

# Control of an Industrial SCR Catalyst Using Ceramic NO<sub>x</sub> Sensors

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Received June 15, 2011; revised July 8, 2011; accepted July 13, 2011

## Abstract

Selective Catalytic Reduction (SCR) catalysts respond slowly to transient inputs, which is troublesome when designing ammonia feed controllers. An experimental SCR test apparatus installed on a slipstream of a Cooper-Bessemer GMV-4, 2-stroke cycle natural gas engine is utilized. Ammonia (NH<sub>3</sub>) feed rate control algorithm development is carried out. Two control algorithms are evaluated: a feed forward control algorithm, using a pre ammonia injection ceramic NO<sub>x</sub> sensor and a feed forward plus feedback control algorithm, using a pre ammonia injection ceramic NO<sub>x</sub> sensor and post catalyst ceramic NO<sub>x</sub> sensor to generate feedback signals. The feed forward algorithm controls to constant user input NH<sub>3</sub>/NO<sub>x</sub> molar ratio. The data show the lack of pressure compensation on the ceramic NO<sub>x</sub> sensors cause errors in feed forward NO<sub>x</sub> readings, resulting in sub optimal ammonia feed. The feedback system minimizes the post catalyst ceramic NO<sub>x</sub> sensor signal by adjusting the NH<sub>3</sub>/NO<sub>x</sub> molar ratio. The NO<sub>x</sub> sensors respond to ammonia + NO<sub>x</sub>; therefore, the feed forward plus feedback algorithm minimizes the sum of NO<sub>x</sub> emissions and ammonia slip. Successful application of the feedback control minimization technique is demonstrated with feedback periods of 15 and 5 minutes with molar ratio step sizes of 5% and 2.5%, respectively.

**Keywords:** SCR, Selective Catalytic Reduction, Ammonia Injection, NO<sub>x</sub> Emissions, NO<sub>x</sub> Sensor, Minimization Algorithm

## 1. Introduction

Selective Catalytic Reduction (SCR) is an aftertreatment technique for reduction of oxides of nitrogen (NO<sub>x</sub>) from the exhaust from combustion devices. SCR requires a reagent be blended with exhaust upstream of the SCR catalyst, which then reacts with NO<sub>x</sub> across the SCR catalyst. The reagent is typically ammonia (NH<sub>3</sub>) or a chemical that breaks down to form ammonia, such as urea. The reagent feed rate must be precisely controlled to achieve high efficiency NO<sub>x</sub> reduction, while limiting ammonia slip [1]. Reagent feed rate control techniques have been studied to improve SCR performance. In the case of mobile applications, the high level of transients requires fast feedback response. In the case of stationary engine applications operating condition changes are slower. Control techniques for slow, stationary applications are developed in this work. Feedforward algorithms are used to follow basic system transitions. Feedback algorithms are used to compensate for feedforward errors, such as sensor drift and ammonia injector nozzle clog-

ging.

Schär *et al.* [2] tested feedback and feedforward algorithms. In that work four feedforward techniques were implemented. The algorithms were tested in a manner that required much faster response than tests described in this paper. Schär *et al.* [2] used a feedback signal generated with a ceramic NO<sub>x</sub> sensor. Ammonia interferes with ceramic NO<sub>x</sub> sensors. Ceramic NO<sub>x</sub> sensors respond approximately as is shown in Equation (1) [2],

$$R_{\text{CNS}} = C_{\text{NO}_x} + 0.65C_{\text{NH}_3} \quad (1)$$

where  $R_{\text{CNS}}$  is the ceramic NO<sub>x</sub> sensor reading and  $C_{\text{NO}_x}$  and  $C_{\text{NH}_3}$  are concentrations of NO<sub>x</sub> and ammonia, respectively. This is important in SCR feedback applications because both ammonia and NO<sub>x</sub> are present post catalyst. As a result, it is difficult to determine whether the sensor is responding to NO<sub>x</sub> or ammonia.

In this work we experimentally explore feedforward and feedback SCR control algorithms on an SCR system for industrial reciprocating natural gas engines. The feedforward approach utilizes a pre catalyst NO<sub>x</sub> sensor measurement to set the ammonia flowrate, given a con-

stant  $\text{NH}_3/\text{NO}_x$  set point. In the feedback algorithm a second  $\text{NO}_x$  sensor is used post catalyst. The feedback approach used is a new approach to SCR control. The post catalyst  $\text{NO}_x$  sensor signal is minimized to determine the optimal  $\text{NH}_3/\text{NO}_x$  ratio, which is then used to set the ammonia feed rate. A catalyst slipstream is used for the experimental evaluation, integrated with a Cooper-Bessemer GMV-4 large bore natural gas engine.

