

53 A STUDY ON THE TANDEM SYSTEM FOR NO_x REDUCTION OF A LIGHT-DUTY DIESEL ENGINE

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ABSTRACT–The effects of a WI(Water Injection) at the intake pipe and an urea injection at the exhaust pipe for a 4-cylinder DI(Direct Injection) diesel engine were investigated experimentally. The water quantity was controlled by temperatures of intake manifold and MAF(Manifold Air Flow). In addition, the urea quantity was controlled by NO_x quantity and MAF. Effects of WI system, urea-SCR system and tandem system were investigated for with and without EGR(Exhaust Gas Recirculation). Several experiments were performed to characterize the urea-SCR system, using engine operating points of varying raw NO_x emissions, space velocity, and SCR catalyst temperature.

As the results, the SUF(Stoichiometric Urea Flow) and NO_x map were obtained. In addition, NO_x results can be visualized with engine speed and engine load. It was concluded, therefore, that the NO_x reduction effects of the tandem system without the EGR were more than those with the EGR base engine.

KEY WORDS: Water injection, Manifold air flow, Urea-SCR, Tandem(combined water injection/urea-SCR) system, Stoichiometric urea flow, NO_x map

1. INTRODUCTION

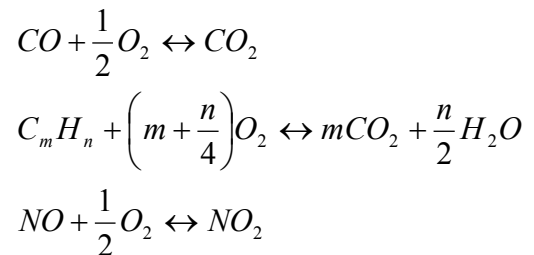
1.1 Motivation

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 (CO₂) emissions known to cause the greenhouse effect). However, lean exhaust conditions render conventional automotive three-way catalysts ineffective, making NO_x reduction a considerable challenge. Urea-SCR is 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],[2]}.

1.2 Urea-SCR system

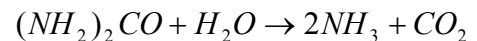
The functionality of urea-SCR catalyst systems is defined by the selective reduction of NO_x in a lean exhaust environment using ammonia, which is generated from ammonia. This makes urea-SCR well suited to use with diesel engines, which always operate significantly lean of stoichiometry. Four catalysts comprise a typical urea-SCR system, including pre-oxidation, hydrolysis, SCR, and post-oxidation catalysts^[3].

The main function of the pre-oxidation catalyst is to balance the NO₂/NO_x ratio for better low temperature NO_x conversion efficiency, as well as to oxidize CO and HC emissions and prevent HC poisoning of the SCR catalysts (for zeolite formulations). The chemical reactions promoted at the pre-oxidation catalyst are listed in Equation 1.



Equation 1: Pre-oxidation catalyst chemical reactions

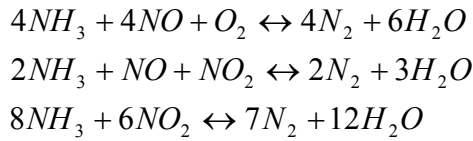
The toxicity of ammonia prohibits its direct use in mobile applications, so a non-toxic chemical (urea) is substituted. The urea is typically carried in aqueous solution, and must be reacted to ammonia through a hydrolysis process. The hydrolysis catalyst (reactions listed in Equation 2) carries out this process, while limiting undesirable hydrolysis.



Equation 2: Hydrolysis catalyst chemical reaction

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The ammonia and exhaust gases then reach the SCR catalyst, where the reduction of NO_x takes place. The chemical reactions for this catalyst are listed in Equation 3, and each reaction has a drastically different reaction rate, depending on operating conditions, which becomes an important system consideration. Unused ammonia either exits the SCR catalyst or stores on the catalyst at active storage sites for later use.



