Combustion Mode Switching for Improved Emissions and Efficiency in a Diesel Engine

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Abstract

We have been exploring the potential of diesel combustion regimes that exhibit simultaneous low engine-out nitrogen oxides (NOx) and particulate matter (PM) emissions. Through proper combustion management, we have achieved significant reductions in NOx (90%) and PM (30%) emissions without the decrease in efficiency typically associated with operating in these regimes. This type of operation is commonly referred to as High Efficiency Clean Combustion (HECC) and was achieved on a multi-cylinder engine using only production-like hardware. The combustion process was characterized using in-cylinder pressure transducers as well as by applying powerful analytical methods to the chemical constituents of the exhaust gases. The combination of thermodynamic and exhaust chemistry information results in a more complete description of the combustion process than is usually available. Another important aspect of operating diesel engines in advanced combustion modes is the ability to transition in and out of these modes with minimal adverse effects on emissions or performance. We were able to demonstrate seamless transitions in and out of diesel HECC operation with no significant emissions excursions or effects on performance.

Introduction

Recent advances in the electronic control of diesel engines have led to much greater flexibility in injection systems as well as sensors and feedback control. This greater flexibility in turn has led to the exploration of parameter spaces which were never accessible with conventional fueling and control systems.

With conventional approaches to diesel combustion, a trade-off is usually observed between NOx and PM emissions. For example, a strategy for reducing NOx emissions may result in an increase in PM emissions [1]. Recent theoretical and experimental studies describe the existence of combustion regimes which exhibit simultaneous low NOx and PM [2-8]. An improved understanding of these combustion modes is critical for lowering the performance requirements for post-combustion emissions control devices and meeting future U.S. emissions and efficiency goals.

Through proper combustion management, we have achieved significant reduction in NOx and PM emissions without the decrease in efficiency typically associated with operating in these regimes. This type of operation is commonly referred to as high efficiency clean combustion (HECC) and was demonstrated at ORNL on a multi-cylinder engine using only production-like hardware. Another important aspect of operating diesel engines in advanced combustion modes is the ability to transition in and out of these modes with minimal adverse effects on emissions or performance. These transitions may be necessary for the regeneration of post-combustion emissions controls or for moving between conventional and advanced combustion modes to better cover the ranges of speeds and loads encountered in a typical drive cycle. We were able to demonstrate seamless transitions with no significant emissions excursions or effects on performance.

Approach

A Mercedes 1.7-L common rail diesel engine is the experimental platform for this study. This engine is equipped with a rapid-prototype, full-pass engine controller capable of actuating the EGR valve, intake throttle, and fuel injection parameters (timing, duration, fuel rail pressure, and number of injections). Additional engine specifications are shown in Table 1.

A heat exchanger was added to reduce the temperature of the re-circulated exhaust gas to avoid damaging the plastic intake. The heat exchanger is a production part for the U.S. version of the Volkswagen TDI engine. The heat exchanger uses engine coolant as the working fluid for removing energy from the re-circulated exhaust gases, which is a realistic implementation of the technology. An intake throttle was also added for increasing the maximum obtainable EGR rate on this engine. While these components were not common when this engine was developed in 1999, these components are now available on some new diesel engines.

In-cylinder pressure measurements were recorded on a 0.1 crank angle degree resolution during the combustion process and 1 crank angle degree resolution during the remainder of the engine cycle. Data sets were typically 1,000 engine cycles and were collected for all four cylin-

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Table 1. Engine specifications for Mercedes 1.7-L engine used in this investigation.

Cylinders	4
Injection System	Bosch Common Rail
Injector Holes	6
Injector Hole Diameter, μm	169
Compression Ratio	19.0
Bore, mm	80.0
Stroke, mm	84.0
Piston Geometry	Re-entrant Bowl
Rated Power, kW	66.0
Rated Torque, N·m	180.0

ders. An AVL IndiModul 621 was used for data acquisition and AVL Concerto software was used for the majority of the analysis. Other pressure data analysis was performed using custom analysis codes.

