I. COMPONENTS & SYSTEMS

I.A. 1000195.00 PHEV Engine Control and Energy Management Strategy

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I.A.1. Abstract

Objective

- Investigate novel engine control strategies targeted at rapid engine/catalyst warming for the purpose of mitigating tailpipe emissions from plug-in hybrid electric vehicles (PHEV) exposed to multiple engine cold start events.
- Validate and optimize hybrid supervisory control techniques developed during previous and on-going research projects by integrating them into the vehicle level control system and complementing them with the modified engine control strategies in order to further reduce emissions during both cold start and engine re-starts.

Approach

- Optimize engine cold start strategies on stand-alone engine
  - Implement best in class engine control strategies in open source controller
  - Improve/optimize strategies to reduce cold start emissions
- Engine-In-the-Loop (EIL) system testing
  - Develop EIL platform suitable for PHEV emulation
  - Port Autonomie™ model into EIL platform
  - Commission and validate EIL system on test cell
- Optimize plug-in hybrid supervisory strategies and engine control strategies as a system in order to reduce tailpipe emissions on the EIL test stand
  - Integrate and improve hybrid supervisory control strategies from previous ANL-ORNL simulation-only study
  - Concurrently optimize both control strategies (engine and hybrid) as a system

Major Accomplishments

- Optimized cranked and motored cold start strategies on stand-alone engine
- Commissioned Engine-In-the-Loop on test cell, therefore allowing the emulation of a virtual vehicle while having actual engine and after-treatment measurements
- Optimized powertrain emissions as a system by coordinating engine control strategies and vehicle supervisory strategies

Future Activities

- FY12 is the final year of this project

I.A.2. Technical Discussion

Background

Plug-in hybrid electric vehicle (PHEV) technologies have the potential for considerable petroleum consumption reductions, 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 have a significant impact on the tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current conventional vehicles as well as 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.

Previous research had focused on the design of a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. Engine cold start events were aggressively addressed by only modifying vehicle supervisory strategies while retaining the base engine control strategies which were intended for a conventional (non-hybrid) powertrain. This led to enhanced pre-warming and energy-based engine warming algorithms that provide substantial reductions in tailpipe emissions over the baseline supervisory control strategy. Yet the system was not thoroughly optimized due to the lack of access to engine control strategies.

During FY11, an open calibration engine controller for a GM Ecotec LNF 2.0l Gasoline Turbocharged Direct Injection engine was obtained thanks to the support of Robert Bosch LLC. That controller allows control strategies to be modified and calibration to be tuned differently from the production settings, so that they can be optimized for our hybrid application. The LNF engine and its open controller were commissioned on an engine test cell at ORNL. A literature search was performed to identify key engine cold start control parameters. Their impact on engine-out emissions was characterized with the LNF engine on a test stand using the Bosch engine controller to calibrate them.

Introduction

This project expands the work performed so far on hybrid vehicle supervisory strategies to include engine control strategies in order to proceed with a system approach of the powertrain control strategies optimization rather than independent component optimization.

Gasoline direct injection engines with variable valve timing, such as the one identified for this project, offer more degrees of freedom to optimize cold start emissions than port fuel injected engines. Their operating envelope will also vary in the case of a hybrid powertrain compared to a conventional powertrain. Therefore engine control strategies should be calibrated first to make the most of those added degrees of freedom specific to the GDI technology and second, to take advantage of the operating conditions specific to hybrid powertrain.

This project will focus on adapting the conventional engine calibration to a hybrid powertrain application as well as optimizing cold start engine strategies. Then cold start emissions will be targeted by jointly optimizing both vehicle supervisory strategies and engine control strategies.

Approach

The LNF engine and its Bosch open controller that was benchmarked during FY11, has been moved out from the ORNL facility and commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility, so that it can be integrated with the Hardware-In-the-Loop system there. This will, in turn, allow emulating a virtual hybrid vehicle and test cold start emissions for that vehicle configuration.