Equation 3: SCR catalyst chemical reactions

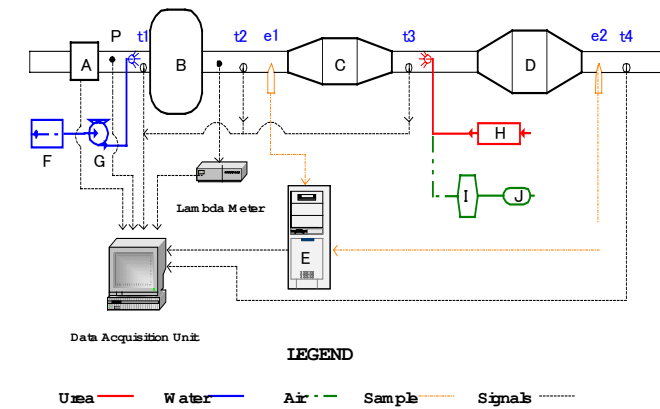
Finally, the exhaust gases and excess ammonia reach the post-oxidation catalyst, where excess ammonia is oxidized, as outlined in Equation 4. Any remaining ammonia exiting the post-oxidation catalyst is known as ammonia slip, and is highly undesirable due to toxicity and human scent perception at concentrations as low as 10 parts per million (ppm).



Equation 4: Post-oxidation catalyst chemical reaction

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 Apparatus

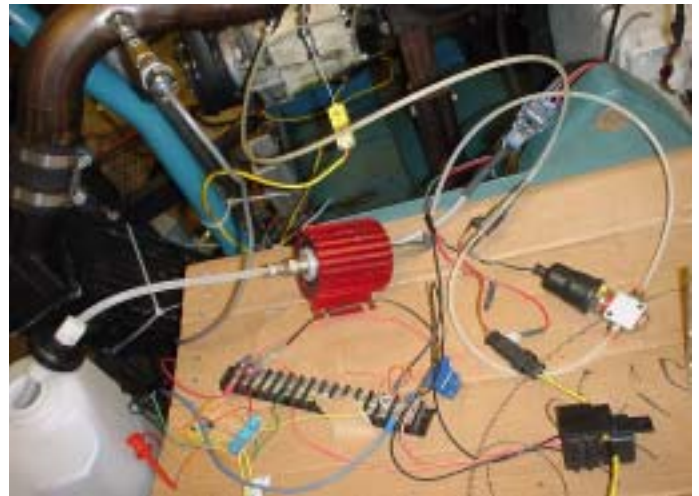


- A. MAF Sensor,
- B. VM 2.5L CIDI
- C. Oxidation Catalyst
- D. Hydrolysis & SCR Catalyst
- E. Horiba MEXA-7500
- (e1: NO_x , THC, CO, CO_2 , O_2 , e2: NO_x , THC)
- F. Water Tank
- G. Water Injection Pump
- H. Urea Syringe Pump
- I. Air Regulator
- H. Compressed Air Tank
- P. Pressur Sensor
- t1 - t4 : Temperature Sensors

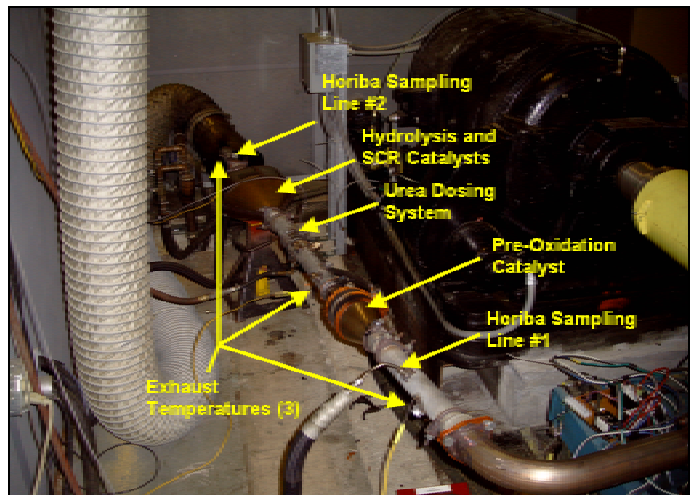
Figure 1. Schematic diagram of experimental measuring apparatus



(a) View of engine equipped with a urea-SCR system



(b) Water injection system



(c) Urea-SCR system experimental setup

Figure 2. Photographs of test equipments

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 exhaust gas recirculation (EGR) system. The engine is 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). Figure 1 shows a schematic diagram of experimental measuring apparatus. Photographs of test equipments are shown in figure 2.

