I. VEHICLE SYSTEMS OPTIMIZATION

I.A. 1000362.00 Powertrain Controls Optimization for HD Hybrid Line Haul Trucks

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I.A.1. Abstract

Objectives

- Develop and validate accurate component models for simulating integrated engine, hybrid energy storage, emissions control, and supervisory control systems in Class 8 trucks.
- Evaluate the merits of specific alternative technologies and control strategies under realistic MD and HD drive cycle conditions.
- Investigate Reactivity Controlled Compression Ignition (RCCI) advanced combustion coupled with series hybrid electric operation
- Introduce emissions controls to minimize criteria pollutants, with emphasis on challenges of low temperature combustion
- Integrate actively actively controlled hybrid energy storage systems (battery plus ultracapacitor) for enhanced regenerative braking energy capture
- Experimentally verify advanced combustion, hybrid energy storage, and aftertreatment systems utilizing actual hardware and virtual vehicle systems.

Major Accomplishments

- Completion of baseline hybrid vehicle model supervisory control algorithms for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks
- Identification and integration of preliminary hybrid energy storage system component data and baseline control strategy for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks
- Completion of first generation energy management strategy involving hybrid energy storage system, RCCI operation, and emissions control for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks

Future Achievements

- Development and integration of RCCI engine model into vehicle simulation for estimated drive cycle efficiencies
- Baseline powertrain testing of system in ORNL VSI Laboratory to establish reference point
- Completion of baseline active control strategies for hybrid energy storage system
- Integration of baseline emissions control strategies into overall supervisory controls
- Conversion of current Cummins ISX 15L engine to RCCI operation (installation of instrumented cylinder head and engine control hooks)
- Baseline engine mapping of the RCCI engine
    - Population of new RCCI engine model with engine map for use in supervisory controls development
    - Emissions data collected will provide insight into proper emissions control strategy variations due to low temperature combustion
    - Revise series hybrid engine operating region to better utilize RCCI
- Powertrain testing of improved system incorporating hybrid energy storage system

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I.A.2. Technical Discussion

Background

Hybrid medium and heavy-duty (MD and HD) powertrains offer large potential reductions in fuel consumption, criteria pollutants, and greenhouse gases. In addition to powertrain electrification, advanced combustion regimes could further reduce the fuel consumption for these vehicles. The most fuel-efficient MD and HD combustion engines are advanced diesels, which require aftertreatment for compliant emissions control. Diesel hybridization is challenging because the integrated aftertreatment, engine, and battery systems must be optimized to meet efficiency targets and simultaneously satisfy drive cycle and emissions constraints.

Introduction

This is a vehicle system level project, encompassing analytical modeling and supervisory controls development as well as experimental verification/validation testing at the component, powertrain, and full vehicle system level. This project supports the goal of petroleum consumption reduction for medium and heavy trucks through the development of advanced hybrid technologies and control systems. VSST has invested previously in R&D to support hybrid energy storage systems (Li-ion plus ultra-caps) for light duty, passenger car applications. This research will be extended to the MD and HD sector where current battery technology is not mature enough to handle the substantial regenerative braking power levels these trucks are capable of producing. With this hybrid energy storage system, substantial gains in overall vehicle efficiency are possible. In addition, advanced combustion technologies, such as RCCI, will be implemented into an advanced hybrid powertrain for a Class 8 line haul application. This powertrain, leveraged from other VSST work (Meritor, a current ORNL/VSST partner), is ideal for taking advantage of the benefits of RCCI operation due to its series hybrid mode of operation. Emissions control is also a focus of this project, especially due to the fact that RCCI creates a low temperature exhaust stream that must addressed.

Approach

The project seeks to leverage multiple research areas into a single vehicle platform. The chosen hybrid powertrain is a fully capable Class 8 powertrain designed for line haul applications, and has the ability to be operated as an all-electric vehicle, series hybrid electric vehicle (at low to moderate speeds), and a parallel hybrid eletrci vehicle at moderate to highway speeds. This powertrain offers itself to improvement by the technologies investigated in this project.

There are four focus areas for this project, ranging from advanced combustion regimes and engine control strategies, emissions control technologies, pulsed energy storage systems (dual energy storage systems), and advanced energy management and supervisory controls. These four areas are shown graphically in Figure 1, and are summarized below.

