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# Water Injection/Urea SCR System Experimental Results for NOx Reduction on a Light Duty Diesel Engine

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**Abstract** : The effects of water injection (WI) and urea injection for NOx on a 4-cylinder Direct Injection (DI) diesel engine were investigated experimentally. For water injection, it was installed at the intake pipe and the water quantity was controlled at the intake manifold and Manifold Air Flow (MAF) temperatures while the urea injection was located at the exhaust pipe and the urea quantity was controlled by NOx quantity and MAF. The effects of WI system, urea-SCR system and the combined system were investigated with and without exhaust gas recirculation (EGR). Several experiments were performed to characterize the urea-SCR system, using engine operating points of varying raw NOx emissions.

The results of the Stoichiometric Urea Flow (SUF) and NOx map were obtained. In addition, NOx results were illustrated according to the engine speed and load. It is concluded that the NOx reduction effects of the combined system without the EGR were better than those with the EGR-based engine.

**Key words** : Water injection(WI), Manifold air flow(MAF), Urea SCR, Tandem (combined water injection/urea SCR) system, Stoichiometric urea flow(SUF), NOx map

## 1. Introduction

Diesel engines offer significant advantages over spark ignited engines in terms of peak torque production, carbon monoxide (CO) emissions, hydrocarbon (HC) emissions, and fuel consumption (and associated carbon dioxide ($CO_2$) emissions known to cause the greenhouse effect). However, lean exhaust conditions render conventional automotive three way catalysts ineffective, making nitrogen oxide ($NO_x$) reduction a considerable challenge. Hence, studies have been conducted using different methods and technology to tackle these problems [1], [2]

One of these technologies is the Urea SCR which has received much attention in recent years and has shown the potential to meet the stringent regulations for $NO_x$ emissions for US 2007/2010 and Euro IV/V [3]-[5]. The urea SCR catalyst systems' function is defined by the selective reduction of $NO_x$ in a lean exhaust

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environment using ammonia. This makes urea SCR well suited to be used with diesel engines, which significantly always operate lean of stoichiometry. Four catalysts comprise a typical urea SCR system, including pre-oxidation, hydrolysis, SCR, and post oxidation catalysts [6].

Another method adopted is the water injection which functions very similarly to that of an exhaust gas recirculation (EGR) system. 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 $NO_x$ formation. Liquid water serves as an excellent diluent due to its high heat of vaporization and specific heat, and offers even better $NO_x$ reduction potential than EGR[7]-[9].

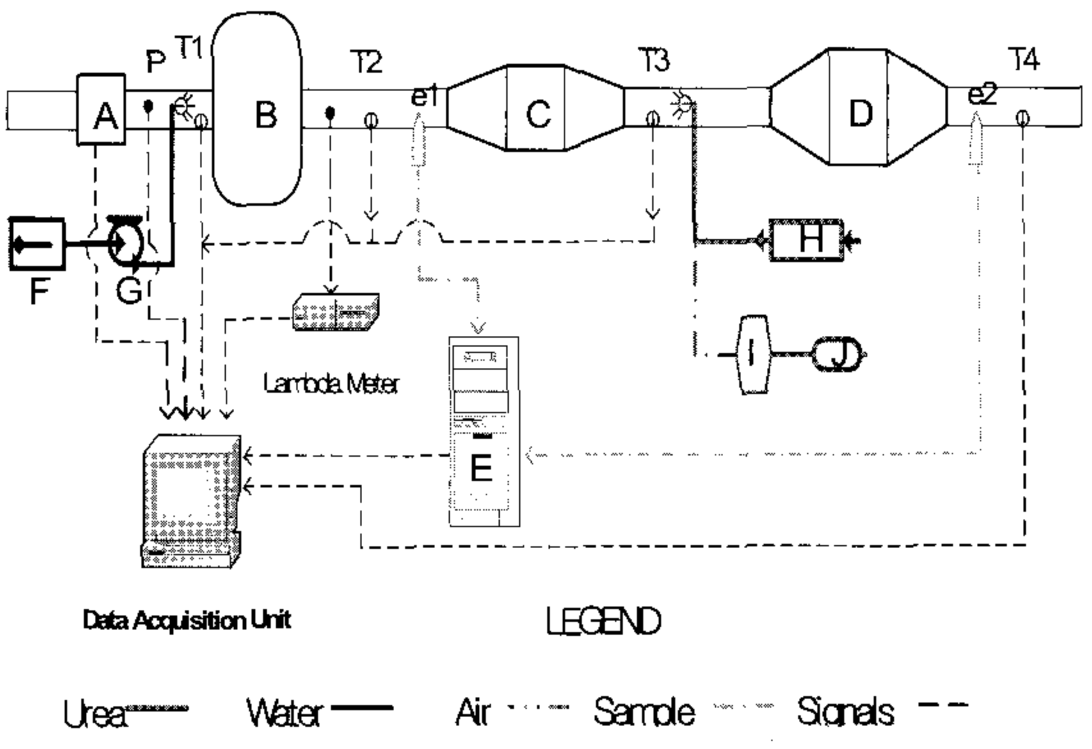
In this study, the combined system of Water Injection/Urea-SCR effect for NOx reduction on light diesel engine was conducted.

## 2. Experimental apparatus and method

### 2.1 Apparatus

The research engine used for these experiments was a 103 kW turbocharged, intercooled, 2.5L VM Motori compression ignition, direct injection(CIDI) engine equipped with a cooled EGR system.

The engine was calibrated to meet the Euro III emissions certification level, and is representative of a modern passenger car diesel engine. Emissions measurements were performed using a Horiba MEXA 7500 exhaust gas analyzer, with $NO_x$ measurements available on two separate lines (for raw and post catalyst measurements). Fig. 1 shows a schematic diagram of experimental measuring apparatus. Photographs of test equipments are shown in Fig. 2.



A. MAF Sensor,
B. VM 2.5L CIDI
C. Oxidation Catalyst
D. Hydrolysis & SCR Catalyst
E. Horiba MEXA 7500
(e1: NOx, THC, CO, $CO_2$,, $O_2$, e2: NOx, THC)
F. Water Tank
G. Water Injection Pump
H. Urea Syringe Pump
I. Air Regulator
J. Compressed Air Tank
P. Pressur Sensor
T1-T4 : Temperature Sensors

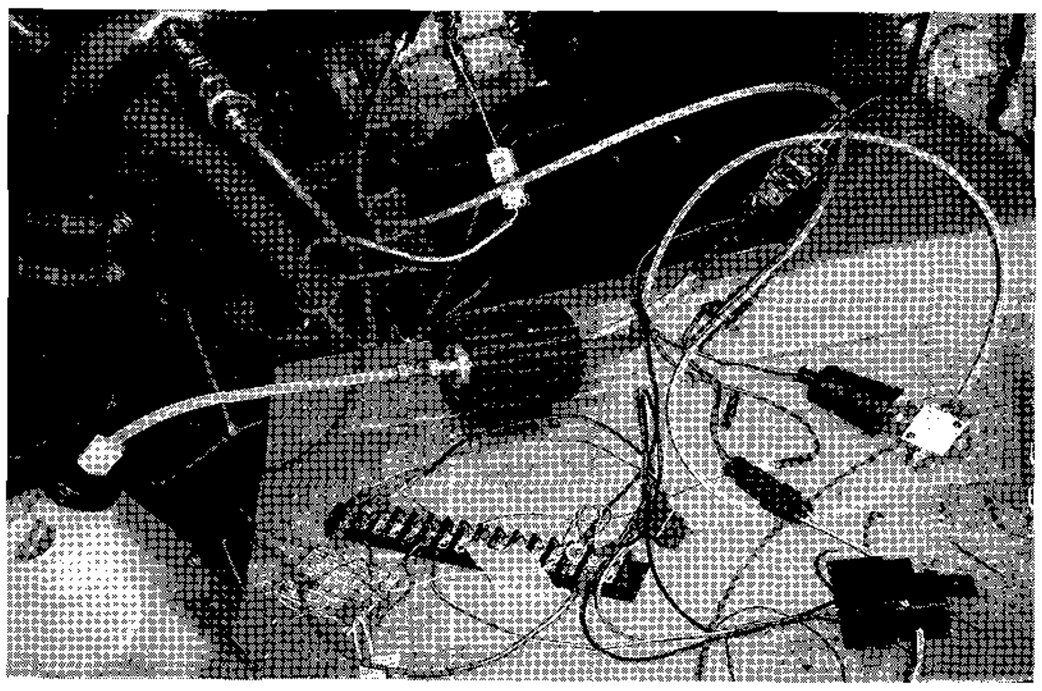
**Fig. 1 Schematic diagram of experimental measuring apparatus**