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 Tandem 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 in intervals of 250 rpm and 30 ft-lb to 150 ft-lb in intervals of 30 ft-lb 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

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 5. The water flowrate was controlled by a pulse-width modulated (PWM) signal driving a high-speed solenoid valve.

$$\dot{V}_{water} = \left(\frac{1}{\rho_{water}} \right) \cdot \dot{m}_{water} = h \cdot \left(\frac{MAF}{1000} \right) \cdot \left(\frac{1}{\rho_{water}} \right)$$

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].

Equation 5. Water flowrate calculation

2.2.2 Stoichiometric urea flowrate calculation

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 6.

$$\dot{m}_{urea,stoich} = \frac{\dot{m}_{NO}}{FW_{NO}} \cdot FW_{NH_3} \cdot \left(\frac{1}{U:NH_3} \right) \cdot \left(\frac{1}{[Urea]} \right)$$

where: m_{NO} is the raw NO flowrate in [g/s],
 FW_{NO} is the formula weight of NO in [g/mol],
 FW_{NH_3} is the formula weight of NH₃ in [g/mol],
 $U:NH_3$ is the NH₃ produced from a unit mass of urea,
 $[Urea]$ is the concentration of the urea solution.

Equation 6. Stoichiometric urea flowrate calculation

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Urea flowrate mapping

Representative results are presented in Figure 3 through Figure 5. The all figures are representative of the majority of the results collected for the static urea flowrate mapping of the Tandem system.

Figure 3 represents a case where high nitrogen oxide (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 water injection (high air flowrate, high intake temperature) at the operating point, as well as the small engine-out NO_x flowrate as a limiting factor for the urea-SCR system.

Figure 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. As a result, a higher NO_x flowrate is available to 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.

