating in transition from CD to CS mode under FTP cycles at 75°F. Because the PHEV is still in CD mode throughout the 600 seconds, the engine does not turn on until speeds reach 34 mph at about 200 seconds into the trace. In Figure 20 emissions and temperatures are close, considering the engine does not operate as much in the middle of the trace because no fuel is being consumed. Figure 21 is a PHEV at full charge in CD mode under a FTP cycle at 75°F. The engine turns on right away for this test instead of using only the battery. The fuel consumption is greater than the CD/CS mode tests and less than the HEV tests. The cumulative HC emissions are greater than all the similar tests. The cumulative NO_x emissions are the same as the HEV, much less than CD/CS mode.

Figures 22 and 23 show the HEV operating under US06 cycles at 75°F. The two graphs have a strong correlation between exhaust and CAT 1 temperatures, fuel consumption, and emissions. A sharp spike in NO_x emissions is produced because of the rapid acceleration of the engine with a cold catalyst. Figures 24 and 25 are both the PHEV in CD mode under US06 cycles at 75°F. The two graphs maintain a close correlation between the exhaust temperatures, CAT 1 temperatures, and fuel consumption. Even with the same fuel consumption, Figure 24 shows a larger spike in HC and NO_x emissions than Figure 25. The PHEV also consumes less gasoline and produces less NO_x emission for the US06 cycle.

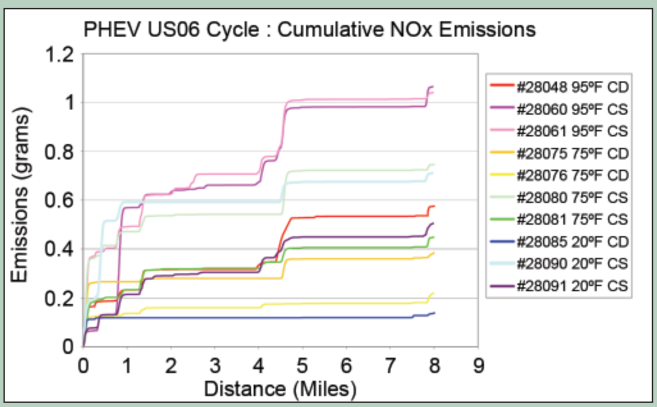

Figure 16. Plug-in hybrid electric vehicle-US06 nitrogen oxide emissions.

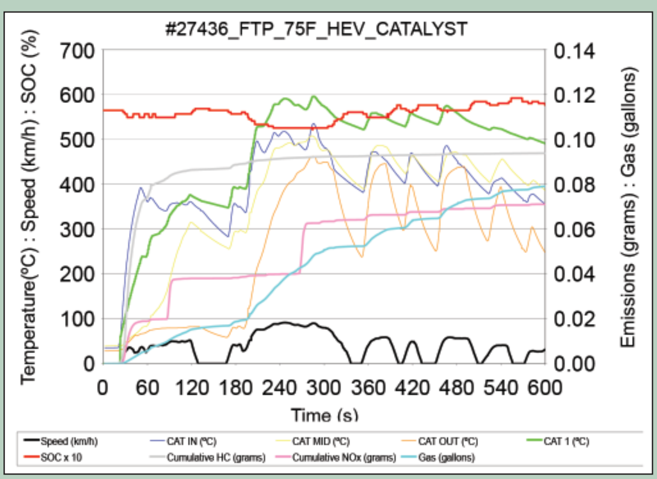

Figure 17. Hybrid electric vehicle-federal test procedure at ambient temperature.

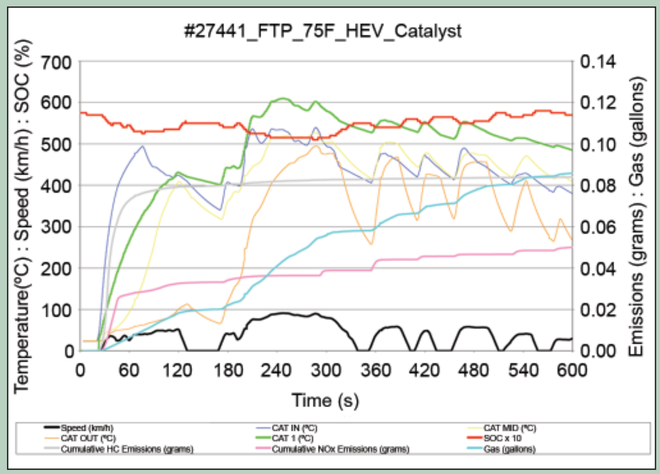

Figure 18. Hybrid electric vehicle-federal test procedure at ambient temperature.

