

# Passive TWC+SCR Systems for Satisfying Tier 2, Bin 2 Emission Standards on Lean-Burn Gasoline Engines

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## ABSTRACT

A laboratory study was performed to assess the potential capability of passive TWC+SCR systems to satisfy the Tier 2, Bin 2 emission standards for lean-burn gasoline applications. In this system, the TWC generates the  $\text{NH}_3$  for the SCR catalyst from the feedgas  $\text{NO}_x$  during rich operation. Therefore, this approach benefits from high feedgas  $\text{NO}_x$  during rich operation to generate high levels of  $\text{NH}_3$  quickly and low feedgas  $\text{NO}_x$  during lean operation for a low rate of  $\text{NH}_3$  consumption. It was assumed that the exhaust system needed to include a close-coupled (CC) TWC, an underbody (U/B) TWC, and an U/B SCR converter to satisfy the emission standards during the FTP and US06 tests while allowing lean operation for improved fuel economy during select driving conditions. Target levels for HC, CO, and  $\text{NO}_x$  during lean/rich cycling were established. With a 30 s lean/10 s rich cycle and 200 ppm NO lean, 1500 ppm NO rich and the equivalent of 3.3 L of SCR volume were required to satisfy the  $\text{NO}_x$  target. The ability of the CC TWC and U/B TWC to promote steam reforming of the HC during the rich periods was crucial for maintaining the HC slip below the target level. A study on the effects of the A/F ratio and temperature on the  $\text{NH}_3$  production from the CC TWC revealed that a temperature of 600°C generated high  $\text{NH}_3$  yields while providing good steam reforming activity. A two-step purge strategy generated high  $\text{NH}_3$  yields while minimizing the CO slip. The two-step purge and a CC TWC + U/B TWC + SCR catalyst system satisfied the HC, CO, and  $\text{NO}_x$  slip targets. Sulfur poisoning decreased the steam reforming activity of the TWC as well as its  $\text{NH}_3$  yield, although the  $\text{NO}_x$  conversion of the SCR catalyst was not significantly affected by the sulfur. It was assumed that the CC TWC would remain naturally desulfated with routine exposure to hot rich conditions during cold starts, accelerations, and high load operation, thus eliminating the need for an active desulfation strategy.

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## INTRODUCTION

Automakers are working diligently to improve the fuel economy of their gasoline-powered vehicles in order to improve customer satisfaction and to satisfy future governmental regulations. Simultaneously, the California LEV III regulations and the Federal Tier 2 and Tier 3 regulations are requiring carmakers to lower the emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides ( $\text{NO}_x$ ), and particulate matter (PM) from their vehicles. One strategy that can improve fuel economy is the use of lean operation during select driving modes such as cruises, as lean operation lowers the pumping losses and improves the thermodynamics of combustion. Depending on the engine and combustion strategy, lean operation can improve the fuel economy by as much as 5 to 15% relative to stoichiometric operation. However, it is well known that the current three-way catalyst (TWC) cannot reduce  $\text{NO}_x$  under lean conditions. Therefore, to allow lean operation while satisfying strict emission regulations, the TWC converter(s) must be supplemented with catalysts that can reduce  $\text{NO}_x$  during lean operation or during lean/rich cycling. Selective catalytic reduction (SCR) catalysts [1] with urea injection systems are currently being used to reduce the  $\text{NO}_x$  from diesel engines. Here an aqueous solution of urea is pumped from a storage tank into the exhaust, where the urea decomposes into

$\text{NH}_3$ . The  $\text{NH}_3$  and  $\text{NO}_x$  react over the SCR catalyst under lean conditions to produce nitrogen ( $\text{N}_2$ ) and water ( $\text{H}_2\text{O}$ ). A popular SCR formulation used on production diesel trucks contains copper in a chabazite zeolite which provides high  $\text{NO}_x$  conversion and good thermal durability. One issue is that this system requires the customer to maintain a sufficient supply of the urea solution in the storage tank. Typically, the urea tank is refilled during vehicle service appointments.