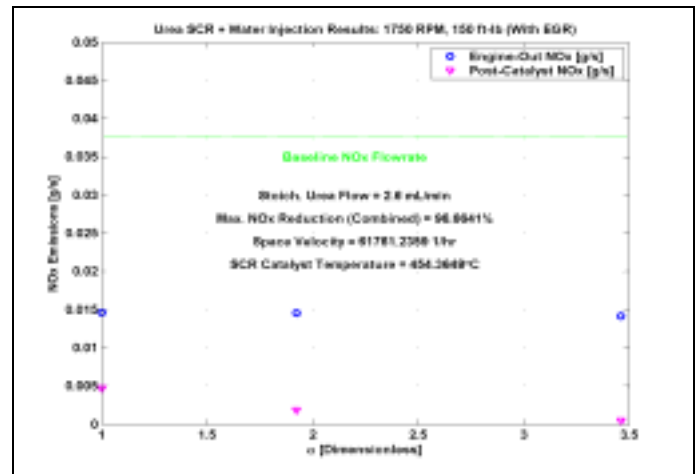


Figure 3. Water injection/urea-SCR results -1750 rpm, 150 ft-lb

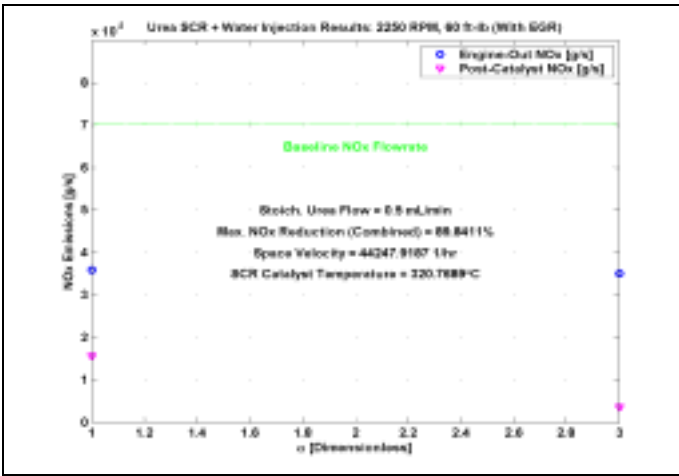


Figure 4. Water injection/urea-SCR results - 2250 rpm, 60 ft-lb

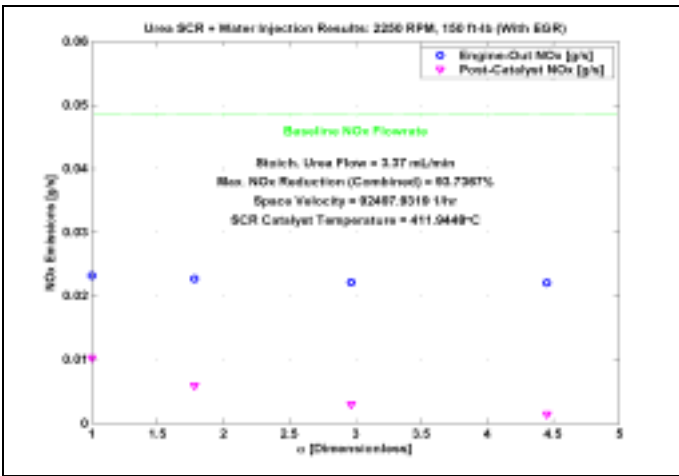


Figure 5. Water injection/urea-SCR results - 2250 rpm, 150 ft-lb

Finally, figure 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 physical limitations of the dosing system.

3.2 NO_x Reduction from Tandem system

Based on the work from the previous sub-section, the NO_x reduction potential of the Tandem system was compiled for cases with active and inactive exhaust gas recirculation (EGR), as well as stoichiometric and beyond stoichiometric urea flowrates. The results are displayed in Figure 6 and Figure 7 for the inactive EGR cases, and in Figure 8 and Figure 9 for the active EGR cases.

Several trends can be extracted from the results presented in the figures above. First, the NO_x reduction from the Tandem 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.

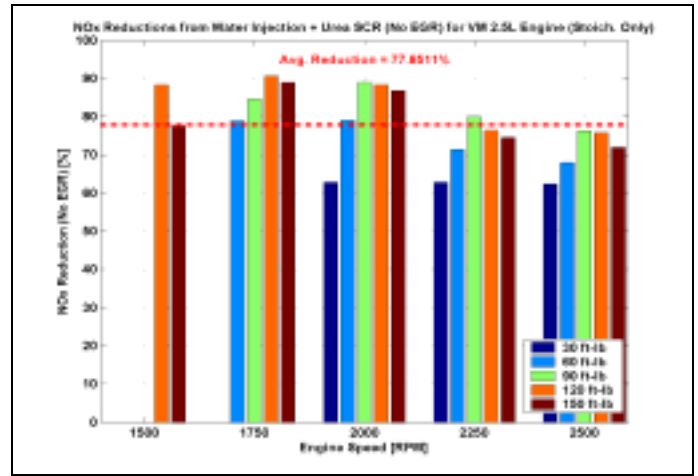


Figure 6. NO_x reduction from water injection/urea-SCR (No EGR, stoich. urea)