### 2.2 Method of testing

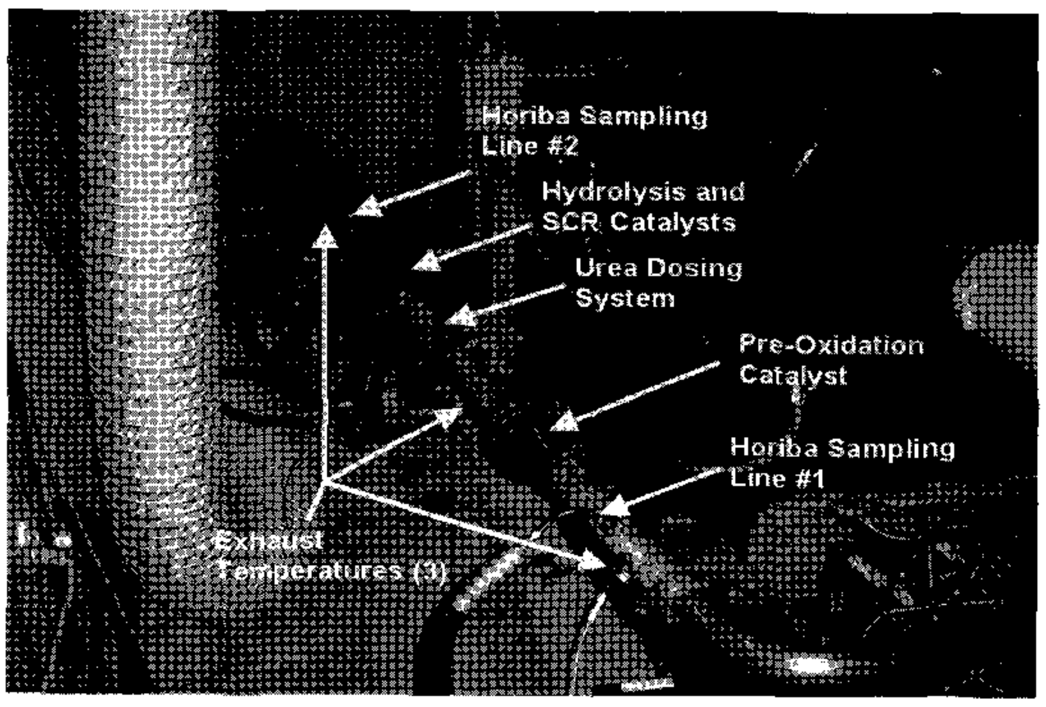
The urea solution was created using reagent grade urea pellets and distilled water.

The urea solution concentration selected for this work was 33% by weight, which is the eutectic solution.

The urea flowrate mapping portion of the combined system involved sweeping through multiple urea flowrates at a fixed water injection flowrate for a fixed engine operating point.



(a) Water injection system



(b) Urea SCR system experimental setup

**Fig. 2 Photographs of test equipments**

A total of 20 operating points ranging from 1500 rpm to 2500 rpm in intervals of 250 rpm and 40 Nm to 200 Nm in intervals of 40 Nm were tested, with the limiting factor being sufficient airflow to be able to inject water in the intake system.

### 2.2.1 Water flowrate calculation[1]

This process allows the desired absolute humidity to be fixed based on intake temperature, which is a vital function of engine torque. Next, the desired volumetric water flowrate can be calculated based on the MAF entering the engine and the target absolute humidity, as outlined in Equation 1. The water flowrate was controlled by a pulse width modulated (PWM) signal driving a high speed solenoid valve.

$$V_{water} = (1/\rho_{water})m_{water} = h(MAF/1000)(1/\rho_{water}) \quad (1)$$

where : $V_{water}$ is the volumetric water flowrate in [mL/s],
$\rho_{water}$ 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].

### 2.2.2 Stoichiometric urea flowrate calculation[2]

The urea flowrates were selected based on the stoichiometric urea flowrate, which is calculated as a function of raw $NO_x$ emissions from the engine and the chemical and physical properties of urea, $NO_x$, and ammonia in Equation 2.

$$m_{urea,stoich} = (m_{NO}/FW_{NO})(FW_{NH_3})(1/[U:NH_3])(1/Urea) \quad (2)$$

Where : $m_{NO}$ : the raw NO flow rate in [g/s],
$FW_{NO}$ : the formula weight of NO in [g/mol],
$FW_{NH_3}$: the formula weight of $NH_3$ in [g/mol],
$U:NH_3$ : the $NH_3$ produced from a unit mass of urea,
Urea : the concentration of the urea solution.

# 3. Results and discussion

## 3.1 Water Injection/Urea SCR Static Experiment Results

### 3.1.1 Urea Flowrate Mapping

The urea flowrate mapping portion of the combined water injection/urea SCR system involved sweeping through multiple urea flowrates at a fixed water injection flowrate for a fixed engine operating point. A total of 20 operating points ranging from 1500 RPM to 2500 RPM and 40 Nm to 200 Nm were tested, with the limiting factor being sufficient airflow to be able to inject water in the intake system. An $\alpha$ equal to one ($\alpha=1$) corresponds to the stoichiometric urea flowrate, and $\alpha$ greater than one ($\alpha>1$) represents urea flow in excess of stoichiometric. The stoichiometric urea flowrate of $\alpha$ equal to one could be delivered without a significant ammonia slip, where as non stoichiometric urea flowrate ($\alpha>1$) can deliver an ammonia slip[2]. Results are presented in Fig. 3~5.

The figures presented illustrate the majority of the results collected for the static urea flowrate mapping of the combined water injection/urea-SCR system.

Fig. 3 represents a case where high $NO_X$ reduction is achieved from water injection alone, and only small gains in $NO_X$ conversion efficiency from the urea SCR system are realized by exceeding the stoichiometric urea flowrate. These phenomena are likely due to the high tolerance for WI (high air flowrate, high intake temperature) at the operating point, as well as the smaller engine-out $NO_X$ flowrate as a limiting factor for the urea SCR system.

Fig. 4 represents a case where relatively small $NO_X$ reduction from water injection is encountered, along with substantial improvement in $NO_X$ conversion efficiency from the urea-SCR system by exceeding the stoichiometric urea flowrate. These results are almost the exact opposite of the first case, and the lower $NO_X$ reduction from water injection can be explained by the lower air flowrate/intake temperature at the operating point, limiting the quantity of injected water.