To avoid the need for the urea tank, urea injection system, and the customer intervention required to keep the urea tank filled, a lean  $\text{NO}_x$  trap (LNT) can be used for lean  $\text{NO}_x$  control [2]. The LNT contains platinum group metal (PGM) such as platinum (Pt), palladium (Pd), and rhodium (Rh) along with  $\text{NO}_x$  storage materials such as barium (Ba) and cerium (Ce). The LNT adsorbs  $\text{NO}_x$  during lean operation and reduces the stored  $\text{NO}_x$  and feedgas  $\text{NO}_x$  to  $\text{N}_2$  during periodic rich periods. Another system that does not require customer interaction is referred to as the passive TWC+SCR approach [3]. Here the TWC generates  $\text{NH}_3$  from the feedgas  $\text{NO}_x$  during periodic rich periods, and the  $\text{NH}_3$  is stored on the downstream SCR catalyst. The SCR catalyst then uses the stored  $\text{NH}_3$  to reduce  $\text{NO}_x$  during lean operation. A third approach referred to as a

TWC+LNT/SCR system combines a LNT with a SCR catalyst for lean NO<sub>x</sub> control [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. This LNT/SCR system was shown to demonstrate equivalent NO<sub>x</sub> conversion, lower NH<sub>3</sub> emissions, and lower PGM costs compared to a LNT of the same total volume [15]. One issue with the LNT, SCR, or LNT/SCR approach is that the rich periods used to purge the LNT and/or to create NH<sub>3</sub> for the SCR catalyst reduce the fuel economy by 1 to 2%. Nevertheless, the overall fuel economy improvement from lean/rich cycling is significantly positive.

In 2011, Ford began a 4.5-year demonstration project under joint funding with the DOE to achieve a 25% improvement in fuel economy while achieving Tier 2, Bin 2 emission levels (later modified to Tier 3, Bin 30 emission levels) on a 2.3 L gasoline turbocharged direct-injection (GTDI) engine in a Ford Taurus [17]. For assessing the fuel economy improvement, the baseline vehicle was a Ford Taurus powered by a 3.5 L port-fuel-injected (PFI) naturally-aspirated (NA) engine with independent variable cam timing (iVCT). Several engine technologies were investigated to achieve the 25% improvement in fuel economy, including turbocharging, downsizing the engine displacement, the use of direct-injection, cooled EGR, and stop-start technology. As an optional action, lean operation during cruises was investigated. To provide NO<sub>x</sub> control during the lean periods, two approaches were investigated that did not require customer maintenance: the TWC+LNT/SCR system and the passive TWC+SCR system. This paper summarizes the work on the passive TWC+SCR system. A companion paper describes the work on the TWC+LNT/SCR approach [16]. For both systems, high emphasis was placed on achieving the HC targets as well as the NO<sub>x</sub> targets due to the low emission levels allowed for the Tier 2, Bin 2 standards.

## EXPERIMENTAL

### Catalysts

The TWC and SCR catalyst samples used in this work were core samples with a length and diameter of 2.54 cm that were extracted from full-size cordierite bricks. It was assumed that the washcoat loadings and platinum group metal (PGM) distributions within the catalyst bricks were uniform. Therefore, the brick locations from where the cores were collected were not recorded.

### TWC Samples

The TWC samples contained various levels of oxygen storage capacity (OSC) and PGM loadings that are listed in Table 1. Samples of a production catalyst with a moderate level of OSC on 400 cell per square inch (CPSI) substrates with 4 mil walls (i.e., 400/4) were used with two PGM loadings. One contained 38 gpcf Pd and 2 gpcf Rh (0.62 g/L Pd and 0.033 Rh), and the other contained 196 gpcf Pd and 4 gpcf Rh (i.e., 3.21 g/L Pd and 0.066 g/L Rh). These will be referred to “mod-OSC-40” and “mod-OSC-200” in this paper, respectively. Samples of two non-OSC formulations were used containing either 116 gpcf (1.90 g/L) Pd or 200 gpcf (3.28 g/L) Pd on 400/4 substrates. These will be referred to as “no-OSC-116” and “no-OSC-200” in this paper, respectively. For tests performed with an U/B TWC, the U/B

catalyst was a model formulation with either 26 gpcf (i.e., 0.43 g/L) Pd or Pt on a washcoat of ceria/zirconia. These will be referred to as “PdCeZr” and “PtCeZr” in this paper.

