Paper Number

A Preliminary Investigation into the Mitigation of Plug-in Hybrid Electric Vehicle Tailpipe Emissions Through Supervisory Control Methods Part 2: Experimental Evaluation of Emissions Reduction Methodologies

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ABSTRACT

Plug-in hybrid electric vehicle (PHEV) technologies have the potential for considerable petroleum consumption reductions, possibly at the expense of increased tailpipe emissions due to multiple "cold" start events and improper use of the engine for PHEV specific operation. PHEVs operate predominantly as electric vehicles (EVs) with intermittent assist from the engine during high power demands. As a consequence, the engine can be subjected to multiple cold start events. These cold start events may have a significant impact on the tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current hybrid electric vehicles (HEVs), the first cold start of the engine dictates whether or not the vehicle will pass federal emissions tests. PHEV operation compounds this problem due to infrequent, multiple engine cold starts.

A continuation of previous analytical work, this research, experimentally verifies a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. Energy management strategies are evaluated and implemented in a virtual environment for preliminary assessment of petroleum displacement benefits and rudimentary drivability issues. This baseline vehicle supervisory control strategy, developed as a result of this assessment, is implemented and tested on actual hardware in a controlled laboratory environment over a baseline test cycle.

Engine cold start events are aggressively addressed in the development of this control system, which leads to enhanced pre-warming and energy-based engine warming algorithms that provide substantial reductions in tailpipe emissions over the baseline supervisory control strategy. The flexibility of the PHEV powertrain allows for decreased emissions during any engine starting event through powertrain "torque shaping" algorithms.

The results of the research show that PHEVs do have the potential for substantial reductions in fuel consumption. Tailpipe emissions from a PHEV test platform have been reduced to acceptable levels through

the development and refinement of vehicle supervisory control methods only. Impacts on fuel consumption were minimal for the emissions reduction techniques implemented.

INTRODUCTION

The supervisory control strategy developed during the analytical phase of this research and targeted to the real-time control system on the Mobile Advanced Technology Testbed (MATT) of the Advanced Powertrain Research Facility (APRF) at the Argonne National Laboratory (ANL) for verification on actual hardware. Testing was conducted in two (2) distinct phases. Phase I represents experimental evaluation of the control strategy that does not include any emissions control constraints, and provides a basis for establishing the merits of the proposed emissions-related control modifications. Phase II mirrors the testing of Phase I, but includes all of the previously developed emissions control constraints.

PHASE II OVERALL FUNCTIONAL SUMMARY

All experimental tests were conducted at the APRF located at ANL on MATT. The test cycle consisted of six (6) Urban Dynamometer Driving Schedules (UDDS) that were ran consecutively. Due to certain limitations, there was an average of ten minutes between each actual UDDS cycle in order to reset the system. Each test began with an assumed full charge of the energy storage system (90% in this case). All of the consecutive cycles assured full charge depletion (CD) and charge sustaining (CS) operation of the vehicle.

Figure 1 represents the functional summary for the Phase II maximum depletion load following case. The maximum depletion engine warming strategy engages at just below 40% SOC. The charge preservation (CP) accomplished as a result allows the vehicle to operate for a short period in an all-electric mode until finally entering into full CS operation. The engine warming strategy for this test operates the engine in a load following manner.

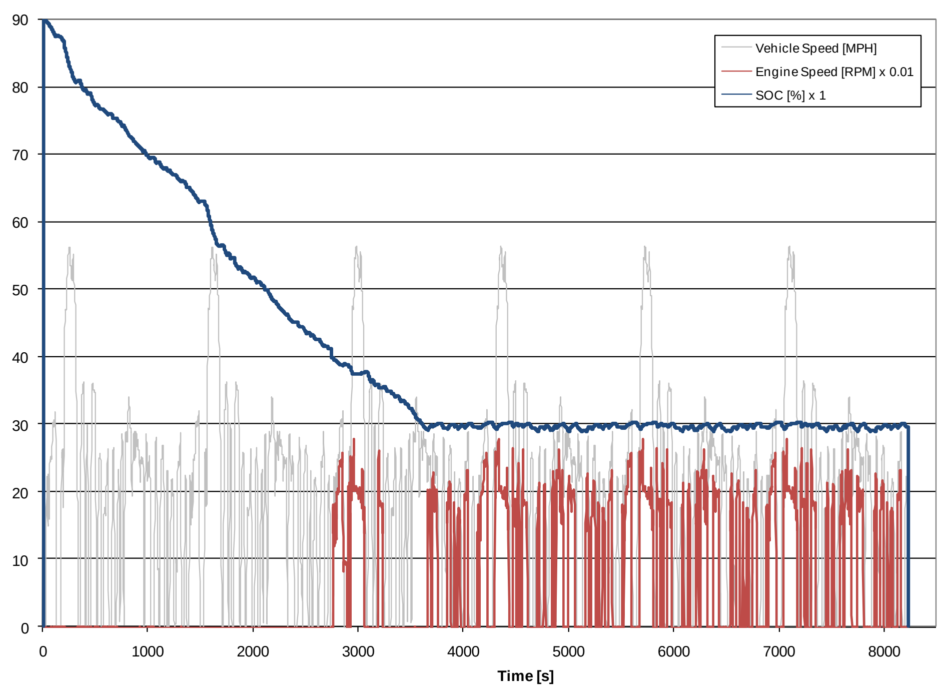

Figure 1. Maximum depletion load following operational summary for Phase II

Figure 2 represents the functional summary for the maximum depletion engine optimal case. Just as in the load following case described above, the engine warming strategy is engaged just below 40% SOC. The main difference here is that the engine is allowed to operate in a (modified) engine optimal manner during engine warm up, as is shown by the slight increase in SOC above 40% during the first engine on event. The vehicle is allowed to operate in all-electric mode after the engine warm up strategy is complete, due to the increased amount of stored electrical energy from the engine optimal approach. This increased electric operation after the engine warm up may appear self defeating, however, the temperatures reached by the primary and secondary catalysts for this type of operation are much greater since the engine is operated at high loads at all times when the engine is running. This increased stored thermal energy inside the catalysts allows the engine extra time to remain off without substantial impacts on catalytic conversion efficiency.

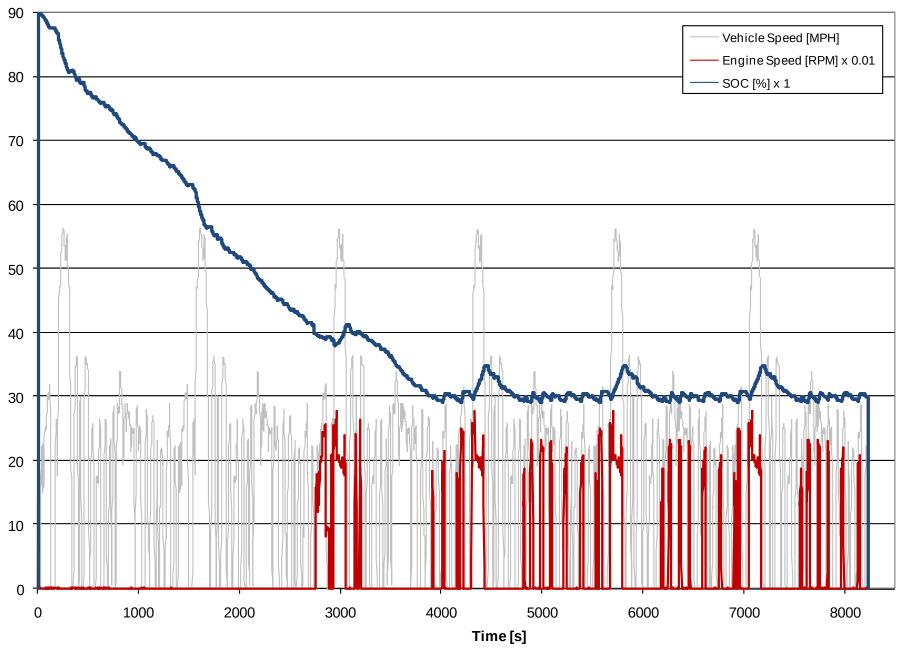

Figure 2. Maximum depletion engine optimal operational summary for Phase II

Figure 3 represents the functional summary of the blended load following case for Phase II. The engine is turned on immediately due to the “cold” catalyst. The secondary warming strategy can be seen to engage around the second series of engine operation near the 1500 second mark, and again around the 3000 second mark. The effect of the variable CD engine-on power threshold can be seen as the frequency of engine operation increases as time moves forward. A period of electric operation is observed when the SOC depletes to approximately 35%. At this point, full CS operation begins and causes a rapid depletion of the battery in order to maintain tight control of the SOC about its 30% target.

