PHEV Engine Control and Energy Management Strategy

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U.S. DEPARTMENT OF ENERGY

VSS013

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Overview

- **Timeline**
  - Project start date: Oct. 2009
  - Project end date: Sept. 2012
  - 70% complete
- **Barriers**
  - Cold start PHEV emissions
- **Budget**
  - FY11 funding: $350k
  - FY12 funding: $350k
- **Partners**
  - Oak Ridge National Laboratory, project lead
  - The University of Tennessee (UT), Knoxville
  - Argonne National Laboratory, Autonomie Series hybrid model and PHEV emissions study
  - Robert Bosch LLC, production controller supply and support

Objectives

- 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.
- Optimize integration of engine control strategies with hybrid supervisory control strategies in order to reduce cold start emissions and fuel consumption of PHEVs.
- Ensure that development of new vehicle technologies complies with existing emission standards

Relevance with regards to VT programs

- Demonstrate market readiness of grid-connected vehicle technologies by 2015
- Develop advanced control strategies to optimize the performance and efficiency of advanced hybrid electric vehicle
- Complete the successful deployment of *Autonomie* as an industry recognized advanced component and vehicle modeling and simulation tool.

Approach

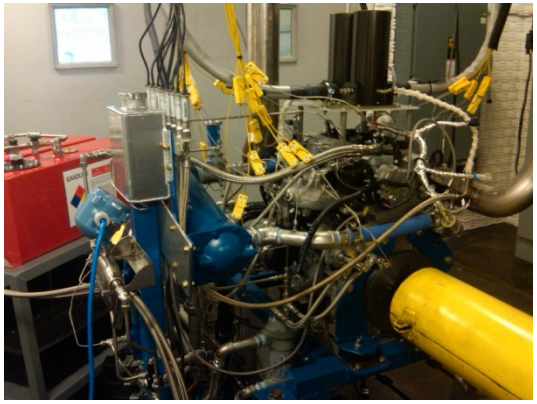
- **Gain full control over stand-alone engine operation in test cell**
  - **Characterize engine performance, emissions and operation**
  - **Develop open source prototype engine controller**
  - **Commission controller on UT test cell**
- **Optimize engine cold start strategies on stand-alone engine**
  - **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**
  - **Leverage Autonomie PHEV model**
  - **Develop EIL platform suitable for PHEV emulation**
  - **Port Autonomie model into EIL platform**
  - **Commission and validate EIL system**
- **Optimize plug-in hybrid supervisory strategies and engine control strategies as a system in order to reduce tailpipes emissions on the EIL test stand**
  - **Integrate and improve hybrid supervisory control strategies from ANL-ORNL simulation study ("Trade-off between fuel economy and Emissions for PHEVs")**
  - **Concurrently optimize both control strategies (engine and hybrid) as a system**