### TWC Aging

Table 1 also lists the durability schedules used to age the TWC samples prior to testing. The rich/stoich/lean schedule was a proprietary schedule that cycled between rich, stoichiometric, and lean conditions every 60 seconds. The inlet temperature was 800°C, and the maximum bed temperature was 960°C. A full-size brick with the mod-OSC-40 formulation was aged for 120 hours on an engine/dynamometer using the rich/stoich/lean schedule, and a 1” diameter × 1” long core sample was extracted from the brick for laboratory testing. 1” long core samples of the mod-OSC-200 and no-OSC-200 formulations were aged on a pulse-flame combustion reactor (a.k.a. pulsator) [18] with the same rich/stoich/lean schedule for 50 hours. The no-OSC-116 catalyst was degreened on the flow reactor for 2 hours at 800°C with 10% O<sub>2</sub>, 5% H<sub>2</sub>O, 5% CO<sub>2</sub>, and the balance N<sub>2</sub>. The U/B TWC samples were oven-aged 175 hours at 800°C with stoichiometric exhaust from a pulsator.

### SCR Samples

The SCR catalyst used in this project was a copper/chabazite formulation on a 400/4 substrate. This SCR formulation is used in production on the Ford medium duty diesel truck. No further details about the SCR formulation will be provided out of respect for the supplier.

### SCR Aging

Some of the early work for this TWC+SCR project was performed with SCR samples that had been aged behind LNTs on the flow reactor for another project [15]. There a 1” long LNT core sample was placed ahead of a 1” long SCR core sample in the flow reactor. One set was aged for 25 hours at an inlet temperature of 800°C with continuously lean exhaust (10% O<sub>2</sub>, 5% CO<sub>2</sub>, 5% H<sub>2</sub>O, balance N<sub>2</sub>), while a second set was aged for 20 hours under the same conditions. After aging, both 1” SCR catalysts were cut into four 0.25” (0.64 cm) long pieces. That allowed various volumes of SCR catalyst to be investigated for this TWC+SCR project. To allow the evaluation of a 3” long SCR catalyst system, another 1” long sample with the same formulation was obtained that had been hydrothermally aged at 800°C for 80 hours. The aging temperature of 800°C was intended to expose the SCR catalyst to the maximum temperature that could be expected in the U/B location and was not intended to represent a certain mileage or full-useful-life (FUL) conditions. Later experiments were performed with SCR catalysts that were aged downstream of the TWC while the TWC samples were aging on the pulsator for 50 hours with the rich/stoich/lean cycle described above. Here the SCR catalysts were aged with inlet temperatures of 600, 700, or 800°C. This was to determine if the SCR performance could be improved with a reduced aging temperature. For all of the SCR samples, small holes were drilled axially through the pieces so that a 1.6 mm thermocouple could be inserted through the samples for measuring the inlet temperature or the catalyst bed temperature during the aging and performance evaluations.

Table 1. TWC Catalyst Formulations, PGM Loadings, Aging Schedules

| Catalyst Designation | OSC Level | PGM loading (gpcf Pt/Pd/Rh) | Aging Protocol                                   |
|----------------------|-----------|-----------------------------|--------------------------------------------------|
| Mod-OSC-40           | Moderate  | 0/38/2                      | Engine – rich/stoich/lean 800°C inlet 120 hours  |
| Mod-OSC-200          | Moderate  | 0/196/4                     | Pulsator – rich/stoich/lean 800°C inlet 50 hours |
| No-OSC-200           | None      | 0/200/0                     | Pulsator – rich/stoich/lean 800°C inlet 2 hours  |
| No-OSC-116           | None      | 0/116/0                     | Flow reactor - lean 800°C inlet 2 hours          |
| PdCeZr               | High      | 0/26/0                      | Oven – stoichiometry 800°C 175 hours             |
| PtCeZr               | High      | 26/0/0                      | Oven – stoichiometry 800°C 175 hours             |