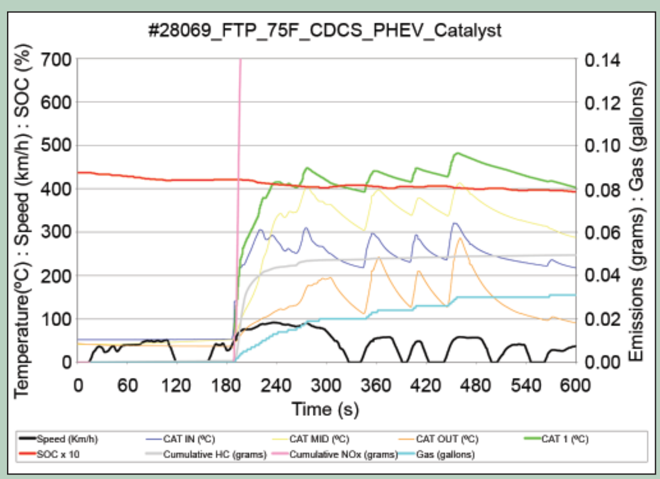

Figure 19. Plug-in hybrid electric vehicle-federal test procedure at ambient temperature.

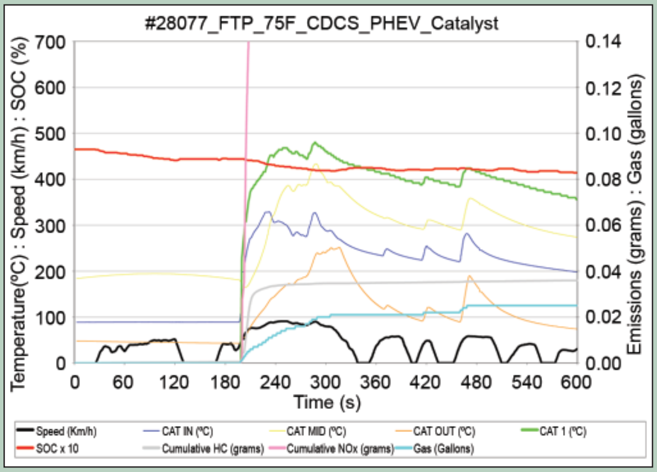

Figure 20. Plug-in hybrid electric vehicle-federal test procedure at ambient temperature.

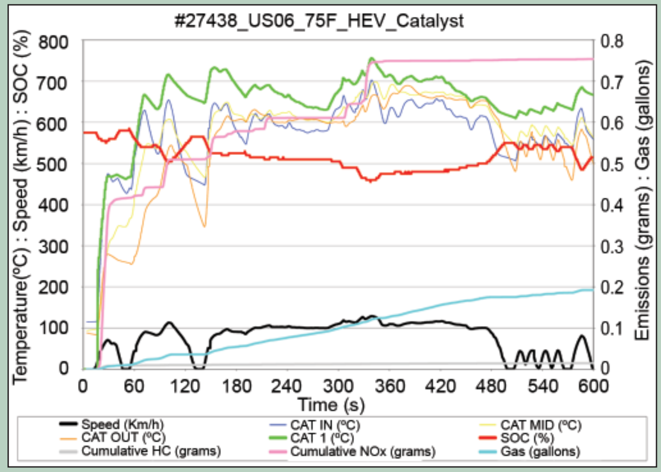

Figure 23. Hybrid electric vehicle-US06 cycle at ambient temperature.

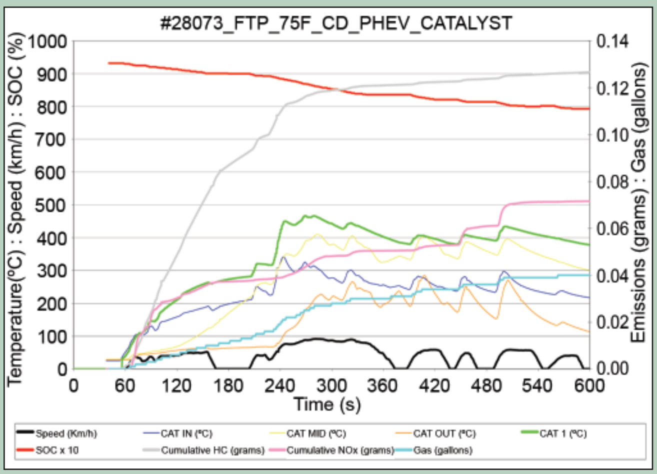

Figure 21. Plug-in hybrid electric vehicle-federal test procedure at ambient temperature.