That testcell was upgraded with a new data acquisition system from DyneSystems based on National Instruments hardware and software, it is integrated with the dyno controller and capable of thermocouples and analog inputs. The testcell was also fitted with a new 2-channel 5-gas emissions bench analyzer from California Analytical Instruments for pre and post catalyst emissions characterization. Those pieces of equipment were commissioned only after the engine-only testing phase. Prior to their installation, a portable emissions measurement system from Sensors Inc, a SEMTEC DS, was used. Thermocouples were also fitted to the exhaust system to measure pre-catalyst temperature as well as catalyst brick temperatures (See Figure 1), thereby allowing to characterize the thermal behavior during a cold start.

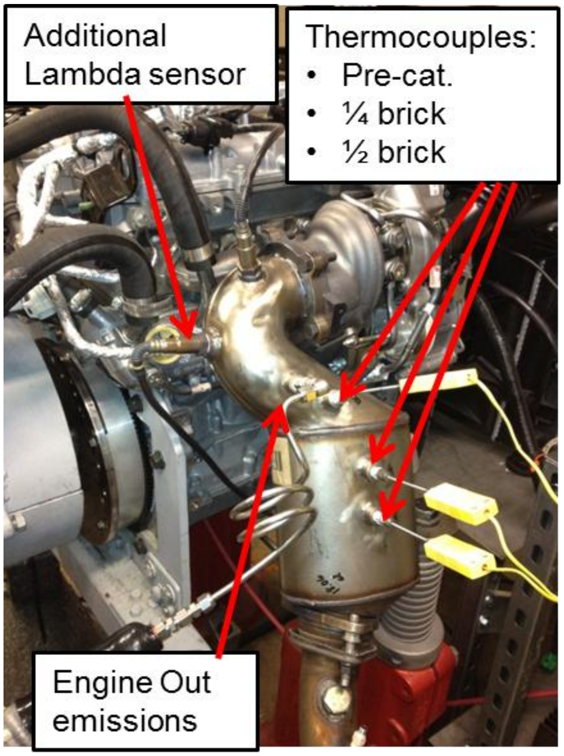

Figure 1. Exhaust and after-treatment instrumentation

In order to ensure that cold start behavior is representative of the in-vehicle installation, the engine was fitted with its production air intake and exhaust system, as well the production coolant loop including thermostat and radiator. The heater core loop was modified to be used as a means to provide external cooling between runs so that, after a true cold that can happen only once a day, subsequent pseudo cold starts can be performed. Pseudo cold starts are defined when the engine coolant has cooled down to 25 degC between tests and the exhaust and catalyst brick temperature has returned to ambient temperature too.

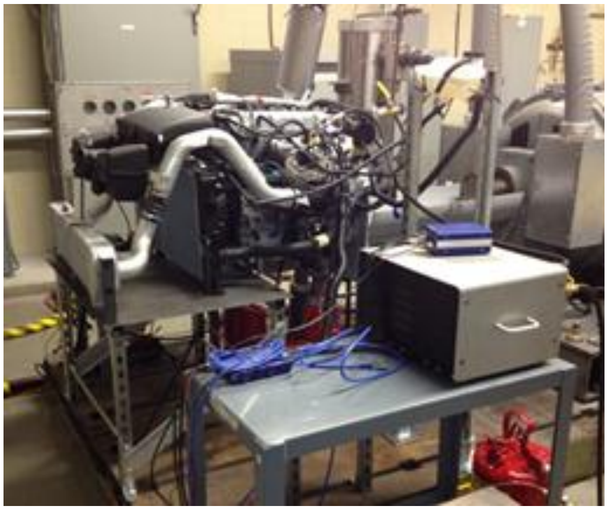

Figure 2. Ecotec LAF engine commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility

The literature search performed prior in this project had identified a few key features to speed up catalyst warm-up on a gasoline direct injection engine: elevated idle speed, elevated idle load, dual injection (early injection during the intake stroke and late injection during the compression stroke), extremely retarded spark timing, limited start enrichment and lean operation during post start, elevated fuel rail pressure, retarded exhaust cam timing and high pressure compression stroke injection cranking (stratified cranking). All those features are currently in–use on the Bosch ECU except for stratified cranking.