### Performance Evaluations

The flow reactor used for the performance evaluations contained 2 ovens. Some tests were performed with only a CC TWC and a SCR catalyst (i.e., without the U/B TWC). For these evaluations, the TWC was placed toward the rear of the first oven, and the SCR catalyst was placed toward the rear of the second oven. The 2 ovens were operated at different temperatures to represent the close-coupled position and the underbody position. For evaluations of the CC TWC + U/B TWC + SCR system, the second TWC was placed toward the rear of the second oven, and the SCR catalyst was placed further downstream, as shown in Figure 1. The total length of the CC TWC was usually 1", and it consisted of either one catalyst formulation or two 0.5" pieces with different catalyst formulations butted together. When one TWC washcoat formulation was used, the PGM loading was uniform; when two different washcoat formulations were used, the total PGM loading was either uniform (e.g., 200 gpcf/200 gpcf) or zoned (e.g., 200 gpcf/40 gpcf). The length of the U/B TWC was 1". The total length of the SCR catalyst was varied during the different experiments. The total flow rate was maintained at 6.4 L/min for all experiments, producing a space velocity of 30,000 hr<sup>-1</sup> for a 1" long catalyst.

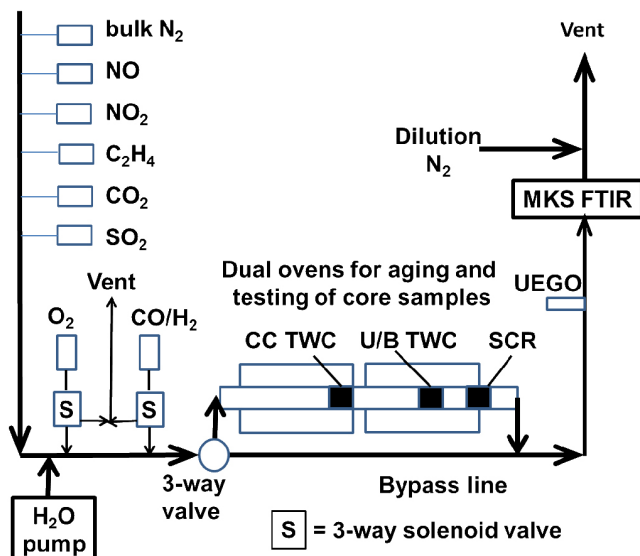


Figure 1. Experimental apparatus

Most tests consisted of alternating lean and rich periods (e.g., 30 seconds lean and 5 seconds rich, referred to as a “30/5” cycle). Tests where the lean duration was held constant and the rich purge time was varied are referred to as “purge tests” in this paper. Mass flow controllers were used to control the flow rates of the different gases, and two electronically-controlled three-way solenoid valves were used to switch between the lean (i.e., O<sub>2</sub>) and rich conditions (i.e., CO/H<sub>2</sub>). The oxygen (O<sub>2</sub>) level was always 10% during the lean periods ( $\lambda=A/F$  ratio/14.6=2.0) and 0% during the rich periods. The H<sub>2</sub>O and CO<sub>2</sub> concentrations were always 5% during the lean and rich periods. Many of the experiments were performed with 2500 ppm C<sub>2</sub>H<sub>4</sub> (i.e., 5000 ppm on a C1 basis) during the lean and rich periods. Different NO levels were used during the lean and rich periods. While these NO levels were varied depending on the type of test, the NO<sub>x</sub> concentration during the lean periods was usually 200 ppm NO. During the rich periods, the NO level was increased to either 500, 1000, 1500, or 2000 ppm to more accurately simulate actual engine operation and to generate more NH<sub>3</sub> for the SCR catalyst. Table 2 shows the CO and H<sub>2</sub> concentrations (always in a 3:1 ratio) used during the rich periods to provide rich lambdas of 0.81, 0.86, 0.91, 0.95, or 0.99; these rich lambdas assume a rich NO level of 2000 ppm, and the C<sub>2</sub>H<sub>4</sub> concentration was 2500 ppm except at 0.99 rich lambda, where it was reduced to 800 ppm. Due to the many different catalyst configurations and test conditions used during this project, the specific details of each experiment will be provided in the section where the results of that experiment are discussed.