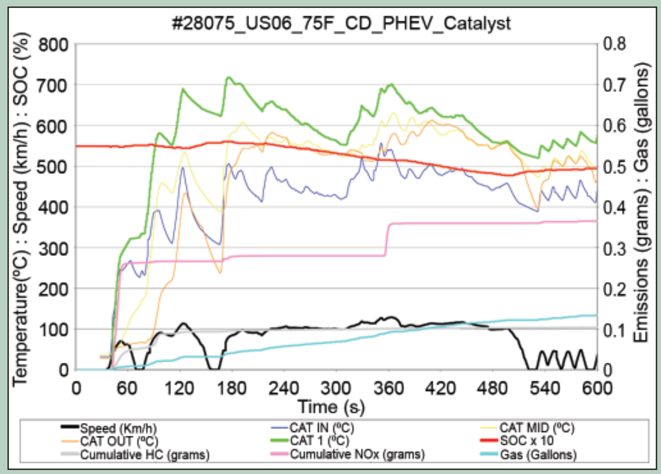

Figure 24. Plug-in hybrid electric vehicle-US06 cycle at ambient temperature.

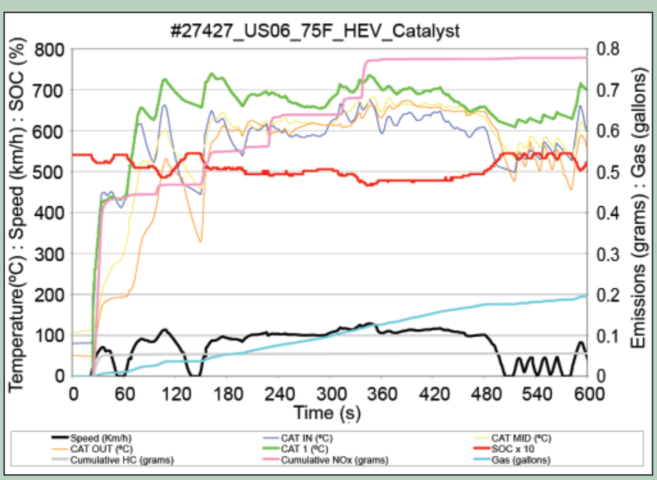

Figure 22. Hybrid electric vehicle-US06 cycle at ambient temperature.

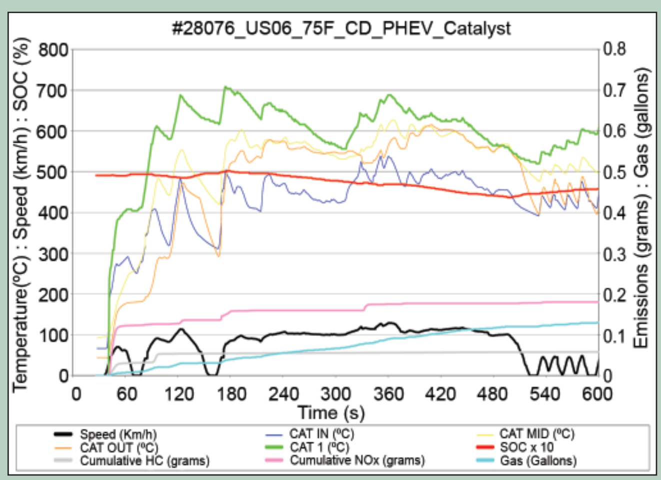

Figure 25. Plug-in hybrid electric vehicle-US06 cycle at ambient temperature.