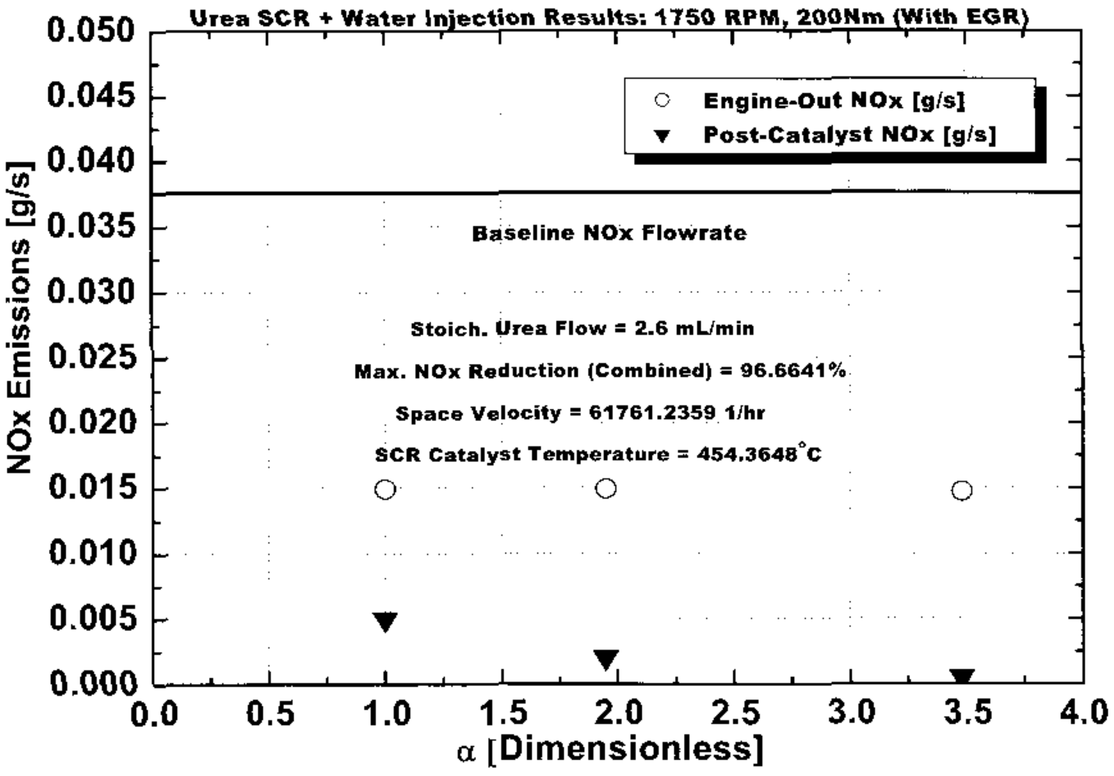


Fig. 3 Water injection/urea SCR results 1750 rpm, 200 Nm

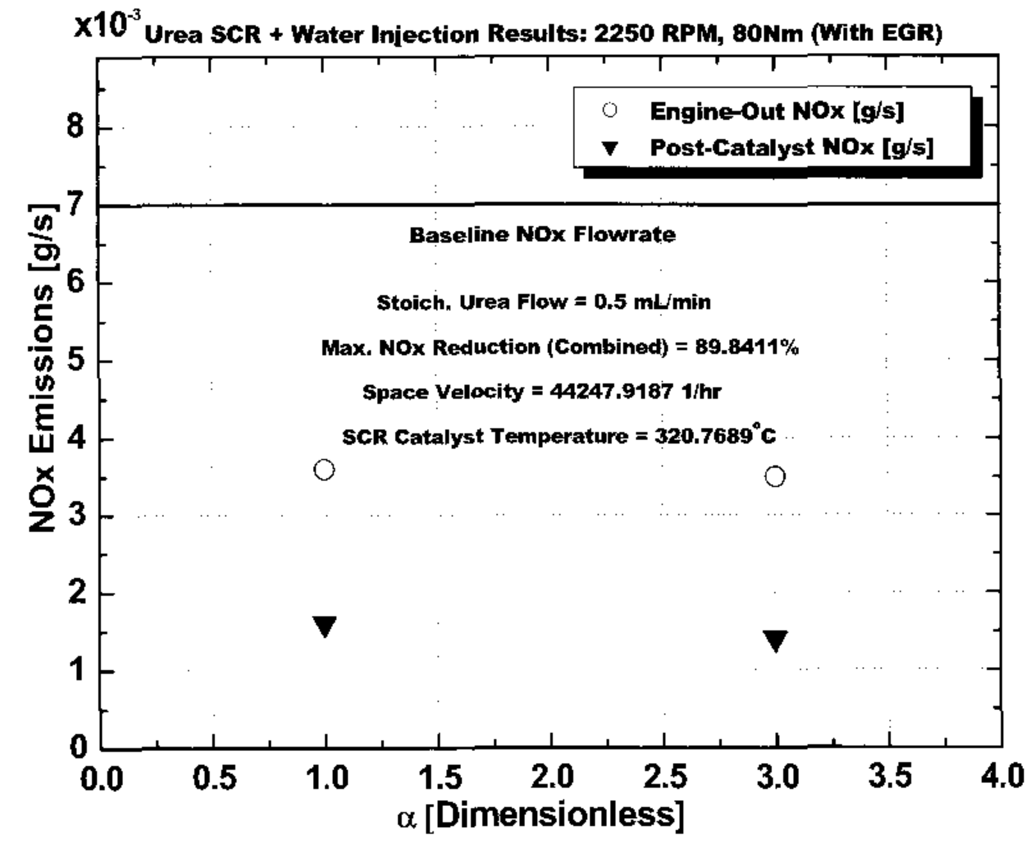


Fig. 4 Water injection/urea SCR results 2250 rpm, 80 Nm

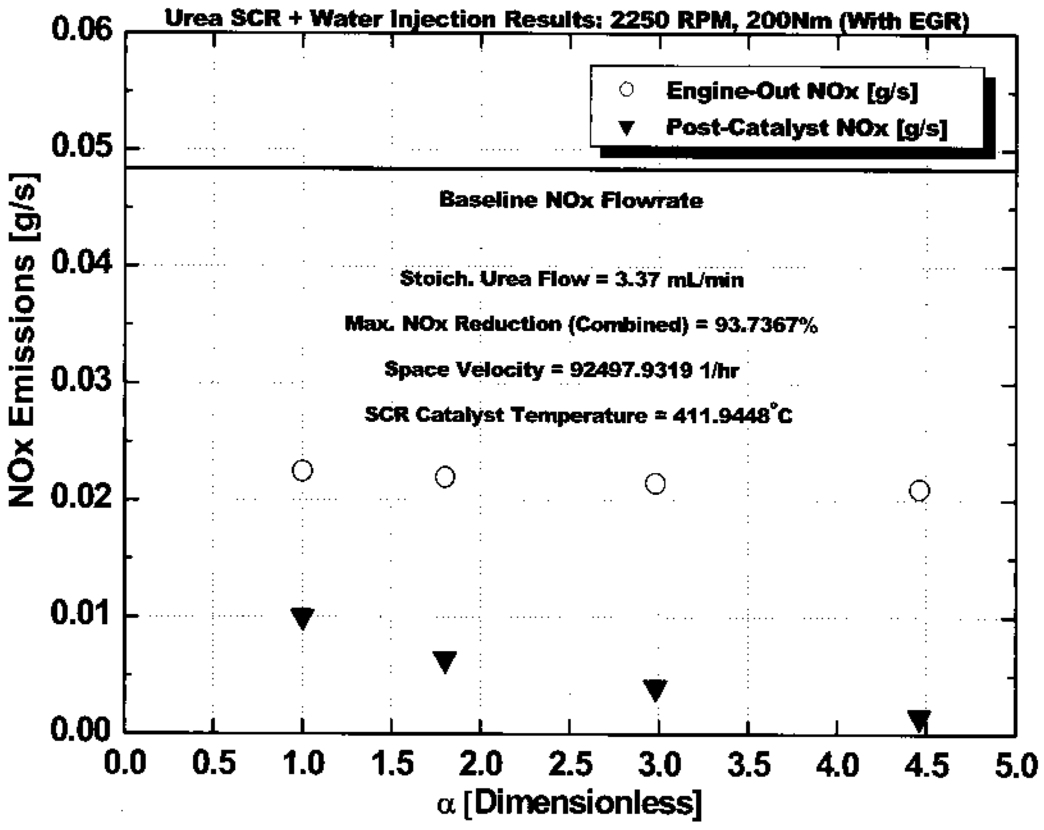


**Fig. 5 Water injection/urea SCR results 2250 rpm, 200 Nm**

As a result, a higher $NO_x$ flowrate can be reduced at the SCR catalyst, and favorable conditions (catalyst temperature, space velocity) exist for the reduction process, which promotes the higher $NO_x$ conversion efficiency, even beyond the stoichiometric urea flowrate.

Finally, Fig. 5 represents cases where large gains in $NO_x$ conversion efficiency from the urea-SCR system are possible, but only far beyond the stoichiometric urea flowrate. $NO_x$ reduction from water injection is somewhat low at this operating point, likely because of mechanical limitations of the dosing system.

### 3.1.2 NOx Reduction from Water Injection/Urea SCR

Based on the work from the previous sub section, the $NO_x$ reduction potential of the combined water injection/urea-SCR system was compiled for cases with active and inactive EGR, as well as stoichiometric and beyond stoichiometric urea flowrates. The results are displayed in Fig. 6 and Fig. 7 for the inactive EGR cases and in Fig. 8 and Fig. 9 for the active EGR cases.

Several patterns can be extracted from the results presented in the figures below. First, the $NO_x$ reduction from the combined system is somewhat insensitive to the use of EGR, particularly for the beyond stoichiometric urea flowrate cases. This is important because it may allow the EGR system to be eliminated, limiting the negative side effects of EGR, including particulate matter emissions and durability issues. Another pattern to note is the limited gain in $NO_x$ reduction achieved by increasing the urea flowrate beyond stoichiometric, particularly with the EGR system active. This is another positive quality of the combined system, because high $NO_x$ reduction is possible under conditions that may limit the ammonia slip that results from exceeding the stoichiometric urea flowrate.