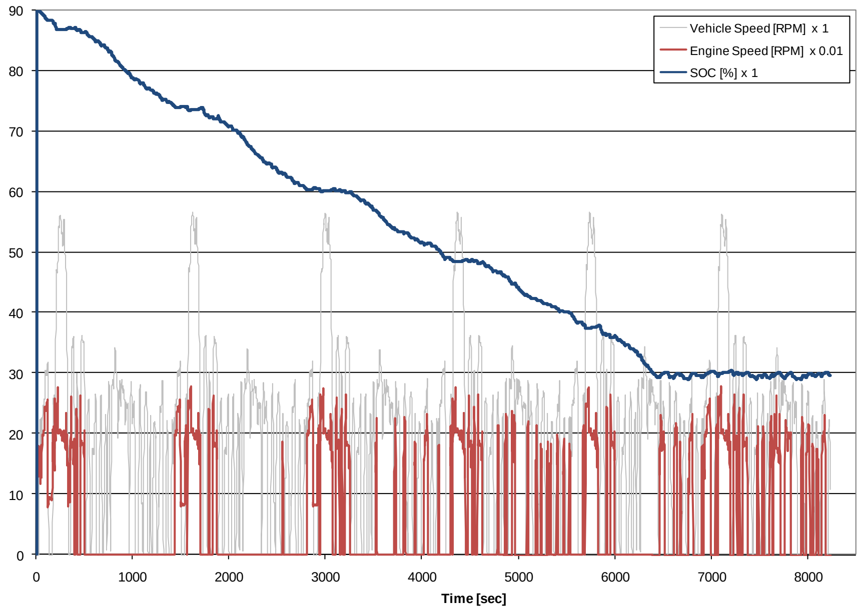

Figure 3. Blended load following operational summary for Phase II

Figure 4 represents the functional summary of the blended engine optimal case for Phase II. The CD region is identical to the load following as described previously. The engine is turned on right away due to the "cold" catalyst. The secondary warming strategy can be seen to engage around the second series of engine operation near the 1500 second mark, and again around the 3000 second mark. The effect of the variable CD engine on power threshold can be seen as the frequency of engine operation increases as time moves forward. During the transition into CS operation, the engine optimal control strategy engages, as can be seen by the increase in SOC due to excess charging. As a result, a longer period of electric operation is observed as compared to the load following case in Figure 3. Another period of electric operation is observed as a result of excess charging during the last high speed section of the drive cycle. In general, less frequent engine operation is required during this series of testing.

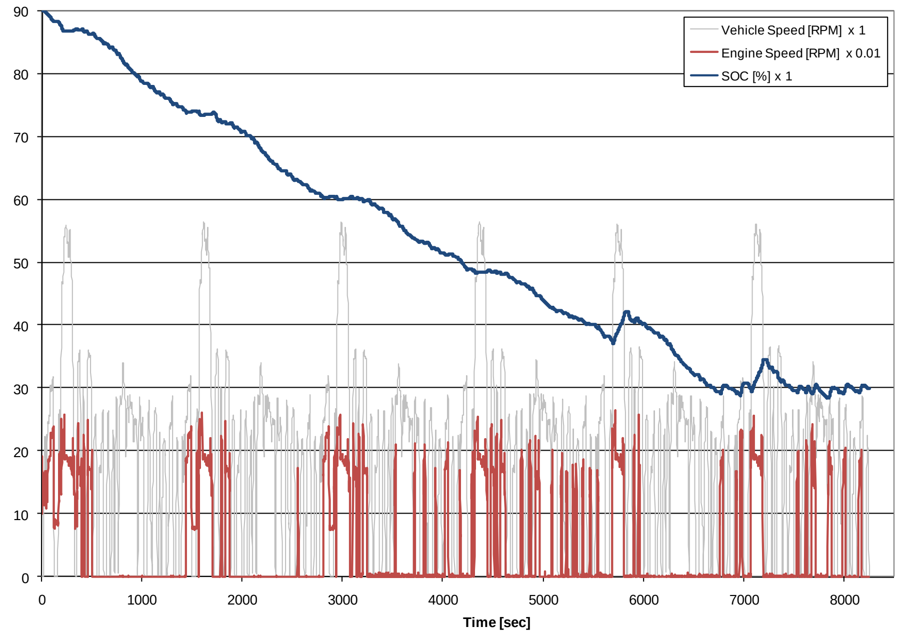

Figure 4. Blended engine optimal operational summary for Phase II

PHASE II ENERGY CONSUMPTION RESULTS

The emissions-related control strategy was implemented into MATT, and subjected to the same test regimen as in Phase I. Figure 5 represents the aggregate energy consumption for the combined set of six (6) UDDS drive cycles compared to Phase I. Both engine optimal strategies yielded results that were expected, which are highlighted in red in the figure and summarized in the bulleted list below:

- The maximum depletion engine optimal case did not vary substantially in going from Phase I to Phase II. This is due to the all electric CD phase being the same. There is a slight increase in electrical consumption, due to the extra electric operation required during the transition phase for the engine warming strategy, and the warm engine start torque smoothing algorithm.
- The blended engine optimal case consumed slightly more fuel in Phase II, resulting from the key-on engine warming strategy at the beginning of the test regimen, and continuous engine running until the pre-warm up and main engine warming phases are complete. There is also a slight decrease in the electrical energy consumption, due to the slight charge preservation mode of operation during the engine warm up period.

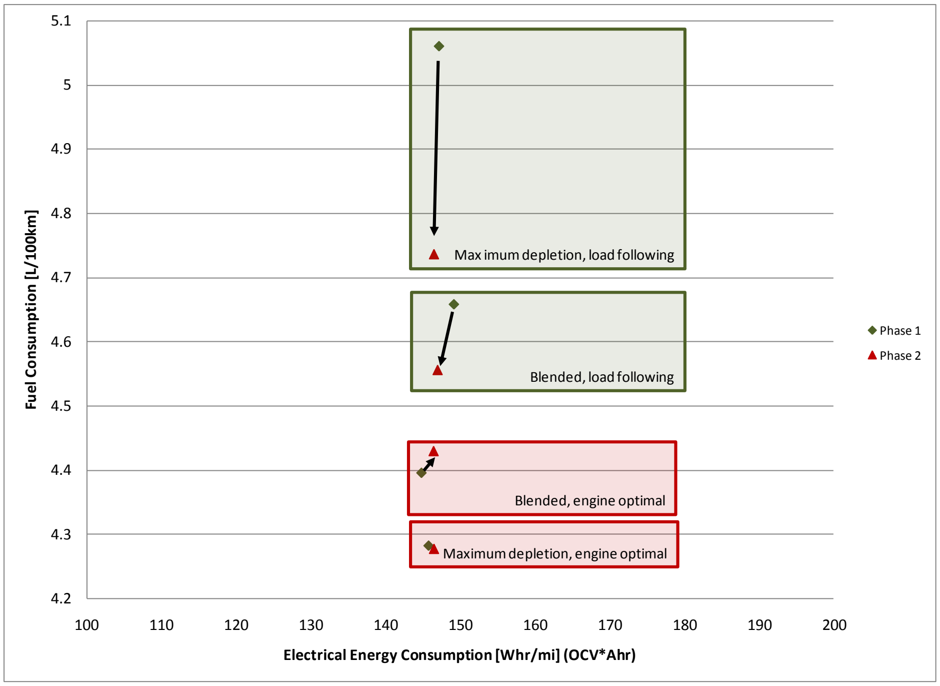

Figure 5. Energy consumption results for Phase II compared to Phase I (aggregate for 6 UDDS cycles)