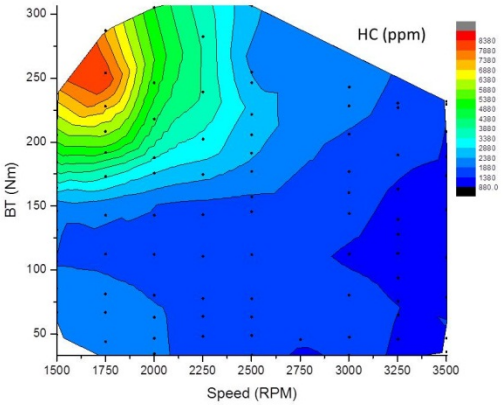
Milestones

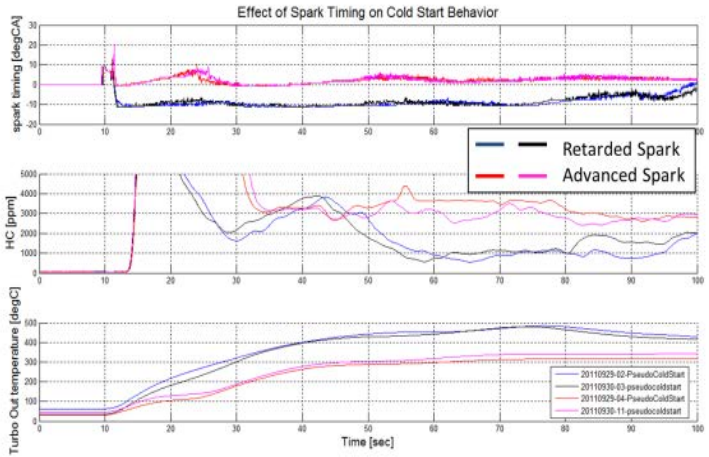
- **Milestone #1, February 28, 2012**
  - **Commission new LNF engine and its controller on engine test cell at the University of Tennessee (February 28, 2012).**
- **Milestone #2, February 28, 2012**
  - **Implement and refine new engine control strategies on production intent engine controller hardware focusing on improving catalyst heating and cold engine emissions (February 28, 2012).**
- **Milestone #3, September 30, 2012**
  - **Optimize cold emissions without consideration for fuel consumption using the production intent engine controller as well as the supervisory hybrid controller (September 30, 2012).**
- **Milestone #4, September 30, 2012**
  - **Optimize cold start emissions as well as fuel consumption (September 30, 2012).**

Accomplishments – Base GTDI LNF Engine Characterization

- Engine selection changed from MY2011 2.4l LAF GDI Ecotec to MY2009 2.0l LNF GTDI Ecotec engine to gain access to production calibration and engine controller supplied by Bosch
- Engine was commissioned with calibratable Bosch ECU and ETAS bypass tools on one of ORNL testcell while UT testcell got upgraded
- Engine steady state performance was characterized for emissions and fuel consumption
- Effect of some individual engine parameters on cold starts was quantified







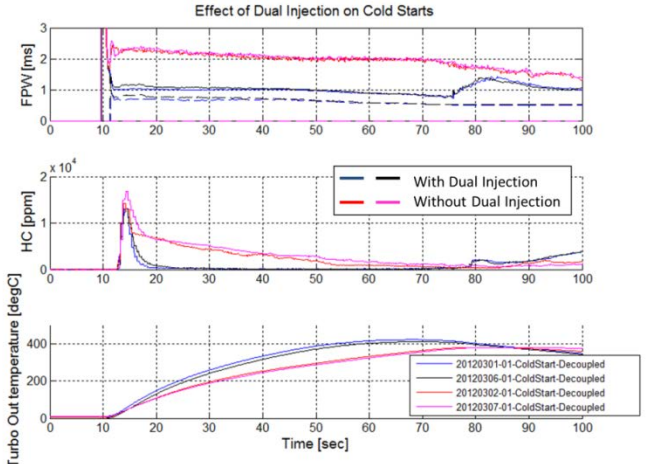
Control features	HC Emissions Increase Relative to Production Calibration
	[%]
Advanced spark Timing	67.7
Advanced Injection Timing	54.8
High rail pressure	-5.0
Low rail pressure	-5.5
No post crank enrichment	-45.3
No enrichment, lean mixture	-46.3
No VVT	-29.2

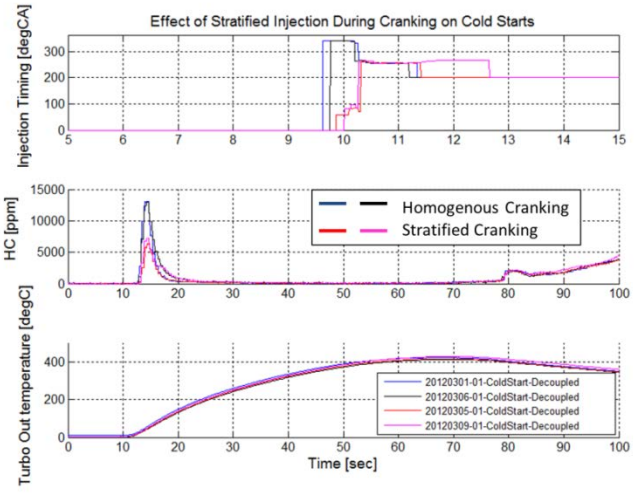
Accomplishments – LNF Engine Commissioning at the University of Tennessee