## 2. Experimental Setup

**Figure 1** shows the exhaust flow schematic. Shown is each component in the slipstream that will be discussed in order of its respective position on the slipstream. The gas flow in **Figure 1** starts at the engine, flows as indicated by the arrows, and ends where exhaust is emitted into the atmosphere. The SCR slipstream removes a small portion of exhaust from each of the four exhaust elbows, conditions it, directs it through the SCR catalyst, then reconnects with the main exhaust. Exhaust conditioning is done through temperature, exhaust flow, and reagent concentration control. Conditioned exhaust flows into the catalyst material where  $\text{NO}_x$  and ammonia are catalytically reduced. After passing through the catalyst and through a flow measurement orifice, the slipstream gas is recombined with the main exhaust stream.

### 2.1. Engine

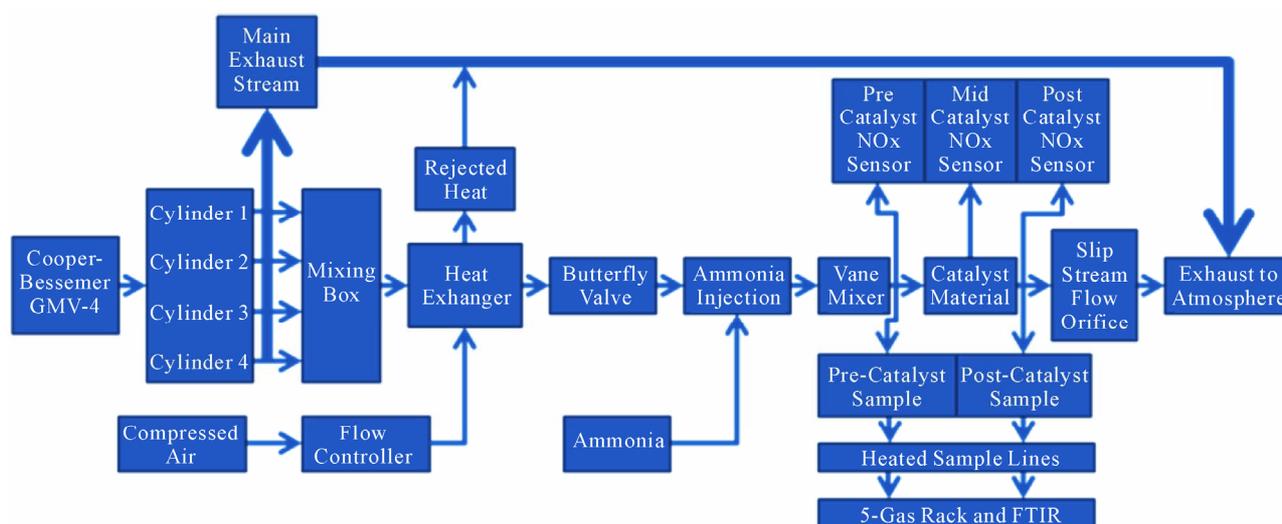
The test engine is a Cooper Bessemer GMV-4TF, four-cylinder, two stroke, lean-burn, natural gas, internal combustion engine, rated at 440 bhp (330 kW). Engine torque is controlled by a water brake dynamometer. Ignition is performed using pre-combustion chambers. Intake and exhaust pressure are controlled, which allows intake

boost to be adjusted from 3.5"Hg (11.8 kPa), to 23"Hg (77.9 kPa) gauge. Exhaust backpressure was always set at 2.5"Hg (8.46 kPa) less than intake pressure, and controlled by a butterfly valve in the main exhaust stream. Engine out  $\text{NO}_x$  was controlled by varying boost at constant load and speed, which varies trapped equivalence ratio. Further description of the test engine is in [4] and [5].

### 2.2. Slipstream

**Figure 2** is a photo of the SCR slipstream. The slipstream was designed to receive exhaust gas from the four exhaust elbows, each of which corresponds to one of the engine cylinders. Each elbow connected the exhaust port of the cylinder to the main exhaust manifold. A heat exchanger controlled temperature of the exhaust gas and the operating temperature of the catalyst. The heat exchanger was a cross flow type, in which compressed air flowed across a finned tube bank. Temperature of downstream exhaust gas was controlled by varying flow rate of compressed air through the heat exchanger. The heat exchanger was able to control catalyst temperature between 450 and 600°F (505 to 589 K). A butterfly valve controlled exhaust flow rate through the slipstream. The butterfly valve was located inside the slipstream pipe and positioned by a Belimo AF24-SR actuator.