The most interesting result of Phase II is the substantial reduction in fuel consumption for the load following strategies. Referring to the green highlighted rectangles in Figure 5, a substantial reduction in fuel consumption is observed. This is counter-intuitive when considering the added engine warming strategies and the perceived increase in inefficient use of the engine.

<u>Phase II Maximum Depletion Energy Consumption Results</u>

Figure 6 represents a comparison of actual energy consumption data for Phase II maximum depletion tests, shown as solid lines, to the original Phase I results. Charge balanced operation has not affected fuel consumption substantially, as shown by the coincident y-intercepts. However, there is a pronounced decrease in fuel consumption around the transition point, with a smaller increase visible around the CS region. A closer look into the transition and full CS portions of the test regimen reveals the source of the fuel consumption benefits associated with the emissions reduction algorithms that were implemented for Phase II.

Figure 7 illustrates the cumulative fuel used for the transition and full CS operation tests for the maximum depletion load following cases of both Phase I and Phase II. The full CS operation for both phases, shown as dotted lines, are virtually identical and offer no insight into the fuel savings offered by Phase II. However, there is a distinct amount of fuel saved during the Phase II transition test even though more fuel is consumed at the beginning of the cycle for the engine warming routines.

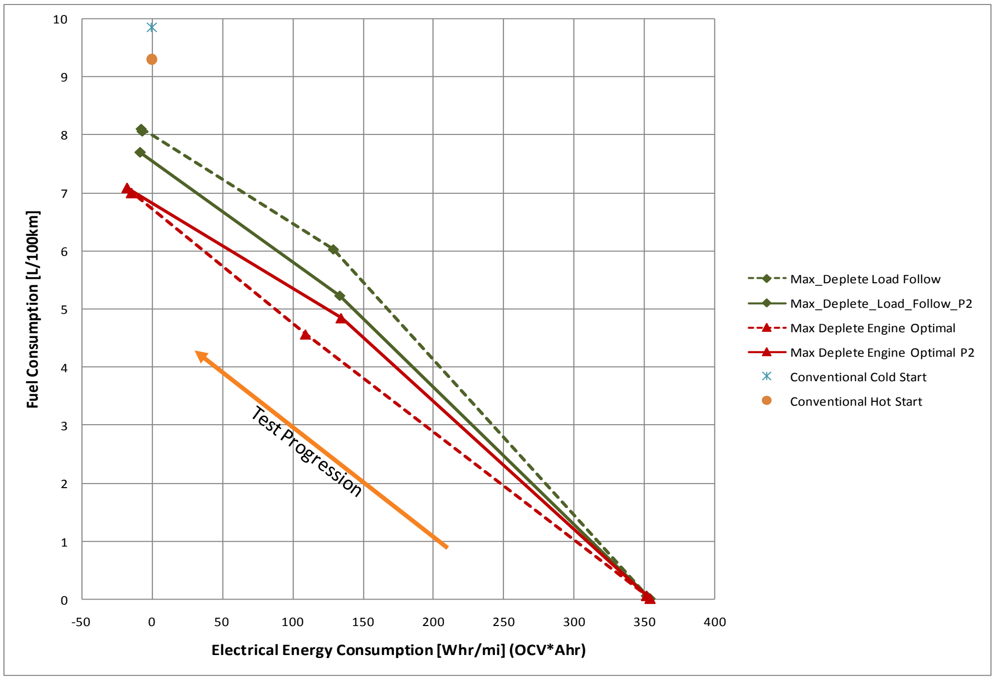

Figure 6. PHEV maximum depletion energy consumption results for Phase II

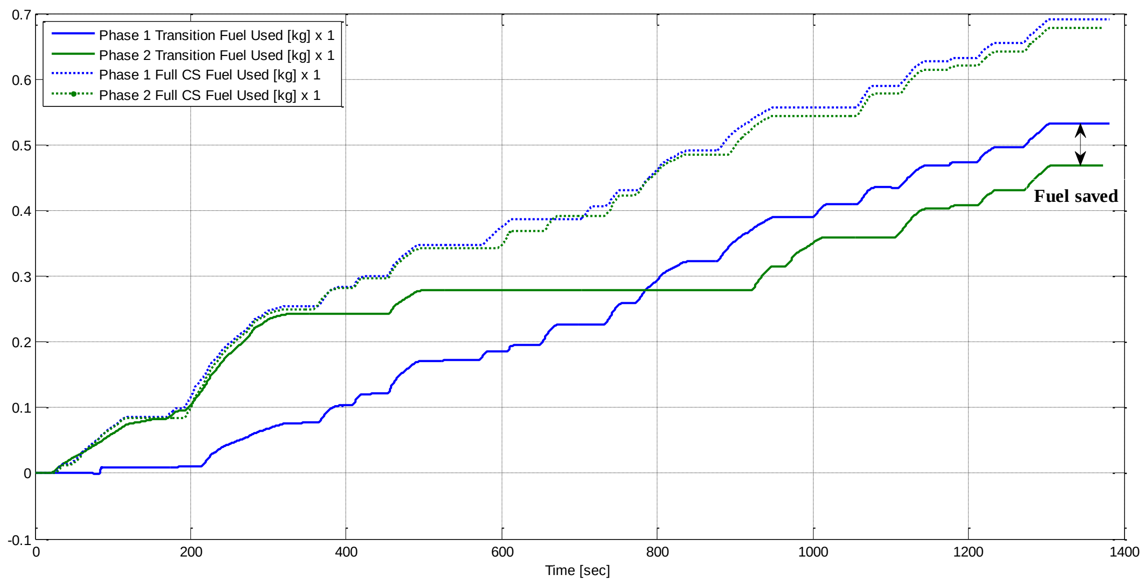

Figure 7. Investigation of fuel consumption reduction for maximum depletion load following strategy

Figure 8 shows the SOC for the same transition test cycle for both Phase I and Phase II. During the transition in Phase II, there is an increase in CP of the battery pack during the engine warming period that is not present in Phase I. This creates the opportunity for a prolonged period of electric only operation that leads into full CS operation later in the test cycle. Therefore, a unique benefit for reduced fuel consumption of PHEVs exists when considering emissions reduction techniques.

The fuel consumption for the maximum depletion engine optimal case exhibits a small increase during the transition cycle as shown in Figure 6. This is due to the cold start warm up routine employed, and the extra fuel required. Figure 9 illustrates actual test data for the cold start events of both Phase I and Phase II. The cumulative fuel data during each cycle clearly shows that even while the Phase II cold start warm up routine consumes more fuel, it is consumed at a much lower rate than for Phase I. Unfortunately, the same fuel consumption benefit is not seen when considering engine optimal operation during the transition period.

