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Exhaust Gas Recirculation/Water Injection Experimental Results for NOx Emission Reduction in Diesel Engine

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Abstract : This paper presents the static characteristics of EGR-WI combined system. The water injection system was statically characterized by recording the engine exhaust outlet NO_x emissions for comparison with baseline NO_x emissions. Effects of the water injection system on CO and HC emissions and fuel consumption were examined. The research engine used for these experiments was a 103 kW turbocharged, intercooled, 2.5 L VM Motori CIDI engine equipped with a cooled EGR system.

Water injection in the intake system demonstrated the potential for significant reductions in engine outlet NO_x emissions. The system has reduced engine outlet NO_x emissions by 40-50%, but caused significant increases in CO and HC emissions, particularly at low loads. Fuel consumption effects were minimal.

Key words : Exhaust Gas Recirculation(EGR), Water Injection(WI), Combined system, Compression-ignition direct-injection(CIDI) engine, Cooled EGR, NOx emissions

1. Introduction

Diesel engines offer significant advantages over spark ignited engines in terms of peak torque production, carbon monoxide (CO) emissions, hydrocarbons (HC) emissions, carbon dioxide (CO_2) emissions (known to cause the greenhouse effect) and fuel consumption. However, lean exhaust conditions render conventional automotive three way catalysts ineffective, making NO_x reduction a considerable challenge. EGR and Water Injection systems are a technology that has received much attention in recent years to combat this problem, and has shown the potential to meet the stringent regulations for NO_x emissions for US 2007/2010 and Euro IV/V[1].

The functionality of water injection is very similar to that of exhaust gas recirculation (EGR). A material, in this case water, is added to the intake system of an engine with the purpose of acting as a diluent within the cylinder, limiting peak combustion temperatures and thus nitrogen oxide (NO_x) formation. Liquid water serves as an excellent diluent due to its high heat of vaporization and specific heat, and offers even better NO_x

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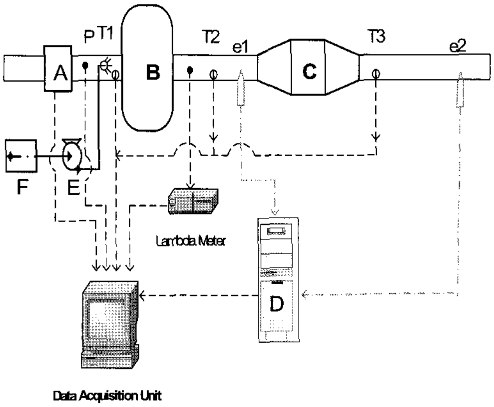
reduction potential than EGR[2]-[6].

Previous experiments have been conducted using EGR and WI separately. It has shown positive results lowering the NOx emission levels. With the idea of combining the two systems and its direct effect on diesel engine's emission, further study was conducted. Hence, this experiment analyzed the effects of the EGR/WI combined system.

2. EXperimental Apparatus and Method

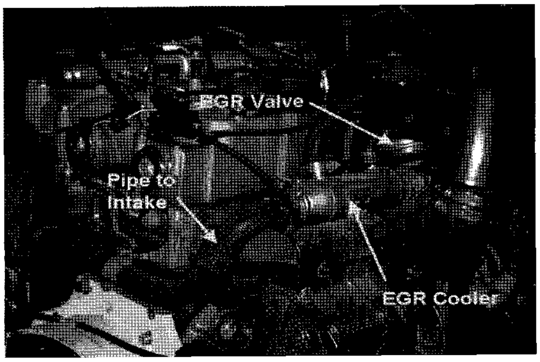
2.1 Apparatus



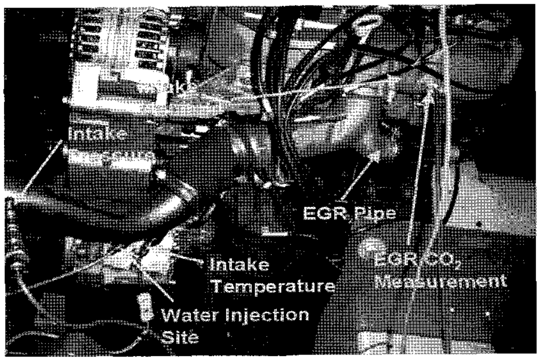
A. MAF Sensor, B. VM 2.5L CIDI
C. Oxidation Catalyst,
D. Horiba MEXA-7500
(e1:NOx, THC, CO, CO_2,, O_2, e2: NOx, THC)
E. Water Injection Pump, F. Water Tank
P. Pressur Sensor,
T1 – T3 : Temperature Sensors