The aqueous ammonia injector was an air assisted type, supplied by CPI International. The design used two concentric stainless steel tubes, one 1/8" (3.2 mm) diameter, and the other 1/16" (1.6 mm) diameter. The smaller tube had a calibrated crimp on its end. Compressed air flowed through the smaller tube, and aqueous ammonia flowed in the annulus. Aqueous ammonia was atomized by high velocity air exiting the calibrated crimp. The aqueous



**Figure 1.** Exhaust flow schematic.

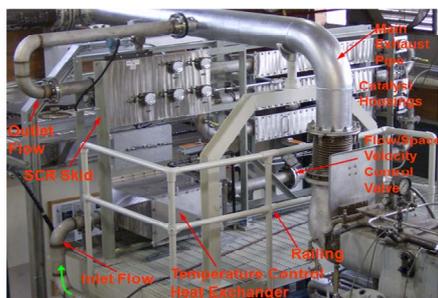


Figure 2. Picture of SCR slipstream.

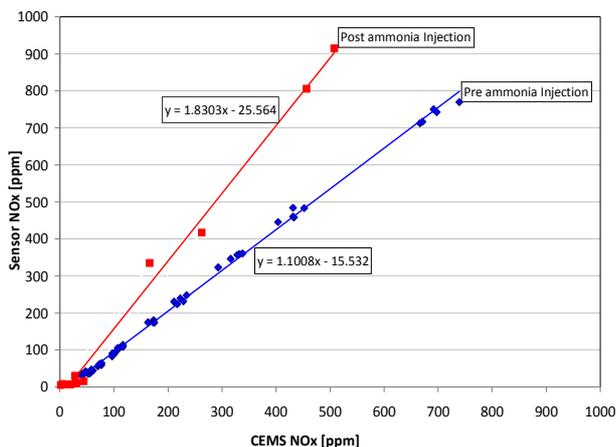


Figure 3. Ceramic NO<sub>x</sub> sensor signal vs CEMS NO<sub>x</sub> in the presence of ammonia and the absence of ammonia.

ammonia air assisted atomizer was mounted to an elbow in the flow stream so that the atomizer could spray in the same direction as the exhaust flow, without modifying or bending the atomizer. A vane mixer was used to ensure gaseous homogeneity. The mixer was placed between the ammonia injector and the catalyst. Experimental and CFD analyses were done by Ivaturi [6] to quantify reagent mixing.

A commercial company provided the catalyst modules. The cylindrical modules were 9" (22.9 cm) diameter by 5" (12.7 cm) long. The cylinders had 1/16" (1.6 mm) square cross hatching, creating channels, or monoliths. A vanadia-titania mixture coated the surface of the catalyst, which catalyzed the chemical reactions between NO<sub>x</sub> and ammonia. The exact composition of the washcoat on the catalyst modules was unknown.

To measure slipstream exhaust flow, a 1.75" (4.45 cm) diameter orifice, with a pressure measurement before and after, was used. Differential pressure across the orifice, static pressure at the orifice, and temperature at the orifice were measured to calculate exhaust flow.

### 2.3. Emissions Measurement

Exhaust was sampled with averaging probes and flowed

through a heated sample line. The heated sample line, temperature controlled to 230°F (383 K), directed the sample into a Rosemount Continuous Emissions Measurement System (CEMS) and a Nicolet Magna Fourier Transform Infra-Red (FTIR) spectrometer. Carbon dioxide (CO<sub>2</sub>), CO, oxygen (O<sub>2</sub>), total hydrocarbons (THC), and NO<sub>x</sub>, were measured using five dedicated measurement modules in the CEMS. The CEMS incorporates a chiller that condensed water out of the sample, so all measurements made by the CEMS analyzer were dry. An FTIR spectrometer was used to measure ammonia, water, and hydrogen cyanide. The FTIR spectrometer sampled wet exhaust gas. For more details on the emissions measurement equipment, see [7].

### 2.4. Data Acquisition and Control

Measurements were made using National Instruments data acquisition systems and LabVIEW software. The National Instruments hardware consisted of a compact field point, cFP 2100 unit with: TC 120, AI 110, AO 200, and DIO 550 input/output modules. A program written in LabVIEW controlled basic functionality of the slipstream system, including catalyst temperature, sample line temperature, space velocity, and NH<sub>3</sub>/NO<sub>x</sub> molar ratio. The LabVIEW program also read and recorded basic system parameters.

During catalyst testing, ECM ceramic NO<sub>x</sub> sensors, part number 06-01, were used to create feedforward and feedback loops. The sensors were mounted to an O<sub>2</sub> bung, which was welded directly to the side of the slip stream pipe. NO<sub>x</sub> sensors were connected to an ECM CANopen NO<sub>x</sub>/O<sub>2</sub> Module, which communicated via ModBus to an ECM NO<sub>x</sub> 5210 module. The 5210 module communicated with two NO<sub>x</sub> sensors at a time, and relayed the signal, via 0 - 5 V analog, to a National Instruments compact field point unit. The sensors detected NO<sub>x</sub>, O<sub>2</sub>, and air/fuel ratio.