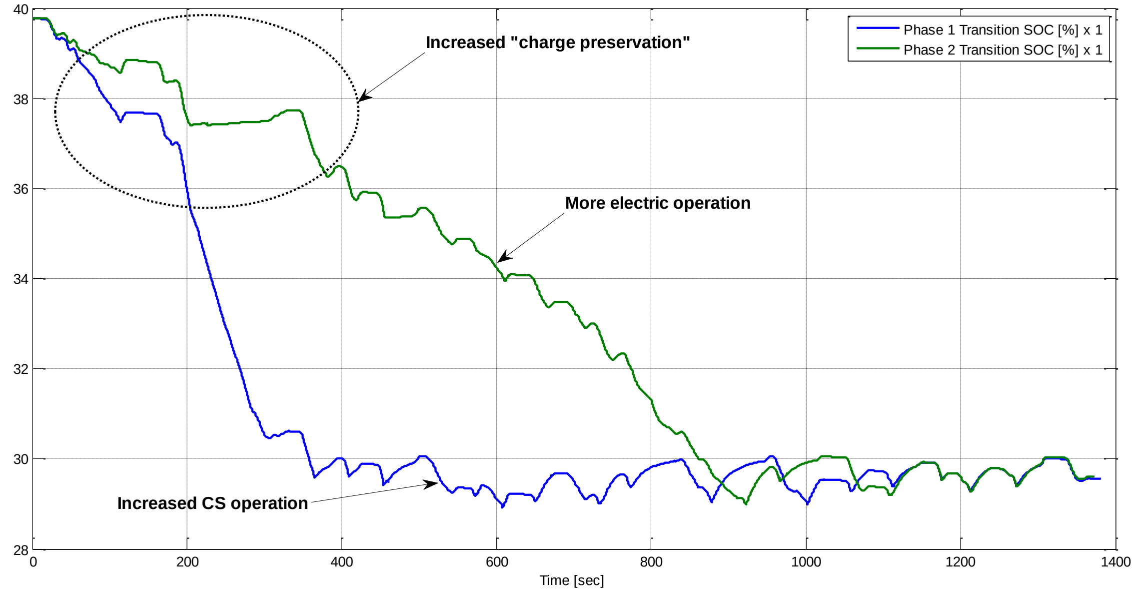

Figure 8. Maximum depletion load following SOC comparison during transition period

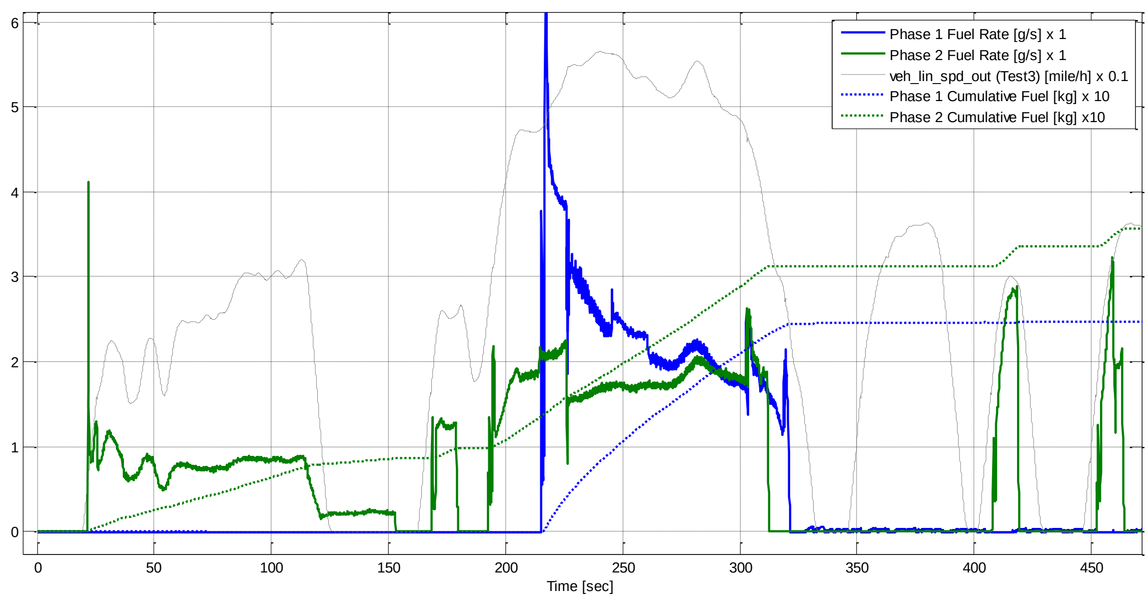

Figure 9. Phase II maximum depletion cold start warm up routine fuel comparison to Phase I (actual test data)

The CP notion does not apply in this case. Figure 10 shows a comparison of the SOC during the transition cycle for both Phase I and Phase II maximum depletion engine optimal tests. While there is still a CP period observed here, it is cancelled out due to the fact that during Phase I the engine is commanded to operate on its most efficient load point. This in turn leads to a very high charge rate for the battery pack. During the same time for the Phase II test, the engine torque is still being limited by the energy based warming strategy, and not charging the battery as quickly. As shown in the figure, the SOC during Phase I almost recovers completely to the level of Phase II, negating the CP region. Each test then exhibits a prolonged period of electric only operation. The fuel penalty for the engine warming strategy is never recovered for the engine optimal case.

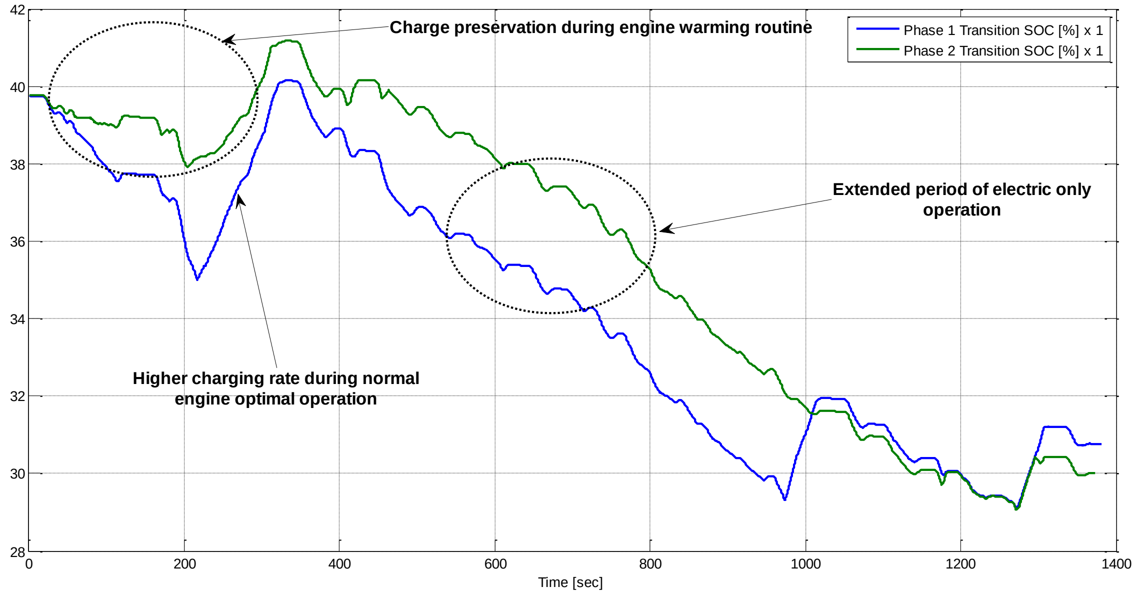

Figure 10. Maximum depletion engine optimal SOC comparison for Phase I and Phase II

Phase II Blended Operation Energy Consumption Results

Figure 11 represents a comparison of actual energy consumption data for Phase II blended operation tests, shown as solid lines, to the original Phase I results. For both engine optimal and load following cases, the Phase II cold start consumes more fuel as compared to Phase I results. This is due to the engine warming strategy and the associated continuous operation of the engine until completely warm. Also, there is more engine operation due to the variable CD engine power on threshold. This creates more CP periods during CD operation. This has divergent effects on the load following and engine optimal approaches.