Advanced engine control strategies

Research in this area is being leveraged with on-going projects at ORNL and being co-sponsored by the DOE VTO Advanced Combustion and Emissions Control program. ORNL has been engaged in the area of Reactivity Controlled Compression Ignition (RCCI) on multi-cylinder engines for improved fuel efficiency and reduced emissions.

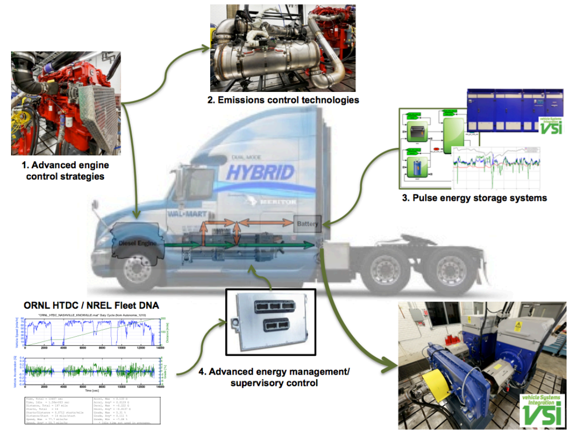

Figure 1 Project focus areas

This mode of combustion offers increased fuel efficiency at the sacrifice of a narrow operating window and reduced exhaust gas tempertaures. For this reason, a series HEV would be a good operating environment for this type of engine control, due to the ability to maintain complete control over the operating envelope of the engine.

Emissions control technologies

Emissions control is essential for the success of RCCI due to lower exhaust temperatures. To further exacerbate the problem, the hybrid powertrain has the ability to operate solely on electric power, as well as intermittent engine start/stop operation. This leads to increased importance of coordinating engine operation and emissions control in order to maximize the benefits of powertrain electrification and advanced combustion.

Pulse energy storage systems

Perhaps the greatest opportunity for powertrain efficiency improvement is new approaches for increased regenerative braking energy collection for Class 8 line haul hybrid trucks. Current battery technology, while reasonably mature for light duty applications, is not capable of absorbing the large amounts of energy that is necessary to slow these trucks down. One approach that has been researched in the past for light duty applications is dual energy storage systems, or the combination of batteries with ultra-capacitors. This section of the research builds upon past research from Argonne National Laboratory that was done for light-duty vehicles. The approaches developed as part of that work will be adapted/extended to this heavy-duty line haul vehicle application.

Advanced energy management/ supervisory control

In order for each of the previous technologies to function seamlessly at the vehicle level, appropriate energy management strategies must be developed that will fully realize the compound benefits of all the candidate technologies being investigated in this project. Past HD HEV supervisory control experience will be leveraged and expanded to incorporate these new technologies in a meaningful and cohesive manner.

Results

Supervisory controls baseline established

Powertrain supervisory controls software was leveraged from a previous program that utilized the Meritor DMHP. This approach kick-started the project by allowing the baseline supervisory control system to be rapidly completed. The baseline supervisory control model was developed for the single ESS case with no advanced combustion or emissions control strategies. Figure 2 shows the baseline supervisory control model architecture for the project.

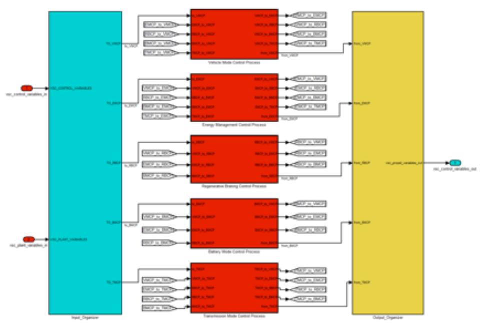

Figure 2 Supervisory controls model architecture

In order to exercise the model, "real world" drive cycles were created. Data was mined from the ORNL Heavy Truck Duty Cycle (HTDC) database (now integrated with the NREL Fleet DNA database) and was used to develop custom real world drive cycles. All of these "real world" drive cycles include grade, which is a key parameter in evaluating hybrid benefits of line haul trucks. An example of primary cycles to be used for this project is shown in Figure 3. This drive cycle represents an approximately 170-mile trip along Interstate I-40 eastbound from Nashville, TN to Knoxville, TN.