Figure 3 shows trends of ceramic NO<sub>x</sub> sensor readings plotted against CEMS NO<sub>x</sub> readings, measured with a Chemi-Luminescence Detector (CLD), of the same exhaust gas. The first series plots the readings absent of ammonia, while the second series plot is in the presence of 0.85 NH<sub>3</sub>/NO<sub>x</sub> molar ratio. The ceramic NO<sub>x</sub> sensors have a positive reaction to ammonia. Ceramic NO<sub>x</sub> sensors have cross sensitivity to ammonia, and when tested, sensitivity was 0.65 that of NO<sub>x</sub> [2]. This means that for every 100 ppm of ammonia, the ceramic NO<sub>x</sub> sensor returned a 65 ppm higher NO<sub>x</sub> concentration. In application, sensitivity to ammonia does not affect feedforward control, but is troublesome in feedback control. While the feedforward ceramic NO<sub>x</sub> sensor can be placed up-stream of ammonia injection, the feedback sensor is always immersed in both ammonia and NO<sub>x</sub>. Therefore,

neither post catalyst  $\text{NO}_x$  concentration nor post catalyst ammonia concentration can be measured accurately using a ceramic  $\text{NO}_x$  sensor.

Filtering the  $\text{NO}_x$  sensor signal is necessary because the sensor noise band was often greater than the slipstream  $\text{NO}_x$  concentration, especially post-catalyst. The noise band was typically 30 ppm, and post catalyst  $\text{NO}_x$  concentrations approached 5 ppm. The filter implemented a least squares linear fit to the previous one minute of data.

Calibration of the  $\text{NO}_x$  sensor was performed using exhaust gas and the CLD. Ammonia was first purged from the slipstream. For one calibration point the engine was operated at 100% load and low boost (large trapped equivalence ratio), which yields higher  $\text{NO}_x$  emissions. For the other calibration point the engine was operated at 100% load and high boost (lower  $\text{NO}_x$  level). Five minute averaged points were used. The upper and lower span concentrations of the pre-catalyst sensor were 314 ppm and 52.8 ppm. These span values corresponded to 3.15 V and 1.85 V, respectively. The post-catalyst  $\text{NO}_x$  sensor was spanned between 11.6 ppm and 52.8 ppm, corresponding to 1.85 V and 2.83 V, respectively.

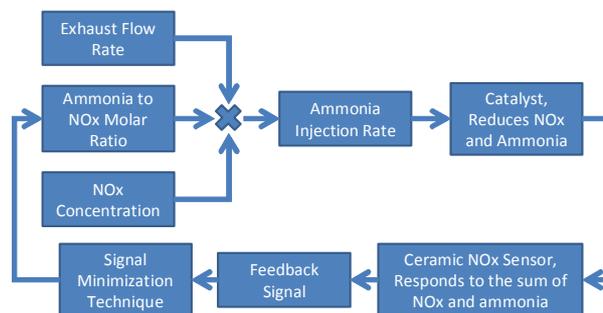
Post-catalyst  $\text{NO}_x$  sensor 0-5V analog communication to National Instruments equipment was set up to include negative  $\text{NO}_x$  concentrations. This was done because when 0 V corresponds to 0 ppm  $\text{NO}_x$  and the actual  $\text{NO}_x$  concentration is 5 ppm, noise fluctuations cause much data to be lost through truncation of the 0 - 5 V analog signal. The analog signal cannot communicate negative voltage, so any part of the  $\text{NO}_x$  sensor noise that is less than zero results in a zero reading, which is incorrect. Instead, 0 V was set to correspond to -50 ppm, so no data was lost in analog communication at low  $\text{NO}_x$  concentrations.

### 3. Results

The feedforward algorithm used a constant molar ratio calculation. The ammonia injection rate is computed from the exhaust flowrate,  $\text{NO}_x$  concentration, and desired  $\text{NH}_3/\text{NO}_x$  molar ratio. **Figure 4** shows the feedback control algorithm loop. The feedback algorithm used feedforward calculations to create ammonia flow rate. The feedback algorithm provided an updated  $\text{NH}_3/\text{NO}_x$  molar ratio to the feedforward algorithm. The parameter space velocity is used in this study. It is proportional to exhaust flowrate and inverse residence time. Space velocity is computed by dividing the standard volumetric flowrate by catalyst envelop volume.