Since more time is now spent in the CD region, there is less full CS operation. Recall that for the engine optimal blended cases, the modified load following algorithm is used during CD operation. Thus, if more time is spent in the CD region, a greater percentage of the total operating regime is load following, and not engine optimal. This leads to the increased fuel consumption demonstrated in Figure 11.

This has the exact opposite effect when considering the load following case. More time in the CD region means more electric operation and less time spent in the CS region. From a load following perspective, this is more efficient. Obviously, less fuel is burned in the CD region for the load following strategy, meaning that more time spent in the CD region is advantageous.

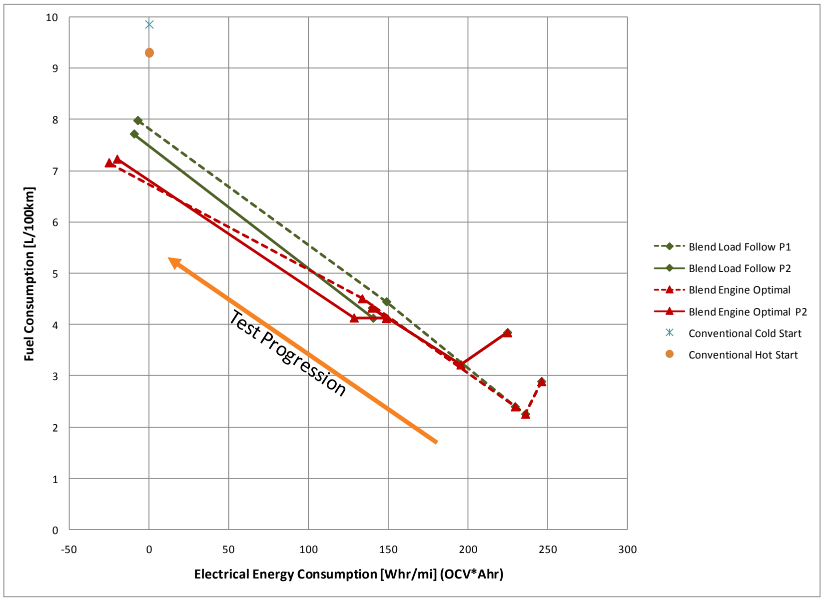

Figure 11. Energy PHEV blended energy consumption results for Phase II

PHASE II TAILPIPE EMISSIONS RESULTS

Now that the energy consumption effects have been identified, the emissions impacts can be explored to determine if the applied cold start algorithms and emissions reduction techniques provide “greener” operation for this test platform.

Figure 12 represents the culmination of Phase I and Phase II in terms of the actual emissions impacts of the improved control strategies. Clearly, the emission reduction methods implemented into each of the control strategies have led to a substantial reduction in both NMOG and NO_x emissions from the test platform. Each of the four (4) strategies now attains SULEV emissions levels, with minimal negative effects on energy consumption as outlined in the previous section. In addition, all four (4) strategies result in NO_x emissions below that of the conventional vehicle.

The following sections discuss the emissions reductions, on a cycle by cycle basis, associated with each version of the maximum depletion and blended control strategy approaches.

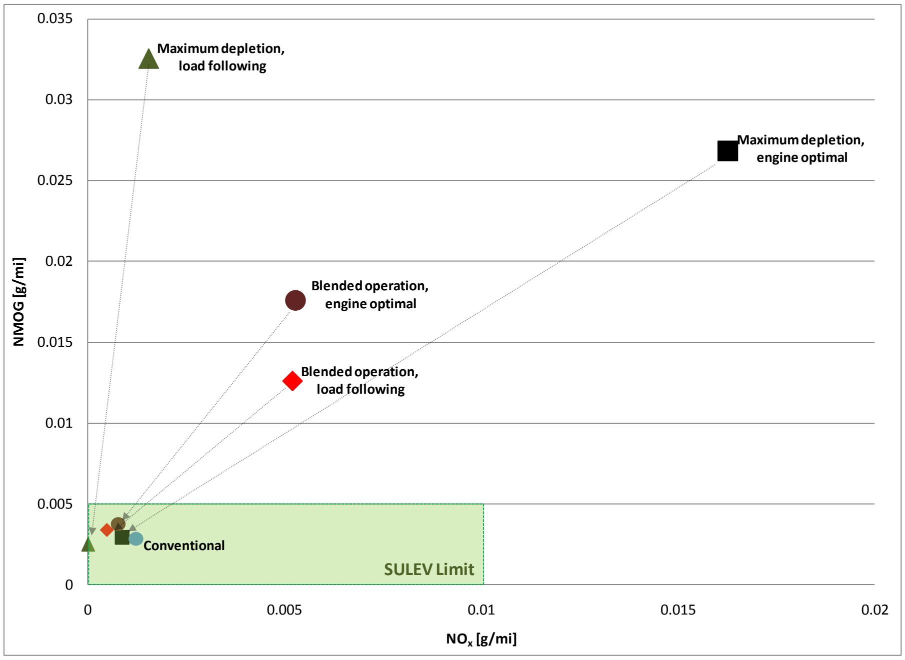

Figure 12. Emissions results summary for Phase II showing overall improvements over Phase I

Phase II Maximum Depletion Emissions Results

Beginning with the maximum depletion cases, Figure 13 presents the cycle by cycle Phase II THC emissions results. The Phase II results, shown by the solid lines, are plotted against the Phase I results discussed earlier. It is clear that the THC emissions levels are significantly reduced, but still exhibit the same trend during the transition cycle due to the first engine cold start.

The engine warming algorithms have the greatest impact on the maximum depletion load following strategy, with a reduction in THC emissions by a factor of approximately ten (10) on a grams per mile basis. Figure 14 shows a comparison of the cold start for this strategy in both Phases I and II. The pre-warm up strategy lightly loads the engine and allows the exhaust temperature to rise to its normal working temperature (the primary catalyst temperature was not logged since it was being used as an input to the VSCM for the purposes of the revised Phase II strategy). For this reason, the THC emissions are very low for the Phase II approach. When the engine starts for Phase I, under high engine speed conditions, a substantial amount of THC emissions are produced for a relatively low load on the engine. This is due to the fact that the engine is being operated under cold conditions at high speeds. Once the exhaust temperature rises, the THC emissions output is reduced.

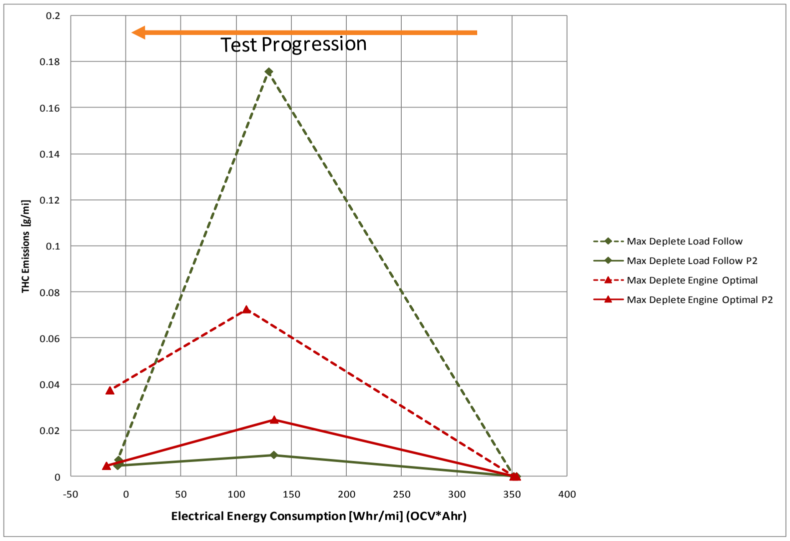

Figure 13. Comparison of THC emissions results for maximum depletion PHEV operation of Phase II to Phase I

