VI. COMPONENT/SYSTEMS EVALUATION

VI.A. [xx] PHEV Engine Control and Energy Management Strategy

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VI.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

- Perform a literature search of engine control strategies used in conventional powertrains to reduce cold start emissions
- Develop an open source engine controller providing full access to engine control strategies in order to implement new engine/catalyst warm-up behaviors
- Modify engine cold start control algorithms and characterize impact on cold start behavior
- Develop an experimental Engine-In-the-Loop test stand in order to validate control methodologies and verify transient thermal behavior and emissions of the real engine when combined with a virtual hybrid powertrain

Major Accomplishments

- Commissioned a prototype engine controller on a GM Ecotec 2.4l direct injected gasoline engine on an engine test cell at the University of Tennessee.
- Obtained from Bosch (with GM’s approval) an open calibration engine controller for a GM Ecotec LNF 2.0l Gasoline Turbocharged Direct Injection engine. Bosch will support the bypass of cold start strategies if calibration access proves insufficient. The LNF engine and its open controller were commissioned on an engine test cell at ORNL.
- Completed a literature search to identify key engine cold start control parameters and characterized their impact on the real engine using the Bosch engine controller to calibrate them.
- Ported virtual hybrid vehicle model from offline simulation environment to real-time Hardware-In-the-Loop platform.

Future Activities

- Validate cold start calibration on a stand-alone engine (decoupled from dynamometer for faster transients)
- Test re-calibrated engine when combined with virtual hybrid powertrain running on Hardware-In-the-Loop platform
- Integrate hybrid vehicle supervisory control strategies targeted at cold starts on Engine-In-the-Loop platform
- Jointly optimize engine controller and hybrid vehicle supervisory strategies to minimize cold start emissions.

VI.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 focused on the design of a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. Energy management strategies were evaluated and implemented in a virtual environment for preliminary assessment of petroleum displacement benefits before being implemented and tested on a powertrain test bed at the Argonne National Laboratories.

Engine cold start events were aggressively addressed by modifying vehicle supervisory strategies while retaining the base engine control strategies as they were developed 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.

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. Furthermore their usage will 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 and second to take advantage of the hybrid powertrain specific operating conditions.

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

During FY10, a GM Ecotec LAF 2.4l direct injected gasoline engine was selected as a test engine and a prototype engine controller was developed to replace the production module, whose strategies and calibration were not accessible and therefore did not provide any opportunity to be optimized for our project.

During FY11, that controller and engine were commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility (see Figure 1). Steady-state closed-loop operation was verified over a restricted speed and load range (1500 to 4800rpm and 20 to 100% load).

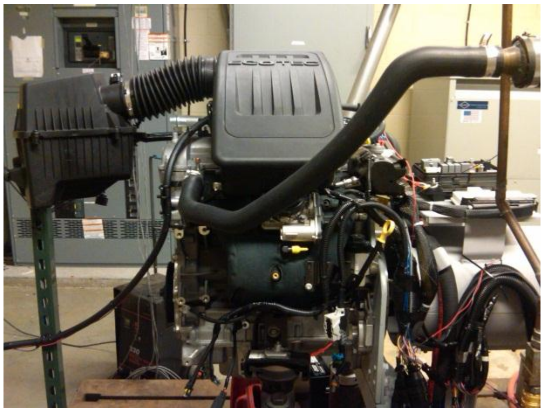

Figure 1. Ecotec LAF engine commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility

That approach consisting of developing of brand new prototype engine controller to replace the production module was selected during FY10 because no OEM was willing to support this project by providing an engine and its controller as well as access to its strategies.

During FY11, discussions with Robert Bosch LLC led the team to reconsider that approach: ORNL's Fuel Engine and Emissions Research Center agreed to share a GM Ecotec LNF 2.0l Gasoline Turbocharged Direct Injection engine, and Bosch offered to provide an open-calibration controller for that engine so that control strategies can be tuned differently from the production settings. Bosch will provide some support as well to bypass cold start strategies if calibration access is not sufficient to achieve our goals and strategies need to be further modified.

This approach consisting of using a modified production engine controller is preferable to the original prototype controller approach because it utilizes an existing proven set of production control strategies and modifies only cold start strategies which are the focus of this project. It therefore allows dedicating resources on cold starts behavior without having to develop and refine the rest of the control strategies required to run an engine over all operating conditions.