Table 2. CO, H<sub>2</sub>, NO, and C<sub>2</sub>H<sub>4</sub> Concentrations for Different Rich Lambdas

| Rich Lambda | NO ppm | CO % | H <sub>2</sub> % | C <sub>2</sub> H <sub>4</sub> ppm |
|-------------|--------|------|------------------|-----------------------------------|
| 0.81        | 2000   | 4.0  | 1.30             | 2500                              |
| 0.86        | 2000   | 2.5  | 0.83             | 2500                              |
| 0.91        | 2000   | 1.5  | 0.50             | 2500                              |
| 0.95        | 2000   | 0.5  | 0.17             | 2500                              |
| 0.99        | 2000   | 0.5  | 0.17             | 800                               |

For all tests, the average concentrations of the feedgas NO<sub>x</sub>, HC, and CO were determined over several lean/rich cycles while the exhaust was bypassed around the reactor. With the exhaust flowing through the catalyst bed, testing was continued until the performance of the catalyst stabilized. The concentrations of the NO<sub>x</sub>, HC, and CO at the reactor exit were then averaged over several lean/rich cycles. The average HC, CO, and NO<sub>x</sub> conversions were calculated from the average feedgas concentrations and the average concentrations in the reactor exit according to:

$$\text{Ave \% conversion} = 100 * [1 - (\text{ave exit level}) / (\text{ave FG level})] \quad (1)$$

The average yield of NH<sub>3</sub> was calculated as a percentage of the feedgas NO level according to:

$$\text{Ave \% NH}_3 \text{ yield} = 100 * [(\text{ave NH}_3 \text{ level}) / \text{ave FG NO level}] \quad (2)$$

The average yield of N<sub>2</sub>O was calculated as a percentage of the feedgas NO level from:

$$\text{Ave \% N}_2\text{O yield} = 100 * [2 * (\text{ave N}_2\text{O level}) / \text{ave FG NO level}] \quad (3)$$

where the factor of 2 accounts for the fact that two molecules of NO are required to produce one molecule of  $N_2O$ .

The feedgas and the exhaust from the reactor were analyzed with a 1 Hz MKS Fourier transform infrared (FTIR) analyzer equipped with a sample line heated to 191°C.

## RESULTS AND DISCUSSION

### Emission Budgeting

Emission budgeting was performed to determine the maximum allowable levels of HC, CO, and  $NO_x$  during lean/rich cycling on cruises that still allowed the Tier 2, Bin 2 standards to be met. The limits for HC, CO, and  $NO_x$  on the FTP after 120,000 miles of driving are 10 mg/mile, 2.1 g/mile, and 20 mg/mile, respectively. Estimates were made for the emissions during the cold-start portion of the FTP and during warmed-up operation at stoichiometry. When possible, data from other vehicles were used to approximate these levels. Table 3 shows these estimates along with the desired engineering tolerances for HC, CO, and  $NO_x$  during the FTP. This left target emission levels during lean/rich cycling of 1 mg/mile, 1.3 g/mile, and 5 mg/mile for HC, CO, and  $NO_x$ , respectively. The PM (particulate matter) standard for Tier 2, Bin 2 is 10 mg/mile; it was assumed that the engine-out level of PM would satisfy this limit, so a gasoline particulate filter (GPF) was not considered for this project.

### Effects of SCR Volume & Rich NO Level

Initial experiments on the passive TWC+SCR system were performed using 1.0", 1.5" and 2.0" of the Cu/zeolite SCR pieces from the previous LNT/SCR study [15]. To allow the evaluation of a 3" long SCR system, a third 1" piece of the SCR catalyst was obtained that had been hydrothermally aged at 800°C for 80 hours. It was assumed that the TWC needed to have a reduced level of oxygen storage capacity (OSC) relative to typical three-way catalysts used on vehicles today in order to promote  $NH_3$  formation. However, the TWC still needed some OSC to provide good 3-way activity and diagnostic capabilities during warmed-up stoichiometric operation. Therefore, the front 0.5" of the TWC consisted of the no-OSC-116 formulation aged 2 h under lean conditions, and this was followed by 0.5" of the mod-OSC-40 formulation aged 120 h on an engine/dynamometer. The TWC and SCR ovens were operated at 550°C and 330°C, respectively; a TWC temperature of 550°C ensured adequate steam reforming activity for HC control during the rich periods, and a SCR temperature of 330°C provided high  $NO_x$  conversion activity and reasonable  $NH_3$  storage capacity. 30 second lean periods were alternated with 10 second rich periods (i.e., 30/10 cycle) at a rich lambda of 0.86. The total exhaust flow rate was constant at 6.4 L/min. The feedgas level of NO during the lean periods was 220 ppm. 2500 ppm of  $C_2H_4$  was injected during both the lean and the rich periods. For all four lengths of SCR catalyst, the feedgas level of NO during the rich periods was varied from 500 to 2000 ppm in order to vary the amount of  $NH_3$  produced by the TWC.