#### 3.1. Feedforward Control Testing

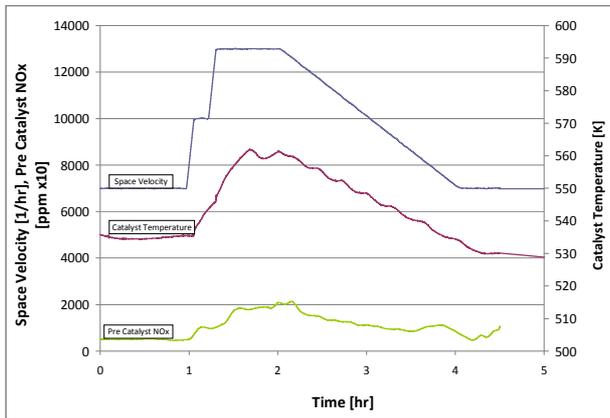
To test the feedforward control algorithm, a set of tran-



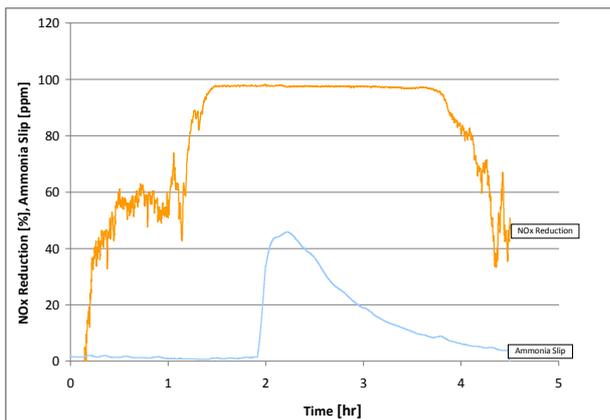
**Figure 4.** Flow diagram of the feedback algorithm.

sient flow conditions was imposed. There were three transitions: 1) at 1.0 hour is a step transition in which space velocity, pre catalyst  $\text{NO}_x$ , and catalyst temperature were increased from 7000 1/hr, 50 ppm, and 500°F [533 K] to 10,000 1/hr, 150 ppm, and 525°F [547 K], respectively; 2) at 1.5 hours, a step transition of space velocity, pre-catalyst  $\text{NO}_x$ , and catalyst temperature from 10,000 1/hr, 150 ppm, and 525°F [547 K], to 13,000 1/hr, 200 ppm, and 550°F [561 K], respectively; and 3) a slow transition, starting at hour two, in which space velocity, pre-catalyst  $\text{NO}_x$ , and catalyst temperature were reduced from 13,000 1/hr, 200 ppm, and 550°F [561 K], to 7000 1/hr, 50 ppm, and 500°F [533 K], linearly over the duration of two hours. This test map was designed to represent loading and unloading of an industrial, natural gas engine. **Figure 5** shows actual space velocity, temperature, and pre-catalyst  $\text{NO}_x$  variables throughout the point. Space velocity followed the two step inputs and the ramp down closely throughout the point. This was because space velocity was controlled by the slipstream, independent of engine exhaust flow. Catalyst temperature did not reach the objective due to slow heat exchanger response and varying engine exhaust temperature from  $\text{NO}_x$  control adjustments. Temperature oscillated on the ramp down, and did not stabilize at 500°F [533 K] at the end of the data point.  $\text{NO}_x$  varied significantly from the objective.  $\text{NO}_x$  was adjusted manually by changing engine boost, which changed trapped air/fuel ratio. The transitions in **Figure 5** are good representations of in-field catalyst operation and provide a good test for the feedforward algorithm.

**Figure 6** shows the results of the feedforward control test for the transients shown in **Figure 5**. When ammonia feed was turned on,  $\text{NO}_x$  reduction approached 60%, and ammonia slip approached 2 - 3 ppm. This is because ammonia feed rate was too low. Low ammonia feed rate is an error that can be explained by ceramic  $\text{NO}_x$  sensor pressure compensation. Ceramic  $\text{NO}_x$  sensors are sensitive to pressure changes, but the sensors used in this application were not pressure compensated. The sensors were calibrated at 10,000 1/hr space velocity, and initial



**Figure 5. Experimental feedforward parameters.**



**Figure 6. Result of feedforward test map.**

startup was 7000 1/hr space velocity. Since the exhaust flow control valve was upstream of the feedforward NO<sub>x</sub> sensor, reduced space velocity caused reduced pressure at the sensor location, resulting in reduced feedforward ceramic NO<sub>x</sub> sensor readings. This caused a lean condition, in which not enough ammonia was injected. NO<sub>x</sub> reduction was less than optimal, and ammonia slip was low.

At hour one, space velocity, temperature, and NO<sub>x</sub> were stepped up. NO<sub>x</sub> reduction increased to 80% after an upward, then downward NO<sub>x</sub> reduction peak. The downward peak was caused by slow ammonia injector response, in which the ammonia to NO<sub>x</sub> ratio decreased, because of slow ammonia injection response. Low ammonia slip and 80% NO<sub>x</sub> reduction is representative of a slightly lean condition.