So the project will proceed with the Ecotec LNF engine running a Bosch controller instead of the Ecotec LAF engine and its prototype controller.

The LNF engine and Bosch controller have been commissioned on an engine test cell at ORNL. Initial tests were performed without the three way catalytic converter and monitored fuel consumption, exhaust and post-turbo temperatures, as well as engine out emissions: hydrocarbons, nitrous oxides and carbon monoxide. The steady state performance and emissions of the LNF engine were characterized over a limited speed and load range (Figure 2 shows an example of the steady state mapping obtained during that phase)

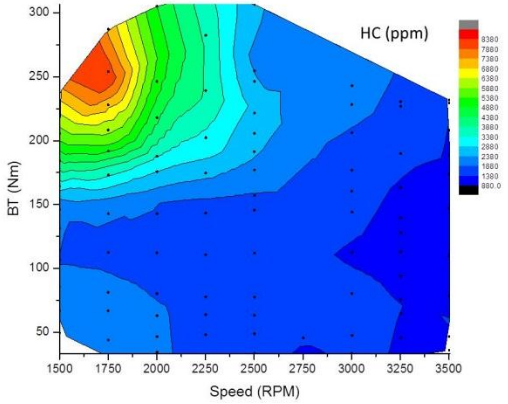

Figure 2. Ecotec LNF engine out hydrocarbon emissions

A literature search was completed to investigate control strategies used on gasoline direct injection engine to speed up catalyst warm-ups and reduce cold start emissions. Bosch and several OEMs published papers on that matter. There is a consensus on several operating modes: running dual injection strategies (early injection during the intake stroke and late injection during the compression stroke, referred to as HSP by Bosch), retarding spark timing, retarding the exhaust valve closing event, running leaner and operating at higher fuel rail pressure.

The various strategies identified during the literature phase were implemented in the open engine controller and tested on our engine test cell set-up. That testing platform proved acceptable for the post crank phase (or warm-up phase) when engine speed settles around 1400rpm. The same test set-up where the engine is coupled to a dynamometer was not suitable to reproduce the fast transient behavior of a cranking event because of the large dynamometer inertia. Therefore the calibration of the cranking phase of a cold start will be investigated on a stand-alone engine decoupled from the dynamometer.

By nature true cold starts happen only once a day; in order to complete testing in a reasonable amount of time, we performed pseudo cold starts where the engine coolant was cooled down to 25degC between tests. This is deemed to be acceptable because this project focuses on PHEV applications where the engine experiences one cold start and several pseudo cold starts during a drive cycle. Therefore it does not have time to settle to a true stabilized cold temperature between multiple starts.

In parallel to the engine development activities, vehicle supervisory strategies were adapted from previous related projects to suit the series PHEV architecture that was selected for this project. An Autonomie vehicle model was developed and Simulink control strategies were modified to optimize cold starts on that vehicle platform.

Finally, a Hardware-In-the-Loop system was set-up to run the virtual vehicle model on a real-time computer while interacting with the actual engine on the test stand so that the hybrid powertrain and drive cycles can be emulated and yet, accurate measurements for fuel consumption and emissions can be obtained from a real engine (this configuration is therefore called Engine-In-the-Loop). National Instruments tools were selected. They allow running in real time and minimum effort the Autonomie vehicle models previously developed for offline simulation, while offering a wide variety of inputs and outputs to interface with the engine and dynamometer controller. Figure 3 shows a diagram of the Engine-In-the-Loop configuration.

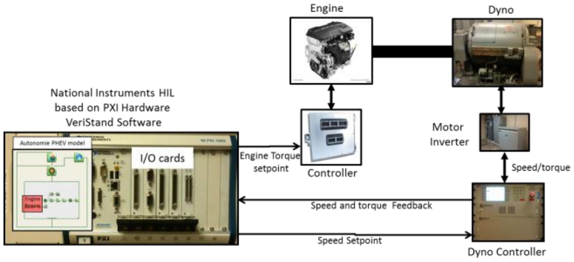

Figure 3. Engine-In-The-Loop diagram

Results

The simulation study refined vehicle supervisory strategies developed for a parallel hybrid application and adapted them to the series hybrid configuration considered in this project.

The focus was placed on pre-warming the engine independently from the vehicle traction requirements to optimize the warm-up phase. Some torque filtering was applied to remove fast transients and to wait for the engine to be fully warm before allowing large torque requests. Those key elements were calibrated on urban drive cycles.

