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An Estimate of Diesel High-Efficiency Clean Combustion Impacts on FTP-75 Aftertreatment Requirements

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ABSTRACT

A modified Mercedes 1.7-liter, direct-injection diesel engine was operated in both normal and high-efficiency clean combustion (HECC) combustion modes. Four steady-state engine operating points that were previously identified by the Ad-hoc fuels working group were used as test points to allow estimation of the hot-start FTP-75 emissions levels in both normal and HECC combustion modes. The results indicate that operation in HECC modes generally produce reductions in NO_X and PM emissions at the expense of CO, NMHC, and H_2CO emissions. The FTP emissions estimates indicate that aftertreatment requirements for NO_X are reduced, while those for PM may not be impacted. Cycle-average aftertreatment requirements for CO, NMHC, and H_2CO may be challenging, especially at the lowest temperature conditions.

INTRODUCTION

Advanced combustion concepts have received considerable attention in the past several years because of their potential for reducing engine-out emissions from diesel engines. These concepts have included both homogeneous-charge compression ignition (HCCI) and various implementations of partially-premixed charge compression ignition (PCCI), including the high-efficiency clean combustion (HECC) technique reported in this study [1-13]. A significant amount of the research attention being paid to these topics has focused on the potential for these approaches to reduce both oxides-of-nitrogen (NO_X) and particulate mass (PM) emissions. It is generally accepted that these approaches achieve these gains at the expense of higher emissions of carbon monoxide (CO) and unburned hydrocarbons (HCs). In many cases the engine's compression ratio is also reduced, resulting in a decrease in the engine thermal efficiency that may or may not be overcome through optimization of the combustion phasing.

Lower engine-out emissions can have a dual benefit for the integrated engine and aftertreatment system. Lower engine-out emissions can reduce the fuel efficiency penalty associated with active regeneration of aftertreatment devices and so may contribute to reducing the system's fuel efficiency penalty associated with meeting emissions standards. Lower engine-out emissions also may reduce the required effectiveness of the aftertreatment components, potentially enabling the use of technologies that might not otherwise have sufficiently high effectiveness to meet the emissions standards for the full-useful life of the vehicle.

As many advanced combustion techniques for diesel engines are still largely in the development stage, estimates of their potential real-world emissions benefits and challenges are at present difficult to quantify. Vehicle-level models can provide estimates of emissions for regulatory driving schedules, but require information about engine performance as an input. Providing this level of input would require calibration of the candidate engine in an advanced combustion mode at a fairly large number of engine speed and power conditions, which is a lengthy and expensive undertaking. Identifying a small number of engine speed and load combinations that are useful for estimating emissions for regulatory driving schedules would allow engine calibration to be performed at a more manageable number of points. This direction is especially attractive given the current level of engineering development of some of the advanced combustion techniques and associated hardware. Once a given technique and its associated hardware have progressed to a sufficiently high level of development more data-intensive models can provide more accurate estimates of its emissions performance.

APPROACH

ENGINE OPERATING CONDITIONS

The Ad-Hoc fuels working group has identified several engine speed and load conditions that allow a loose approximation of the U.S. FTP-75 driving schedule emissions [14-16]. Several operating points were considered by the group and eventually narrowed to four conditions. The composite result of these conditions is a rough estimate of the emissions performance for the U.S. FTP-75 cycle. The approximation is limited in that it does not allow inclusion of cold-start or other transient phenomena, which are very important to the overall emissions results. Nevertheless, this methodology represents a means of estimating the magnitude of drive-cycle emissions results from engine-dynamometer studies. Table 1 shows the engine operating conditions that were developed by the Ad-Hoc working group and that were used for this study. The weighting factors were developed by the Ad-hoc group and are indicative of the amount of time spent at similar conditions during the FTP driving cycle.

Table 1. Ad-Hoc engine operating points.

Engine Speed (RPM)	Engine BMEP (kPa)	Weighting Factor
1,500	100	400
1,500	262	600
2,000	200	200
2,300	420	200

ENGINE

The engine utilized for this study was a modified Mercedes 1.7-liter direct-injection, common-rail diesel engine. This platform is a production engine in Europe that is used in the Mercedes A-class product line. The factory calibration for this engine was developed to meet Euro 3 emissions regulations as installed in the A170 vehicle. Additional engine design details are included in Table 2. Operation in both baseline and HECC modes was conducted with the 19.5 compression ratio and utilizing direct-injection fueling strategies. The maximum fuel rail pressure for this fuel system was 130 MPa.