When the second transition was made at 1.5 hr, space velocity, temperature, and NO<sub>x</sub> inlet concentration increased. After this transition, NO<sub>x</sub> reduction increased to around 97%, followed by an ammonia slip spike about 30 min later. This ammonia slip spike is due to ceramic

NO<sub>x</sub> sensor pressure compensation. When space velocity was increased to 13,000 1/hr, exhaust flow and pressure were higher than that at which the sensor was calibrated, causing a high NO<sub>x</sub> reading, and ammonia overfeed. Thirty minutes later, an ammonia surge occurred. This is because ammonia had been overfed for a half hour, during which the catalyst became oversaturated with ammonia. Subsequently excess adsorbed ammonia released and ammonia slip remained high for about one hour before slowly decreasing.

Space velocity, temperature, and NO<sub>x</sub> decreased slowly and linearly during the third transition. At the start of the downward ramp, ammonia was just starting to spike from the ammonia overfeed, so NO<sub>x</sub> reduction was high throughout the ramp. Ammonia slip slowly decreased from the overfeed incident, and at about 3 hr and 50 min the catalyst approached a lean condition. NO<sub>x</sub> reduction and ammonia slip decreased, approaching NO<sub>x</sub> reduction and ammonia slip of 80% and 2 - 3 ppm, respectively.

Purely open loop, feedforward control is poor if ceramic NO<sub>x</sub> sensors are used without pressure compensation. When using feedforward control, catalyst performance is only as good as the accuracy of the feedforward sensors. In this case, without pressure compensation, the NO<sub>x</sub> sensor is accurate within about 40%, and the ceramic NO<sub>x</sub> sensor is the limiting factor in emissions reduction.

Adsorbed ammonia can build up and, when released, can cause high ammonia slip for an hour or more. Ammonia adsorption is extensive at these temperatures. The catalyst adsorbs ammonia in the form of a wave propagating from the front of the catalyst material, ending at the back of the catalyst material. Because of this, ammonia slip does not increase until the entire catalyst is saturated. Once excessive ammonia begins to slip, ammonia continues to slip until the catalyst is no longer saturated. Ammonia desorption propagates through the catalyst front to back, and the ammonia desorption wave must propagate through the entire catalyst before ammonia slip stabilizes.

When adequate ammonia is in the catalyst, the catalyst does not transmit high frequency inputs. As stated by Schär *et al.* [2], the SCR catalyst can act like a low pass filter when proper ammonia is adsorbed in the catalyst. Inadequate ammonia flow is indicated by high frequency NO<sub>x</sub> concentration variation (peaks and valleys), and low ammonia slip, which can be seen in the first hour of catalyst operation, in **Figure 6**. NO<sub>x</sub> reduction increases and decreases rapidly during the first two hours of testing and, when the catalyst had adsorbed sufficient ammonia, NO<sub>x</sub> reduction stabilized and high frequency peaks and valleys disappeared.

### 3.2. Feedback Control Testing

Feedback algorithms, or closed loop control techniques, are effective at compensating for long term calibration errors. In this case, long term error can be caused by inaccurate initial  $\text{NO}_x$  sensor calibration or sensor drift. The ceramic  $\text{NO}_x$  sensor signal feedback algorithm (**Figure 4**) was designed to correct these calibration errors. Fast transient effects caused by engine load transitions, space velocity transitions,  $\text{NO}_x$  concentration variation, and temperature changes, are handled by the feedforward system. Most long term errors progress slowly over hours or days, so the stabilization timeframe of the feedback system should be able to compensate for these errors over a few hours. Feedback testing was done at steady state, and stabilization time was the focus.

If the ceramic  $\text{NO}_x$  sensor responds proportionally to the sum of ammonia and  $\text{NO}_x$ , minimizing this signal would minimize the sum of ammonia and post-catalyst  $\text{NO}_x$ . To initiate the process, a small transition in  $\text{NH}_3/\text{NO}_x$  molar ratio is made. In response, catalytic reduction either improves or diminishes, and the ceramic  $\text{NO}_x$  sensor signal either increases or decreases.