Figure 4 shows the catalyst slow warm-up behavior when the engine is operating in load following mode without any warm-up conditioning (blue trace) whereas more or less aggressive pre-warm-up phases and as well as torque filtering (green and red traces) lead to faster temperature gradients.

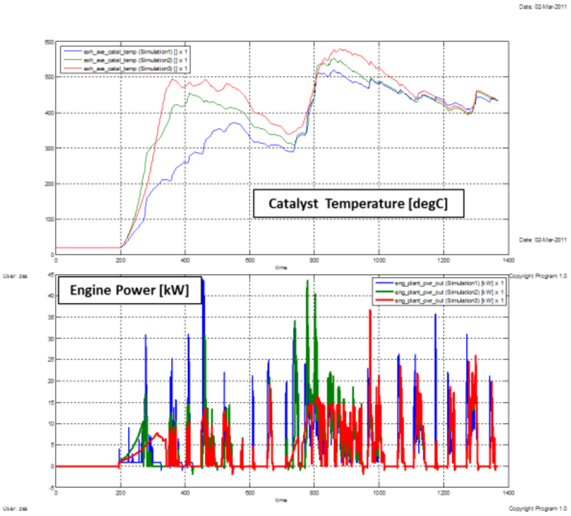

Figure 4. Series PHEV catalyst temperature behavior based on engine warm-up patterns

Figure 5 shows the emissions improvements associated with vehicle supervisory strategies that pre-warm the engine and filter out transient conditions while the engine is cold. Those results do highlight as well the fuel penalty associated with those strategies.

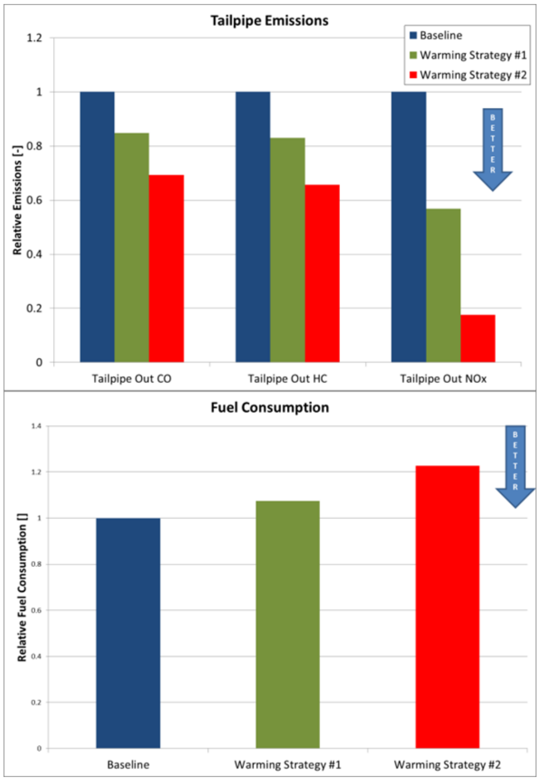

Figure 5. Tailpipe emissions improvement and fuel penalty associated with torque shaping strategies

Engine tests were performed to evaluate the effectiveness of several engine control parameters on exhaust temperature gradients and engine out emissions during the warm-up phase. Parameters selection was based on the literature search:

- Retarded spark timing
- Retarded injection timing
- Elevated fuel rail pressure
- Retarded exhaust valve closing
- Leaner mixture

As discussed earlier on, our dynamometer was not suitable to reproduce the fast transient behavior of a cranking event because of the large dynamometer inertia. Therefore the cranking phase lasts too long and leads to a larger hydrocarbon spike than expected. That spike should be ignored in the subsequent graphs and only the post crank behavior is deemed representative of an in-car cold start.

Figure 6 shows the effect of retarding spark timing on both hydrocarbons and exhaust temperature: it leads to an increase of about 200degC in post turbo temperature and decreases hydrocarbons by one to two thousand ppm.

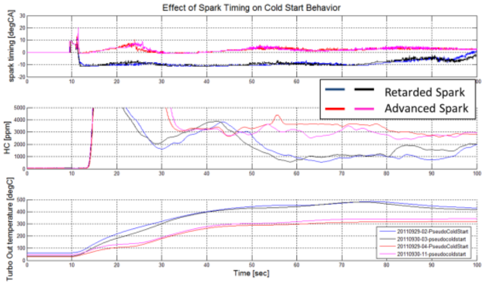

Figure 6. Effect of spark timing on LNF engine cold start behavior

Injection timing retard was shown to have a more modest influence but yet significant (see figure 7).