Fig. 1 Schematic diagram of experimental measuring apparatus

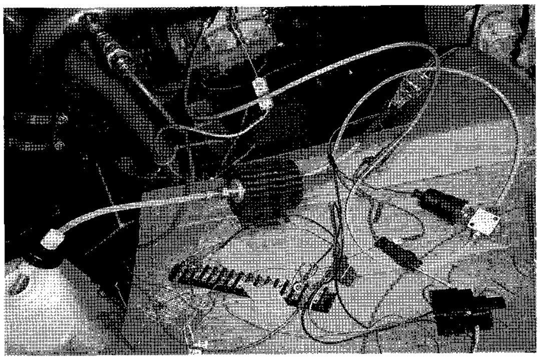
The research engine was calibrated to meet the Euro III emissions certification level, and is representative of a modern passenger car diesel engine. Emissions (NOx, THC, CO, CO_2, O_2) measurements were performed using the Horiba MEXA-7500 exhaust gas analyzer. Figure 1 shows the schematic diagram of experimental measuring apparatus. Photographs of test equipments are shown in Figure 2.



(a) 2.5 L VM-Motori EGR system



(b) Intake manifold side of 2.5L VM-Motori



(c) Water injection system

Fig. 2 Photographs of test equipments

2.2 Method of testing

2.2.1 EGR Experimental Procedure

The experimental procedure followed for the experiments involving the EGR system is outlined below. Note that this procedure also applies to the baseline case with the EGR system disabled. These experiments were purely static in nature. This procedure was used to collect baseline data with and without EGR for all 29 operating points

1. Activate all experimental equipment necessary for engine functionality and data collection (including cooling water, exhaust fan, power supplies, dynamometer electronics, etc.)
2. Warm up and calibrate Horiba MEXA-7500 for exhaust emissions sampling
3. Start engine, set speed/torque to 1750 RPM, 90 ft-lb, and allow engine coolant to warm up (at least 80 °C)
4. Select engine torque/speed to begin experiments.
5. Run the engine at the selected torque/speed for several minutes to allow equilibrium conditions to be met. Equilibrium was defined by steady levels of intake temperature, engine-out exhaust temperature, and engine-out NOx emissions.
6. Once equilibrium has been achieved, collect 20 seconds of data through the LabView data acquisition system at a scan rate of 10 Hz.
7. Change torque or engine speed and repeat steps 5-7

2.2.2 Water Injection Experimental Procedure

The second set of experiment involved the use of a water injection system for engine-out NO_x reduction, and the necessary procedure for the completion of these experiments is outlined below. Again, these experiments were static in nature.

1. Water injection experimental procedure is the same as that of the above EGR experimental procedure [(1) ~ (5)].
2. Select appropriate water injection valve duty cycle for desired water flowrate. Desired water flowrate is selected based on mass airflow (MAF) sensor signal and intake temperature and pressure.
3. Activate function generator to output pulse train at desired duty cycle.
4. Run the water injection system at a constant water flowrate for several minutes until equilibrium is achieved based on the criterion outlined in step (5).
5. Once equilibrium has been achieved, collect 20 seconds of data through the LabView data acquisition system at a scan rate of 10 Hz.
6. Change torque and/or engine speed and repeat steps 2 ~ 6.

This experimental procedure applies to cases where the water injection system is active and the EGR is either active or inactive.

3. Results and Discussion

3.1 EGR Experimental Results

3.1.1 EGR Rate

To better understand the resulting NO_x reduction from the EGR system, the EGR rate was determined for each engine operating point of the 2.5L VM-Motori engine. To do so, CO_2 measurements were made in the intake manifold and exhaust, and Equation 1 was applied.

$$EGR[\%]=\left(\frac{m_{egr}}{m_i}\right)\times 100 \qquad (1)$$

where: EGR[%] is the EGR rate in [%],
m_{egr} is the mass flowrate of EGR in [g/s],
m_i is the mass flowrate of fresh air charge entering the engine in [g/s].