Table 3. Emission Budgeting to Satisfy Tier 2, Bin 2 Emission Standards

| Tier 2, Bin 2 Standards                  | HC         | $NO_x$     | CO         |
|------------------------------------------|------------|------------|------------|
| Emission Requirement                     | 10 mg/mile | 20 mg/mile | 2.1 g/mile |
| Engineering tolerance                    | 1.7        | 5          | 0.5        |
| Cold-start emissions                     | ~7         | 7          | 0.3        |
| Stoichiometric emissions (Post-lightoff) | ~0         | 3          | ~0         |
| Lean/rich cycling emissions              | 1          | 5          | 1.3        |

It was desired to convert the  $NO_x$  concentrations from the reactor (measured in ppm) into the weighted mg/mile  $NO_x$  during lean/rich cycling on the intended DOE vehicle to allow easier comparison with the 5.0 mg/mi target from Table 3. Estimates were made for the total weighted exhaust flow on the vehicle during lean operation on the FTP. Using the mileage for Bags 1 and 2 of the FTP (i.e., 7.5 miles) and assuming that all of the  $NO_x$  is emitted as  $NO_2$  (46 g/mole) per EPA protocol, the ppm  $NO_x$  from the reactor and the exhaust flow rate from the vehicle were used to project the weighted mg/mile  $NO_x$  on the vehicle during lean/rich cycling.

Figure 2 shows the weighted  $NO_x$  slip as a function of the rich NO concentration for SCR lengths of 1.0", 1.5", 2.0", and 3.0". These catalyst lengths on the reactor corresponded to 1.7, 2.5, 3.3, and 5.0 L of SCR catalyst on the intended DOE vehicle, based on the space velocity from the reactor and the estimated exhaust flow rate from the vehicle. For all four volumes, the  $NO_x$  slip decreased as the rich NO concentration increased from 500 ppm to 1500 ppm; there was little improvement when the rich NO level was further increased from 1500 ppm to 2000 ppm. The  $NO_x$  slip also decreased as the length of SCR catalyst increased from 1" to 3". The  $NO_x$  slip was near the target of 5.0 mg/mile with the 2" long SCR when the rich NO level was at least 1500 ppm, while the 3" long SCR satisfied the target level comfortably when the rich NO level was at least 1500 ppm.

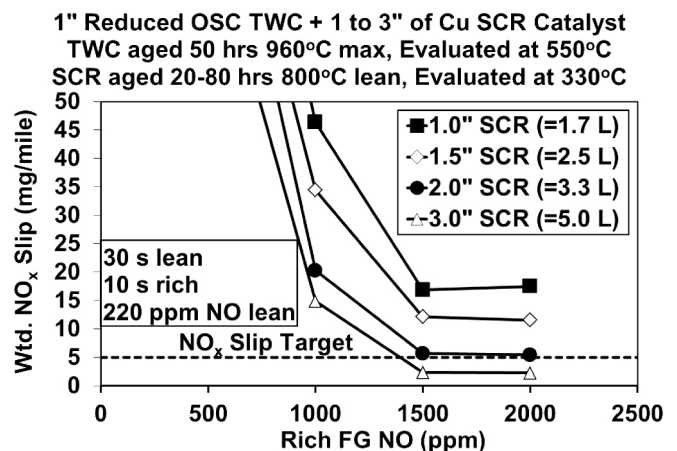


Figure 2. Weighted  $NO_x$  slip as a function of rich feedgas NO level for 1" TWC + SCR catalyst with lengths of 1.0", 1.5", 2.0", and 3.0". 30/10 cycle, 0.86 rich  $\lambda$ , 550°C in TWC and 330°C in SCR catalyst.