The high-pressure EGR (HP-EGR) system was modified by the addition of an EGR cooler (from a Volkswagen 1.9-liter TDI engine) that used engine coolant as the working fluid. As the rate of flow of EGR gases through this cooler increased, the temperature of the EGR / fresh air charge also increased. A catalyzed diesel particle filter (CDPF) was installed in the exhaust approximately 1 meter downstream of the turbocharger exit. The CDPF was a cylindrical cordierite monolith of 144-mm diameter and 152-mm length. A low-pressure loop EGR (LP-EGR) system was added with recirculation of the exhaust from the exit of the CDPF through a heat exchanger to the suction side of the turbocharger compressor. The LP-EGR heat exchanger used ambient-temperature water as the cooling medium and was sufficiently effective that the LP-EGR gas flow rate did not impact the EGR / fresh-air mixture temperature at the compressor inlet. The supply air to the engine was conditioned to provide constant temperature and humidity levels at the engine air intake.

The engine was operated by a PC-based flexible engine control system and accompanying injector drive unit. The control system was set up to emulate the factory engine calibration and to allow departures from the factory calibration as needed. The injector drive unit allows multiple injections per engine cycle without restrictions on the timing of the injection events. However, the minimum injection duration is limited to 160 μs.

Table 2. Mercedes engine characteristics.

Specification	**Value**
Displacement, liters	1.7
Bore x Stroke, mm	80 x 84
Number of Cylinders	4
Piston Bowl	Re-entrant
Valves per Cylinder	4
Compression Ratio	19.5:1
Rated Power, kW	66 @ 4,200 RPM
Fuel System	Bosch Common Rail
Injector Orifice Diameter, mm	0.169
Injector Number of Orifices	6

Engine emissions were studied in both normal combustion mode (approximating the factory engine calibration) and in HECC mode. HECC mode was achieved at each engine condition by increasing the EGR rate to target an O_2 concentration in the intake of 14 – 15%. The fuel rail pressure was also increased to allow the same fuel rate to be injected in one short injection event rather than a pilot and main injection, as was the case for the normal mode. Table 3 shows the engine operating parameters for each of the ad-hoc operating conditions in both the normal and HECC modes. The HP-EGR system was used for the 1,500 and 2,000 RPM points. The majority of the EGR flow for the 2,300 RPM point was provided by the LP-EGR system, with the balance from the HP-EGR system. The HP-EGR system was found to produce intake temperatures that were high enough to cause significant PM production in the HECC mode at 2,300 RPM. Providing the majority of the EGR flow through the LP-EGR system reduced the intake temperature and resulted in much less PM formation.

The engine was fueled with a commercially available certification diesel fuel with cetane number of 47. The

Table 3. Engine operating parameters. (Baseline Value / HECC Value)

Parameter Normal / HECC	1,500 RPM 100 kPa	1,500 RPM 262 kPa	2,000 RPM 200 kPa	2,300 RPM 420 kPa
Pilot Duration (μs)	317 / NA	274 / NA	258 / NA	200 / NA
Pilot Timing (CAD BTDC)	18.2 / NA	18.2 / NA	26.6 / NA	30.7 / NA
Main Duration (μs)	431 / 347	591 / 430	510 / 400	611 / 423
Main Timing (CAD BTDC)	2 / 8.5	2 / 8	5 / 10	5.8 / 8.5
Fuel Rail Pressure (MPa)	30.0 / 57.5	32.3 / 58.0	34.4 / 57.0	43.0 / 85.0
EGR Rate (% Volume)	23 / 50	19 / 47	26 / 48	15 / 45
Intake O_2 (% Volume)	19.8 / 16.7	19.1 / 14.2	19.0 / 15.5	19.5 / 14.8
Air / Fuel Ratio	66.3 / 35.7	38.5 / 21.9	41.4 / 26.3	33.6 / 21.9
Fuel Rate (cc/s)	0.32 / 0.32	0.52 / 0.52	0.64 / 0.64	1.24 / 1.24

fuel contained 30.6% aromatics and 386 ppm sulfur. This fuel was selected instead of an ultra-low sulfur fuel because of concerns that currently-available ultra-low sulfur research fuels might not represent the formulations that are likely to be in the marketplace very well. Specifically, many of these fuels contain a large fraction of the aromatic content as a single compound, which often present at levels comparable to or greater than the saturated alkanes. This is not typically observed with marketplace or other full-formulation diesel fuel.