The EGR rate is plotted as a function of torque and engine speed in Figure 3. EGR rates are significantly higher at low loads (to a maximum of about 45%), and steadily decrease with increasing load. Virtually no EGR is used at higher loads (greater than 120 ft-lb) for two main reasons: combustion stability and particulate formation. Good combustion stability is necessary to produce the peak torque and power ratings of the engine, and EGR slows combustion and decreases stability. EGR rates are limited by particulate formation primarily because significantly lean air-fuel ratios are required to limit particulate formation, and increases EGR rates would limit the fresh charge entering the cylinder and result in a richer air-fuel ratio. The air-fuel ratio at higher loads for the 2.5L VM-Motori diesel engine are already richer than low-load conditions, further limiting EGR usage. Air-fuel ratio for the engine in question is plotted as a function of torque and engine speed in Figure 4.

3.1.2 NOx Reduction from EGR

The NO_x reduction effects of the EGR system on the 2.5L VM-Motori diesel engine are outlined in Figure 5 as a function of torque and engine speed. As expected, the highest NO_x reduction is achieved under low-load conditions, with the NO_x reduction benefit from EGR decreasing with increasing load. Another effect to note is the decreased NO_x benefit of EGR with increasing engine speed at a given load. This effect is likely caused by decreased EGR rates with increasing engine speed, particularly at mid-to-high load.

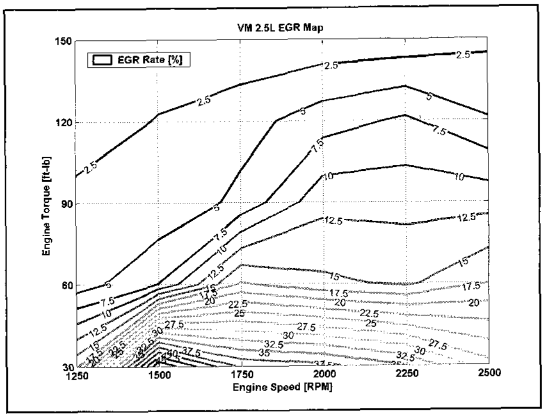


Fig. 3 2.5L Diesel Engine EGR Map

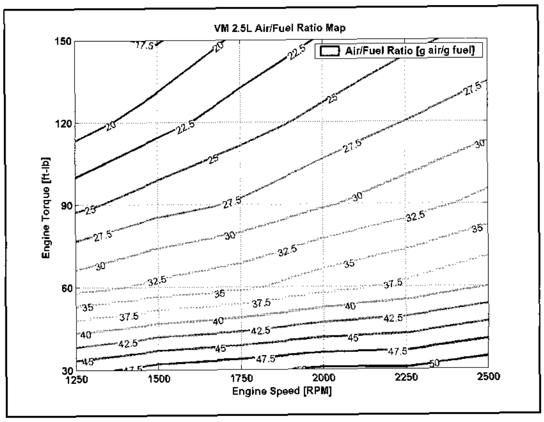


Fig. 4 2.5L Diesel Engine Air-Fuel Ratio Map

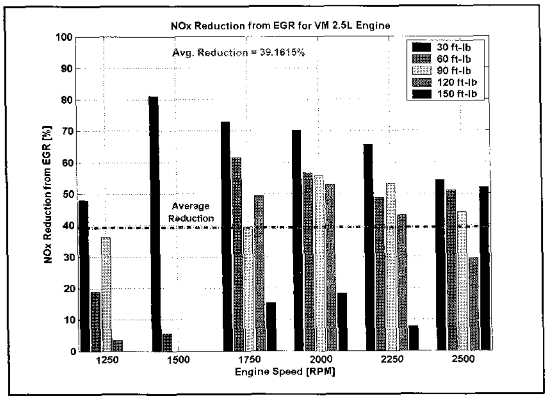


Fig. 5 NOx Reduction from EGR for the 2.5L Diesel Engine

3.1.3 Baseline and EGR NOx Maps

A common method used to express emissions flowrates is in the form of maps in the torque/speed plane. NO_x emissions results for each combination of EGR and water injection will be presented in this format throughout this paper. NO_x emissions will be expressed in grams per second [g/s].