These results indicated that an aged TWC+SCR system had the potential to satisfy the  $\text{NO}_x$  slip target of 5.0 mg/mile with a reduced-OSC TWC, sufficient SCR volume, low feedgas  $\text{NO}_x$  lean, and high feedgas  $\text{NO}_x$  rich. High feedgas  $\text{NO}_x$  levels during rich operation increase the  $\text{NH}_3$  production and thereby improve the  $\text{NO}_x$  conversion while reducing the rich purge times required.

In the companion paper on the TWC+LNT/SCR system [16], exhaust modeling was used to determine that the LNT/SCR converter needed to be placed approximately 44" downstream of the U/B TWC to maintain the LNT/SCR converter in its optimum temperature range of 300–350°C during the FTP. The SCR converter needs to be placed in a similar location to maintain its temperature near 300 to 320°C during the FTP.

### Effects of Lean Duration

Similar tests were performed on the 1" TWC + 3" SCR system where the rich periods were maintained at 10 seconds but the lean durations were extended to 45 and 60 seconds. Figure 3 shows the weighted  $\text{NO}_x$  slip of the 1" TWC + 3" SCR system for lean durations of 30, 45, and 60 seconds as a function of the rich  $\text{NO}$  level. While the  $\text{NO}_x$  slip target was met with a rich  $\text{NO}$  level of 1500 ppm when the lean duration was 30 seconds, a lean duration of 45 seconds required a rich  $\text{NO}$  level of approximately 2000 ppm to achieve the  $\text{NO}_x$  slip target. As expected, a longer lean period required additional  $\text{NH}_3$  to maintain the same overall  $\text{NO}_x$  slip. The lean duration of 60 seconds did not achieve the  $\text{NO}_x$  slip target even with 2000 ppm  $\text{NO}$  during the rich periods. However, the slope of the line suggests that the target could have been met with a slightly higher rich  $\text{NO}$  level (e.g., 2100 to 2200 ppm).

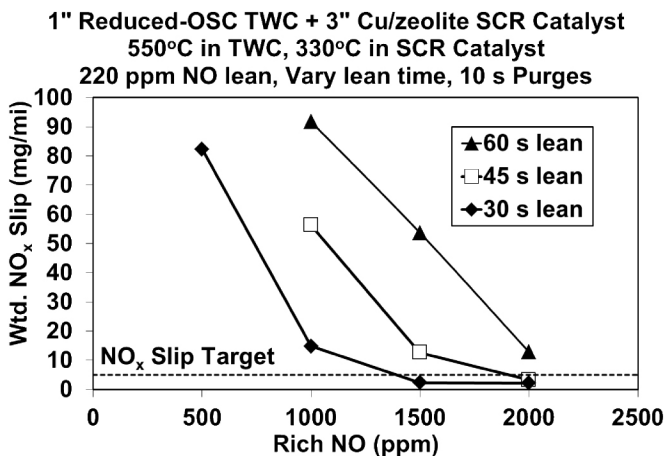


Figure 3. Weighted  $\text{NO}_x$  slip as a function of rich feedgas  $\text{NO}$  level for 1" TWC + 3" SCR system with 10 s rich periods and lean durations of 30, 45, and 60 s. 220 ppm  $\text{NO}$  lean and 0.86 rich  $\lambda$ . 550°C in TWC and 330°C in SCR catalyst.

### Effects of Lean NO Level

To determine if the system could satisfy the  $\text{NO}_x$  target with higher feedgas  $\text{NO}$  levels during lean operation, purge tests were performed on the 1" TWC + 3" SCR system with lean  $\text{NO}$  levels of 320 and 420 ppm, while the rich  $\text{NO}$  level was maintained at 2000 ppm. The lean duration was 30 seconds, and the rich duration was varied from 5 to 15 seconds. Figure 4 shows the weighted  $\text{NO}_x$  slip of the 1" TWC + 3"

SCR system as a function of the rich duration for lean  $\text{NO}$  levels of 220, 320, and 420 ppm. The  $\text{NO}_x$  slip target was satisfied for all three lean  $\text{NO}$  levels. The  $\text{NO}_x$  slip target was met with 10 second rich periods when the lean feedgas  $\text{NO}$  level was 220 or 320 ppm. When the lean feedgas  $\text{NO}_x$  level was 420 ppm, the rich duration had to be increased to 12 seconds to produce additional  $\text{NH}_3$  in order to achieve the  $\text{NO}_x$  slip target.