Standard automotive gas instrumentation was used to provide a basic knowledge of exhaust chemistry. Steady state measurements of CO, CO_2, HC, NOx, and O_2 concentrations in the raw engine-out exhaust were measured using Rosemount and California Analytical gas analyzers. Particle mass concentration and total mass accumulation as a function of time were measured using an R&P Tapered Element Oscillating Microbalance (TEOM). Smoke emissions were measured using an AVL Smokemeter.

A microdiluter device was configured to provide a dilute (non-condensing) exhaust stream for analyzing exhaust chemistry based on a design by Abdul-Khalek and Kittleson [9]. The raw exhaust sample is supplied to the microdiluter through a heated stainless steel sample line maintained at 190 °C. The microdiluter is heated and insulated to maintain a sample temperature of 50 °C within the device. A range of samples were extracted from the diluted sample stream and acquired for off-line analysis. Dilution ratio was determined by observing gas concentrations in the raw exhaust gas stream and the dilute sample, and was confirmed by periodic volume flow measurements. Aldehyde emissions were analyzed by trapping analytes using di-nitro phenylhydrazine (DNPH) cartridges. The analytes were eluted from the cartridges with acetonitrile and analyzed by high-pressure liquid chromatography (HPLC). Gas-phase hydrocarbons were analyzed by trapping a dilute exhaust sample in a tedlar bag followed by analysis with a gas chromatograph equipped with a mass selective detector (GC/MS).

An EPA certification diesel fuel was used as the fuel in this study. The fuel was sourced from Chevron-Phillips Chemical Company and was an off-the-shelf product.

Results and Discussion

Extensive experiments have been performed to develop strategies for achieving HECC operation in a light-duty diesel engine. The results of an example road-load condition are summarized in Table 2. The baseline condition is 1500 rpm at 2.6 bar BMEP. Results are shown for the baseline condition, the low-NOx low-PM condition (LTC), and the HECC condition, which may also be referred to as an “efficient LTC” condition. Note that the phrase LTC as used in the literature typically refers to a low-NOx low-PM condition only and provides no information concerning efficiency. In this document, the LTC condition should be thought of as an intermediate condition which was explored during the search for HECC operation.

The baseline condition is very similar to the original manufacturer calibration. This was confirmed by comparing engine parameter settings as well as engine-out emissions. With all engine parameters maintained constant, the EGR rate was increased until the engine entered a “clean combustion” (i.e., simultaneous low NOx and low PM) condition. In previous experiments and reports [7, 8], the engine was transitioned into the clean combustion mode over a period of several hours due to the time required to conduct data at intermediate conditions. The transition rate between conventional and clean combustion modes has an impact on the thermodynamic state of the engine and will be discussed in more detail later in this document. Since the intermediate points were of less interest for these experiments, the engine was transitioned rapidly by moving the EGR valve to the fully open position in one continuous step. As observed in previous studies, the introduction of high levels of EGR results in a

Table 2. Comparison of conventional and HECC operation at 1500 rpm and 2.6 bar BMEP.

	Base	**LTC**	**HECC**
EGR (%)	21	49	48
BSFC (g/hp.hr)	211	240	209
NOx (g/hp.hr)	1.2	0.1	0.1
PM (g/hp.hr)	0.38	0.51	0.29
THC (g/hp.hr)	2.68	4.54	2.46
Intake Temp (C)	43	129	94
Exhaust Temp (C)	205	244	199
Main Timing (BTDC)	2	2	12
Pilot Timing (BTDC)	18	18	Off
Rail Pressure (bar)	320	320	328

decrease in engine efficiency and torque. Efficiency and torque were recovered by adjusting the fuel injection parameters, specifically timing and number of injections. We observed pilot injection had negligible effect on engine operation under these conditions but did contribute significantly to PM and HC emissions. Therefore, the pilot event was removed and the main event was increased to maintain sufficient fueling and torque. Injection timing was then advanced to improve combustion phasing and the corresponding efficiency. Comparing the base and HECC conditions in Table 2 shows a 90% reduction in NOx and a 30% reduction in PM between the two cases with no degradation to engine efficiency or increase in HC emissions. Although not shown, there is a significant increase (>30%) in CO emissions between the base and HECC conditions. A more accurate estimation is not available at the moment because the CO concentration for the HECC conditions was higher than the full-scale capability of the CO instrument.