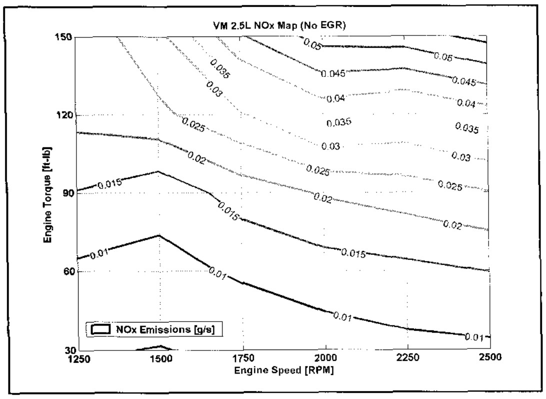


Fig. 6 Baseline (No EGR) NO_x Map for 2.5L Diesel Engine

The baseline (no EGR) and EGR only NO_x maps are presented in Figure 6 and Figure 7, respectively. Note the significant reduction in NO_x emissions at low loads, and the fact that NO_x emissions are 5-10 times higher at high load than they are at low load. This allows significant room for improvement from the water injection system at high load, where EGR is not used significantly.

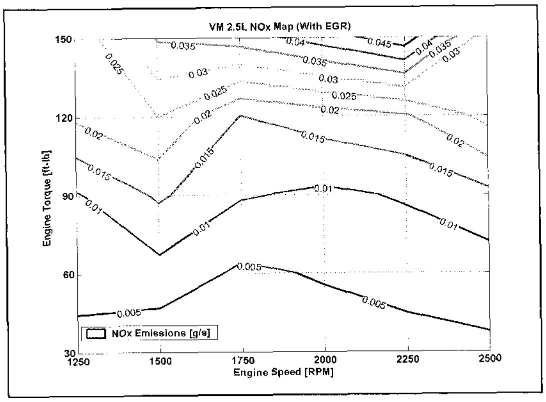


Fig. 7 EGR Only NO_x Map for 2.5L Diesel Engine

3.1.4 Effects of EGR on Other Emissions Species

An analysis was also conducted to determine the effects of the EGR system on other emissions species, specifically CO and HC. The impact of EGR on CO and HC emissions is displayed graphically in Figure 8 and Figure 9, respectively, as a function of torque and engine speed. Particulate matter emissions should also be impacted by the EGR system, but no equipment was available for particulate emissions measurement.

CO emissions are generally decreased by EGR usage at higher loads, and experience only a slight increase at lower loads. The results are fairly insensitive to engine speed. HC emissions on average are insensitive to the use of EGR. However, slight increases in HC emissions are encountered at higher engine speeds. In general, CO and HC emissions are fairly insensitive to the use of EGR for the 2.5L VM-Motori diesel engine.

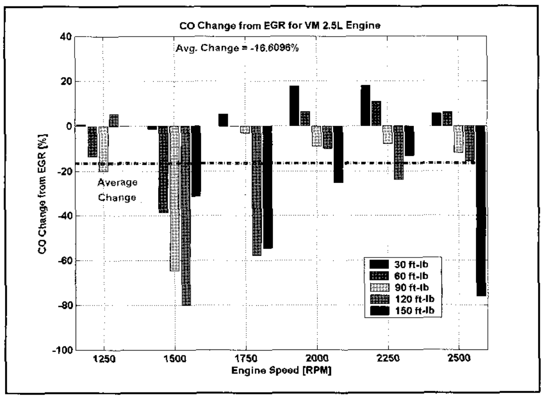


Fig. 8 CO Sensitivity to EGR for 2.5L Diesel Engine

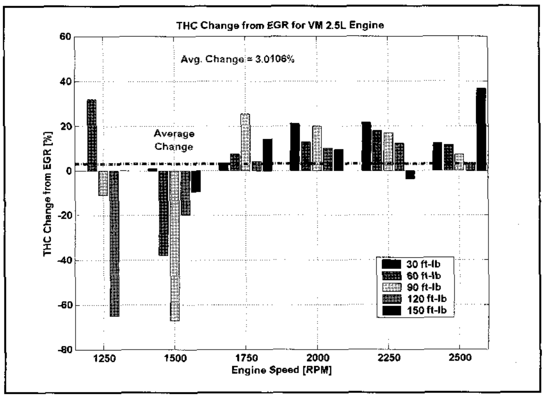


Fig. 9 HC Sensitivity to EGR for 2.5L Diesel Engine

3.2 Water Injection Experimental Results

3.2.1 Water Flowrate Selection and Actuation

A methodology for selecting an appropriate water flowrate for a given engine operating point was developed based on previous testing. The selection of the water flowrate is based on a target relative humidity level for the intake air post-intercooler. Due to the increased temperature of the intake air from the turbocharging process, there is a higher capacity for water. To select the water flowrate, a target relative humidity of 70% was selected. This is a conservative target to allow for ambient humidity and imperfect mixing of the injected water with the intake air to prevent damage to the engine. With the target humidity level selected, a psychrometric chart was utilized to record absolute humidity as a function of dry bulb temperature for 70% relative humidity. An exponential curve was fitted to these points to allow the selection of the absolute humidity level based on intake temperature (see Figure 10), and the curve fit equation is listed in Equation 2.