The engine-only testing phase of that project will characterize the effect of that additional feature (stratified cranking). Then the effort will focus on optimizing the engine operation and calibration envelope to make the most of the properties of the series PHEV powertrain architecture, where the electric generator can supplement the engine. For instance, the engine can be motored up to various speeds by the hybrid drive generator. So the effects of motored starts compared to starter motor starts will be quantified, as well as the effects of different idle speed during catalyst warm-up. Another operating mode specific to series hybrid is that the engine does not need to generate torque early on after being fired since the engine is decoupled from the wheels. So the generator can be used to smooth out engine operation, allowing the generator to push the operating envelope of the engine. Two examples of different operating conditions whose effects have been characterized are increased idle load and idle speed as well as additional spark retard during warm-up.

A Hardware-in-the-loop platform was fully commissioned on the University of Tennessee testcell to run as an engine-in-the-loop configuration of a virtual plug-in hybrid vehicle. The real engine and after-treatment are physically installed on the test stand while a real time computer runs a virtual model of hybrid powertrain and vehicle implemented with Autonomie^{TM}. It also runs a virtual drive cycle and model of a driver. The real time platform is interfaced to the dynamometer controller and engine controller over analog and digital inputs and outputs (see Figure 3).

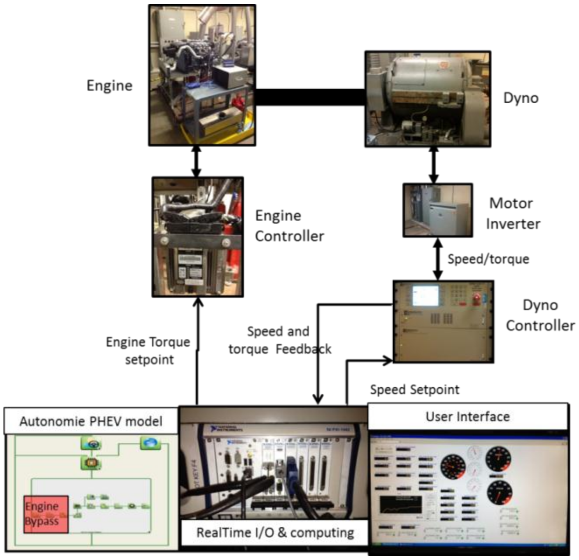

Figure 3. Diagram of Engine-In-the-Loop configuration

This set-up enables the evaluation of an actual engine behavior for a specific virtual vehicle configuration providing the flexibility to change virtual powertrain configurations and test conditions of virtual test environment, as well as offering the accuracy of real engine and after-treatment measurements. This set-up is therefore critical to optimizing the vehicle as a system by coordinating both engine control strategies and hybrid supervisory control strategies.

Results

ENGINE-ONLY OPTIMIZATION

Comparison of starter motor starts and motored starts

A starter motor start is defined as a conventional start where the engine is decoupled from the dynamometer, and the starter motor is used to crank the engine. By contrast, a motored start is when the engine is coupled to an electric machine powerful enough to motor up the engine to an elevated idle speed. For evaluation purposes, the engine is coupled to the dynamometer and motored up to the elevated idle speed of 1400rpm but fired once engine speed exceeds 1100rpm. This method has the benefit of removing a highly transient phase when engine is cold and therefore has the potential to reduce tailpipe emissions.

The dynamometer maximum ramp up rate was limited to 500rpm/s due to its large inertia. This is much slower than would be achievable by a properly sized machine in a series PHEV configuration. Yet, test results showed that motored starts with delayed injection showed a 12% improvement of engine out total hydrocarbon emissions over a conventional cold start, whereas the reduction reaches 38% on stratified starts. See Figure 4 for instantaneous results in the case of homogenous injection during cranking.