The results of these experiments indicate a simultaneous reduction in NOx and PM emissions is possible without a BSFC penalty at road-load conditions. Note that increasing the EGR rate has a detrimental effect on the volumetric efficiency due to the increase in the temperature of the inducted intake charge. The temperature of the inducted mixture increases from the baseline case of 43 °C to the LTC case of 129 °C to the HECC case of 94 °C. An analysis of the volumetric and thermal efficiencies indicates a decrease in volumetric efficiency between the base and HECC conditions from 84% to 72%, respectively, while the thermal efficiency and BSFC of the two conditions is nearly identical. Since the overall fueling rate was maintained constant and the volumetric efficiency of the engine was decreased between the base and HECC conditions, the energy losses must have been reduced somewhere within the engine system. Further analysis is necessary to determine whether the reduction in losses is due to heat transfer effects or the combustion process. A more detailed first and second law thermodynamic analysis will be applied to this data in the future.

The average heat release profiles for the conditions in Table 2 are shown in Figure 1. A significant shift in the heat release profile was observed with increasing EGR as seen in comparing Figures 1(a) and 1(b). The heat release profile is recovered (or improved) by re-phasing the combustion process with injection timing to achieve HECC operation as illustrated in Figure 1(c). Recall from Table 1 that the pilot injection was disabled during HECC operation. The 10-50% heat release interval was shorter for HECC operation as compared to base operation, indicating a higher fraction of premixed (or kinetically controlled) combustion. Conversely, the 50-90% heat release interval was longer for HECC operation indicating a slower mixing-controlled combustion phase, potentially due to the increased EGR level under the HECC condition. Not shown in the average heat release profiles is the

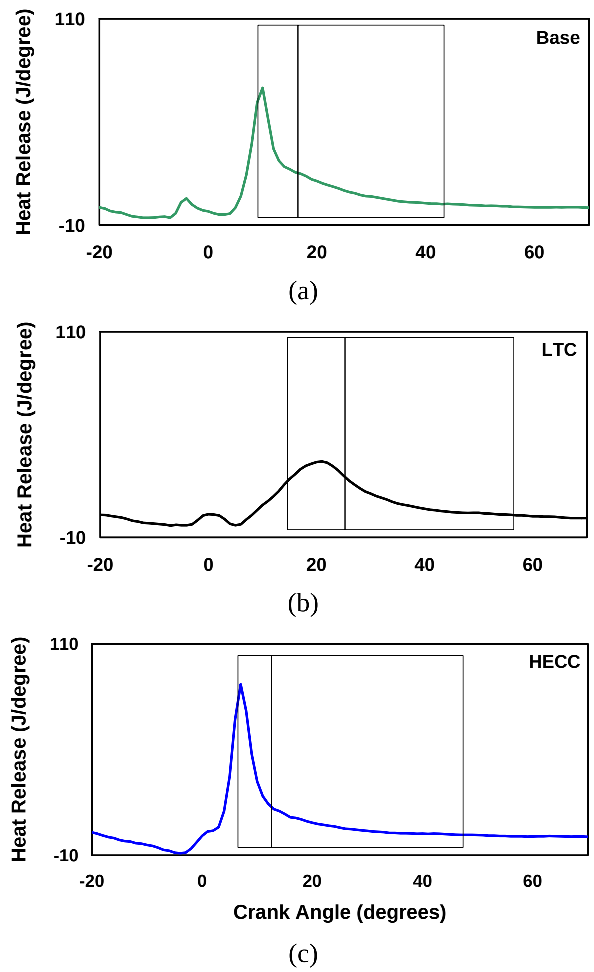

Figure 1. Average heat release profiles for (a) base, (b) LTC, and (c) HECC engine operation under road-load conditions (1500 rpm, 2.6 bar BMEP). Highlighted regions correspond to the 10-50% and 50-90% heat release intervals, respectively.

effect of these different operating modes on engine stability. The COV in IMEP increased with EGR level but returned to a comparable baseline level during HECC operation.

