Real-Time Control of Diesel Combustion Quality (CRADA with Detroit Diesel Corporation)

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Objectives

- Commission prototype DDC heavy-duty diesel engine at ORNL.
- Explore operational range of high efficiency clean combustion (HECC) on DDC engine.
- Perform detailed emissions characterization for improved understanding of the combustion process.

Approach

- Install prototype DDC heavy-duty diesel engine and develop supporting data acquisition and measurement systems at ORNL.
- Determine boundaries of HECC operation on DDC supplied heavy-duty engine with detailed combustion and emissions characterization.
- Begin construction of physical and statistical based models for use in evaluating potential control approaches for expanding operational range of HECC.

Accomplishments

- Commissioned DDC engine and supporting infrastructure at ORNL.
- Performed extensive experiments under low and medium load conditions to characterize effects of EGR rate, rail pressure, and injection timing on achieving HECC operation.
- Selected commercially available software package and have begun development of low-order combustion model for engine simulations.

Future Directions

- Continue analysis and interpretation of recent data.
- Continue model development for multi-cylinder simulations and control.
- Explore potential of achieving HCCI-like operation and further expanding HECC operating range on heavy-duty multi-cylinder platform.

Introduction

This CRADA focuses on expanding the operational range of HECC through improved simulation and control with emphasis on the unique dynamics in multi-cylinder engines. Expansion of the stable HECC speed-load range is a key step to operating advanced diesel engines at 2010 and beyond regulated emissions levels. Achieving HECC in a diesel multi-cylinder engine requires operation under conditions which are often inherently unstable. These instabilities result in the occurrence of poor or marginal combustion events which cause excessive hydrocarbon and particulate emissions. Practical solutions to the problem are especially difficult to achieve because of the extreme sensitivity of combustion and after-treatment performance on engine parameters as well as "communication" between cylinders on multi-cylinder platforms. The experimental setup has been commissioned this year and extensive experiments have been performed to understand the potential of achieving HECC operation on the DDC multi-cylinder engine. We have also begun the selection and development of models for future simulations of engine operation and evaluations of potential control approaches.

Approach

The overall objective of this work is to expand the operational range of HECC through improved simulation and control with emphasis on the unique dynamics of multi-cylinder engines. Achieving this objective requires extensive experimentation as well as the development of new low-order models and control strategies. A key target in satisfying this objective will be to minimize the addition of new engine hardware and rely as much as possible on existing actuators, sensors, and signal processors.

This objective is being pursued utilizing a unique multi-cylinder engine provided by DDC to ORNL. The research engine sized for Class 7-8 heavy trucks is fully operational and is installed in a transient-capable dynamometer cell with full instrumentation. The engine is equipped with an electronic control package, exhaust gas recirculation, and other features that are essential for this type of research.

Results

Extensive experiments have been performed to determine the "natural" boundaries of HECC operation in the DDC engine. Engine parameter ranges for these experiments are summarized in Table 1. Note that all of these experiments were carried out using a single injection event to keep the parameter space reasonable for this stage of experiments. The frequency and timing of multiple injection events will be included in the next round of experiments.

The initial exploratory experiments performed on this engine involved studying the effect of load and EGR on emissions and efficiency. Specifically, the purpose of these experiments was to

Table 1 Engine parameter ranges investigated in recent experiments.

Parameter	Range
Speed, rpm	1500 (fixed)
Torque, % full load	10, 20, 50
EGR rate, %	0 to 65
BOI, deg BTDC	17.5 to 0
Fuel Pressure, bar	600 to 1600

determine whether high EGR is sufficient to cause a simultaneous reduction in NOx and PM as has been observed on some light-duty diesel engines. An EGR level sweep was performed for three loads and 1500 rpm with all other engine parameters held constant. The results in Figure 1 show a significant decrease in NOx and a significant increase in smoke number with increasing EGR level for all three engine loads. The increase in EGR level also results in a decrease in efficiency (increase in BSFC) and a significant increase in CO emissions. Although not shown, the 10-50% and 50-90% HR intervals increased with EGR level, and the COV in IMEP was relatively constant in the 1-2% range for all conditions.

The effects of BOI and fuel pressure were investigated at 20% and 50% load for a fixed speed of 1500 rpm. A summary of the results are shown in Figures 2 and 3 for 20% and 50% load, respectively. EGR rate was held fixed at a slightly elevated level to improve NOx suppression. In general, smoke number decreased and NOx increased with increasing fuel pressure. Note that the scales are the same in Figures 2 and 3, and the effect of rail pressure on PM was much stronger for the lower loads. Constant injection timing lines are also shown in Figures 2 and 3 and indicate a decrease in NOx as injection timing is retarded toward TDC. Although not shown, BSFC increased with the later injection timings. Also note that a simultaneous reduction in NOx and smoke number was observed for later injection timings. This is opposite of the classic NOx-PM tradeoff typically observed under conventional operating conditions (see Figure 1). Although not shown, the 10-50% HR interval decreased with fuel pressure and was only slightly influenced by rail pressure, and the 50-90% HR interval decreased with retarding injection. All parameters investigated had little to no effect on stability as indicated by COV in IMEP.

Parameter effects are summarized for the above experiments in Table 2. Note that the effect of each parameter is influenced by a variety of engine conditions including speed and load. For example, the effect of fuel rail pressure on smoke number appears weaker at high loads. Trends summarized in Table 2 are only for the evaluated parameter combinations.

Table 2 Summary of parameter effects observed in recent experiments.

Parameter	NOx (g/hp-hr)	PM (g/hp-hr)	BSFC (g/hp-hr)	10-50% HR (deg)	50-90% HR (deg)
EGR increase	↓	↑	↑	↑	↑
Fuel Pressure increase	↑	↓	—	↓	
BOI retard	↓	↑↓	↑	—↓	↓

Conclusions

A simultaneous reduction in NOx and PM emissions was observed with retarded (later) injection timings. A simultaneous reduction was not observed for elevated EGR levels for the conditions investigated in this study but may be possible depending on the settings of other operational parameters such as fuel injection rate and timing. This will be investigated in more detail in the next phase of this study. Increasing rail pressure appeared to be most effective at reducing PM while maintaining efficiency, particularly at lower loads. This study indicates simultaneous reductions of NOx and PM emissions (as compared to baseline) are possible with single-injection approaches. More advanced injection strategies involving multiple injections and early injection are expect to provide greater reductions with the ability to maintain efficiency. More advanced injection strategies and their effects on engine emissions and stability will be investigated in the next phase of this activity.

FY 2004 Publications/Presentations

CRADA review meeting at ORNL on September 30, 2004.

Acronyms

BSFC	Brake Specific Fuel Conversion
BOI	Beginning of Injection
CRADA	Cooperative Research and Development Agreement
COV	Coefficient of Variation
DDC	Detroit Diesel Corporation
EGR	Exhaust Gas Recirculation
HR	Heat Release
IMEP	Indicated Mean Effective Pressure
HECC	High Efficiency Clean Combustion
HCCI	Homogeneous Charge Compression Ignition
NOx	Oxides of Nitrogen
PM	Particulate Matter
TDC	Top Dead Center

Figure Captions

Figure 1. EGR rate sweep at 1500 rpm and 10% (blue diamonds), 20% (green squared), and 50% (red circles) load. All other engine parameters are held constant.

Figure 2. Fuel pressure and injection timing sweep at 1500 rpm, 20% load, and 39% EGR rate. Shaded lines correspond to fixed injection timings.

Figure 3. Fuel pressure and injection timing sweep at 1500 rpm, 50% load and 29% EGR rate. Shaded lines correspond to fixed injection timings.