$$h = 3.4177 \cdot e^{0.0565 \cdot T_{intake}} \qquad (2)$$

where: h is the absolute humidity in [g water/kg dry air], T_{intake} is the intake temperature in [°C].

This process allows the desired absolute humidity to be fixed based on intake temperature, which is a strong function of engine torque. Next, the desired volumetric water flowrate can be calculated based on the air flowrate (MAF) entering the engine and the target absolute humidity, as outlined in Equation 3.

$$V_{water} = \left(\frac{1}{\rho_{water}}\right) \cdot m_{water} = h \cdot \left(\frac{MAF}{1000}\right) \cdot \left(\frac{1}{\rho_{water}}\right) \qquad (3)$$

where: V_{water} is the volumetric water flowrate in [mL/s],
ρ_{water} is the density of water in [g/mL],
m_{water} is the water mass flowrate in [g/s], and;
MAF is the air flowrate in [g/s].

With the water flowrate now known, the method of actuation must be examined. The water flowrate was controlled by a pulse-width modulated (PWM) signal driving a high-speed solenoid valve. The water flowrate is directly proportional to the valve duty cycle, and a calibration was performed to determine the proportionality (see Figure 11).

A curve fit was performed, and the relationship between the water flowrate and valve duty cycle is listed in Equation 4.

$$duty\ cycle = \frac{V_{water} - 0.6081}{0.0336} \tag{4}$$

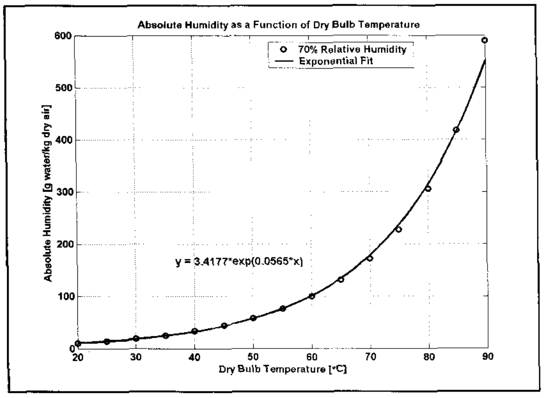


Fig. 10 Absolute Humidity as a Function of Temperature for 70% Relative Humidity

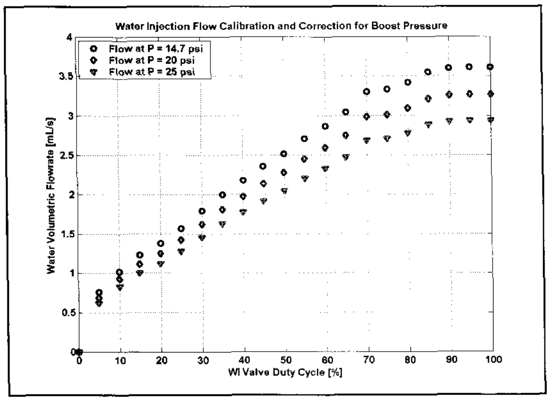


Fig. 11 Water Injection Valve Flow Calibration

3.2.2 NOx Reduction from Water Injection

The NO_x reduction effects of the water injection system for the 2.5L VM-Motori diesel engine are presented in Figure 12 for the case where EGR is inactive, and in Figure 13 for the case where EGR is active.