Exhaust constituents were analyzed in detail to characterize the production of aldehyde emissions for the base, LTC, and HECC cases summarized in Table 2. The results of this analysis are shown in Figure 2 and indicate a sharp increase in aldehyde emissions as EGR is increased to achieve LTC operation. The increase in aldehyde emissions is believed to be the result of slower or delayed combustion and not necessarily due to increased locally rich combustion. Re-phasing of the combustion process and removal of the pilot injection to achieve HECC operation resulted in a reduction in aldehyde emissions to levels similar to those observed for the base condition.

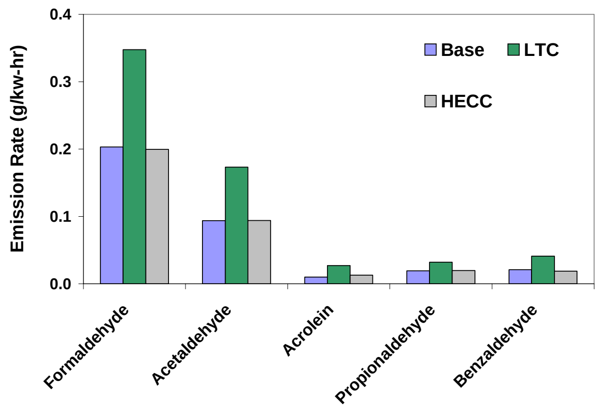

Figure 2. Adehyde emissions for base, LTC, and HECC engine operation under road-load conditions.

The analysis of gas-phase hydrocarbon emissions revealed a number of interesting trends which are shown in Figure 3. The hydrocarbon emissions were mostly long-chain normal paraffins including decane, undecane, dodecane, and tridecane. The first three of these compounds are found in the fuel and are indicative of unburned fuel in the exhaust stream. Tridecane emissions are not shown but follow the same trends as these compounds. The fuel hydrocarbon emissions decrease from baseline at the LTC and HECC conditions. This suggests these compounds are either entirely consumed during combustion to form CO_2 and H_2O or are processed into shorter chain compounds.

Pentene emissions for the LTC and HECC conditions are double the concentration observed for the base condition. Pentene is a product of fuel-cracking and has been previously observed in the exhaust from experiments where post-injection is used for the regeneration of diesel lean NOx traps [10]. Benzene emissions for the base and HECC conditions were comparable but were much higher for the LTC condition. The trend is especially interesting since benzene is a known precursor for particulate emissions [11]. Unfortunately, other known particulate precursors such as acetylene, methylacetylene, and 1,3 butadiene were not measured during these experiments. Measurement of these compounds is planned in future experiments and may provide insight into the mechanisms of PM formation which appear to be inhibited in clean combustion modes.

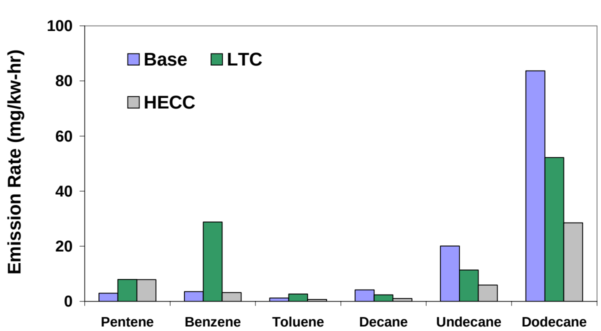

Figure 3. Selected gas phase hydrocarbon emissions for base, LTC, and HECC engine operation under road-load conditions.