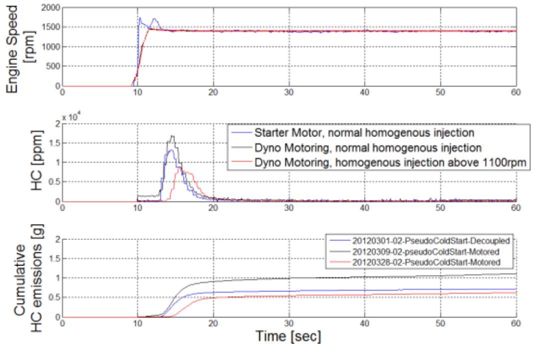

Figure 4. Starter motor starts versus motored starts.

<u>Effect of stratified cranking</u>

Stratified cranking is defined as high pressure late compression stroke injection during engine start. That injection mode was performed both for starter motor starts, as well as motored starts.

In both cases, it did not affect the engine out thermal behavior: post turbo temperature rise time was within half a second of each other which is about the test-to-test variability. Both injection strategies demonstrated a reduction in total hydrocarbon: 53% when motoring and 34% when cranking with a starter motor. Figure 4 shows a trace of injection timing, total hydrocarbons and post turbo temperatures when cranking the engine with a starter motor.

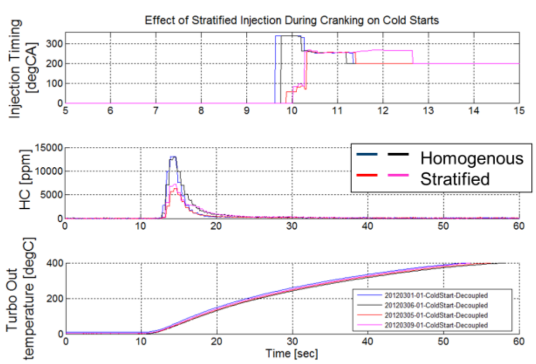

Figure 5. Injection timing, total hydrocarbons and post-turbo temperature for homogenous and stratified cranking when cranking the engine with a starter motor

<u>Effect of elevated idle load</u>

In order to speed up catalyst warm-up, the idle speed and load were increased. The expectation is that more hot gases going through the catalyst will speed up its warm-up.

For those tests, only one gas analyzer was available. It was used to sample engine out emissions. Different cold start strategies are compared my measuring the time it takes for the temperature at the front of the catalyst brick (2inches inside the brick) to reach 350deg which is considered the light off temperature. Emissions are integrated up to that point to estimate what would go past the catalyst as it would be inefficient before light off.

Controlling idle speed alone is not enough because the ECU regulates airflow down to the same level regardless of the idle speed. So there was no impact on catalyst warm-up, though it did generate lower NO levels.

Idle load level was increased by 10, 20 and 30%, while maintaining idle speed at 1400rpm and keeping all other cold start calibration parameters unchanged too. It resulted in faster catalyst light off (as much as 32%) without any hydrocarbon penalty but it yielded higher NO emissions (see figure 6)

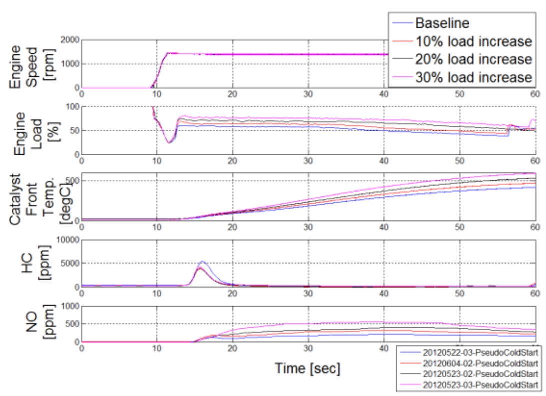

Figure 6. Effect of higher idle load on catalyst warm-up

Elevated idle loads were tested at different idle speeds (1400, 1700 and 2000rpm) on pseudo cold starts conditions and as well as true cold starts.

For all speeds, increasing idle load yields:

- Faster catalyst warm-up
- Comparable HC emissions
- Larger NO emissions

NO emissions increase can be offset by operating at higher speeds, but higher speeds yields higher HC too.