A replacement set of fuel injector nozzles was acquired from Bosch to investigate the impact of improved atomization and mixing on the HECC mode emissions. Studies in constant-volume combustion vessels have shown that use of injectors with reduced orifice size can promote better mixing and longer flame lift-off length, both of which can contribute to lower soot formation. [9] These nozzles were direct-replacements for the existing fuel injector nozzles. The new nozzles had orifice diameters of 0.100 mm but were otherwise identical to the original nozzles. The number of holes was not increased for this study so that interactions between two adjacent fuel jets would be similar to those present with the original injector nozzles. This resulted in reduced maximum fuel rate for this engine, lowering the maximum torque rating. This was deemed acceptable for this study. The HECC fuel pressure was kept constant for both sets of injector nozzles. Fuel rate was equalized with conditions using the original injectors by increasing the main injection duration for the replacement nozzles. The main injection durations were 400 μs for the 1,500 RPM 100 kPa point, 518 μs for the 1,500 RPM 262 kPa point, 454 μs for the 2,000 RPM 200 kPa Point, and 428 μs for the 2,300 RPM 420 kPa point. These durations were shorter than the injection durations used for the factory injector nozzles in normal combustion mode.

SAMPLING AND ANALYSIS METHODS –

CO, CO_2, O_2, HC, NO_X – Standard heated chemiluminescence and flame ionization instruments were utilized for measuring the NO_X and unburned hydrocarbons, respectively. CO and CO_2 were measured using non-dispersive infrared (NDIR) instruments. Paramagnetic detection (PMD) was used to measure O_2 concentration. The sample was chilled prior to measurement by PMD and NDIR instruments to achieve a non-condensing sample condition. These instruments sampled from the raw engine exhaust using a heated filter for removal of particulates. The sample stream was conveyed from the heated filter to the instruments through a heated transfer line maintained at 190 °C.

Dilute Sampling Apparatus – A micro-dilution device was configured to provide a dilute (non-condensing) exhaust stream for analyzing exhaust particulate and chemistry. The device was based on a design by Abdul-Khalek and Kittleson [17]. The raw exhaust was routed to the microdiluter through a heated sampling line maintained at 190 °C. The microdiluter walls were heated so that the gas temperature was held constant at 50 °C. The dilution ratio was determined at the start of each sample by measuring volumetric flow rates. Various samples were extracted from the dilute gas stream for subsequent analysis.

Unregulated Gas-Phase Species – A Nicolet Nexus 670 Fourier-Transform Infrared (FTIR) Spectrometer was utilized to measure a number of gas phase species. The spectrometer was equipped with a heated gas cell with an optical path length of 10 meters. The species of principal interest were acetylene (C_2H_2), ethylene (C_2H_4), and propylene (C_3H_6) because of the propensity for these species to participate in the formation of particulate matter. The FTIR also allowed measurement of other species of concern, such as methane (CH_4), formaldehyde (H_2CO), acetaldehyde (C_2H_4O), and nitrous oxide (N_2O). The FTIR sampled from the raw engine exhaust, using a heated filter for removal of particulates.

Particulate Matter (PM) – A smoke meter (AVL model 415S) provided for checks of the PM emissions. The smoke meter sampled from the raw engine exhaust. The smoke meter utilizes an optical reflectometer to determine the amount of blackening of filter paper by the PM contained in a fixed volume of exhaust gas. Hence, it is not a direct measurement of particulate mass, but is nonetheless useful because it provides a rapid and generally accepted estimate of the PM emissions at a given steady-state engine condition. Since the measurement is an optical one, it may not accurately account for condensable organics in the PM, and hence may underestimate gravimetric PM measurements. Soot concentration (ρ) in mg/m^3 is determined from the following correlation:

$$\rho = (1 / 0.405) * \alpha * FSN * (\exp(\beta * FSN))$$

The correlation is valid for filter smoke number (FSN) values up to and including 8. FSN is determined by a linear measurement of filter paper blackening using a gas column of 405 mm effective length. The values of the constants are $\alpha = 5.32$ and $\beta = 0.31$ [18].

RESULTS

Successful operation in HECC combustion modes results in simultaneous reductions in NO_X and PM emissions. These reductions are accomplished while the engine brake thermal efficiency remains equivalent to that of the baseline engine with compression ratio of 19.5. The emissions results described in this study are from successful HECC operation at each of the engine conditions described, and therefore are accomplished without a fuel efficiency penalty compared with the baseline conditions. Unless noted otherwise, all emissions measurements were conducted upstream of the CDPF. This sampling location was selected so that estimates of emissions rates could be produced that would allow others to estimate the tailpipe emissions based on the effectiveness of various exhaust treatment technologies independent of those utilized for this study.

PM EMISSIONS

The PM emissions as estimated from the Smokemeter measurements are shown in Figure 1. The results show that the engine produced lower levels of PM emissions in the HECC mode with both the original and replacement injector nozzles. HECC mode at the lowest load condition of 1,500 RPM, 100 kPa BMEP were essentially non-sooting. Operation in HECC mode using the original injector nozzles resulted in a 30 – 50% decrease in estimated PM mass emissions. Operation in HECC mode using the replacement injector nozzles resulted in an 85 – 100% reduction in estimated PM mass emissions.