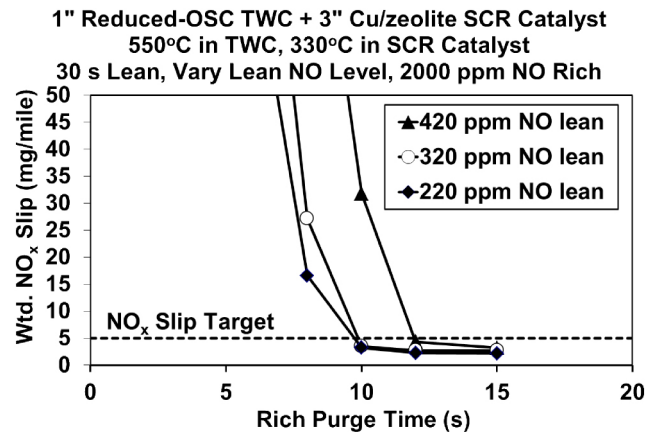


Figure 4. Weighted  $\text{NO}_x$  slip as a function of rich purge time for 1" TWC + 3" SCR system. Lean  $\text{NO}$  levels of 220, 320, or 420 ppm, rich  $\text{NO}$  level of 2000 ppm. 30 s lean periods and variable rich purge times. 0.86 rich  $\lambda$ . 550°C in TWC and 330°C in SCR catalyst.

### Effects of Purge A/F Ratio

Purge tests were performed on the 1" TWC + 3" SCR system with rich lambdas of 0.91 and 0.95 lambda, achieved by decreasing the rich  $\text{CO}/\text{H}_2$  levels to 1.5/0.5% and 0.5%/0.17%, respectively, while maintaining the 2500 ppm  $\text{C}_2\text{H}_4$  during the lean and rich periods. The lean duration was 30 seconds, and the lean and rich  $\text{NO}$  levels were 200 and 2000 ppm, respectively. Figure 5 shows that, for a given rich purge time, the weighted  $\text{NO}_x$  slip of the 1" TWC + 3" SCR system increased as the rich lambda increased from 0.86 to 0.91 to 0.95. As a result, longer purge periods were required to achieve the  $\text{NO}_x$  slip target (i.e., 10, 13, and 14 seconds for rich lambdas of 0.86, 0.91, and 0.95, respectively).

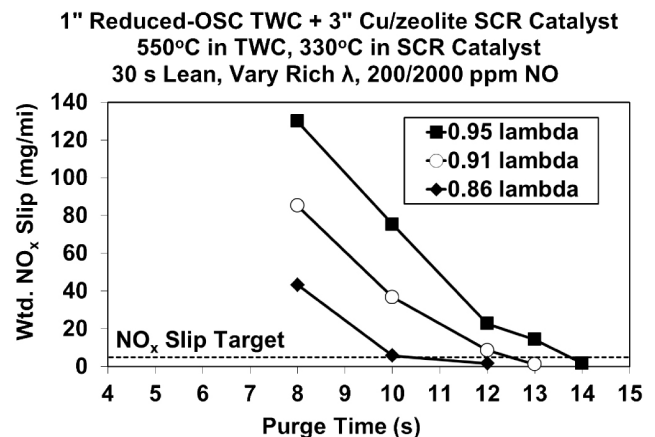


Figure 5. Weighted  $\text{NO}_x$  slip as a function of rich purge time for 1" TWC + 3" SCR system.  $\text{NO}$  levels of 220 ppm lean and 2000 ppm rich. 30 s lean periods and variable rich purge times. Rich  $\lambda$  of 0.86, 0.91, and 0.95. 550°C in TWC and 330°C in SCR catalyst.