Finally, the $NO_x$ reduction potential of the combined system with EGR is much less sensitive to the engine operating point than the inactive EGR combined system is, particularly at low loads. This is because minimal water injection can be performed at low loads, which drastically reduces $NO_x$ reduction for the inactive EGR case. However, for the active EGR case, significant EGR rates are utilized especially at low loads, which offset the lack of water injection at these operating points and maintains high $NO_x$ reduction across all operating points.

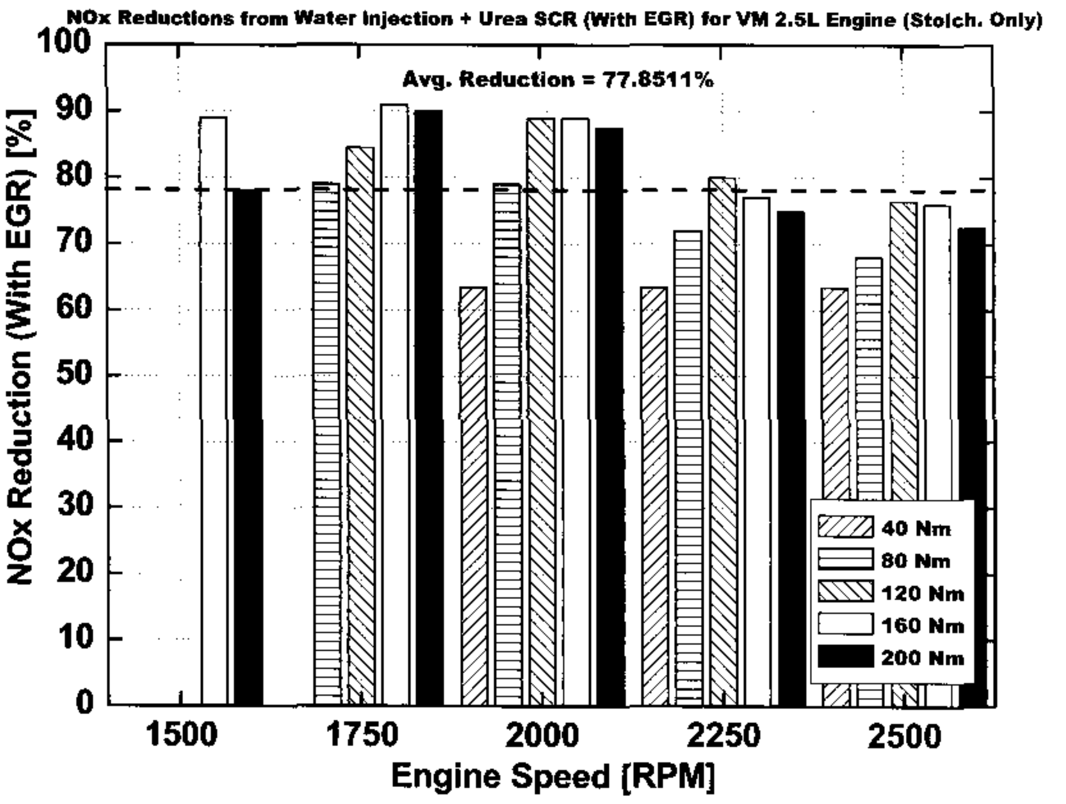


**Fig. 6** $NO_x$ reduction from water injection/urea SCR (No EGR, stoich. urea)

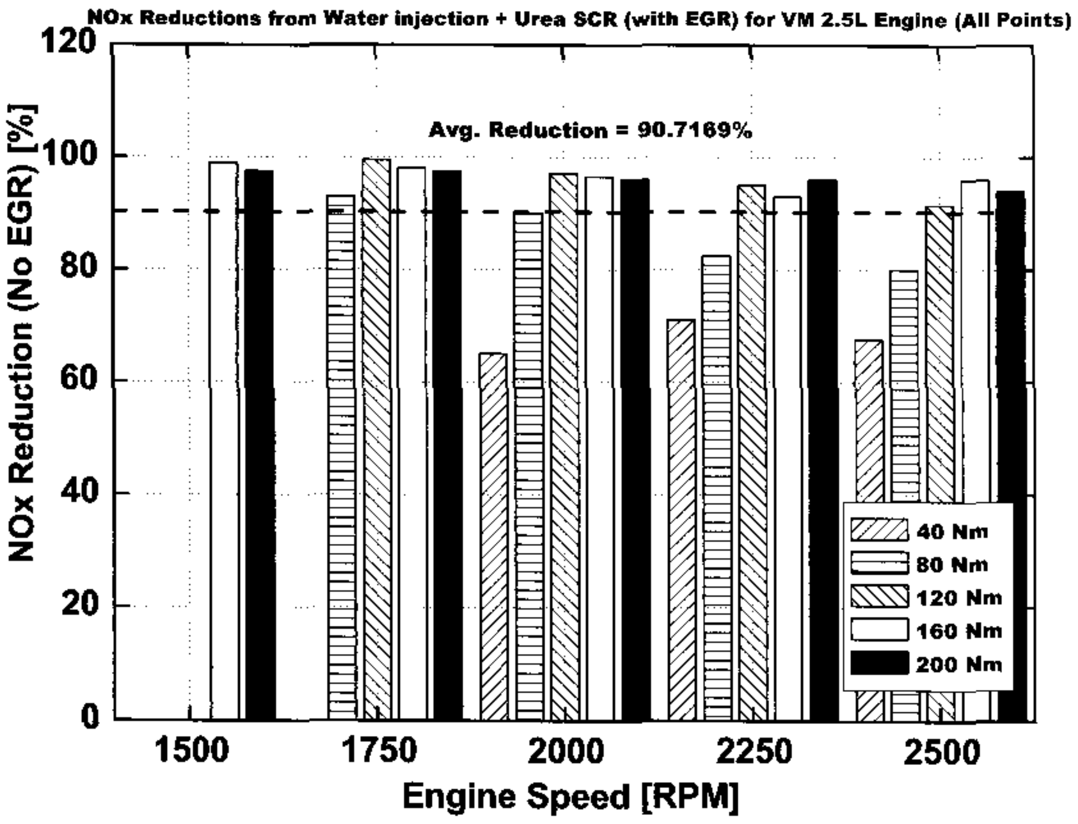


**Fig. 7** $NO_x$ reduction from water injection/urea SCR (No EGR)

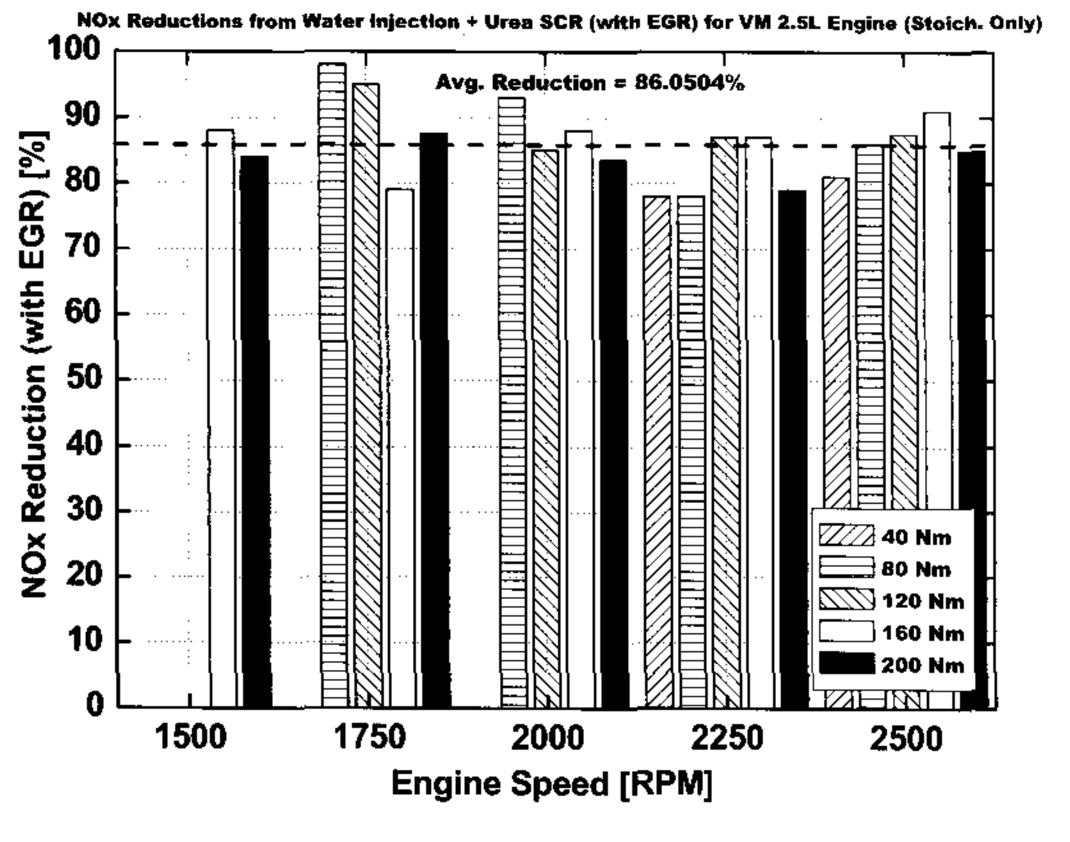


**Fig. 8** $NO_x$ reduction from water injection/urea SCR (Stoich. urea)

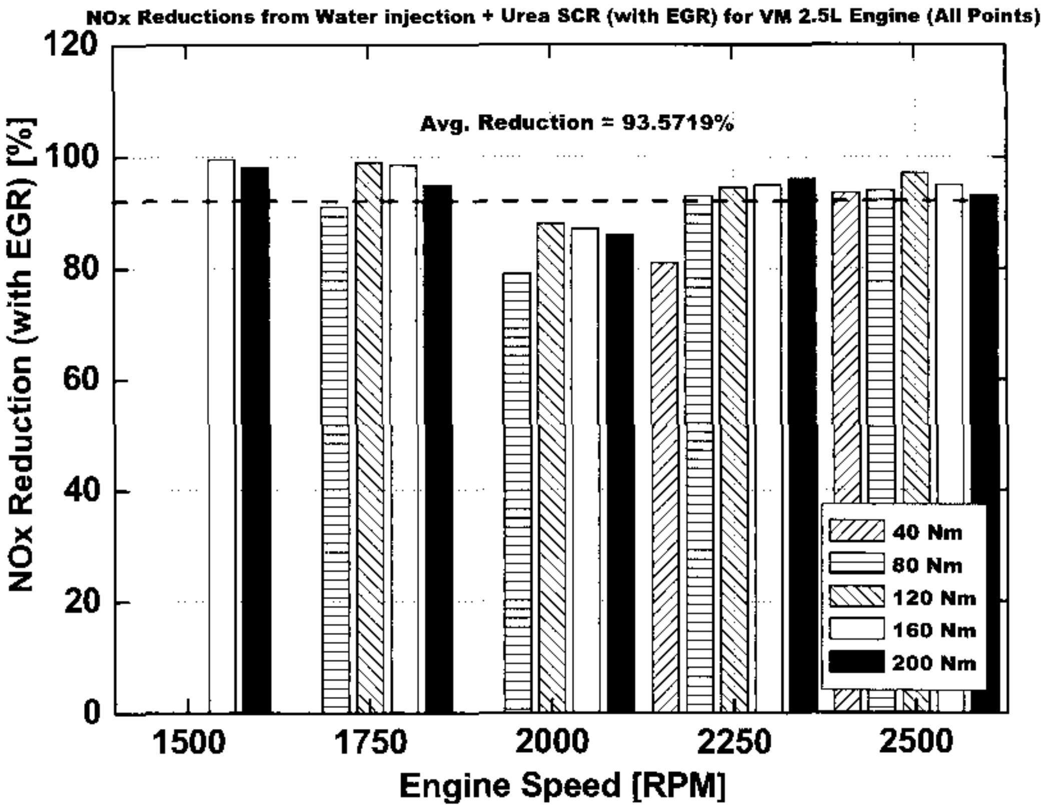


**Fig. 9** $NO_x$ reduction from water injection/urea SCR

### 3.2 Analysis of NOx Reduction Effects

To understand the functionality of the combined WI/urea SCR system, an analysis of the $NO_X$ reduction effects of each system was conducted. Specifically, $NO_X$ reduction from water injection and urea SCR was analyzed at each engine operating point tested to determine which operating points were favorable for water injection, urea-SCR, or both. This analysis was conducted only for cases where the EGR was active. Selected results are presented in Fig. 10 ~ 13.