- University of Tennessee upgraded their engine testcell facilities:
  - New data acquisition system from DyneSystems
  - New 5-gas emissions bench analyzer from California Analytical Instruments
  - Several safety features improvements to conform to ORNL's Research Safety Summary for engine testcell operation
- Engine set-up duplicating vehicle installation to ensure representative cold start behavior:
  - Production air intake and exhaust
  - Production coolant loop
  - Production engine controller from Bosch
- Production coolant loop was slightly modified to provide additional cooling during tests to speed up cool down duration and allow to perform several "pseudo cold" starts a day
- Engine was commissioned with calibratable Bosch ECU and ETAS bypass tools

Accomplishments – Stand-Alone Engine Cold Start Improvements

- **Strategies selection based on literature search:**
  - **Retarded spark timing**
  - **Split homogenous-stratified (HSP) injections**
  - **Optimized air-fuel ratio**
  - **High fuel pressure**
  - **Retarded exhaust valve timing**
  - **Stratified cranking**
- **Current production calibration uses all of the above except for stratified cranking**
- **Preliminary study focused on conventional starter motor cold starts and showed effect on engine out temperature and hydrocarbon emissions of:**
  - **Split homogenous-stratified injections**
  - **Stratified cranking**
- **Next, study will focus on motored cold starts that are more representative of full plug-in hybrid powertrains.**

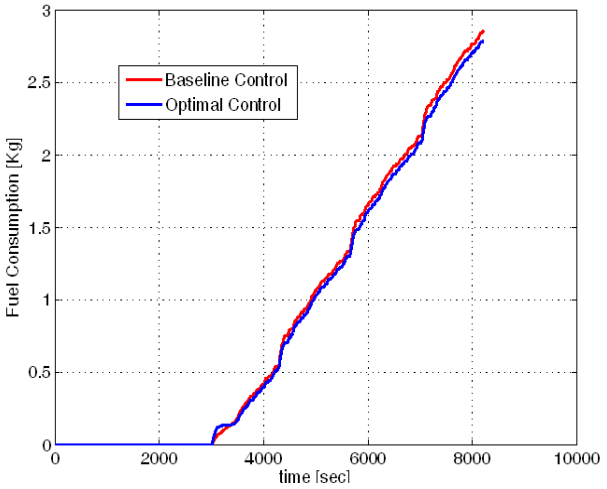




Control features	HC Emissions Increase Relative to Production Calibration
	[%]
Without HSP	326.8
Stratified Crank	-30.3
No post crank enrichment	-14.2

Accomplishments – Vehicle Simulation

- Leverage ANL/ORNL collaboration project (Tradeoff Between Fuel Consumption And Emissions for PHEV's) whose focus is on hybrid supervisory strategies optimization (engine is a "black box" that can not be modified)
- Simulation work completed by Andreas Malikopoulos, ORNL Weinberg Fellow
- Design of optimal control strategies to reduce emissions and fuel consumption during warm-up phase
- Strategies are yet to be ported into engine-in-the-loop platform to be coordinated with engine cold start strategies