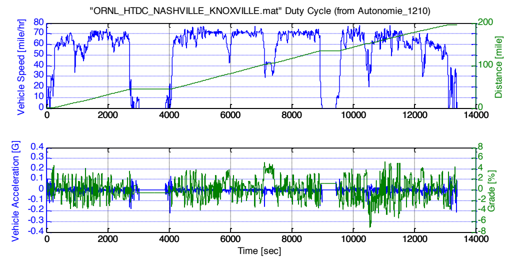

Figure 3 ORNL HTDC "real world" drive cycle from Nashville, TN to Knoxville, TN

System and component models completed

ORNL has implemented past transient engine modeling experience to develop a transient model of a Cummins ISX-450 15 liter engine. The model has been validated against actual test data from a Cummins ISX450 15 liter engine. A graphic of the engine installed in the ORNL VSI laboratory is shown in Figure 4.

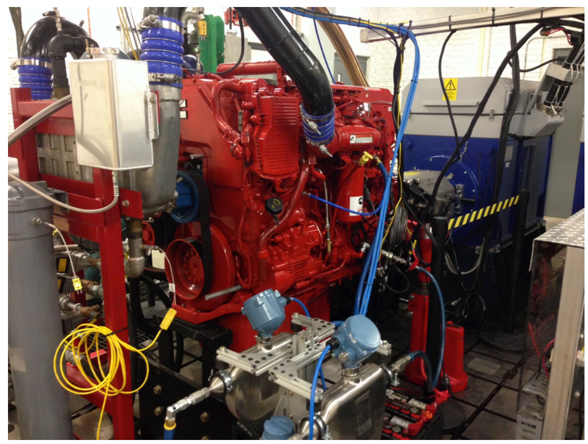

Figure 4 Cummins ISX-450 installed in the ORNL VSI laboratory

In addition, a full aftertreatment suite of models has been "built" and is currently being validated against experimental data from the same engine. Figure 5 outlines the high level Autonomie implementation of the transient engine model, including a snapshot of the aftertreatment models.

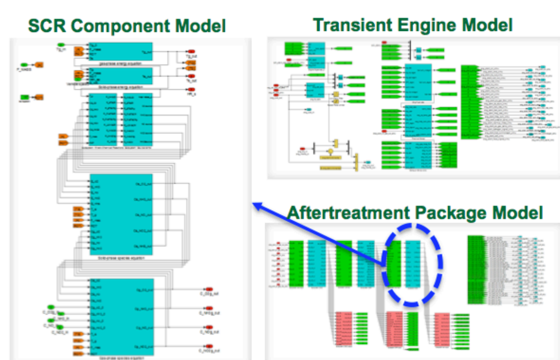

Figure 5 ORNL transient engine model and associated aftertreatment models

The baseline dual energy storage system model has been completed. This model builds upon the previous work performed by ANL in light duty systems, and utilizes the model framework currently available in the public release of Autonomie. The control system has been completely changed, with most of the active control relocated to the supervisory control model outlined earlier in this text. The li-ion battery model is based upon proprietary data from Meritor on an actual vehicle energy storage system (ESS), but is sized such that the ESS can provide sufficient energy capacity to power all electrified accessories for during the normal hoteling period. The ultra-capacitor model is being reviewed and modified based upon input form an industry subject matter expert. Once complete, the ultra-capacitor bank will be sized appropritately for the project. Figure 6 gives an overview of the model acrchitecture being used for the dual energy storage system.

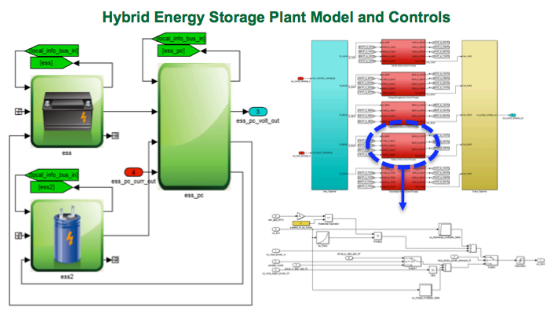

Figure 6 Model framework for the dual energy stoarge system model

Conclusions

The project is focused on advanced heavy-duty powertrain systems that will reduce energy consumption and criteria emissions for Class 8 line haul vehicles. A multi-faceted approach is being taken to minimize the fuel consumption and emissions of a Class 8 line haul powertrain utilizing advanced combustion, hybridization, and dual energy storage systems. Progress on the project includes establishing a reference supervisory controls based upon experimental powertrain results for ORNL VSI Laboratory, a completed literature review of various approaches to hybrid energy storage systems, as well as development of a transient engine and aftertreatment modeling "package," as well as an actively controlled hybrid energy storage system model.