The transition rate from base to LTC to HECC operation has a noteworthy effect on the combustion process. In the experiments reported in this document, the transition from base to LTC conditions was accomplished with a step change in EGR rate. In previous experiments, the engine was transitioned into clean combustion modes over a period of several hours due to the time required to collect data at intermediate conditions. This slow transition rate (hours) resulted in higher PM as compared to a fast transition rate (seconds). In addition, the ability to recover efficiency to the HECC mode was difficult if the transition to LTC occurred at a very slow rate. Future experiments are planned to better characterize the effects of transition rate on the combustion process and to determine whether the differences are due to thermal or dynamic path effects.

Controlled transition experiments were performed to investigate potential emissions and performance problems which may be associated with transitioning in and out of HECC operation. The results shown in Figure 4 are for conditions similar to those summarized in Table 2. The most significant differences are the base condition for the transition experiments is 0% EGR and a different engine (same model, MB 1.7-L) was used for these experiments. In Figure 4, the HECC condition corresponds to 44% EGR. No significant PM or NOx spikes were observed during transitions in and out of HECC operation. Note that PM or soot was measured with Laser Induced Incadescence (LII) with an instrument on loan from Dr. Pete Witze from Sandia National Laboratory. The brief excursions seen in the torque and LII in the HECC operation results are believed to be due to a problem with the controller and not a result of the HECC combustion mode. In addition, BSFC was the same for both modes with no significant excursions in performance. A potential problematic issue observed in the transition experiments is the order of magnitude (on a % basis, not brake-specific) increase observed in the CO emissions during HECC operation. Further experiments need to be performed to determine whether this excursion is treatable with an oxidation catalyst. These large excursions in CO may potentially be useful in the regeneration of after-treatment devices. Seamless transitions between conventional and advanced modes may be very important for the near-term implementation of these strategies in real world situations. These transitions may be necessary for the regeneration of post-combustion emissions controls or for moving between conventional and advanced combustion modes to better cover the ranges of speeds and loads encountered on a typical drive cycle.