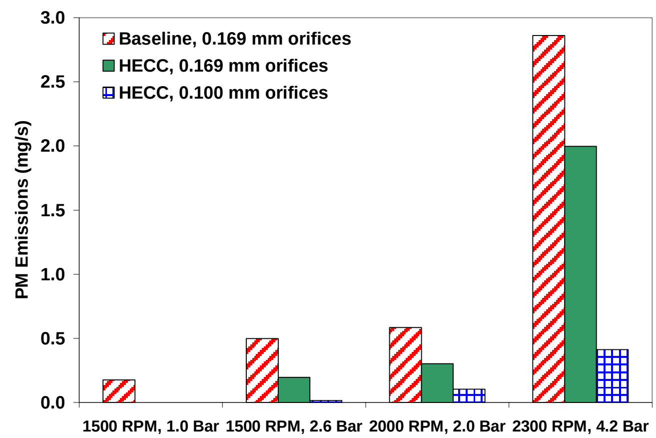

Figure 1. Estimated PM mass emissions results.

NO_X EMISSIONS

NO_X emissions are shown in Figure 2. Operation in HECC mode produces much less NO_X than baseline, with reductions of greater than 80% at all four engine conditions. The NO_X emissions were comparable for both sets of injector nozzles.

The makeup of the NO_X emissions was found to be largely NO for the baseline conditions, although the 2 lowest BMEP points showed significant amounts of NO_2. NO_X in HECC modes was dominated by NO_2. This result is consistent with a shift towards lower flame temperatures during the combustion event, as expected with HECC combustion modes. Figure 3 shows the NO_2 / NO ratio for each of the 4 engine conditions.

It is noteworthy that the HECC mode with the original injector nozzles at the 2,300 RPM condition exhibited mostly NO, rather than NO_2, as was observed with the other HECC mode data. While the estimated PM mass emissions for that point were lower than baseline, the PM mass concentration (as measured with the Smokemeter) was actually slightly higher, 51 mg/m^3 compared with 48 mg/m^3 at the baseline condition. The higher volumetric PM production indicates that the engine was operating just outside the edge of low-temperature HECC combustion. The overall reduction in

PM mass emissions at this point resulted from lower overall exhaust mass flow associated with higher EGR rates. Thus, the NO_2 / NO ratio difference is consistent when considered as an indicator of a shift to lower flame temperatures rather than as an indicator of low-PM conditions.

HC EMISSIONS

Non-methane hydrocarbon emissions (NMHC) results are shown in Figure 4. NMHC emissions nearly double at the lowest speed and load condition but decrease approximately 20% at the highest speed and load condition. Determining the cause of this behavior was not possible within the scope of this study; however, it seems likely that the different mixing timescales present at the different engine speeds would play a role in the HC emissions. Methane (CH_4) emissions during HECC operation were considerably higher at all engine conditions. These results are shown in Figure 5. The CH_4 emissions were in most cases a small fraction of the total hydrocarbon emissions. CH_4 emissions increases generally trended with the NMHC emissions increases. Comparison of the two injector orifice sizes in the HECC mode shows that use of the 0.100 mm orifices generally produced incrementally higher levels of both NMHC and CH_4 emissions.

CO EMISSIONS

CO emissions also increased substantially in HECC modes. These emissions results are shown in Figure 6. Operation at the 1,500 and 2,300 RPM points in HECC mode resulted in at least a two-fold increase in the emissions of CO. The 2,000 RPM set point did not exhibit this same tendency. This may be due in part to differences in the mixing processes at the different speeds, as hypothesized above in the discussion of HC emissions trends.

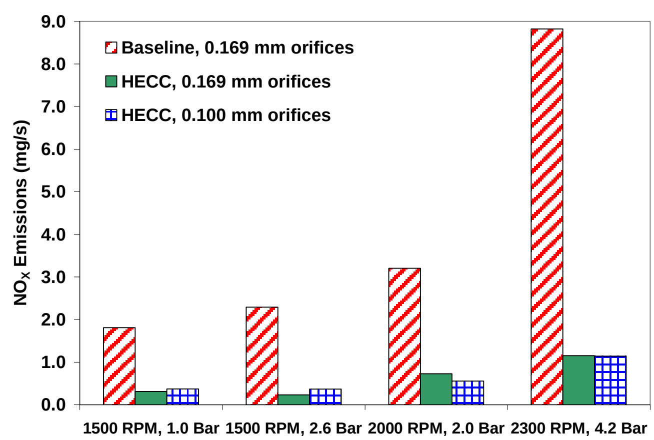

Figure 2. NO_X emissions results.