The optimum point is measured to be 1700rpm and 20% increased idle load, where catalyst warm-up is 22% faster, hydrocarbons emissions are 27% smaller and Nitrogen Oxide emissions are comparable to baseline. See figure 7, 8 and 9

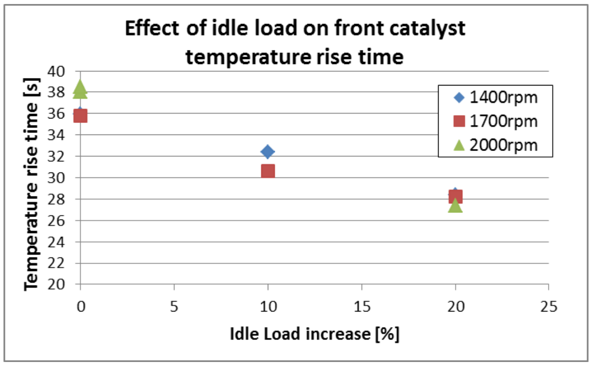

Figure 7. Effect of higher idle load and speed on catalyst warm-up

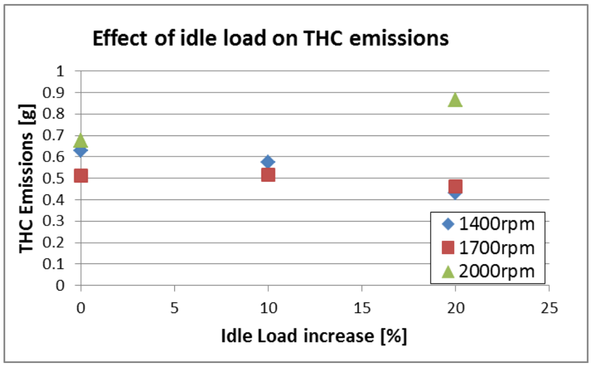

Figure 8. Effect of higher idle load and speed on Total Hydrocarbon engine out emissions

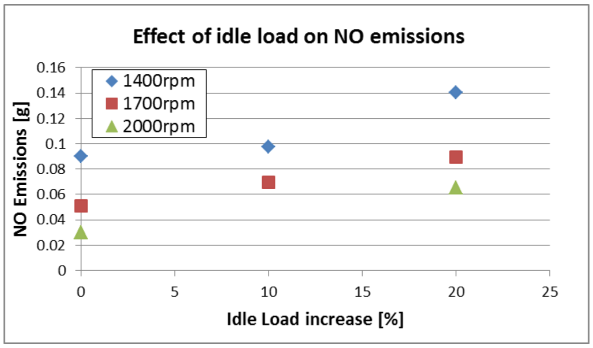

Figure 9. Effect of higher idle load and speed on Nitrogen Oxide engine out emissions

Effect of additional spark retard

The following tests evaluate the benefits of retarding spark even more during catalyst heating mode to increase exhaust heat and speed up catalyst light off.

Baseline calibration runs about 20deg spark retard in HSP mode during catalyst heating mode at 1400rpm. The calibration is modified to further retard spark timing (3, 6 and 12 deg). All other parameters (such as load, injection mode and timing) are left unchanged. Increasing spark retard did heat up the catalyst faster (as much as 13%) without any hydrocarbon penalty and slightly higher NO emissions.

Several levels of spark retard were tested at different idle speeds (1400, 1700 and 2000rpm) on pseudo cold starts. For all speeds, increasing spark retard yields faster catalyst warm-ups. HC emissions trend higher at 1700rpm, trend lower at 1400rpm and deteriorate drastically when increasing spark retards past 6deg at 2000rpm. NO emissions tend to trend higher with spark retard. The optimum setpoint was measured at 1700rpm where it speeds up catalyst heating (up to 12% faster) without affecting emissions. See Figure 10.