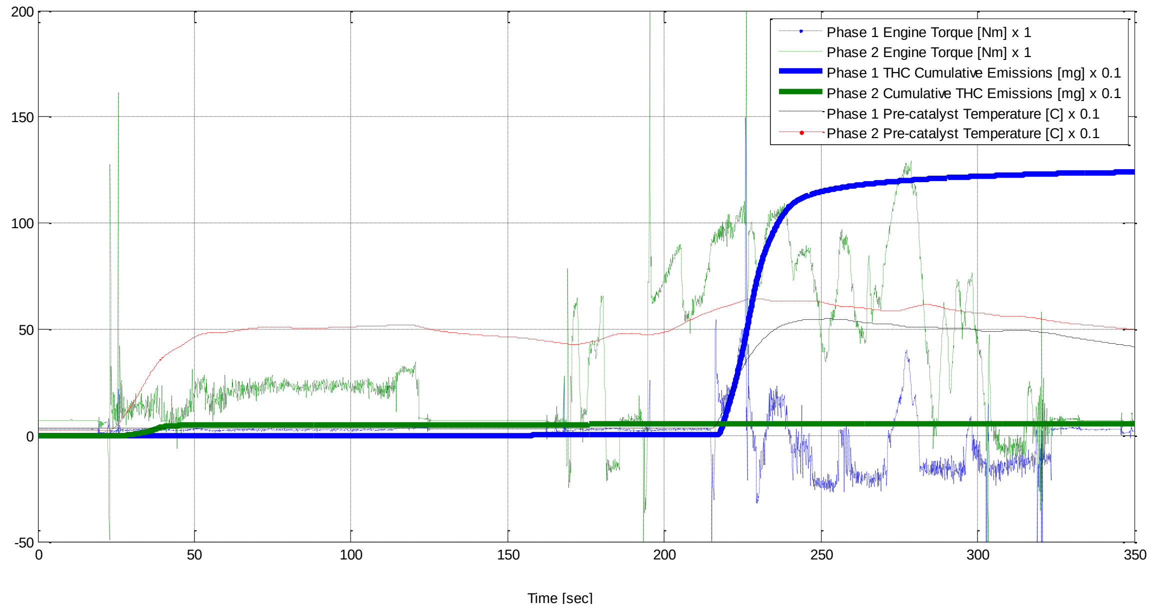

Figure 14. Comparison of THC emissions for Phase I and Phase II maximum depletion load following strategy

The full CS operation THC emissions have also been reduced as shown in Figure 13. The engine and relevant subsystems are all up to normal operating temperatures for this stage of the test. The hot start engine torque ramping algorithm can be credited with the reduced THC emissions for Phase II. Figure 15 shows a magnified portion of the UDDS during CS operation. Here, the Phase II engine torque is ramped up more gradually, as compared to the almost immediate torque output of the engine for Phase I. A very large spike in THC emissions results from the immediate loading of the engine, even under warm conditions. The THC emissions associated with Phase II are far lower, indicating the positive effects of engine torque ramping on the reduction of THC emissions.

It should also be pointed out that there are drivability concerns with the engine optimal operation, particularly with Phase I. The sudden torque demand was noticeably rough. The torque ramping algorithm provided a much smoother transition of the engine torque to the wheels, and did not seem as "violent" or aggressive as Phase I.

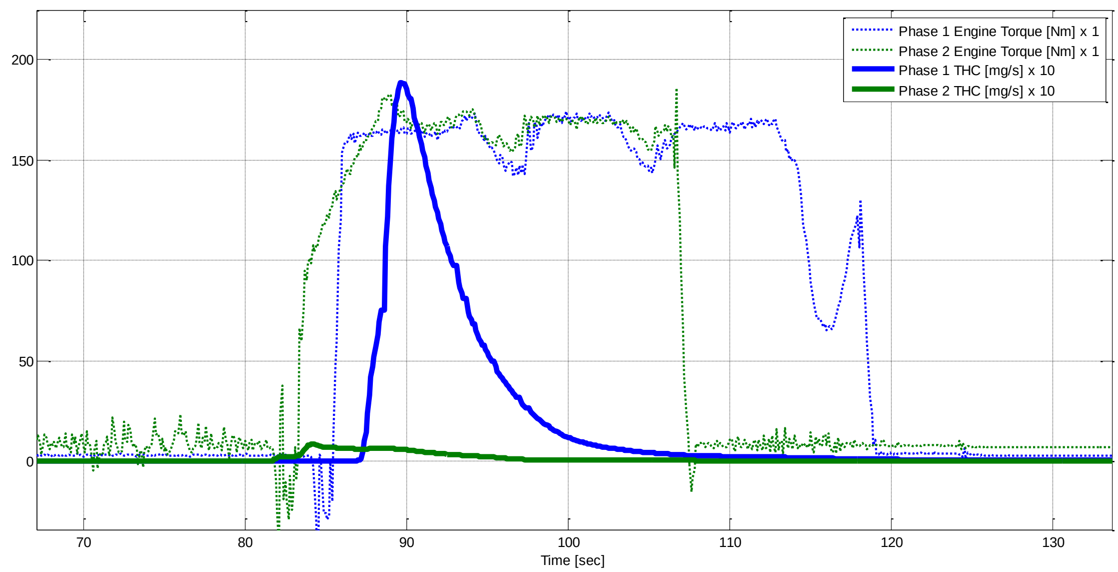

Figure 15. Engine optimal full CS operation showing benefits of engine torque ramping on THC emissions

Figure 16 depicts the NO_x results on a cycle by cycle basis for the maximum depletion tests ran for Phase II, and plots them against Phase I for comparison. Here, the NO_x emissions were virtually eliminated for all portions of the test. The reduced loading of the engine during the main warm up and subsequent torque smoothing are very effective for reducing NO_x emissions.

Figure 17 illustrates the CO emissions results for Phase II. The load following strategy exhibits typical CO producing behavior, and appears to still be proportionate to the number of engine starts. The engine optimal case actually exhibits a reduction in CO emissions for full CS operation. CO typically follows the same trends as THC, and as such, the engine torque smoothing algorithm is credited with this reduction.

It is worth noting that the reduction in tailpipe emissions for the maximum depletion cases was achieved while simultaneously preserving the all electric CD operation. Assuming the operator commutes a distance of no greater than 15 miles of urban driving, these algorithms would provide zero emissions and infinite fuel economy (with the cost of grid electricity being ignored) due to all-electric operation and an assumed fully charged battery pack. In addition, should the driver desire to drive further, SULEV emissions are attainable with no preliminary engine start at key-on.