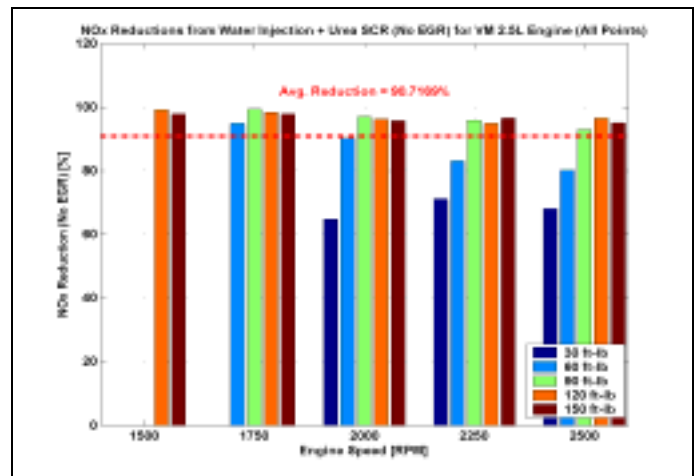


Figure 7. NO_x reduction from water injection/urea-SCR (No EGR)

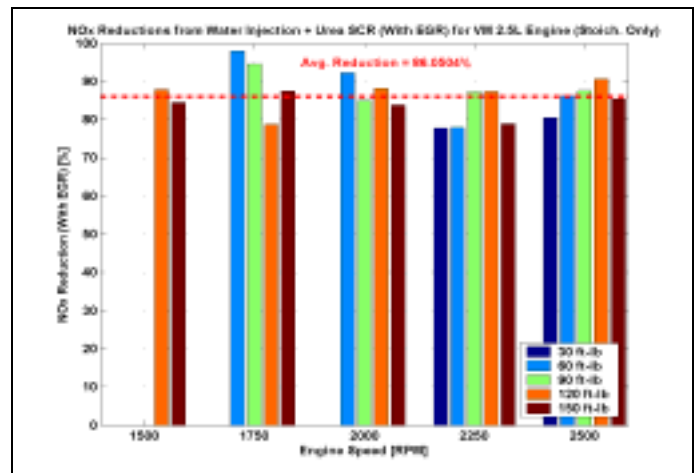


Figure 8. NO_x reduction from water injection/urea-SCR (Stoich. urea)

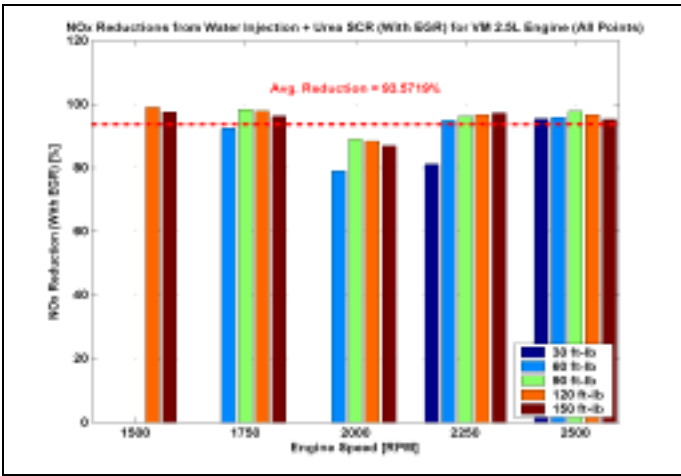


Figure 9. NO_x reduction from water injection/urea-SCR

Another trend 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 yet another positive quality of the Tandem 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 Tandem system with EGR is much less sensitive to the engine operating point than the inactive EGR Tandem 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 offsets the lack of water injection at these operating points and maintains high NO_x reduction across all operating points.

3.3 NO_x maps

NO_x maps as a function of engine torque and speed were also generated for the combined urea-SCR system for cases with EGR active and inactive.