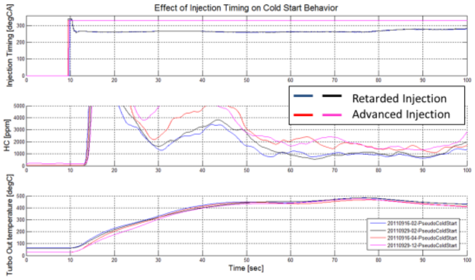

Figure 7. Effect of injection timing on LNF engine cold start behavior

Elevating fuel rail pressure from 15bar to around 60bar did provide some improvement with lower emissions and marginally higher temperatures (Figure 8) but taking it even higher (around 90bar) did not provide additional benefits.

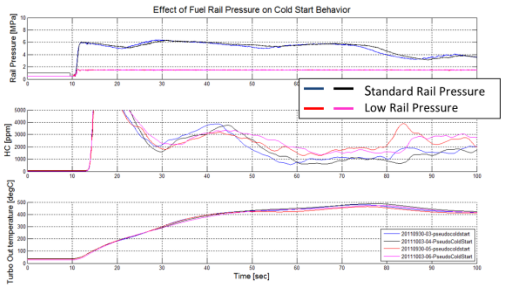

Figure 8. Effect of fuel rail pressure on LNF engine cold start behavior

Exhaust valve closing timing was investigated and demonstrated higher post turbo temperatures (Figure 9).

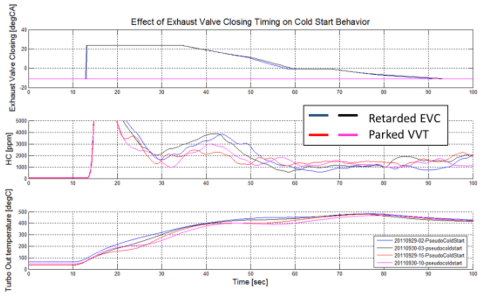

Figure 9. Effect of exhaust valve closing timing on LNF engine cold start behavior

Air Fuel ratio control during the post crank phase as well as the warm up phase showed promising hydrocarbons reduction results. By running less fuel enrichment during the post crank phase and running lean (lambda of 1.03) during the warm-up phase, engine out hydrocarbon can be further reduced and turbo out temperatures can be made higher (Figure 10).

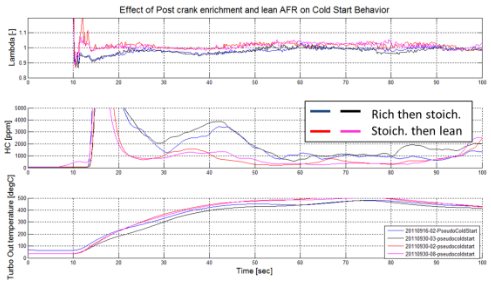

Figure 10. Effect of air fuel ratio on LNF engine cold start behavior

One of the main features that a direct injection gasoline engine is capable of is dual injection (HSP) during the warm-up phase. This creates a richer mixture concentrated around the spark plug and lean mixture elsewhere. This promotes an overall leaner mixture compared to homogenous port fuel injection, while stabilizing the combustion when retarding the spark timing, which in turn provides more heat to the after-treatment. Unfortunately, that feature could not be tested so far because of it is disabled in our engine controller and the team has not managed to enable it yet.

Conclusions

A control system for a gasoline turbocharged direct injection engine has been commissioned and tested to demonstrate the impact of various engine control parameters on cold starts emissions. This was made possible thanks to the support off Robert Bosch LLC who supplied the engine controller.

That set-up was used to demonstrate the potential for further emissions reduction and faster catalyst warm-up by modifying engine cold start calibration.

Previously, cold start emissions had been targeted using vehicle supervisory strategies instead of engine control strategies. This was achieved with Autonomie simulations of a series plug-in hybrid electric vehicle.

A Hardware-In-the-Loop system capable of running the Autonomie PHEV model and interfacing with the real engine on a dynamometer test stand was developed so that, during FY12, the project can proceed with a combined optimization of both engine and vehicle level strategies to achieve lower cold start emissions in the hybrid powertrain configuration.