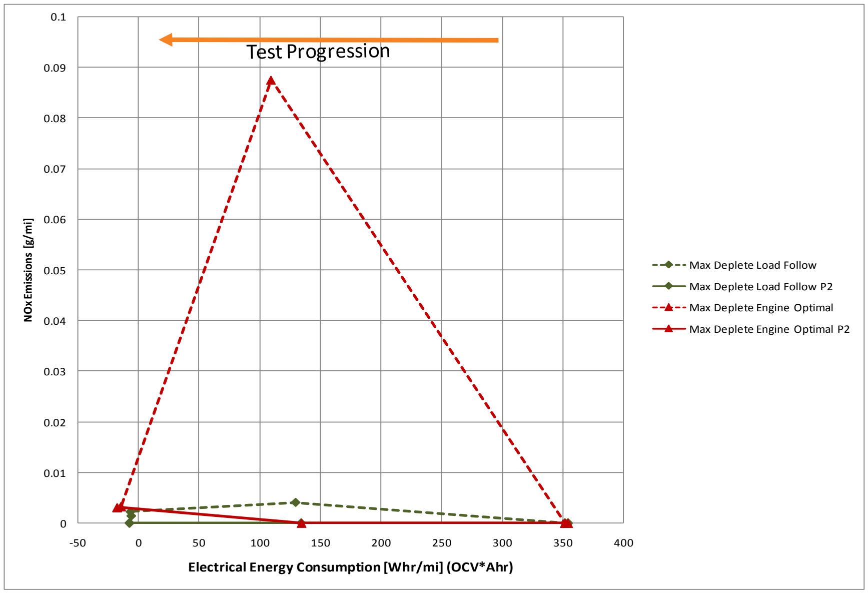

Figure 16. Comparison of NO_x emissions results maximum depletion PHEV operation of Phase II to Phase I

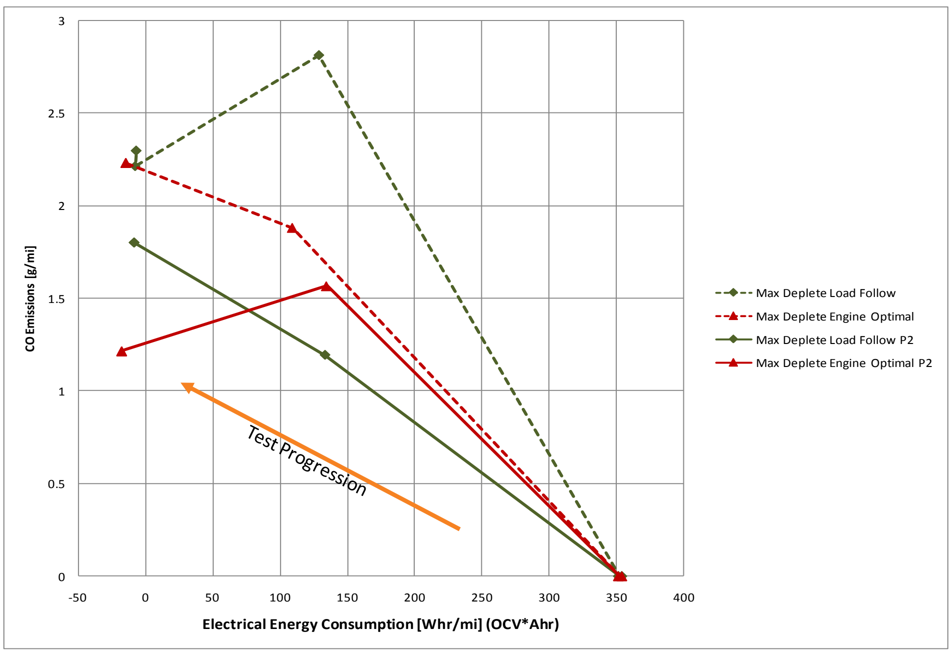

Figure 17. Comparison of CO emissions results maximum depletion PHEV operation of Phase II to Phase I

<u>Phase II Blended Strategy Emissions Results</u>

As shown earlier, the blended strategy offers superior fuel economy for the load following case, and comparable fuel economy for the engine optimal case when compared to the maximum depletion strategies. Figure 18 shows the THC emissions for Phase II blended strategies compared against Phase I. Dramatic reductions in THC emissions are achieved, particularly with respect to the first engine cold start. The effects of the engine warm up strategy can also be seen as a reduction in the electrical energy consumption, represented by a shift of the first cycle data point on the far right of the graph. This is simply due to the more frequent use of the engine, and the additional CP periods provided by this strategy. Another interesting characteristic of this control strategy is the “zig-zag” in the trace as the test cycle progresses from right to left. This is where the control strategy transitions from CD operation into full CS operation.

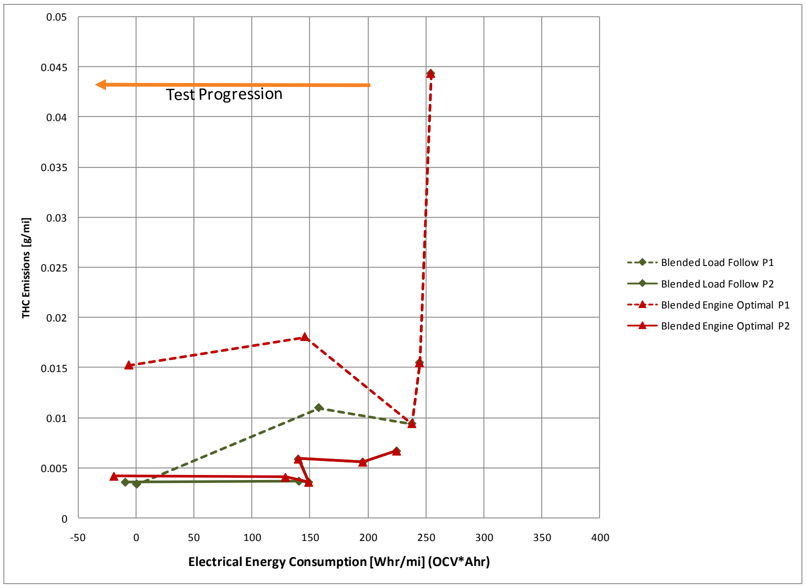

Figure 18. Comparison of THC emissions results blended PHEV operation of Phase II to Phase I

Figure 19 summarizes the NO_x emissions results for each of the Phase II blended strategies. Again, superior reductions in NO_x emissions are achieved. This is due primarily to the gradual warming of the engine through the pre-warm strategy and energy based main warming strategy coupled with torque smoothing during engine starts. The large spike in NO_x, as a result of the cold engine start from Phase I, has been eliminated.

Figure 20 illustrates the carbon monoxide results for the Phase II blended strategies. Here, a large reduction in CO emissions is evident, particularly with respect to the first engine cold start of Phase I. The load following case for Phase II still exhibits the increasing CO emissions trend as the SOC approaches full CS operation. This is attributed again to the increasing number of engine starts for each successive test cycle.

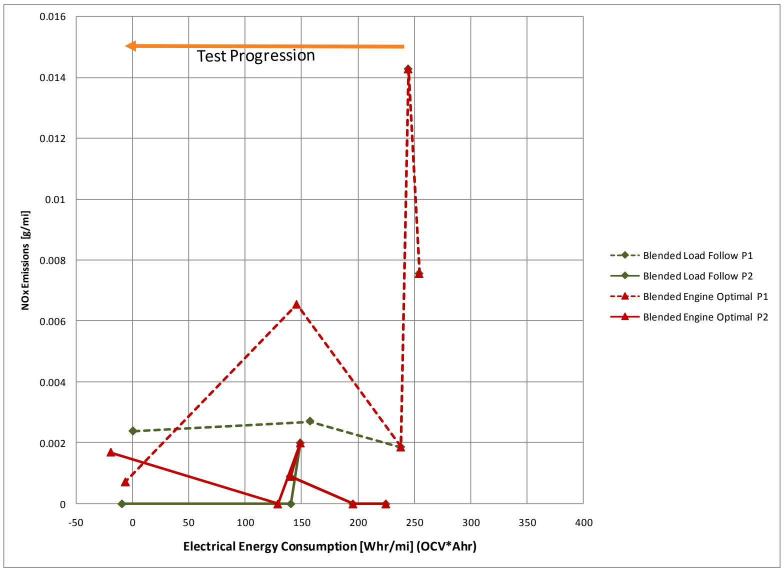

Figure 19. Comparison of NO_x emissions results blended PHEV operation of Phase II to Phase I