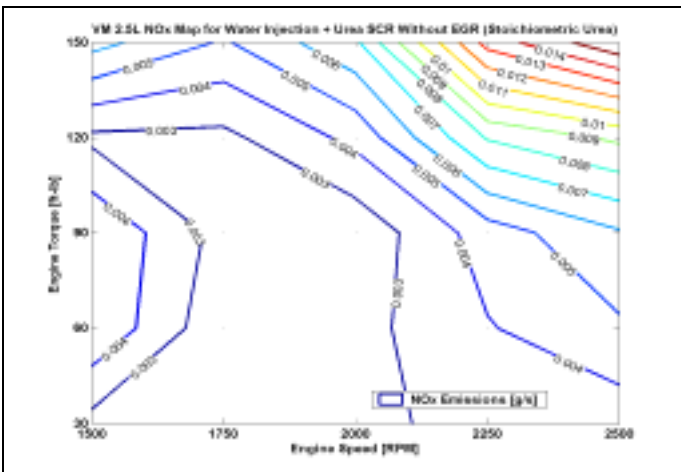


Figure 10. Water injection/urea-SCR NO_x map (No EGR, stoich. urea)

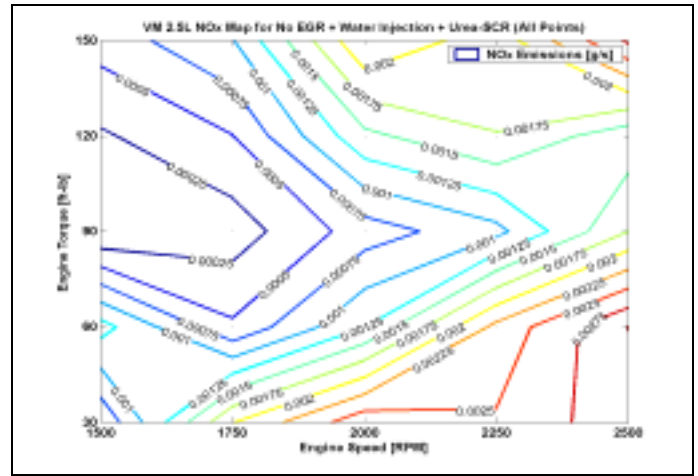


Figure 11. Water injection/urea-SCR NO_x map (No EGR)

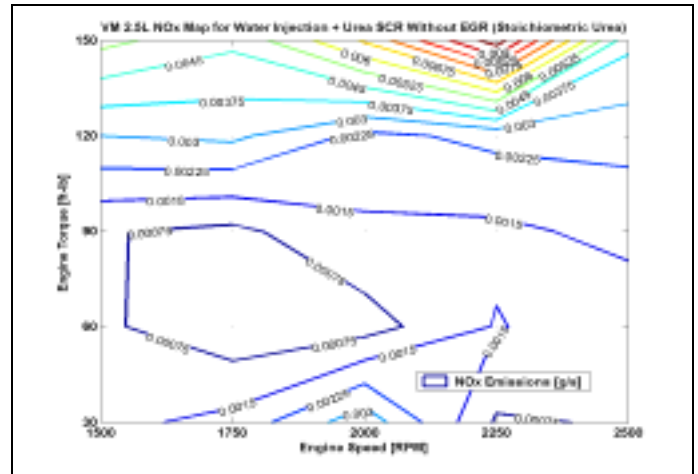


Figure 12. Water injection/urea-SCR NO_x map (Stoich. urea)

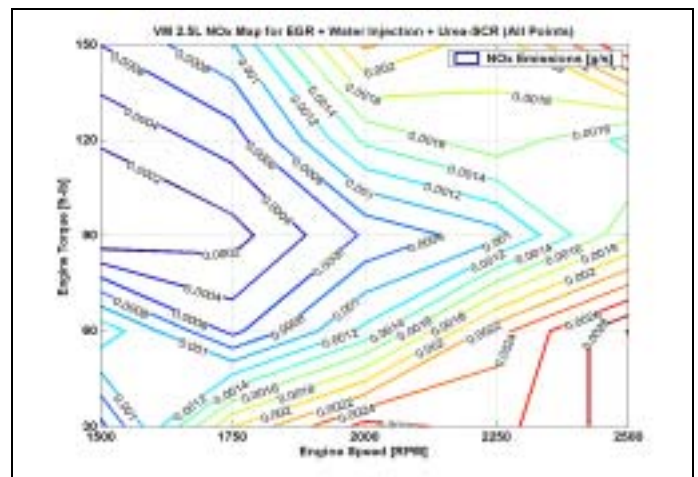


Figure 13. Water injection/urea-SCR NO_x map

The NO_x maps are displayed for the inactive EGR cases in Figure 10 and Figure 11, with the maps for the active EGR cases in Figure 12 and Figure 13.