From the figures below, the NO_x reduction potential of the water injection system is fairly insensitive to the use of EGR, and is actually quasi-additive. This is especially true at high loads, where only small EGR rates are used. The water injection system's NO_x reduction potential is particularly beneficial because the highest NO_x reductions occur

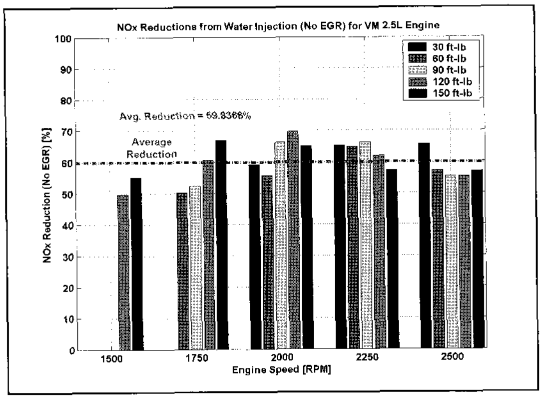


Fig. 12 NOx Reduction from Water Injection(No EGR)

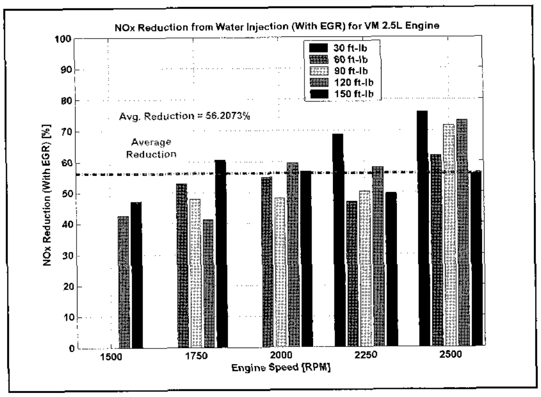


Fig. 13 NO_x Reduction from Water Injection(With EGR)

at mid-to-high loads that are common operating points during suburban and highway driving. Note that several operating points, including all operating points at 1500 RPM, show no NO_x reduction. This is due to the fact that no water could be added to the intake system due to insufficient intake temperature and/or air flowrate.

3.2.3 Water Injection NOx Maps

The NO_x maps in the torque/engine speed plane for the water injection system without EGR and with EGR are displayed in Figure 14 and Figure 15, respectively. The combined EGR/water injection system offers significant benefit over the water injection only system, particularly at low-to-mid loads where

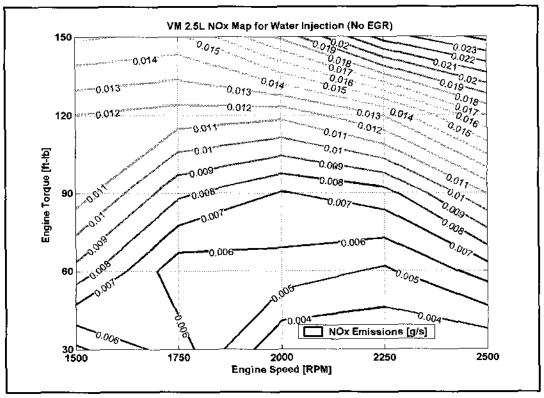


Fig. 14 NOx Map for Water Injection (No EGR)

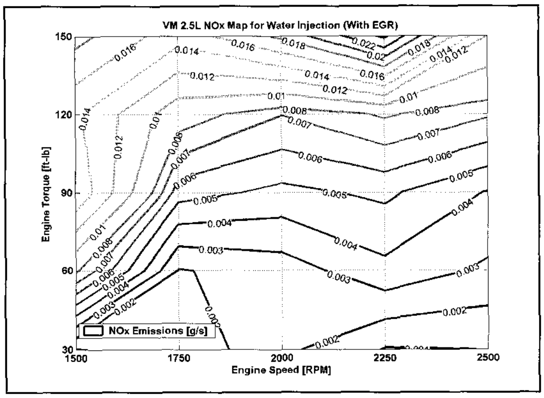


Fig. 15 NO_x Map for Water Injection (With EGR)