There are four possibilities:

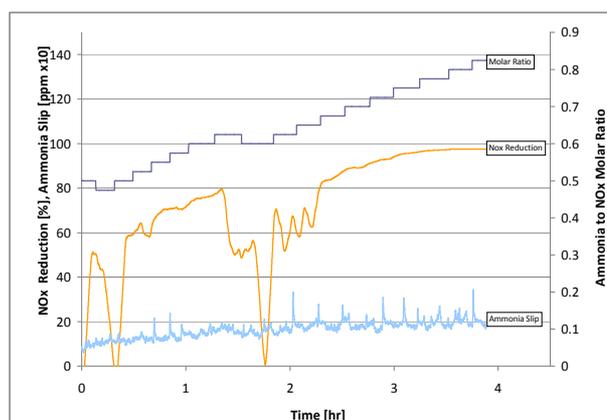
- 1) The system is operating lean (too little ammonia) and the feedback system steps ammonia down;
- 2) The system is lean and the feedback system steps ammonia up;
- 3) The system is rich (too much ammonia) and the feedback system steps ammonia up;
- 4) The system is rich and the feedback system steps ammonia down.

The second and fourth operations improve SCR performance, while the first and third operations reduce catalytic performance. If the transition decreased the signal, another step is taken in the same direction. If the transition increased the signal, the next step is taken in the opposite direction. Eventually, the algorithm will cross the feedback ceramic  $\text{NO}_x$  sensor minimum, and reverse direction, oscillating back and forth across the optimum  $\text{NH}_3/\text{NO}_x$  molar feed ratio. Through this method, the ceramic  $\text{NO}_x$  sensor signal is minimized.

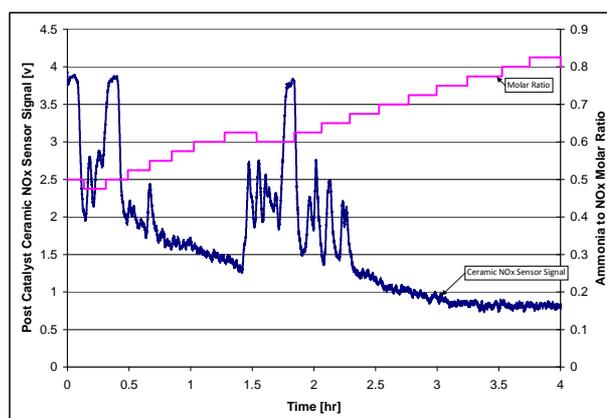
The first test was performed with a 15 min decision time and 5% step increment, and the second test was done with a 5 min decision time and 2.5% step increment. A step increment is a step in  $\text{NH}_3/\text{NO}_x$  molar ratio. The size of the step increment is relative to stoichiometric molar ratio. Decision time is the time between steps. The 15 min test was started at 0.5  $\text{NH}_3/\text{NO}_x$  molar ratio, and the 5 min test was started at 0.8  $\text{NH}_3/\text{NO}_x$  molar ratio. The test was done to see if the algorithm approached an appropriate molar ratio, and how long the algorithm took to stabilize.

**Figure 7** shows the result of the first feedback control test. Ammonia was turned on at time zero. Molar ratio was the controlled parameter in the feedback system.  $\text{NO}_x$  reduction increased to about 50%, which is expected since  $\text{NH}_3/\text{NO}_x$  molar ratio was around 0.5. At about 15 min, when  $\text{NO}_x$  reduction dropped off momentarily, the ammonia feed pump malfunctioned. After this, the algorithm increased the molar ratio appropriately. At about 1 hr and 45 min, when  $\text{NO}_x$  reduction dropped off again, there was another pump malfunction. At this point, the algorithm made one incorrect step, but corrected, and the system took about four hours to stabilize.

**Figure 8** shows  $\text{NH}_3/\text{NO}_x$  molar ratio and post catalyst ceramic  $\text{NO}_x$  sensor signal. In the figure, molar ratio begins low, and the signal is resultantly high. As the feedback loop increases the molar ratio, the catalyst approaches stoichiometric operation, ammonia and  $\text{NO}_x$  slip decrease, and the ceramic  $\text{NO}_x$  sensor signal decreases. At 1 hr and 30 min, the feedback algorithm made an incorrect decision and decreased  $\text{NH}_3/\text{NO}_x$  feed ratio. At this point,  $\text{NO}_x$  increased, increasing the ce-



**Figure 7.** Feedback control with 15 min decision time.



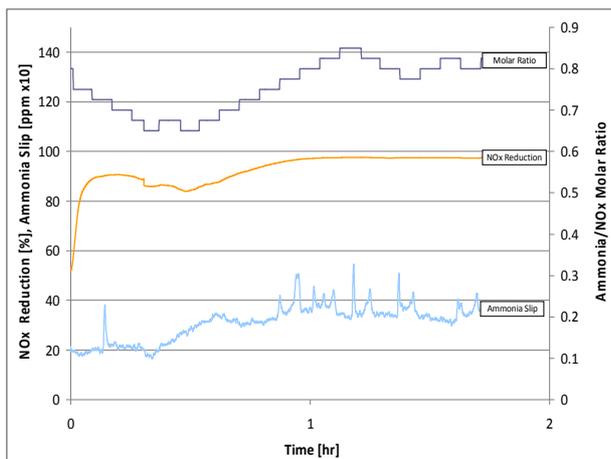
**Figure 8.** Post catalyst  $\text{NO}_x$  sensor signal and  $\text{NH}_3/\text{NO}_x$  molar ratio for feedback control during 15 min decision time test.

ramic NO<sub>x</sub> sensor signal. The algorithm reversed its direction, and continued to an appropriate molar ratio.