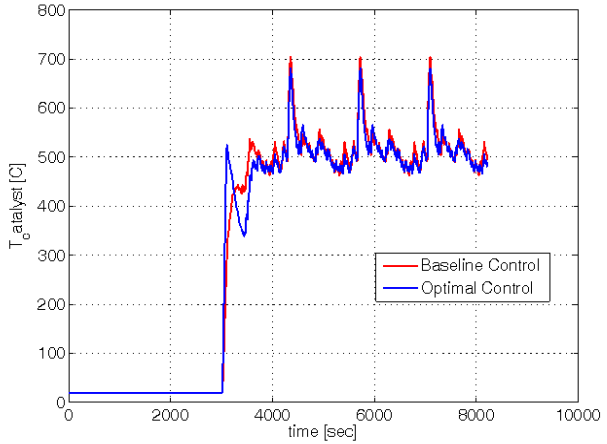


TABLE 1
SUMMARY OF OPTIMAL CONTROL RESULTS

EMISSIONS	OPTIMAL CONTROL IMPROVEMENT [%]
FUEL CONSUMPTION	3
CO	10
HC	-13

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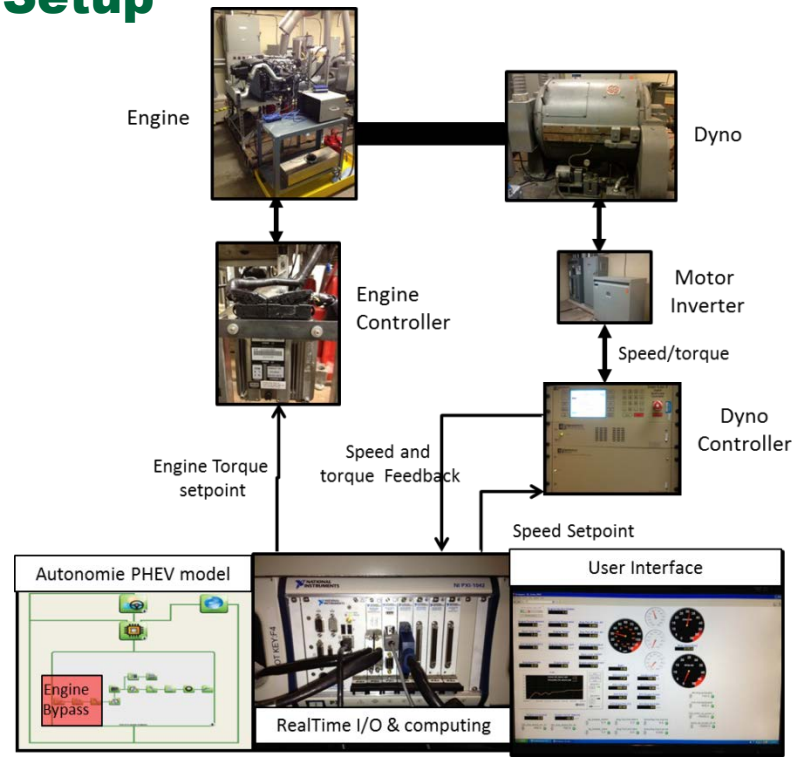
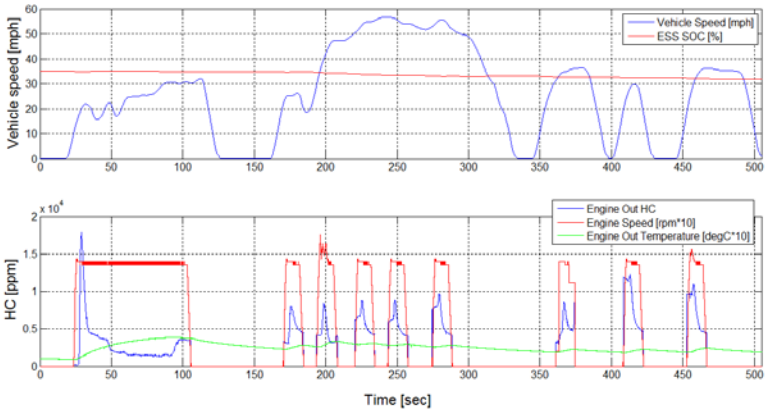
Accomplishments – Engine-In-the-Loop Setup

- **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 :**
  - **Real engine and after-treatment on test stand**
  - **Virtual Autonomie model of hybrid powertrain and vehicle computed on real time platform, interfaced to dynamometer controller and engine controller**
  - **Virtual drive cycle and driver running on real time platform**
- **This set-up enables the evaluation of an actual engine behavior for a specific virtual vehicle configuration providing:**
  - **Flexibility to change virtual powertrain configurations and test conditions of virtual test environment**
  - **Accuracy of real engine and after-treatment measurements**