Once again, the NO_x maps presented in the figures above indicate a significant reduction in NO_x emissions over the baseline engine, and over the water injection and urea-SCR systems alone. The NO_x emissions for these cases are particularly low at engine operating points less than 120 ft-lb, and these are common operating points for a passenger car application.

3.4 Space velocity effects

Space velocity is a key consideration in catalyst design, and it has a significant impact on the NO_x conversion efficiency of urea-SCR system. Space velocity is defined as the inverse of space time, which is the time exhaust gas equivalent to one catalyst volume takes to move through the catalyst. The significance of space velocity is that it defines the time period that the exhaust gases are in contact with the catalyst.

As a design consideration, a balance must be reached between time for catalytic activity and excessive by-product formation and/or heat transfer. Space velocity is defined mathematically in Equation 7.

$$SV = \left(\frac{\dot{m}_{exhaust}}{\rho_{exhaust}} \right) \cdot \left(\frac{1}{V_{cat}} \right)$$

where: SV is space velocity in [1/hr],
 $\dot{m}_{exhaust}$ is the exhaust mass flowrate in [g/hr],
 $\rho_{exhaust}$ is the exhaust gas density in [g/L],
 V_{cat} is the catalyst volume in [L].

Equation 7. Space velocity definition

A map of NO_x conversion efficiency as a function of space velocity and catalyst temperature was generated based on the static urea mapping results presented previously, and it is displayed in Figure 14. The figure shows the trends in NO_x conversion efficiency for varying catalyst temperature and space velocity. As expected, NO_x conversion efficiency increases greatly with increasing catalyst temperature.

The secondary effect of varying space velocity is also displayed, and NO_x conversion efficiency is adversely affected by increasing space velocity above the threshold of 40,000-50,000 1/hr. This was anticipated because of the decreased time available for the catalytic reduction of NO_x over the catalyst as space velocity increased.

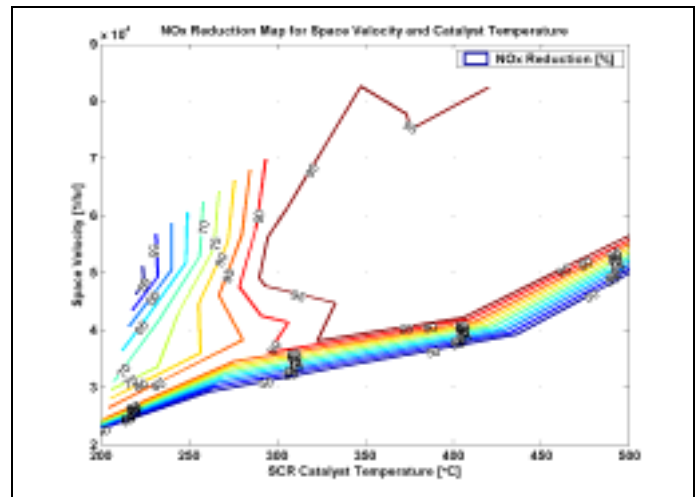


Figure 14. NO_x conversion efficiency map as a function of space velocity and catalyst temperature

4. CONCLUSION

The NO_x maps of the Tandem system presented a significant reduction in NO_x emissions over the baseline engine, and over the water injection and urea-SCR systems alone. The NO_x emissions for these cases are particularly low at engine operating points less than 120 ft-lb, and these are common operating points for a passenger car application. The NO_x conversion efficiency of the catalysts has proven to be very sensitive to the engine operating point, as well as factors such as space velocity and catalyst temperature.

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