

PHEV Cold Start Emissions Management

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ABSTRACT

Plug-in hybrid electric vehicles (PHEV) operate predominantly as electric vehicles (EV) with intermittent assist from the engine. As a consequence, the engine can be subjected to multiple cold start events. These cold start events have a significant impact on tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current conventional vehicles, 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.

ORNL, in collaboration with the University of Tennessee, developed an Engine-In-the-Loop (EIL) test platform to investigate cold start emissions on a 2.0l Gasoline Turbocharged Direct Injection (GTDI) Ecotec engine coupled to a virtual series hybrid electric vehicle. The end-goal of this project is to demonstrate the benefits of coordinating engine and powertrain supervisory control strategies to minimize cold start emissions.

First, this paper provides a summary of the results obtained by optimizing engine cold start strategies on their own within the context of a PHEV application where the engine can be motored up to speed and supplemented with the electric machine. These specific operating modes open up new engine calibration opportunities. This study investigated the effect of different cranking injection, post-start load, idle speed and spark timing strategies.

The paper then reports on the second phase of the project which focuses on the coordination of engine control strategies and hybrid energy management strategies. Stand-alone optimization of each component's algorithms does not guarantee that the resulting hybrid powertrain will operate efficiently. Therefore cold start strategies have to be controlled and optimized as a system to minimize tailpipe emissions. Comparison results of different coordination algorithms are presented to demonstrate the benefit of system coordination and optimization.

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INTRODUCTION

Plug-in hybrid electric vehicle 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 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 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 engine's first cold start dictates whether or not the vehicle will pass federal emissions tests [1-2]. 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 [3]. 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.

This project expands the work performed so far on hybrid vehicle supervisory strategies to include engine control strategies. Gasoline direct injection engines with variable valve timing, such as the 2.0l GTDI Ecotec engine tested in this project, offer more degrees of freedom to optimize cold start emissions than port fuel injected engines [4, 5, 6]. 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 provided by GDI technology and, second, to take advantage of operating conditions specific to hybrid powertrains.

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

ENGINE COLD START ALGORITHMS OPTIMIZATION

Engine Testbed Set-Up

A GM Ecotec LNF 2.0l Gasoline Turbocharged Direct Injection engine was selected because direct injection and variable valve timing offer more control possibilities to optimize cold start emissions. An open calibration engine controller was provided by Robert Bosch LLC. This 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 at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility. In order to ensure that cold start behavior is representative of its in-vehicle installation, the engine was installed with its production air intake and exhaust system, as well the production coolant loop including thermostat and radiator (see Figure 1). The heater core loop was modified to flow externally cooled coolant thru the engine cooling loop and return the engine block back to ambient temperature between tests.

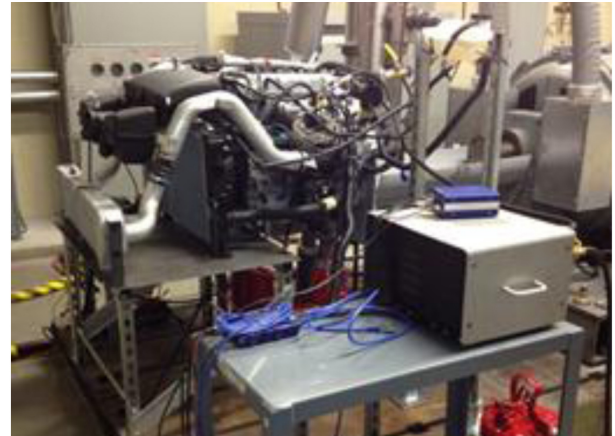


Figure 1. Ecotec LNF engine commissioned at the University of Tennessee's Advanced Powertrain Controls and System Integration (APCSI) facility

During the engine cold start algorithms optimization phase, a portable 5-gas emissions measurement system from Sensors Inc, a SEMTEC DS, was sampling engine out emissions only. Later on, during the system optimization phase, the engine after-treatment was fitted with a new 2-channel 5-gas emissions bench analyzer from California Analytical Instruments for pre and post catalyst emissions characterization. Thermocouples were also fitted to the exhaust system to measure pre-catalyst temperature as well as catalyst brick temperatures (See Figure 2), thereby allowing to characterize its thermal behavior during a cold start. Engine controller data was also logged through an ETAS INCA interface.