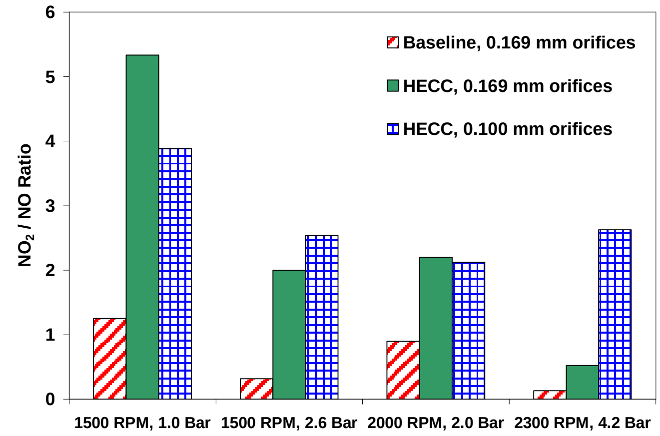

Figure 3. NO_2 / NO ratios for baseline and HECC combustion modes.

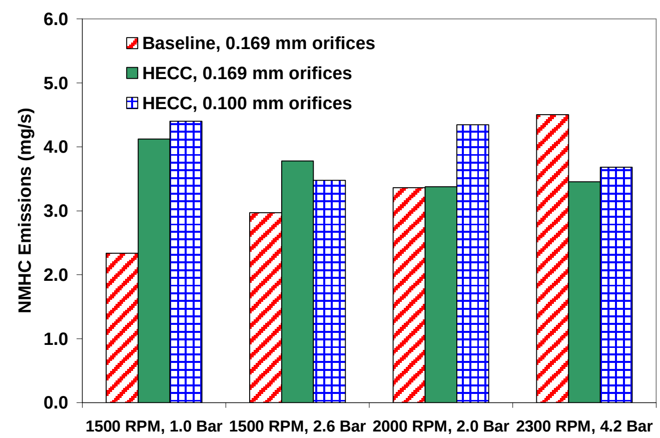

Figure 4. Non-methane hydrocarbon emissions results.

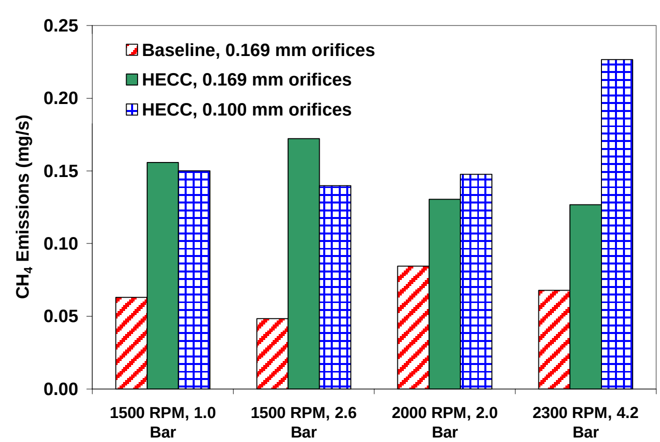

Figure 5. Methane emissions results.

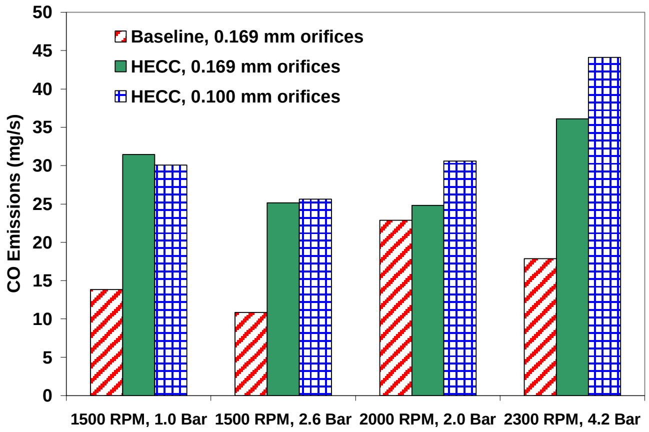

Figure 6. CO emissions results.