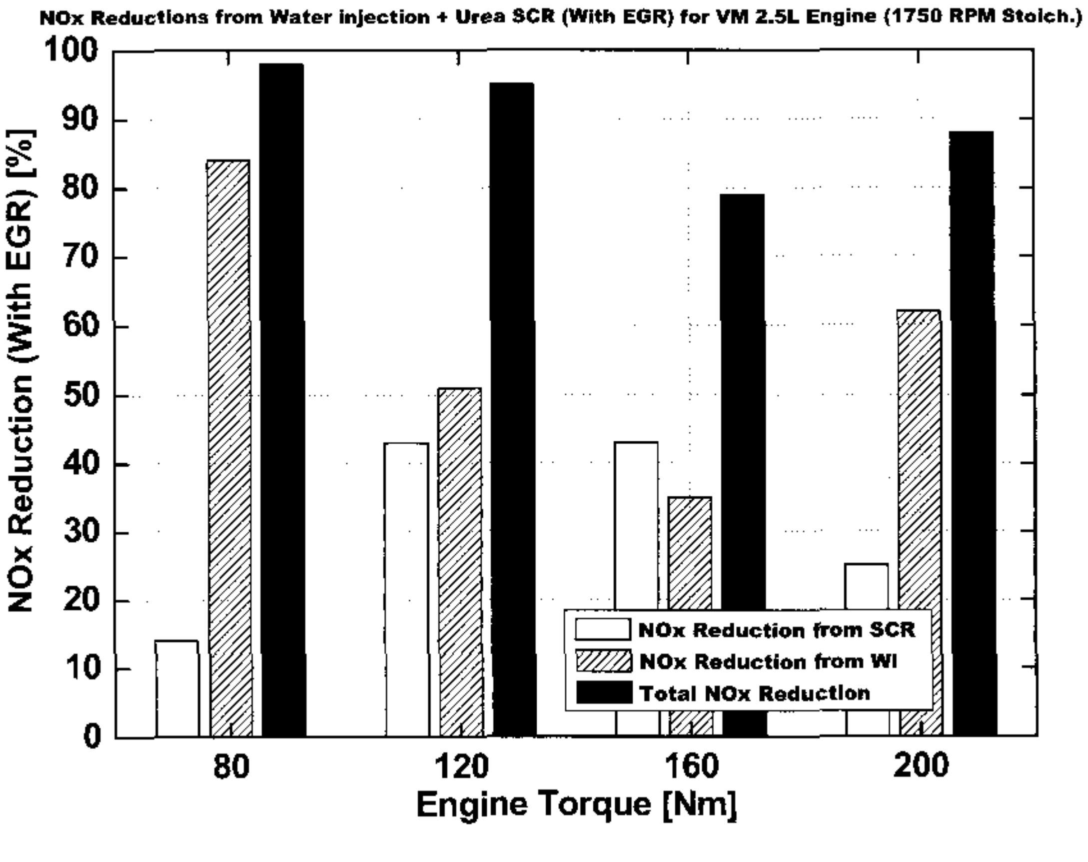


**Fig. 10** $NO_x$ reduction from water injection/Urea SCR 1750 RPM (Stoich. Urea)

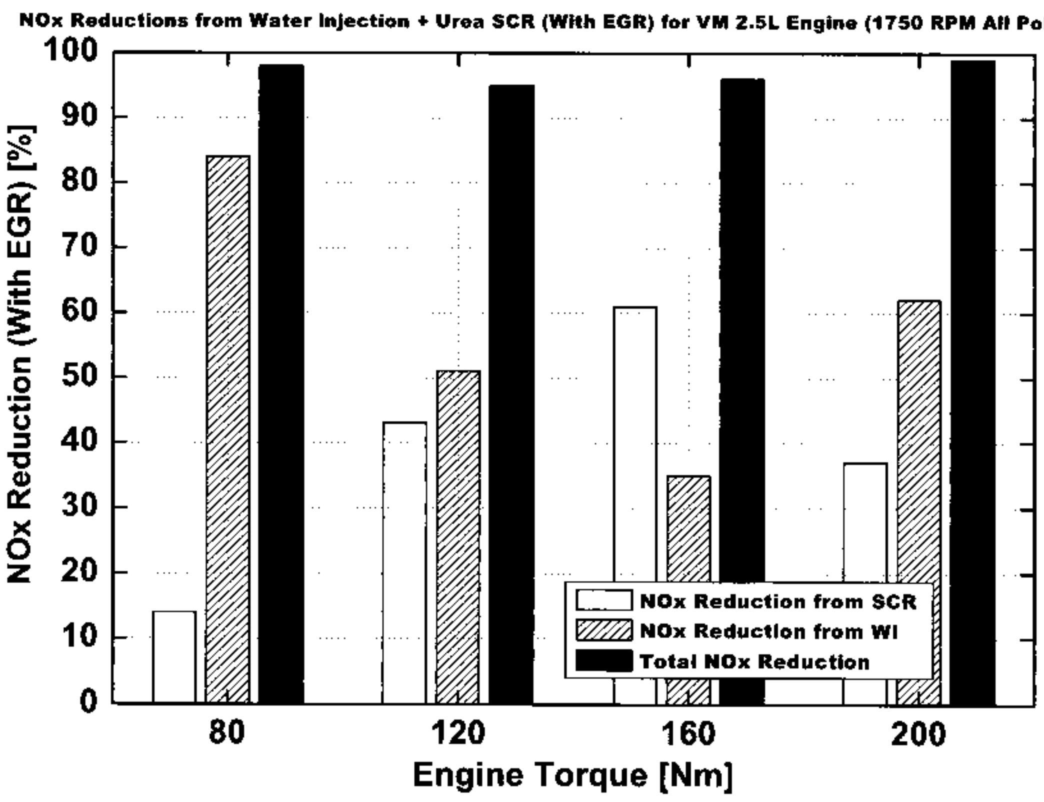


**Fig. 11** $NO_x$ reduction from water injection/Urea SCR 1750 RPM

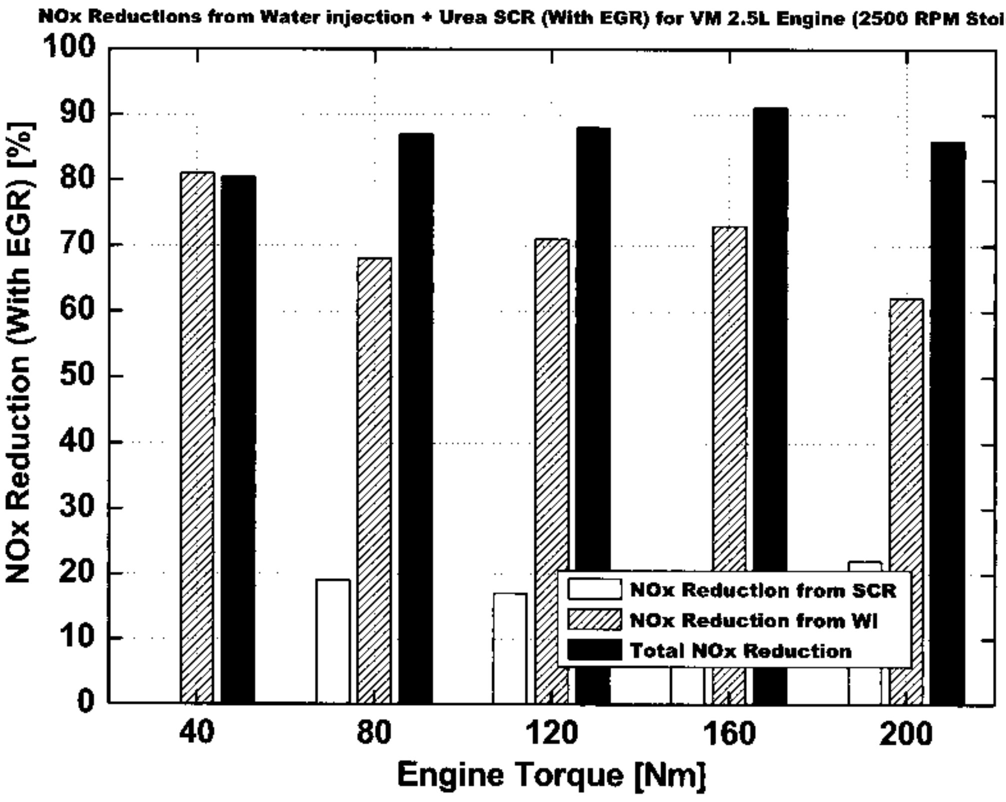


**Fig. 12** $NO_x$ reduction from water injection/Urea SCR 2500 RPM (Stoich. Urea)

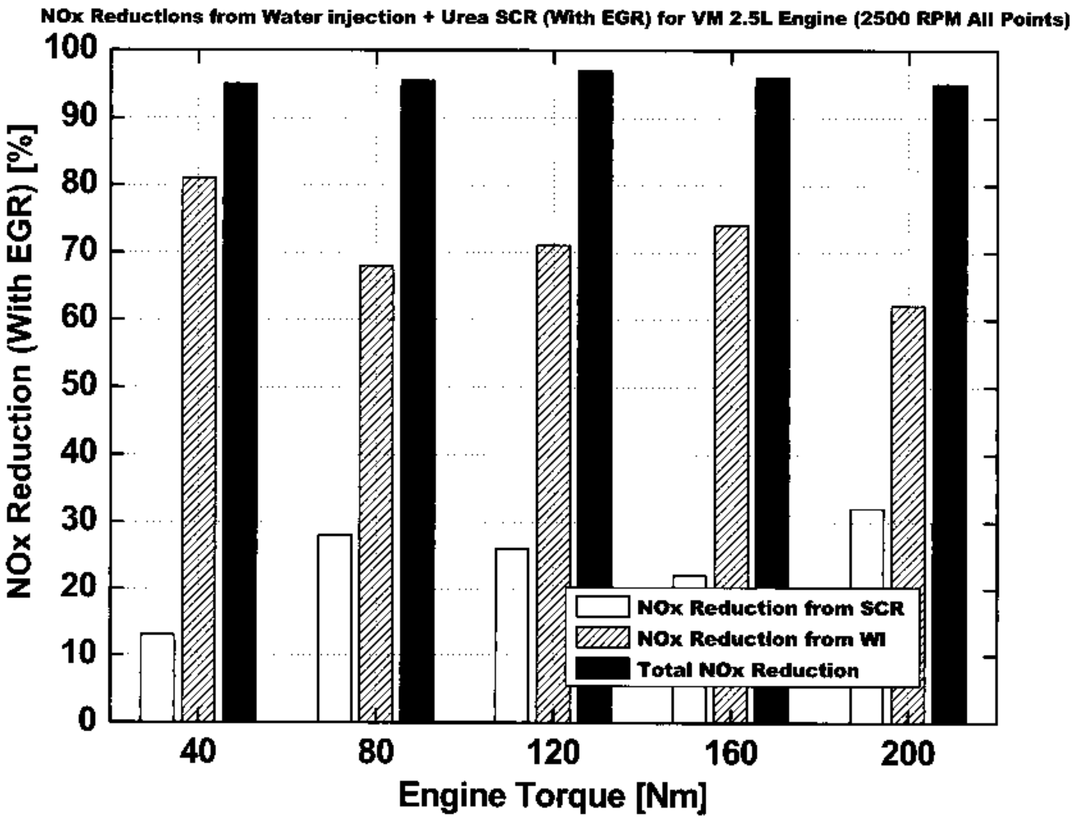


**Fig. 13** $NO_x$ reduction from water injection/Urea SCR 2500 RPM

The results showed the two general patterns encountered in the data. Fig. 10 and Fig. 11 represent the case where the $NO_X$ reduction from water injection increases with increasing load due to the ability to inject greater quantities of water (higher air flowrate and/or intake temperature).

A point is reached (at 160 Nm in this case) where the water injection rate can no longer be increased due to mechanical limitations of the dosing system, and the $NO_X$ reduction from water injection then decreases. Fig. 12 and Fig. 13 are representative of cases where the $NO_X$ reduction from water injection is generally small across all torques ranging from 40 Nm to 200 Nm, again due to flowrate limitations from the WI system. In this case, urea SCR is the dominant basis of $NO_X$ reduction.

### 3.3 Effect of Varying Urea and Water Flowrates

To determine any additional nitrogen oxide ($NO_X$) reduction benefit could be achieved by varying the water injection flowrate in conjunction with the urea flowrate, additional experiments were performed. The procedure in this case was to sweep through several water injection flowrates at a fixed (beyond stoichiometric) urea flowrate for each engine operating point. A total of three operating points were tested in this manner: 1750 RPM - 160 Nm, 2250 RPM - 120 Nm, and 2500 RPM - 200 Nm. These experiments were performed with the EGR active, and only for cases of beyond stoichiometric urea flowrates. The $NO_X$ reduction results for each operating point as a function of the water injection valve duty cycle (proportional to flowrate) are displayed in Fig. 14 through Fig. 16.