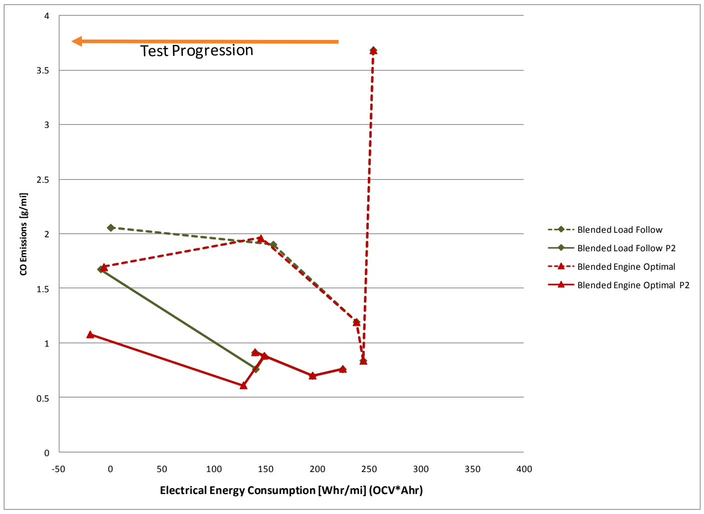

Figure 20. Comparison of CO emissions results blended PHEV operation of Phase II to Phase I

The engine warming algorithms implemented into the VSCM produce much lower tailpipe emissions than the Phase I approach for these blended strategies. The net effect of these algorithms is two-fold. The first benefit of this approach is to reduce and smooth the loading of the engine during both cold and hot engine starts. The second effect is to operate the engine more frequently. In doing so, the operating temperatures of the engine system remain higher during the test cycles, allowing for increased conversion efficiencies in the primary and secondary catalysts.

Figure 21 illustrates the comparison of pre-catalyst exhaust gas temperatures for the blended load following strategies implemented for Phase I and Phase II, respectively. The effects of the pre-warming strategy can be clearly seen at the beginning of the test cycle. During CD operation, the pre-catalyst temperature stays significantly higher for the Phase II application, and the secondary catalyst warming strategy is shown taking effect when the gas temperature drops below 200 °C. The pre-catalyst exhaust gas temperature is higher throughout all of the UDDS drive cycles for Phase II, indicating that the primary and secondary catalysts remain effective for a greater percentage of the time (due to the thermal mass of the catalyst bricks, the catalysts cool much slower than the pre-catalyst exhaust gas).

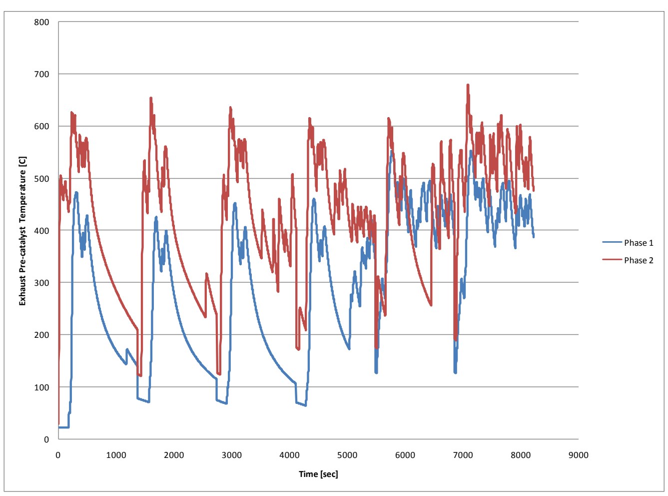

Figure 21. Comparison of pre-catalyst exhaust gas temperatures for blended load following PHEV operation

SUMMARY/CONCLUSIONS

PHEVs do have the potential for substantial reductions in fuel consumption for the transportation sector. However, care must be taken when designing and implementing PHEV supervisory control strategies such that the tailpipe emissions are not adversely effected. When and how the engine is operated in PHEVs is critical to the success and of these perceived “green” vehicles.

In this research, tailpipe emissions from a PHEV test platform have been reduced through the development and refinement of vehicle supervisory control methods. Baseline energy management strategies were developed with respect to maximizing fuel economy alone. These strategies include “cold” engine starting under high load demands, which was verified to be ineffective with respect to emissions reduction. Lower emissions were achieved with improved control algorithms for this representative PHEV with substantial EV operation over that of a conventional vehicle.

Engine cold start events were aggressively addressed, which led to enhanced engine warming and pre-warming algorithms. Key–on engine starting was employed to mimic conventional vehicle operation; however, the results of this research indicate that this is not mandatory for successful reduction of tailpipe emissions. The engine pre-warming and warming techniques provided substantial reductions in emissions over the baseline PHEV control strategies.

The flexibility of the PHEV powertrain allowed for decreased emissions during engine starting events through powertrain “torque shaping” algorithms. The focus of these enhancements was to replace high engine torque demands during starting with “clean” electric motor torque. This approach proved very effective for the reduction of NO_x emissions.

The results of the research indicate that the impacts on fuel consumption were minimal for the emissions reduction techniques that were applied. In fact, the engine start torque ramping and warming strategies actually decreased fuel consumption for each of the load following strategies due to “engine optimal” like operation.

REFERENCES

1. Advanced Energy Initiative. The White House National Economic Council, 2006.
2. Carlson, Richard W. "Testing and Analysis of Three Plug-In Hybrid Electric Vehicles." SAE 2007-01-0283, 2007.
3. Gonder, Jeffrey, and Andrew Simpson. "Measuring and Reporting Fuel Economy of Plug-In Hybrid Electric Vehicles." EVS-22. Yokohama, Japan, 2006.
4. Gonder, Jeffrey, and Tony Markel. "Energy Management Strategies for Plug-In Hybrid Electric Vehicles." SAE 2007-01-0290, April 2007.
5. Karbowski, Dominick, Chris Haliburton, and Aymeric Rousseau. Impact of Component Size on Plug-In Hybrid Electric Vehicle Energy Consumption Using Global Optimization. Argonne National Laboratory, 2008.
6. Lohse-Busch, Henning. "A Modular Automotive Hybrid Testbed Designed to Evaluate Various Components in the Vehicle System." 2009.
7. Muta, K. "Development of new-generation hybrid system THS II - Drastic improvement of power performance and fuel economy." SAE 2004-01-0064, 2004.
8. O'Keefe, M.P., and Tony Markel. Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-In HEV. NREL/CP-540-40376, National Renewable Energy Laboratory, November 2006.

9. Plug-In Hybrid Electric Vehicle R&D Plan. Washington D.C.: US Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Program, February 2007.
10. Rajagopalan, G. Washington, G. Rizzoni, and Y. Guezennec. Development of Fuzzy Logic and Neural Network Control and Advanced Emissions Modeling for Parallel Hybrid Vehicles. NREL/SR-540-32919, Ohio State University, December 2003.
11. Rousseau, Aymeric, and Sylvain,Gao,David Pagerit. Plug-In Hybrid Electric Vehicle Control Strategy Parameter Optimization. Argonne National Laboratory, 2008.
12. Sharer, Phil, Aymeric Rousseau, Sylvain Pagerit, and Dominick Karbowski. "Plug-In Hybrid Electric Vehicle Control Strategy: Comparison between EV and Charge-Depleting Options." Presentation to US DOE. Argonne National Laboratory, May 2008.
13. Stone, Richard. Introduction to Internal Combustion Engines Second Edition. Society of Automotive Engineers, 1995.
14. United States Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Program. Vehicle Technologies Program: Plug-in Hybrid Electric Vehicles. 2008. http://www1.eere.energy.gov/vehiclesandfuels/technologies/systems/phev.html (accessed 2008

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