Injection Timing Effects on Premixed LTC Particle Emissions from Light and Heavy Duty Diesel Engines

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Extended Summary

Much work has been performed in recent years by Diesel engine researchers to simultaneously decrease engine-out particulate matter and nitrogen oxides (NO_x) emissions to meet stringent upcoming engine emissions regulations.[1,2,3] One of the solutions to reducing these engine-out emissions is operating the engine in a combustion regime known as premixed Diesel Low Temperature Combustion (LTC).[4,5,6] In this combustion regime, exhaust gas recirculation (EGR) is used to reduce the maximum combustion temperature, thereby decreasing the engine-out NO_x emissions. Research has shown that increased use of EGR to decrease engine intake oxygen concentration and in-cylinder combustion temperature has caused increased particulate matter emissions through reductions in in-cylinder particle oxidation. But additional research has shown that it is possible to decrease particulate matter emissions by further increases in EGR (further decreases in intake oxygen concentration and combustion temperature).[1] Beyond decreases in engine intake oxygen concentration, parameters such as injection timing must be optimized to find the engine operating condition which provides the lowest hydrocarbon and carbon monoxide emissions at the same time as these very low NO_x and particulate matter emissions.[5,6]

Although LTC researchers have been able to operate Diesel engines with particulate matter emissions below the minimum detection limit of traditional opacity-based particulate matter instruments (which are very commonly used in most Diesel combustion research facilities), other work has still measured significant changes to the particle size and number emissions with changes to engine operating conditions.[7,8,9] One of these works has found the injection timing to have a major effect on the particulate size and number emissions of a heavy duty Diesel (HDD) engine operating in the LTC regime.[9] The present investigation goes one step further by making a comparison of injection timing effects on particulate size and number emissions between a light duty Diesel (LDD) and HDD single-cylinder research engine, in which both were operated in the premixed LTC regime. Optimizing LTC in a small bore LDD engine can be more difficult than a large bore HDD engine because of the combustion chamber space limitations. One common problem is impingement of the liquid core of the fuel spray on the combustion chamber surface, either the piston or the cylinder wall. This can result in increased hydrocarbon, carbon monoxide, or particulate matter emissions. Actions taken in this study to reduce the fuel jet liquid spray length included increasing the charge air density in the combustion chamber (increased compression ratio, increased intake pressure, and reduced intake temperature in comparison with the HDD engine) and reducing the injector nozzle orifice diameter (while increasing the number of orifices). Reduction in particulate matter emissions (by increasing ignition delay) was performed by decreasing the intake temperature and intake oxygen concentration, in comparison with the HDD engine.

The LTC exhaust of both engines was diluted with filtered and dehumidified compressed air by a heated primary and ambient temperature secondary dilution. Particle size distributions of the diluted exhaust were measured with a TSI Scanning Mobility Particle Sizer. Although the LDD and HDD research engines differed in hardware configurations (bore diameter, size of combustion chamber, swirl, injector nozzle geometry, etc.) and LTC engine operating conditions (by engine speed, load, intake pressure, intake temperature, intake oxygen concentration, etc.), very similar trends were measured regarding the effect of injection timing on the particle size distributions.

Both engines (in their minimum particulate matter emissions injection timings) were able to achieve less than 25ppm NOx emissions and less than 0.05 filter smoke number, while maintaining hydrocarbon and carbon monoxide emissions below 550ppm and 5,200ppm, respectively. Hydrocarbon emissions for both engines similarly increased as the carbon monoxide emissions decreased for advances in injection timing. Although carbon monoxide emissions began to increase at injection timings earlier than -21°aTDC in the HDD engine tests.

It was common between both engines that the opacity-based smoke measurement decreased with earlier injection timing. It is proposed that these decreases in filter smoke number are the result of longer ignition delay and thus less in-cylinder particulate matter formation due to better fuel and air premixing before ignition. Decreases in particulate matter mass concentration (opacity-based measurement) at earlier injection timings were accompanied by decreases in particles larger than 30nm. With both engines, decreases in particles larger than 30nm for advances in injection timing coincided with increased particles smaller than 30nm.