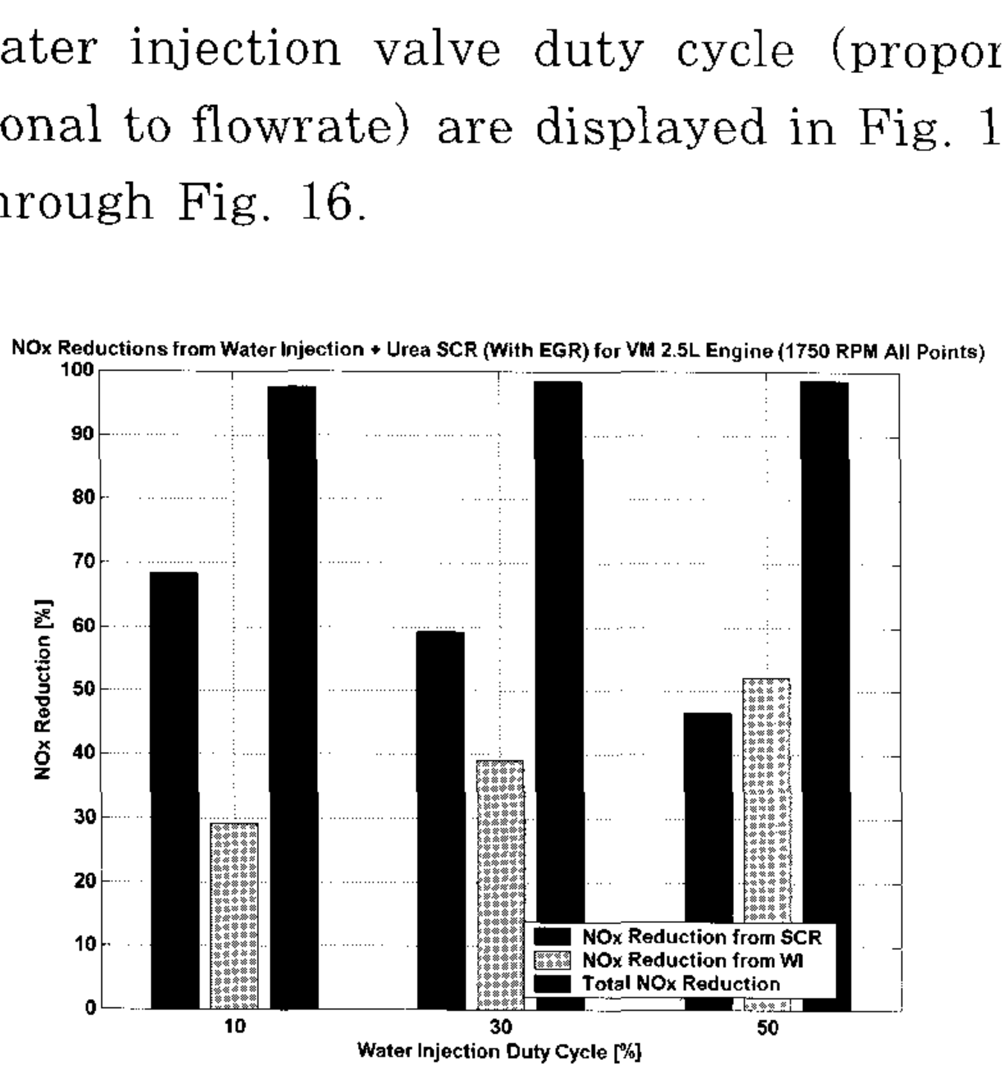


**Fig. 14 Effect of variable water flowrate on $NO_x$ reduction 1750 RPM**

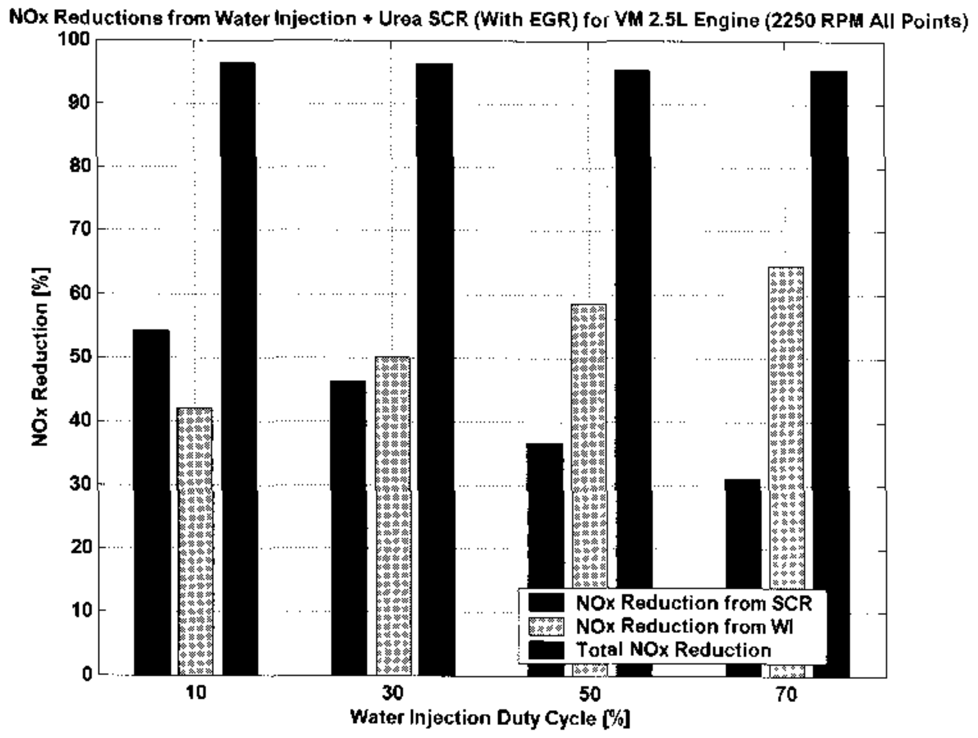


**Fig. 15 Effect of variable water flowrate on $NO_x$ reduction 2250 RPM**

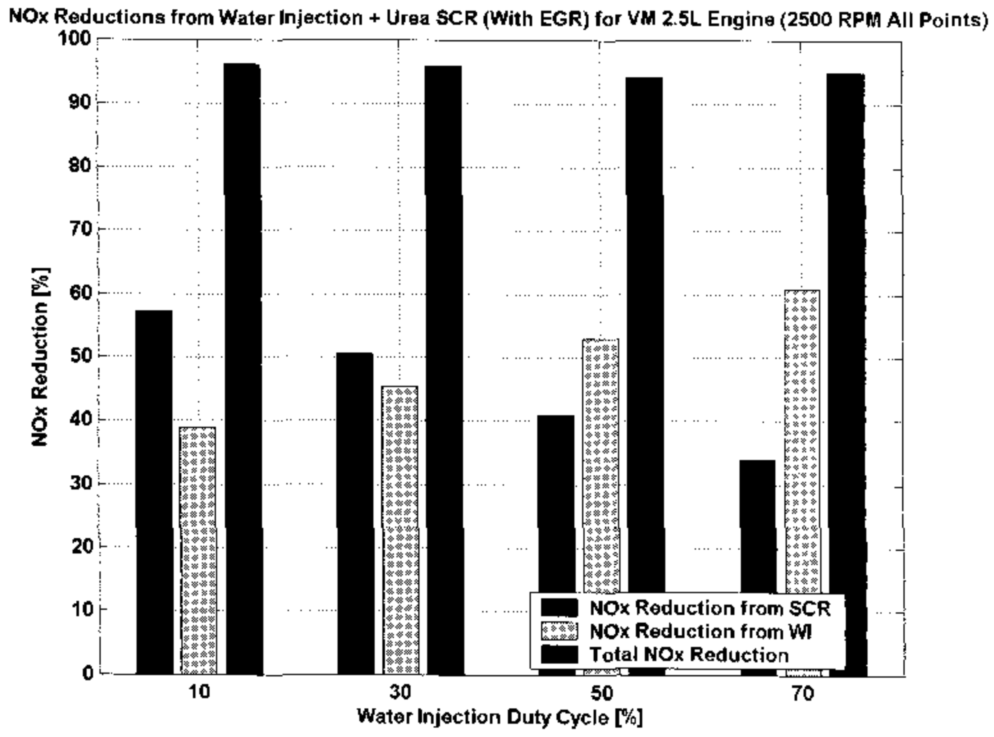


**Fig. 16 Effect of variable water flowrate on $NO_x$ reduction 2500 RPM**

The figures indicated that the overall $NO_x$ reduction from the combined system is fairly insensitive to variation of the water injection flowrate. However, use of higher water injection flowrates limited the urea flowrate to reasonable multiples of the stoichiometric flowrate, which in turn should limit ammonia slip. From this perspective, the water injection flowrate for the combined system should be maximized to limit ammonia slip while maintaining high $NO_x$ reduction.