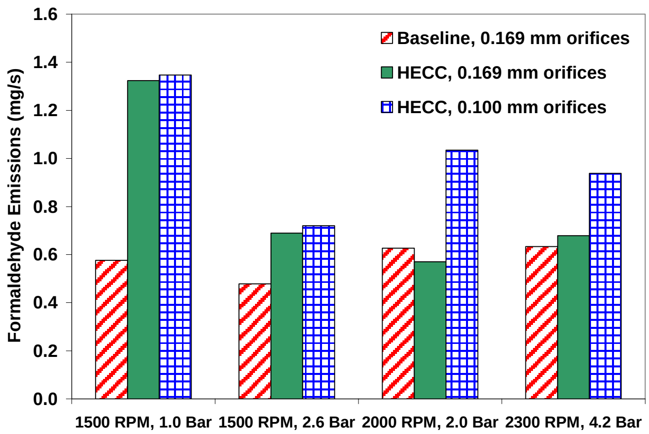

Figure 7. Formaldehyde emissions results.

MOBILE SOURCE AIR TOXIC EMISSIONS

The United States Environmental Protection Agency (EPA) has established a list of toxic compounds that are related to vehicles [19]. The list of mobile source air toxic (MSAT) compounds includes formaldehyde, acetaldehyde, 1,3 butadiene, and benzene. The EPA included a gram/mile regulatory standard for formaldehyde (H_2CO) in the Tier 2 emissions regulations [20]. Figure 7 shows the formaldehyde emissions results. Acetaldehyde (C_2H_4O) emissions results are shown in Figure 8. Both the formaldehyde emissions levels in HECC are considerably higher than baseline levels. 1,3 butadiene was also detected at levels of approximately 1 part-per-million (PPM) at baseline conditions and at concentrations as high as 5 PPM for HECC modes. FTIR measurements of benzene were not conclusive, as the measurements were generally the same order-of-magnitude as the measurement error.

EXHAUST TEMPERATURE AND SPACE VELOCITY

Exhaust temperatures and space velocities for each of the engine conditions are shown in Table 4. The exhaust temperatures were measured at the

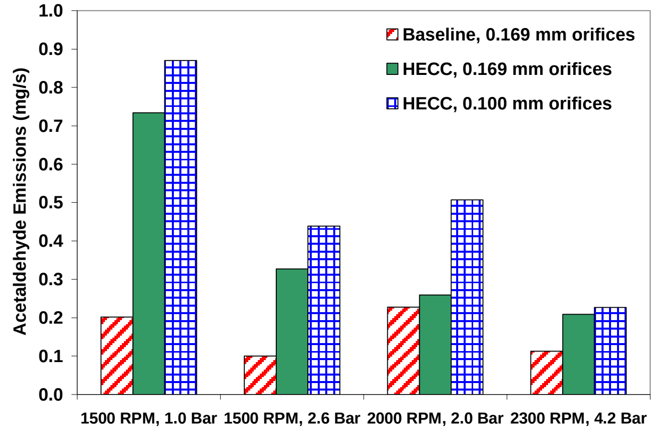

Figure 8. Acetaldehyde emissions results.

Table 4. Exhaust temperature and space velocity data. (Baseline value / HECC value)

Engine Condition	Exhaust Temp °C	Space Velocity $kHours^{-1}$
1,500 RPM, 100 kPa BMEP	128 / 142	20 / 12
1,500 RPM, 262 kPa BMEP	213 / 211	21 / 12
2,000 RPM, 200 kPa BMEP	214 / 217	27 / 17
2,300 RPM, 420 kPa BMEP	314 / 294	43 / 29

turbocharger exhaust exit flange. Space velocities were calculated based upon a 2.5 liter catalyst volume and assume the measurement is made downstream of the particle filter, after the exhaust flow has been diminished by the removal of the low-pressure EGR flow. The baseline and HECC data shown are for the original injector nozzles with 0.169 mm orifices. The exhaust temperatures in HECC mode are generally comparable to the baseline temperatures. The HECC mode space velocities are considerably lower than baseline because of the use of elevated levels of EGR.

COMPOSITE EMISSIONS ESTIMATES

The emissions and fuel consumption results for each engine condition and each species were used to calculate an emissions index for each species at each operating condition. These indices were then weighted using the corresponding weighting factors to produce a composite emissions factor that expressed the pollutant levels relative to the mass of fuel consumed (e.g. grams of NO_X produced per gram of fuel consumed). The composite emissions index was then divided by the vehicle fuel economy for the FTP-75 cycle and multiplied by the fuel density. The fuel economy for the Mercedes A170 was 45 miles per gallon for the FTP-75 schedule

[21]. This procedure resulted in an FTP-75 emissions estimate for each regulated pollutant species that was used to calculate the required cycle-average aftertreatment efficiency.