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Abstract:

Much work has been performed in recent years by Diesel engine researchers to simultaneously decrease engine-out particulate matter and nitrogen oxides emissions to meet stringent upcoming engine emissions regulations.[1,2,3] One of the solutions to reducing these engine-out emissions is operating the engine in a combustion regime known as premixed Diesel low temperature combustion.[4,5,6] In this combustion regime, exhaust gas recirculation (EGR) is used to reduce the maximum combustion temperature, thereby decreasing the engine-out nitrogen oxides emissions. Research has shown that increased use of EGR to decrease engine intake oxygen concentration and in-cylinder combustion temperature has caused increased particulate matter emissions through reductions in in-cylinder particle oxidation. But additional research (Figure 1) has shown that it is possible to decrease particulate matter emissions by further increases in EGR (further decreases in intake oxygen concentration and combustion temperature).[1] Beyond decreases in engine intake oxygen concentration, parameters such as injection timing must be optimized to find the engine operating condition which provides the lowest hydrocarbon and carbon monoxide emissions at the same time as these very low nitrogen oxides and particulate matter emissions.[5,6]

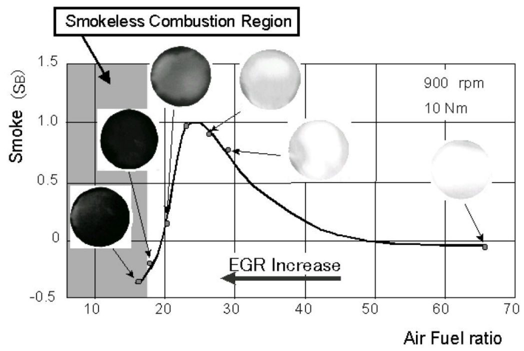

Figure 1. Reduced smoke emissions from added EGR.[1]

Although low temperature combustion researchers have been able to operate Diesel engines with particulate matter emissions below the minimum detection limit of traditional opacity-based particulate matter instruments (which are very commonly used in most Diesel combustion research facilities), other work (Figure 2) has still measured significant changes to the particle size and number emissions with changes to engine operating conditions.[7,8,9] One of these works has found the injection timing to have a major effect on the particulate size and number emissions of a heavy duty Diesel engine operating in the low temperature combustion regime.[9] The present investigation goes one step further by making a comparison of injection timing effects on particulate size and number emissions between a light duty and heavy duty single-cylinder Diesel research engine, in which both were operated in the premixed low temperature combustion regime. Low temperature combustion exhaust of both engines was diluted with filtered and dehumidified compressed air by heated primary and ambient temperature secondary dilutions. Particle size distributions of the diluted exhaust were measured with a TSI Scanning Mobility Particle Sizer. Although the light duty and heavy duty Diesel research engines differed in hardware configurations (bore diameter, size of combustion chamber, swirl, injector nozzle geometry, etc.) and low temperature combustion engine operating parameters (engine speed, load, intake pressure, intake temperature, intake oxygen concentration, etc.), very similar trends were measured regarding the effect of injection timing on the particle size distributions.

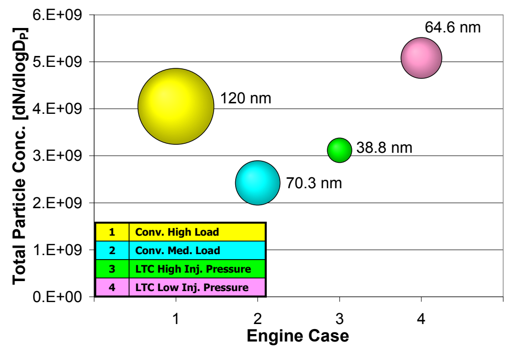

Figure 2. Variations in particle size (geometric mean diameter) and number for conventional (Cases 1 & 2) and low temperature (Cases 3 & 4) Diesel combustion.[8]

Both engines (in their minimum particulate matter emissions injection timings) were able to achieve less than 25ppm nitrogen oxides emissions and less than 0.05 filter smoke number, while maintaining hydrocarbon and carbon monoxide emissions below 550ppm and 5,200ppm, respectively. Decreases in particulate matter mass concentration (opacity-based measurement) at earlier injection timings were accompanied by decreases in particles larger than 30nm. With both engines, decreases in particles larger than 30nm for advances in injection timing coincided with increased particles smaller than 30nm.

Equipment:

The research engines used in this study were both single-cylinder adaptations of their full multi-cylinder production engines. Optimizing the light duty Diesel engine for low temperature combustion operation with minimal increases in hydrocarbon and carbon monoxide emissions (compared to conventional Diesel combustion) was difficult due to the limited free spray length available in the combustion chamber. Adequate in-cylinder charge air density during early injection was important to limit (or avoid completely) liquid spray impingement on the combustion chamber surface, such as the piston bowl or cylinder wall. For this reason, the light duty Diesel engine employed a compression ratio of 17:1 and a 10 orifice number injector nozzle with relatively small orifice diameters to decrease liquid spray length in this small bore engine.