Another factor must be considered, though, and that is the emissions of CO and HC, which have previously been shown to be sensitive to the water injection flowrate. Therefore, an additional data processing was performed to determine the effect of varying the water injection flowrate on the raw CO and HC emissions, with the results presented in Fig. 17 and Fig. 18, respectively.

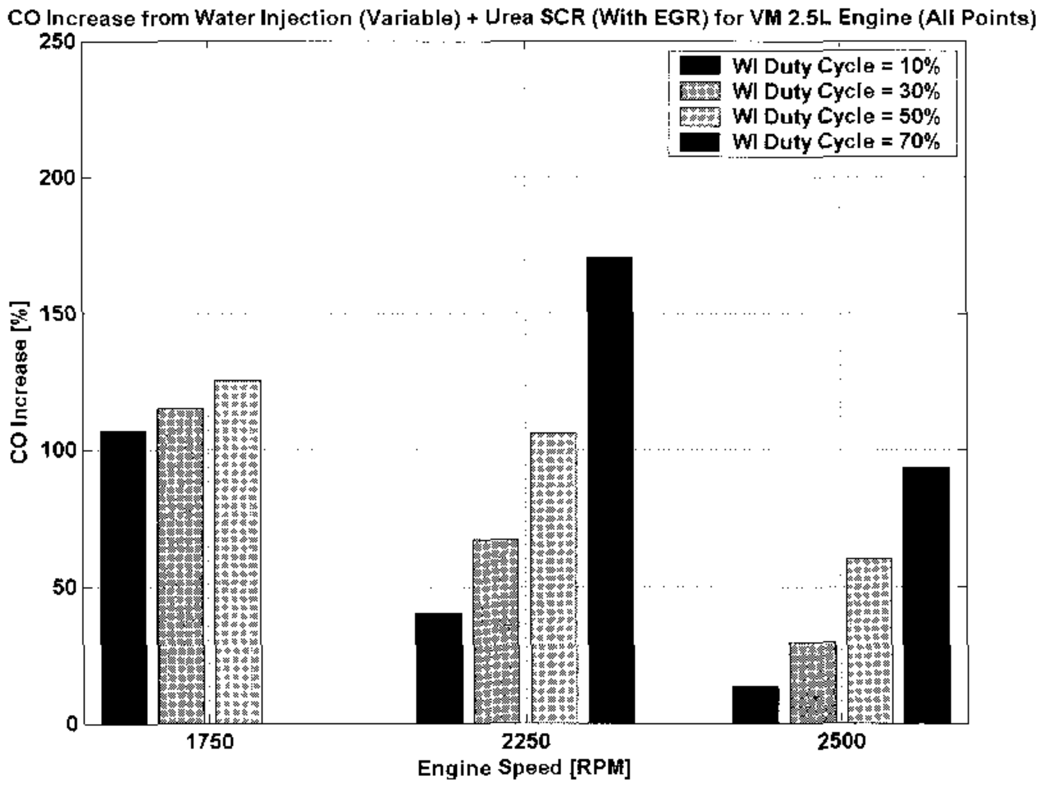


**Fig. 17 Sensitivity of CO emissions to changes in the water injection flowrate**

The results indicated that CO and HC emissions generally increase with increasing water injection flowrate, as expected. From this perspective, it may be desirable to operate the combined system at lower water injection flowrates to limit CO and HC emissions while maintaining high $NO_x$ reduction. However, the use of an oxidation catalyst may be sufficient to neutralize these effects.

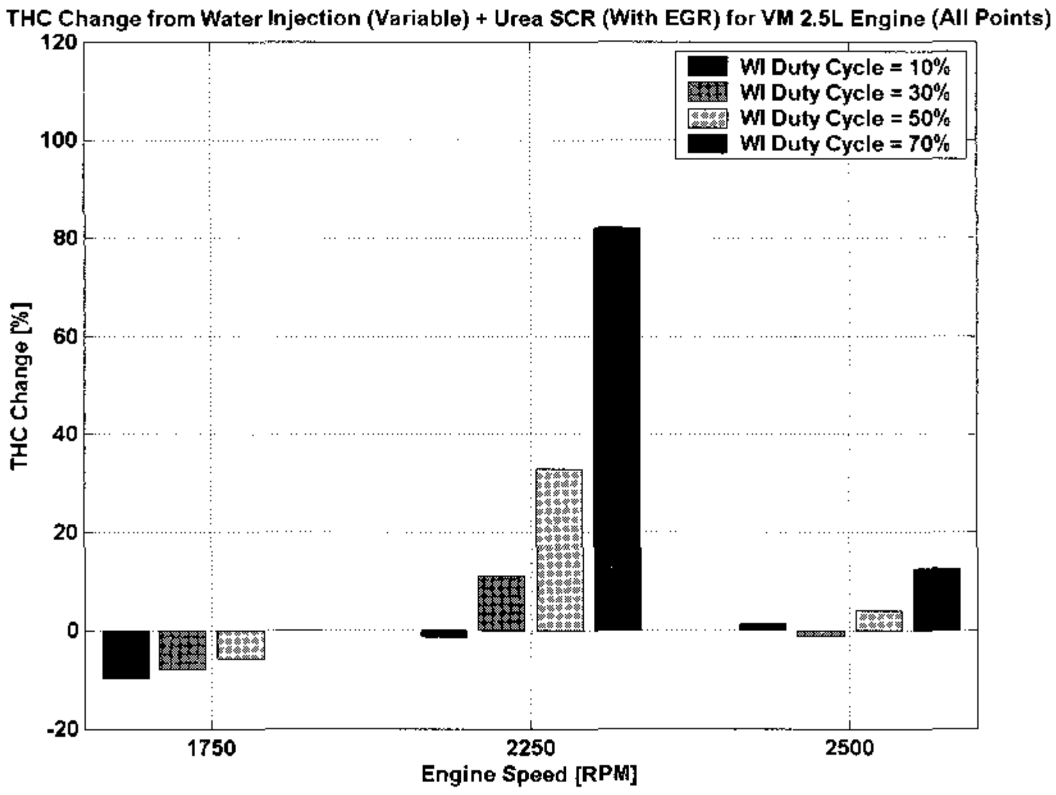


**Fig. 18 Sensitivity of HC emissions to changes in the water injection flowrate**

## 4. Conclusion

The final set of experiments involved the use of a combined water injection and urea-SCR system with active and inactive EGR. Initially, the water injection flowrate was fixed and urea flowrates were swept at a fixed engine operating point. The $NO_x$ reduction effects of the water injection and urea-SCR systems were quasi-additive at most engine operating points. This study showed following results:

1. The average $NO_x$ reduction with stoichiometric urea flow only was 86% while $NO_x$ reduction using beyond stoichiometric urea flowrate has average of 93%. In addition, an analysis of the $NO_x$ reduction effects from each method was conducted. $NO_x$ reduction from water injection generally increased with increasing load, until the point where $NO_x$ reduction was automatically limited by the maximum flowrate of the Aquamist water injection system was reached. Conversely, $NO_x$ reduction effects from urea SCR were generally higher at low loads.
2. Both the water injection and urea flowrates were varied simultaneously to determine whether any additional benefit in terms of $NO_x$ reduction could be achieved. The results showed only minimal improvement in $NO_x$ reduction on both varying flowrates.

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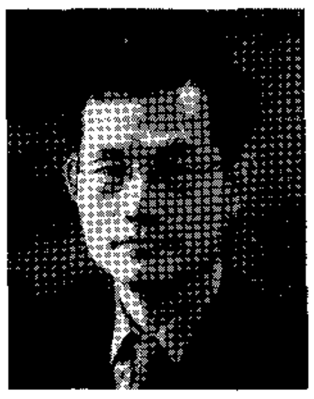
## Author Profile



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