The composite emissions indices are shown in Figure 9. CO emissions are shown divided by 10 to allow them to be shown on the same graph. The index for CO shows a factor of 2 increase, from 0.035 to 0.070 g CO / g fuel. NMHC emissions also increased, from 0.007 to 0.0095 g NMHC / g fuel. This is an increase of nearly 36%. The NO_X index shows a decrease of approximately 85% to 0.0009 g NO_X / g fuel. The estimated PM mass emissions index also decreases, from 0.0012 to 0.0006 g PM / g fuel. Formaldehyde emissions increase 64%, from 0.0014 to 0.0023 g H_2CO / g fuel. Acetaldehyde emissions have not been shown on Figure 9, as no exhaust emissions limits have been established for this species.

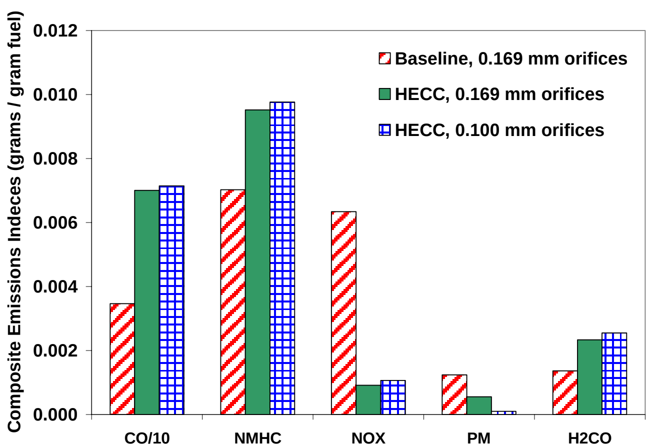

Figure 9. Composite emissions indices.

Table 5. Tier 2, Bin 5 Full-Useful Life Emissions Standards.

Pollutant	Allowable Level (g/mi)
NO_X	0.07
NMOG	0.09
CO	4.2
PM	0.01
H_2CO	0.018

DISCUSSION

The composite emissions indices demonstrate the potential for significant reductions in engine-out NO_X and PM, with corresponding overall increases in NMHC, CO, and H_2CO emissions. Table 5 shows the U.S. Tier 2, Bin 5 full-useful-life regulatory levels for the purpose of this discussion. It is important to underscore the limitations of the approach taken in this study. Since these emissions indices are based upon fully-warmed, steady-state data, they do not include the important effects associated with cold-start and transient load/speed operation.

The baseline level of NO_X pollution requires substantial reduction to meet bin 5 requirements and is why there has been intense focus for several years on improving NO_X aftertreatment for diesels. The HECC results show that a substantial amount of this reduction can be accomplished by operation in HECC modes. Similarly, PM may be reduced by approximately half by operating in HECC modes. The elevated CO emissions imposed by operating in HECC modes are estimated to be in excess of the 4.2 g/mi standard for bin 5, requiring modest reduction for compliance. NMHC emissions (as a surrogate for non-methane organic gases as specified in the standard) and H_2CO emissions for HECC modes are estimated to be far in excess of the standards and require large reductions for compliance.

These comparisons show that in an overall sense HECC combustion modes can reduce the requirements for NO_X and PM aftertreatment systems, but at the expense of increasing the requirements for hydrocarbon aftertreatment systems. This may be a reasonable trade-off since hydrocarbons are generally more easily treated than NO_X. The increased CO emissions do not seem to pose as much of an issue in comparison with need for reductions in NMHC emissions and may even assist with catalyst light-off. An aftertreatment system that can bring the NMHC emissions into compliance will likely also sufficiently oxidize the CO emissions.

The baseline NMHC index indicates that a cycle-average aftertreatment effectiveness of at least 82% would be required to comply with bin 5 levels. This requirement increases to at least 87% for the HECC NMHC estimates. The two 1,500 RPM conditions are responsible for most of the increase in NMHC emissions and also have very low exhaust temperatures. Achieving sufficiently high oxidation effectiveness at these temperatures may be a challenge, especially since partial oxidation may result in higher emissions of formaldehyde or acetaldehyde. This tendency was observed at some conditions for the catalyzed particle filter utilized in this study. Recent HCCI studies have also shown hydrocarbon emissions to be quite high, and suggest that HCCI implementations likely share the NMHC aftertreatment challenges observed in this study with HECC. [22-23]

The baseline and HECC formaldehyde emissions require cycle average reductions similar to the NMHC emissions to approach compliance with bin 5 standards. The lowest-temperature condition of 1,500 RPM and 100 kPa BMEP was most responsible for the increases in the aldehyde emissions, but significant increases were observed at the higher temperature conditions as well. The CDPF utilized for this study did not provide enough oxidation of the aldehyde emissions at any of the engine conditions to approach the bin 5 requirements, as the peak conversion efficiency was observed to be approximately 60%. HCCI studies have also indicated that high levels of aldehyde emissions are not uncommon for these engines. [22-23] Acetaldehyde and higher-aldehydes have been reported to be key species in the reduction of NO_X over zeolyte and silver catalysts in oxygen-rich environments [24-25]. Increases in the production of these species may be of benefit to certain aftertreatment technologies if the overall hydrocarbon concentrations are not problematic in terms of competition for catalyst sites.