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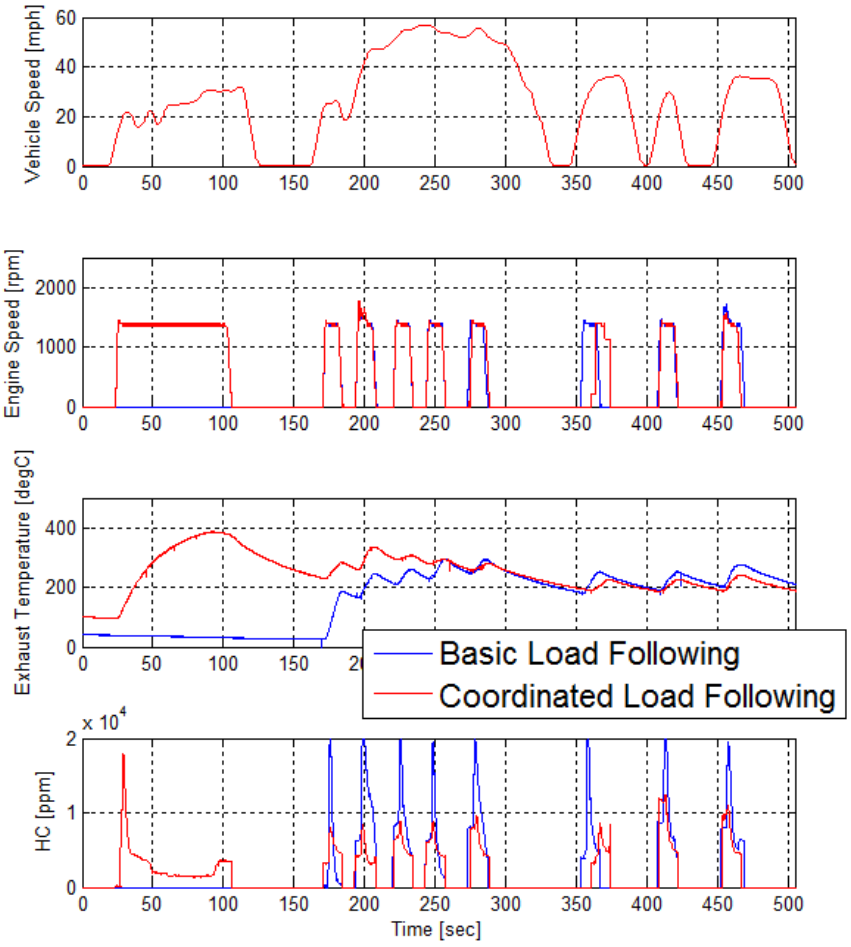
Accomplishments – Coordination of Engine and Hybrid Cold Start Control Strategies

- Series PHEV configuration offers great opportunity to optimize engine warm-up because engine is decoupled from driver demand
- Optimized stand-alone engine strategies can be negated by poor coordination with hybrid supervisory strategies
- By coordinating engine cold start control strategies and the flexibility of series plug-in hybrid configuration, powertrain cold start emissions can be improved over conventional load-following strategies.
- Preliminary results of coordination are available but more optimization work is yet to be performed to make the most out of the system.



Collaboration and Coordination with Other Institutions

- **Oak Ridge National Laboratory**
  - Lead
  - Control systems development
  - Emissions and after-treatment expertise (FEERC group)
- **The University of Tennessee Knoxville**
  - Former DOE Graduate Automotive Technology Education (GATE) center concentrated on hybrid powertrains and control systems.
  - Testing performed at UTK's Advanced Powertrain Controls and System Integration (APCSI) facility
  - Training graduate students in some of the unique aspects of advanced powertrain control development (two students worked on this project)
- **Argonne National Laboratory**
  - Hybrid supervisory strategies optimization study (This project draws from a collaborative project between ANL and ORNL: Tradeoff between Fuel Consumption and Emissions for PHEV's).
- **Bosch**
  - Supply of development engine ECU and production calibration (with GM's approval)
  - Engineering support to set up engine control system

Proposed Future Work

- **FY12**
  - **Motored cold starts optimization**
  - **Integration of hybrid supervisory strategies developed off line with Autonomie**
  - **Coordination and optimization of engine-only emissions control strategies and hybrid supervisory strategies to minimize emissions**
  - **System optimization with fuel economy as an additional constraint**

- **Beyond FY12**
  - **This project ends at the conclusion of FY12**
  - **Proposed follow-on project**
    - **Experimental validation/investigation of passive HC traps results obtained on task VSS041 (Advanced LD Engine Systems and Emissions Control Modeling and Analysis)**

Summary

- Commissioned new LNF engine on testcell with production hardware and open controller provided by Bosch. Test platform allows to perform several pseudo cold starts per day, and offers software calibration and bypass capabilities of the engine controller to customize its behavior to hybrid applications

- Investigated effect of individual engine parameters for conventional (starter motor) cold starts

- Commissioned engine-in-the-loop system on testcell at the University of Tennessee Advanced Powertrain Controls and System Integration (APCSI) facility

- Optimized hybrid cold start strategies in offline Autonomie environment

- Performed preliminary coordinated engine-in-the-loop testing for series plug-in hybrid configuration

Acknowledgements and Contacts

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