Discussion

Testing confirmed that the Toyota Prius HEV met SULEV standards under the EPA's FTP cycle at ambient temperatures. Figure 2 illustrates that when the PHEV operates in CD mode, the HC emissions are higher than CS mode. It would be expected that the transition from CD to CS produces emissions between the CD and CS modes, and Figure 2 demonstrates this. When looking at the PHEV in Figure 2, it makes sense that the CS mode produces similar HC emissions as the HEV in Figure 1 because the software defaults back to normal HEV operation. The PHEV meets the ULEV standard under the FTP cycle at all temperatures except at 20°F. Figure 4 showed high NO_x emissions over the entire cycle. After looking at Figures 19 and 20, it was found that NO_x spikes when the PHEV's engine turns on at 50 km/h. Under the large initial load with a cold catalyst the resulting emissions can be expected. If the catalyst was at operating temperature like in Figures 17 and 18 the spike in emissions caused by the large engine load might have been eliminated by the catalyst. The stair-step emissions displayed in Figure 12 account for half the emissions produced during the cycle. For some reason the catalyst is not eliminating NO_x emissions at different times during the cycle. The PHEV also failed the SULEV HC standard under the FTP cycle in CD mode. Figure 21 represents a PHEV fully charged at home beginning its daily commute. From Figure 21, the cumulative HC emissions climbs steadily until the catalyst warms up to the maximum efficiency temperature of 400°C. While the figure shows fuel consumption, the engine is running at low loads and is unable to produce high temperature exhaust. The emissions fail to flat-line because the catalyst is unable to achieve the maximum efficiency temperature and drops below the minimum operating temperature further into the cycle. The initial engine usage in CD mode is part of a battery protection strategy employed by EnergyCS in this prototype conversion. Future PHEVs will likely incorporate alternatives to protect the battery at high SOC.

The cumulative HC emission decreases for the US06 cycle in Figures 13 and 14 compared to the FTP cycle, Figures 9 and 10. The aggressive initial acceleration in the US06 cycle quickly heats the catalyst up keeping the HC emissions low for the US06 cycle. Conversely, when looking at the cumulative NO_x emission graphs for the US06 cycle, Figures 15 and 16, the emissions increase compared to the FTP cycle, Figures 11 and 12. Within the US06 cycle, the HEV experiences a larger spike in NO_x emissions than the PHEV even though its engine exhaust and CAT1 temperatures are greater by about 100°C, Figures 22–25. The HEV's engine appears to be under more load because the SOC in Figures 22 and 23 show the engine is charging the battery. The PHEV's engine appears to be under less load because the SOC in Figures 24 and 25 do not change, which suggests that the PHEV's software is better utilizing the battery and engine. NO_x continues to stair-step throughout the cycle for the HEV, even after reaching maximum efficiency temperature.

The PHEV's emissions did increase. However, they are still 50 percent lower than the minimum LEV standards. The EnergyCS conversion and other aftermarket conversions are only prototypes. There are technology options available to address emissions issues in production vehicles. The PHEV also experienced reduced fuel consumption during testing. A vehicle designed as a stand alone PHEV, not a modified HEV, could further reduce fuel consumption. In conclusion, PHEVs hold promise in reducing gasoline consumption and meeting emission standards.

Future Work

The most important lesson from these emission tests is that a cold catalyst is unable to effectively control emissions. No matter the load size on the engine, a hot catalyst will eliminate emission spikes. Research needs to find cost-effective solutions to the initial cold catalyst problem. Research has been conducted by NREL on variable conductance catalyst technology in the past and may be of value in reducing HEV and PHEV emissions [6]. Once the cold catalyst problem is solved, focus should be placed on the NO_x stair-step problem. Even though the engine exhaust is monitored to regulate A/F ratios, the catalyst is failing to control NO_x emissions consistently. Research needs to explore richer A/F ratios to provide the catalyst with emissions to reduced NO_x. To counteract the richer A/F ratios, an extra air intake may need to be incorporated to oxidize HC emissions. Next generation HEVs and PHEVs will need to address these issues to meet real world driving conditions.

Acknowledgements

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References

[1] Clean Car Campaign, "Emissions," http://www.cleancarcampaign.org/emissions.shtml [Accessed: June 25, 2007].

[2] Richard W. Carlson, Michael J. Duoba, Theodore P. Bohn, Anantray D. Vyas "Testing and Analysis of Three Plug-in Hybrid Electric Vehicles," SAE Technical Papers., 2007-01-0283.

[3] M. H. Westbrook, The Electric and Hybrid Electric Car. London: The Institution of Electrical Engineers, Warrendale, PA: Society of Automotive Engineers, 2001.

[4] http://www.avt.nrel.gov/emis_tour/ftp-75.html [Accessed: July 18, 2007].

[5] Toyota Motor Sales, U.S.A., "Emission Sub Systems – Catalytic Converter," http://www.autoshop101.com/forms/h64.pdf [Accessed: July 26, 2007].

[6] Steven D. Burch, Matthew A Keyser, Chris P. Colucci, Thomas F. Poter, and David K Benson "Applications and Benefits of Catalytic Converter Thermal Management," SAE Technical Papers., 961134.