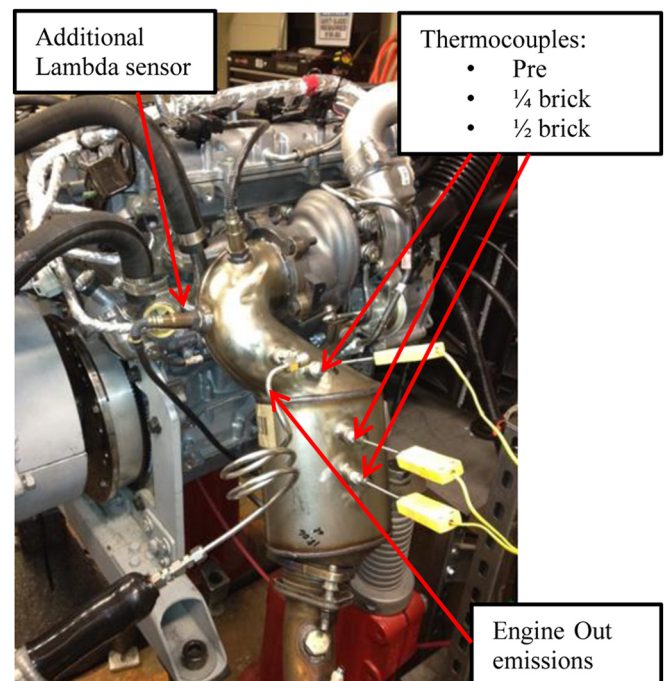


Figure 2. Exhaust and after-treatment instrumentation

Cold Start Test Procedure

The engine test cell temperature could not be regulated; tests were performed with an ambient temperature between 70 and 80degF. Because of that limitation, this study could not evaluate the impact of colder ambient temperatures. Cold starts are defined as the first start on any given day after at least 10hours of soak since the last time the engine ran. Therefore only one cold start can be performed per day. In order to speed up testing, “pseudo cold” starts were performed following a true cold start. “Pseudo cold” starts are defined as one of the subsequent starts following a true cold start when engine coolant has been cooled down to 25degC by the external cooler, and exhaust and catalyst brick temperatures have returned to ambient temperature by flowing ambient air through them when motoring the engine at wide open throttle without firing nor injecting fuel for 15-20minutes. Even though coolant and brick temperatures are back to ambient level, bearings are warm because the engine was previously spun, and rail pressure is elevated because it is a return-less system. Pseudo cold starts are not quite equivalent to true cold starts but they allow performing more tests in one day, therefore reducing overall project duration. Pseudo cold starts exhibit lower initial hydrocarbons (HC) spike because the base engine calibration runs less rich (See Figure 3). Thermal behavior does not change significantly. Investigations will be performed based on pseudo cold starts and confirmed using true cold starts.

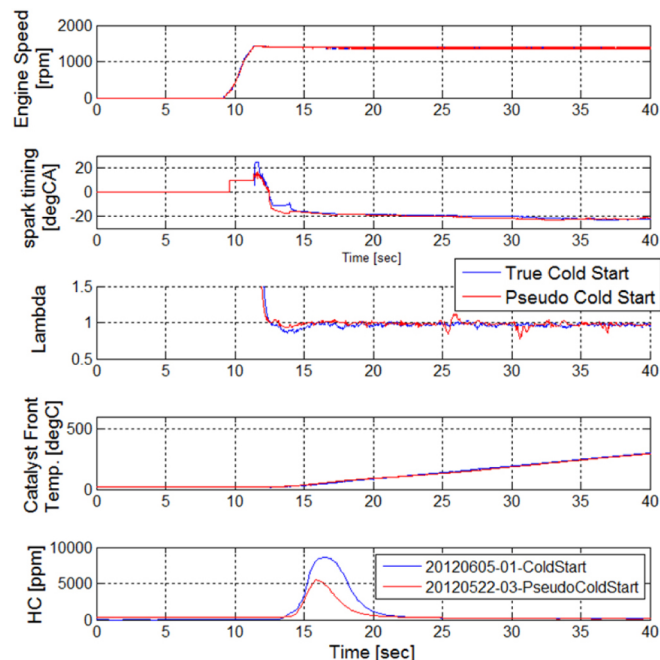


Figure 3. True cold start vs. pseudo cold start comparison

Engine-Only Optimization

The engine operation and calibration envelope were optimized 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. Another operating mode specific to series hybrid configurations is that the engine does not need to generate torque early on after being fired up since it is decoupled from the wheels, so the idle warm-up phase can be completed without interruption and run higher speeds and loads. The generator can also smooth out engine operation, allowing additional spark retard during warm-up.

Comparison of Conventional Starts and Motored Starts

A conventional start is defined as a 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 without firing the engine. For evaluation purposes, the engine is coupled to the dynamometer and motored up to the elevated idle speed of 1400rpm. It is only fired once engine speed exceeds 1100rpm. This method has the benefit of removing a highly transient phase when the 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 generator in a series PHEV configuration and could have some negative effect on engine cold start emissions by lengthening the initial transient phase. Tests were conducted on a pseudo cold engine averaging at least three repeats for each test condition.

Test results showed that motored starts with injection above 1100rpm improve engine out total hydrocarbon emissions by 12% over a conventional cold start, whereas that reduction percentage reaches 38% using stratified injection (see Table 1). Figure 4 shows instantaneous HC traces for those two cranking methods using conventional homogenous injection.

Table 1. Conventional starts vs motored starts

Start Type	Injection Mode	THC Emissions (first 30 seconds) [g]	Improvements: Motored vs conventional [%]
Conventional Start	Homogenous	0.63	\
Motored Start	Homogenous	0.55	12%
Conventional Start	Stratified	0.42	\
Motored Start	Stratified	0.26	38%