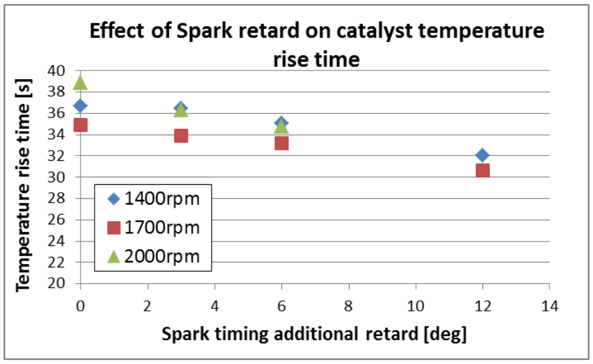

Figure 10. Effect of additional spark timing retard on catalyst warm-up

Additional tests were carried out by combining increased idle load and spark retard during catalyst heating mode. They showed that that phase can be shortened by 25-30% from 35-36seconds to 25seconds (See Figure 11).1400rpm maintains HC levels but worsen NO whereas 1700rpm maintains NO (relative to production calibration) and worsen HC. The selection of optimal idle speed will therefore be determined based on cycle emissions whether the emphasis is on NO or HC reduction for that platform.

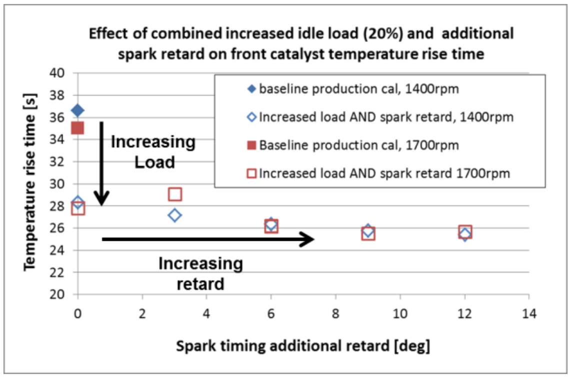

Figure 11. Effect of combining increased idle load and additional spark timing retard on catalyst warm-up

Table 1. Hydrocarbon emissions over 505 cycle depending on coordination strategies between engine and hybrid strategies.

Test condition	Engine out HC accumulation [g]	Improvement [%]
Baseline, no warm-up standard 200rpm injection	10.76	NA
No warm-up. Injection above 1100rpm	6.05	-44%
Idle Warm-up only. Injection above 1100rpm	3.21	-70%
Low load warm-up. Injection above 1100rpm	5.14	-52%
Idle warm up then low load warm-up . Injection above 1100rpm	3.65	-66%

SYSTEM LEVEL OPTIMIZATION

Series PHEV configuration offers great opportunity to optimize engine warm-ups because the engine is decoupled from the driver demand. But gains obtained by optimizing stand-alone engine strategies can be negated by poor coordination with hybrid supervisory strategies. Hybrid powertrain cold start emissions can be further improved over conventional load-following strategies by designing supervisory control strategies that make the most of the flexibility of series plug-in hybrid configuration by considering the engine warm-up and transient conditions restrictions.

Coordination strategies were tested over the first 505seconds of a UDDS cycle since this is sufficient to warm up the engine and its after-treatment and longer tests would only dilute the effect of a cold start. The virtual series PHEV model emulates hybrid strategies entering charge sustaining mode at the beginning of the second hill of that cycle. From that point on, the engine is started so that the generator can recharge the battery. Supervisory strategies are essentially load-following strategies with consideration for warm-up conditions and re-starts. The engine power can be modulated but the engine speed is selected accordingly so that power is obtained at its peak efficiency. Power requests are only authorized above a minimum threshold so that the engine does not have to operate at low speed, low load, and inefficient regions.