Table 1. Description of Engine Hardware

Research Engine	Heavy Duty Diesel	Light Duty Diesel
Configuration	Single-Cylinder	Single-Cylinder
Displacement	1.8L	0.4L
Bore x Stroke	123mm x 152mm	76mm x 88mm
Compression Ratio	14.4:1	17:1
Injector Nozzle Orifices	7 x 190µm	10 x 100µm
Injection Angle	120°	145°

A Dekati FPS-4000 dual-stage diluter (Figure 3) was used in tests with both engines to prepare the particle-laden exhaust sample for analysis with the TSI Scanning Mobility Particle Sizer (SMPS) 3936. This SMPS setup consisted of the TSI 3080L classifier with long differential mobility analyzer and a condensation particle counter 3010. The total dilution ratio for tests with the heavy duty Diesel engine was approximately 40:1, except for the -15°aTDC injection timing which was 62:1 due to higher particulate matter emissions at that injection timing. The total dilution ratio with the light duty Diesel engine was approximately 28:1, except the -23°aTDC injection timing which was increased to 60:1 because of that timing's higher particulate matter emissions. The dilution ratios were measured by comparing carbon dioxide concentrations of the exhaust sample before and after the dilution. The exhaust sample dilution was performed with a heated primary perforated tube type dilution and an ambient temperature ejector dilutor secondary dilution.

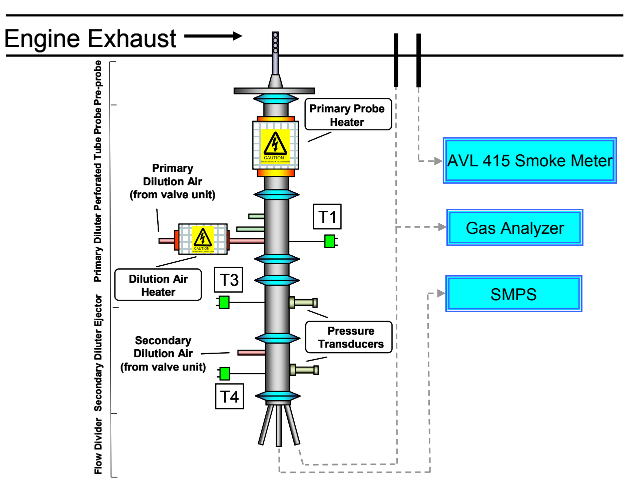

Figure 3. Layout of exhaust gas sampling instruments.

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Engine Test Conditions:

The heavy duty engine's load and speed were selected based on that engine's 25% load, low speed operating condition. The light duty engine's load and speed were selected by indicated mean effective pressure (IMEP) as the heavy duty engine, but at a much higher engine speed. The size and geometry of the combustion chamber of each engine had a large effect on the engine operating parameters necessary to achieve premixed Diesel Low Temperature Combustion. For the same reasons as having a higher compression ratio in the light duty Diesel engine, the intake pressure was also increased to increase in-cylinder charge air density and reduce/restrict liquid fuel impingement. Along with the higher compression ratio and intake pressure, the intake air temperature was reduced to 40°C. This not only increased the intake charge air density, but also delayed the kinetically-controlled start of combustion. The lower intake oxygen concentration of the light duty engine condition also helped delay the start of combustion. This delay between the start of injection and the start of combustion, called the ignition delay, was crucial in increasing pre-combustion fuel and air mixing, thus reducing particulate matter and other pollutant emissions. The ranges of injection timings were selected based on their abilities to reduce pollutant emissions concentrations (hydrocarbons, carbon monoxide, particulate matter, etc.).

Table 2. Description of Engine Test Conditions.

Research Engine	Heavy Duty Diesel	Light Duty Diesel
Speed [RPM]	1200	2250
IMEP [bar]	7	6
M_{fuel} [mg/cycle]	70	12
SOI [°aTDC]	-24 → -15	-32 → -23
$P_{injection}$ [bar]	1450	1400
EGR [%_vol]	50	67
$X_{O2,intake}$ [%_vol]	12.1	10
Equiv. Ratio [-]	0.83	0.74
T_{intake} [°C]	45	40
P_{intake} [bar]	1.35	1.75
$T_{exhaust}$ [°C]	366-375	234-236
P_{intake} [bar]	1.45	1.95

IMEP = Indicated Mean Effective Pressure
SOI = Start of Injection Command
EGR = Exhaust Gas Recirculation
X_{O2} = Intake Oxygen Percent

Results:

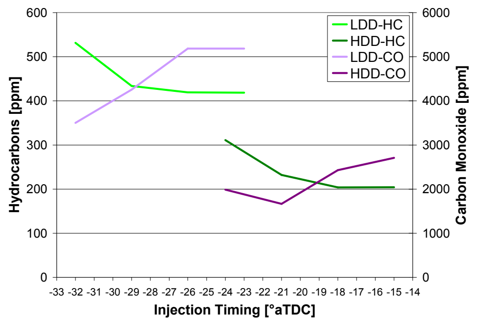

Figure 4. Hydrocarbon and carbon monoxide emissions from both engines for advances in injection timing.