While the NO_X and PM emissions were substantially reduced in HECC operation, aftertreatment technologies for these species are likely still required. Reductions in PM emissions associated with HECC modes are not sufficient to reliably comply with the standard when using the 0.169 mm injector nozzles. Possible under-prediction of PM emissions associated with the use of the smokemeter rather than gravimetric analysis would result in increases in PM above the levels estimated in this study. Use of the 0.100 mm injector nozzles produced a large decrease in PM emissions without significant penalties in the other pollutants compared with HECC modes using the 0.169 mm nozzles. However, use of the 0.100 mm nozzles led to increased combustion rate-of-pressure rise that limited the engine output to less than its rated performance levels. Furthermore, the use of LP-EGR for HECC operation requires the use of a particle filter prior to the EGR cooler and turbocharger to prevent degradation of these components. The NO_X reduction in HECC modes approached the levels needed for compliance. However, it is doubtful that even this level of reduction would be sufficient when a transient, cold-start test is conducted. As has previously been published, it is possible to further reduce the NO_X emissions to the point that NO_X aftertreatment is no longer required, but at the expense of decreased engine efficiency and further increases in CO, NMHC, and H_2CO emissions [26-27]. The observed decreases in NO_X and PM levels may represent an opportunity for decreasing the cycle-average performance requirements of the aftertreatment system.

NO_X reduction in HECC modes may also be complicated by the NO_2 / NO ratio in those modes. The relatively high NO_2 content may be beneficial for NO_X traps, particularly for operation at low exhaust temperatures. However, the opposite may be true for SCR systems, which can produce large amounts of N_2O in the presence of NO_2 / NO ratios greater than unity [28-29]. An aftertreatment system that can effectively treat NO_X emissions in both normal and in HECC modes will need to accommodate the widely variant NO_2 / NO ratio.

In applying these estimates to practice, it is appropriate to anticipate that higher levels of pollution and therefore higher aftertreatment effectiveness requirements than are enumerated here will be encountered. More traditional diesel operation is also likely during high-load conditions such as those typical of the US06 cycle, which is a part of the US Supplemental Federal Test Procedure (SFTP). It seems likely, however, that the trends observed in these estimates will hold for the FTP test cycle. When HECC techniques are used NMHC and H_2CO emissions and corresponding aftertreatment effectiveness are likely to occupy an increasing amount of attention in terms of certification. CO emissions may not be an issue given the higher cycle-average oxidation needed for NMHC compliance. The PM emissions solution may not be impacted, since a particle filter is still required both from a regulatory standpoint and as a means of preventing degradation of the EGR cooler and turbocharger. However, regeneration of the particle filter may not be required as often since the engine-out PM emissions rate is considerably lower for HECC operation; this is potentially a benefit to the overall efficiency of the vehicle system. NO_X emissions will likely continue to be a challenge for aftertreatment, but the required effectiveness may not be as high as had previously been anticipated.

The temperature tolerance of HECC (and other low-temperature combustion modes) may not be sufficiently high to allow immediate use of this combustion mode during cold-starts. This may limit use of HECC to portions of the test cycle where the engine has warmed up, and consequently reduces the benefits of these combustion modes.

CONCLUSIONS

- Data from this study shows that HECC operation significantly reduces NO_X and estimated PM mass emissions indices at the expense of increased CO, NMHC, and H_2CO emissions indices. No fuel efficiency penalty was observed for these data.

- Observed reductions in NO_X and PM emissions, while potentially very significant, are not likely to eliminate the need for effective NO_X and PM aftertreatment systems for the FTP cycle. These potential gains are likely to reduce low-temperature NO_X and PM aftertreatment performance requirements and regeneration frequency.

- Increases in the estimated emissions levels of NMHC and H_2CO point to the need for effective (perhaps improved) aftertreatment oxidation performance at low temperatures and oxygen levels. These requirements may hold for engines employing either HCCI or PCCI combustion techniques.

- Increases in the estimated levels of CO emissions may not be a dominant factor in aftertreatment system design given the higher level of reduction in NMHC and CH_2O emissions needed for compliance.

- Effective NO_X aftertreatment for engines that use both HECC and normal combustion modes will need to be tolerant of a wider range of NO_2 / NO ratios than have been historically encountered.

ACKNOWLEDGMENTS

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DISCLAIMER

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