Table 1 shows engine out emissions of several coordination strategies. The baseline case corresponds to hybrid strategies ignoring engine warm-up requirements: engine is fired at low cranking speeds, power requests are passed on to the engine without any filtering even if engine is cold, so the engine is considered as if it were in a conventional powertrain application. The second case still does not implement a warm-up and can request full torque from the cold engine but the engine is motored up to speed and fired only above 1100rpm. That yields a 44% improvement in engine out hydrocarbon emissions over the 505 cycle. The “idle warm-up only” test implements strategies that monitor the warm-up and let the engine complete that phase without requesting any other load until catalyst has reached its light off temperature. Subsequent transients are also filtered. That provided a 70% improvement in engine out emissions. Figure 12, shows temperature, emissions and speed traces for the baseline (“un-coordinated”) algorithm and the idle warm-up (“coordinated”) algorithm.

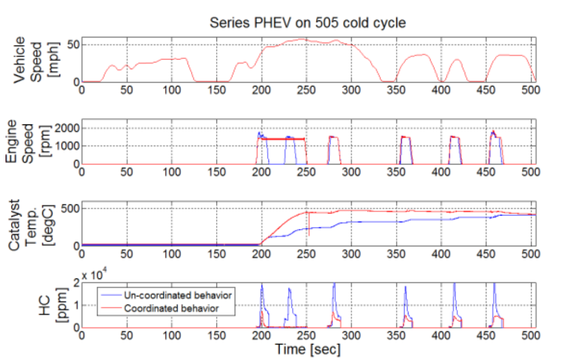

Figure 12. Warm-up behavior comparison between uncoordinated strategies and idle warm-up coordinated strategies.

A fourth configuration applied a small load of 15kW (“low load warm-up”), instead of warming the engine by idling. HC Emissions were much worse when warming up under load than idling, this resulted in 60% larger HC emissions over the cycle, and it did not speed up the catalyst warm-up (see Figure 13). Trying to combine idle load and low load warm-up (5^{th} configuration in Table1), by sequencing them, only generated more engine out HC emissions without helping tailpipe emissions since light-off temperature was achieved during the idle phase.

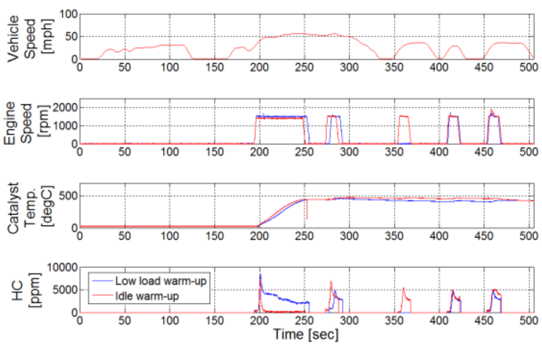

Figure 13. Warm-up behavior comparison low load warm-up and idle warm-up strategies.

Conclusions

An engine was commissioned on a testcell at the University of Tennessee, with its production in-vehicle hardware configuration (included cooling loop) but with calibration and bypass authority over its cold start behavior to optimize it for conditions specific to a series PHEV configuration.

First, engine-only optimization was performed. It was shown that, using an electric machine to motor up the engine and having the engine injecting only above 1100rpm does help HC emissions by 13% compared to a conventional cranking start with a starter motor. Stratified cranking tests were performed. Combined with motored starts, they can improve HC emissions by 22%. Increasing idle load by 20% at 1700rpm can reduce the catalyst heating phase by 25% with comparable HC and NO emissions. Additional spark timing retard can also heat up the catalyst up to 12% faster. Finally, combining elevated speed, elevated load and additional spark retard can yield 25-30% faster catalyst heating phase but trade off on emissions will determine optimum operation conditions when tested on actual vehcile for specific drivecycle.

The second phase of the project looked at coordinating engine only and hybrid supervsiory strategies to ensure that the gains obtained by calibrated the engine appropriately are not negated by poorly designed hybrid supervisory startegies. It showed that, using the same engine control strategies, HC emissions can be reduced by as much as 70% with proper coordination compared to hybrid strategies commanding the engine without consideration for cold starts.

I.A.3. Products

Publications

1. “PHEV Cold Start Emissions Management”, SAE technical paper, 13PFL-0868, World Congress 2013
2. “PHEV Engine Cold Start Emissions Management”, DEER Conference Oct 18, 2012