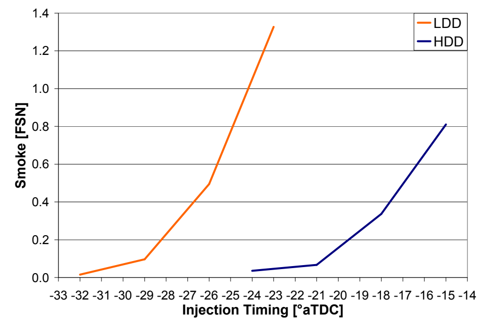

Figure 5. Smoke emissions from both engines for advances in injection timing.

Hydrocarbon emissions for both engines similarly increased as the carbon monoxide emissions decreased for advances in injection timing. Although carbon monoxide emissions began to increase at injection timings earlier than -21°aTDC in the heavy duty Diesel tests. It was common between both engines that the opacity-based smoke measurement decreased with earlier injection timing. It is proposed that these decreases in Smoke are the result of longer ignition delay and thus less in-cylinder particulate matter formation due to better fuel and air premixing before ignition.

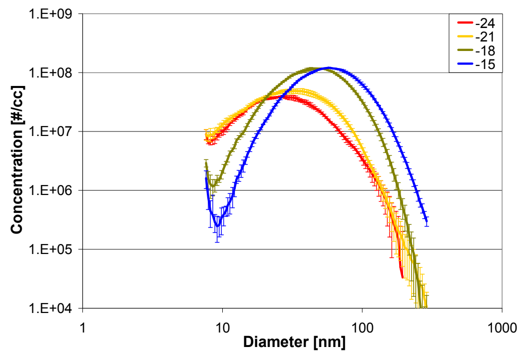

Figure 6. Particle size distribution measurements for multiple injection timings from a heavy duty Diesel engine operating in the premixed low temperature combustion regime.[9]

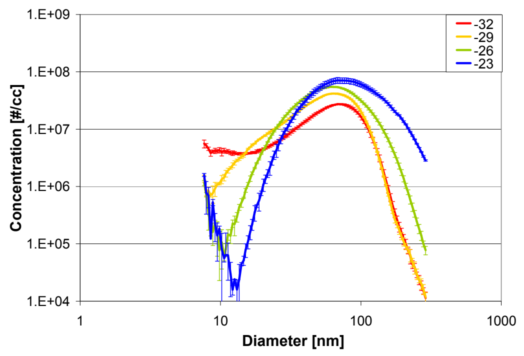

Figure 7. Particle size distribution measurements for multiple injection timings from a light duty Diesel engine operating in the premixed low temperature combustion regime.

Previous Low Temperature Combustion work with a heavy duty Diesel engine (Figure 6) has shown that injection timing can have a large influence on the particulate matter size and number emissions.[9] In Figure 7, large effects are also seen with changes to injection timing in the light duty Diesel engine particle size distributions. The red lines signify the particle size distribution of the most advanced injection timing of each engine, and the blue lines signify the latest injection timing. From Figures 4 and 5, it is seen that the earliest injection timings had the lowest Smoke emissions but highest hydrocarbon emissions. Perhaps this helps explain why the earliest injection timings had the fewest particles larger than 27nm, but the most number of particles smaller than 27nm. One possible effect is that since the reduction in large particles caused a reduction in available surface area, perhaps more volatile material condensed in the smaller particle size range rather than condensing on/in the larger particles. Another possible effect could be that the increased hydrocarbon emissions increased the amount of material with "condensation potential", thus increasing the number of smaller particles due to higher amount of volatile material.

Conclusions:

- The small bore light duty Diesel engine needed higher compression ratio, higher intake pressure, and lower intake temperature than the heavy duty Diesel engine to reduce or avoid completely liquid spray impingement on the combustion chamber surface.
- In general, for this range of injection timings, hydrocarbons increased and carbon monoxide decreased with advancements in injection timing.
- Smoke emissions decreased with advanced injection timing in both engines.
- For both engines, the earliest injection timing had the lowest Smoke measurement and fewest number of large particles.
- In both engines, the latest injection timing had the highest Smoke measurement and highest number of large particles.
- Number of smaller particles (<30nm) had an inverse effect with the number of larger particles.

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