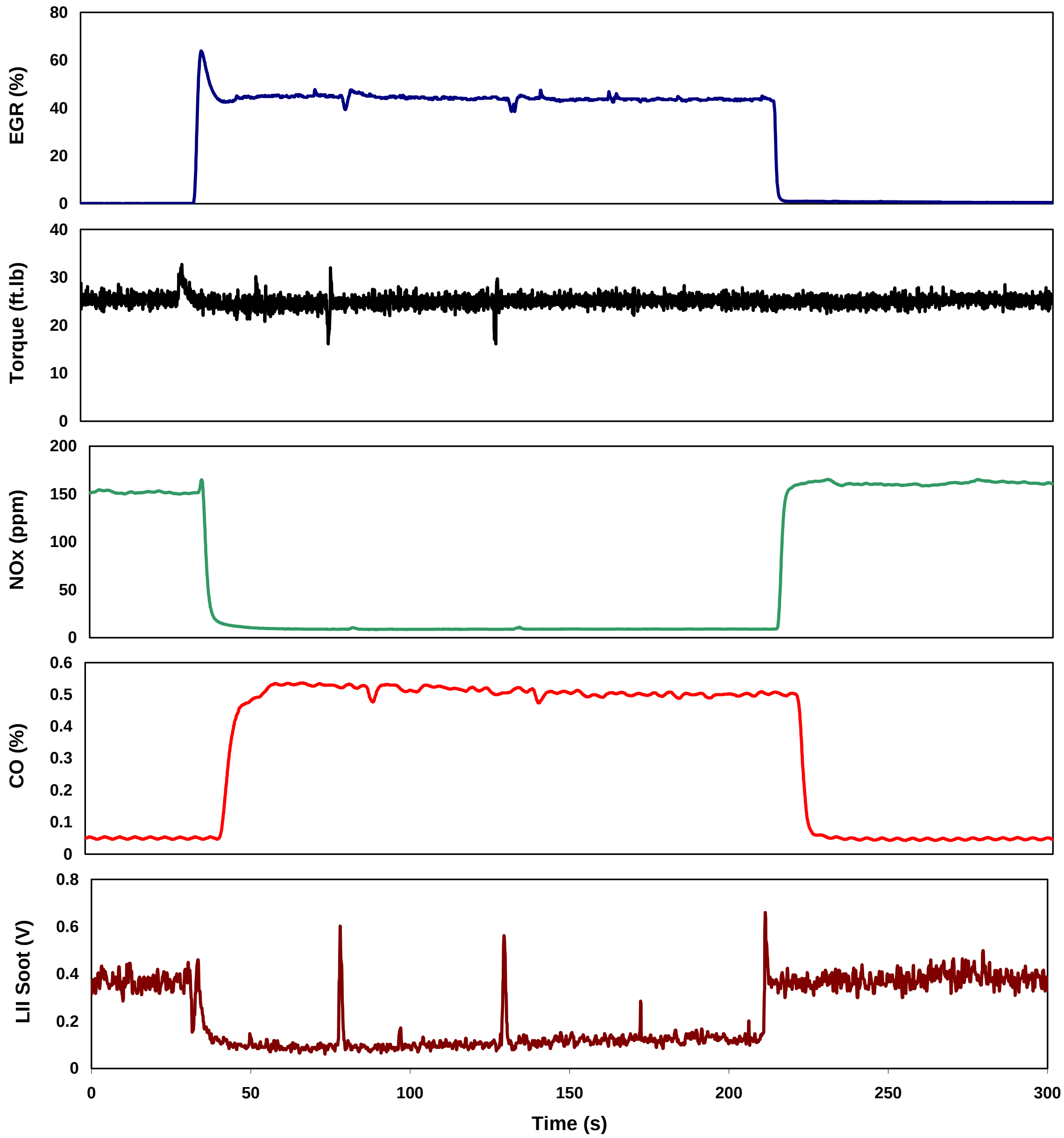

Figure 4. Example of controlled transition between base and HECC operation under road-load conditions. The transition corresponds to the change in EGR shown in the top figure. For this example, the base condition corresponds to 0% EGR and the HECC condition corresponds to 44% EGR. The recovery strategy for achieving HECC is the same as the one described for the results in Table 2.

Summary and Conclusions

- HECC operation was demonstrated under road-load conditions in a light-duty diesel engine and resulted in a reduction of engine-out NOx (90%) and PM (30-50%) without excessive HC emissions and no efficiency penalty. However, an order of magnitude increase in CO emissions was observed during HECC operation.
- HECC operation is characterized by an increased fraction of premixed combustion.
- Engine-out aldehyde emissions do not increase with HECC operation but are of levels similar to those observed for the base condition.
- Transitioning between OEM and HECC conditions does not result in significant PM or performance excursions under road-load conditions.

Future and Ongoing Research

HECC combustion modes are expected to have a critical role in meeting future U.S. emissions and efficiency goals. However, a significant amount of research needs to be completed before this technology is ready for real world applications in the U.S. market. We are currently addressing several of these issues.

- HECC operation has been difficult to achieve on this platform under high-load conditions. We are currently developing a low-pressure EGR system to alleviate problems with achieving boost under high EGR conditions.
- A range of fuel properties are being investigated to better understand the role of fuels in enabling efficient clean combustion.
- A detailed thermodynamic analysis is being performed on the data from these experiments as well as other HECC experiments. This analysis is necessary to understand how BSFC is maintained with HECC operation while there is a clear reduction in volumetric efficiency associated with operation in this mode.
- The effect of transition rate between base and HECC modes on emissions and efficiency is being investigated to determine whether the differences are thermal or dynamic path effects.
- More detailed emissions data is being acquired to better characterize the presence of PM precursors. These results are being shared with combustion simulation experts at Lawrence Livermore National Laboratory for the improved understanding and simulation of HECC combustion modes.

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Disclaimer

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