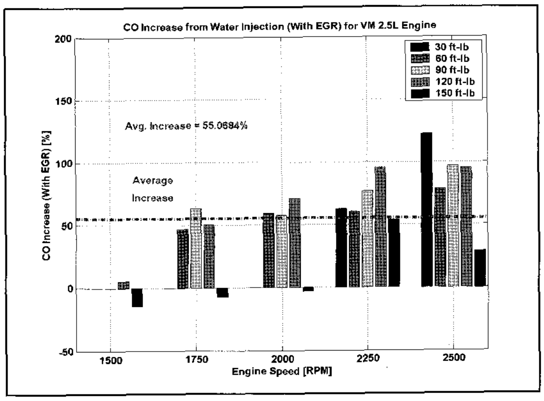


Fig. 16 Impact of Water Injection on CO Emissions

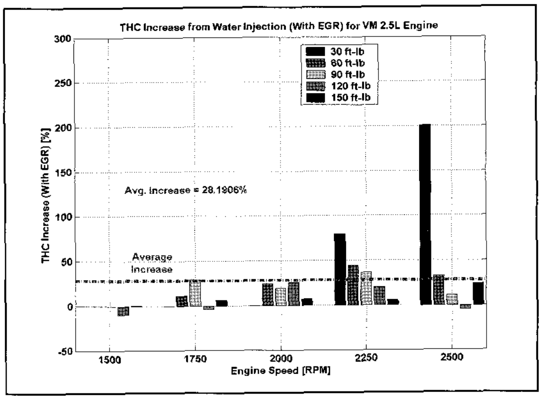


Fig. 17 Impact of Water Injection on HC Emissions

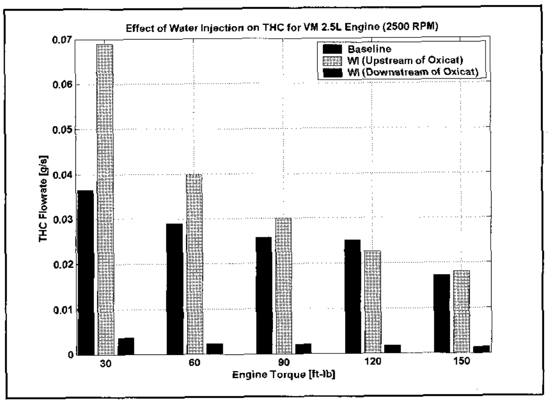


Fig. 18 Comparison of HC Emissions at Engine-Out and Post-Catalyst Locations

EGR is used at fairly high rates. The high load performance of both systems is virtually identical. Both systems represent significant improvements over the baseline (no EGR) and EGR cases.

3.2.4 Effect of Water Injection on Other Emissions Species

The water injection system, much like the EGR system, was expected to have a negative impact other emissions species, including CO, HC, and particulate matter emissions. The effects on CO and HC emissions are displayed in Figure 16 and Figure 17, but particulate matter emissions measurements were not available, so the impact of water injection on particulates could not be assessed. From the figures above, significant increases in CO and HC emissions are encountered with the use of water injection, particularly at low loads. The CO and HC emissions were expected to be effected more at low engine speeds based on previous testing, but those effects were not encountered here. While the increases in CO and HC emissions are significant, CO and HC emissions are normally much lower for diesels than for spark-ignited (SI) engines, so the increases would most likely be acceptable. Further, the use of an oxidation catalyst will most likely decrease CO and HC emissions with the water injection system active to levels lower than the baseline case. To verify this intuition, HC emissions were sampled at engine-out and post-oxidation catalyst locations at 2500 RPM for torques between 30 ft-lb and 150 ft-lb with the water injection system active for comparison with the baseline case. The results are displayed graphically in Figure 18. From the figure above, the HC emissions at the post-oxidation catalyst location are significantly lower than the raw HC emissions for the baseline case, even with the water injection system active. Similar trends can be expected for the CO emissions, but CO emissions measurements were not available on two sampling lines for confirmation.

4. Conclusions

The analysis of the EGR and water injection systems indicated that significant NO_x emission reduction potential existed for both systems. The EGR system generally offered 30-40% reduction in raw NO_x emissions, particularly at low-load operating points. The EGR rate is limited at high loads, though, to maintain lean air-fuel ratios while still producing high torque, limiting NO_x reduction at high loads. The impact of EGR on other emissions species, such as CO and HC, was minimal.

The water injection system proved to be an excellent compliment to the EGR system for in-cylinder NO_x reduction. Water injection is actually very similar in functionality to EGR, with a material (water or exhaust gas) with high specific heat added to the fresh charge for the purpose of lowering peak combustion temperatures and thus NO_x formation rates. Water injection was limited to operating points with relatively high air flowrate to allow for the evaporation of the water and to mid-to-high load operation, making it the perfect compliment to EGR, which is used at low-to-mid load.

The water injection system offered 50-60% NO_x reduction across the range of engine operating points tested. However, significant increases in CO and HC emissions were encountered, with increases in smoke emissions also expected.

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