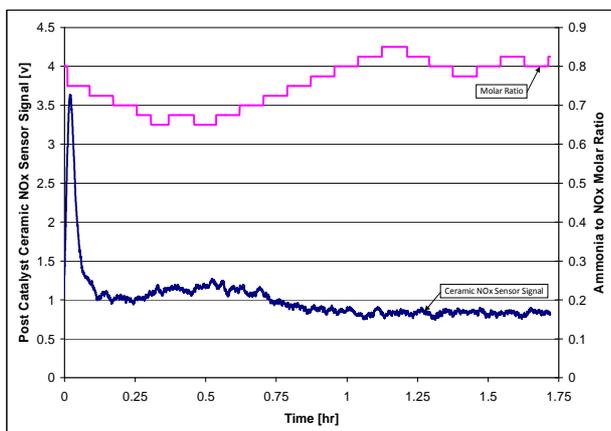
The minimization algorithm proved very effective and robust with a 15 minute decision time and a 5% increment. The system approached an appropriate molar ratio, despite equipment malfunctions. The equipment malfunctions, although unplanned, displayed control algorithm robustness.

**Figure 9** shows the result of the second feedback control test. In **Figure 9**, ammonia was turned on and NO<sub>x</sub> reduction increased to about 90%. The algorithm, at this point, made incorrect decisions, decreasing molar ratio to 0.7, until NO<sub>x</sub> reduction decreased to 85%, and the controller began making correct decisions. Over the course of the next hour and a half, the system increased molar ratio to somewhere between 0.8 and 0.85, and stabilized.

**Figure 10** shows the inputs and outputs of the feedback algorithm during the test. In the beginning, the post catalyst ceramic NO<sub>x</sub> sensor detected a surge. This is because NO<sub>x</sub> reduction was low at the beginning of this



**Figure 9.** Feedback control with 5 min decision time.



**Figure 10.** Post catalyst ceramic NO<sub>x</sub> sensor signal and NH<sub>3</sub>/NO<sub>x</sub> molar ratio during five minute decision time test.

data point. As ammonia feed was turned on, NO<sub>x</sub> reduction dropped quickly. As the algorithm initially made incorrect decisions, the post catalyst ceramic NO<sub>x</sub> signal increased. Around 0.5 hours, the algorithm began making correct decisions. The post catalyst ceramic NO<sub>x</sub> sensor signal began decreasing. At about 1.25 hours, the system stabilized. The post catalyst ceramic NO<sub>x</sub> signal leveled, and the molar ratio control signal oscillated above and below the optimum.

With a 5 min decision time and 2.5% step size, the system made incorrect decisions, but stabilized much faster than the 15 min decision time algorithm. When the system was turned on, NO<sub>x</sub> reduction increased, decreasing the feedback signal from the ceramic NO<sub>x</sub> sensor. The algorithm reduced molar ratio for several steps, which was incorrect. Although the 5 min decision time is significantly faster than the 15 min decision time feedback system, the 15 min system is fast enough to correct for sensor drift, and more robust than the 5 min system. The 15 min decision time system made very few incorrect decisions during stabilization, whereas the 5 min decision time system made many incorrect decisions. The feedback system should ensure that long term sensor drift does not significantly affect engine emissions. Since sensor drift occurs in the timeframe of hours and days, both the 5 min and 15 min systems should be sufficiently fast. NO<sub>x</sub> reduction was around 98% on both systems at the stabilization point, while maintaining ammonia slip under 5 ppm. This shows that the control technique is very effective at ensuring the catalyst is operating properly.

These tests showed the algorithm response given constant space velocity, temperature, and NO<sub>x</sub> concentration. The tests did not test the feedback algorithm sensitivity to varying inputs. If NO<sub>x</sub> were to increase rapidly, causing rapid ammonia slip or NO<sub>x</sub> reduction transition, the feedback algorithm might respond to the varying input, as if the transition was initiated by a feedback step. More research is needed to evaluate the feedback algorithm with variable inputs. Incorporation of pressure compensated NO<sub>x</sub> sensors may be necessary to achieve acceptable performance with variable inputs.

## 4. Conclusions

Control systems were developed for SCR systems to control ammonia injection flow rate. Two algorithms were experimentally evaluated. The first was a feedforward control algorithm that used a ceramic NO<sub>x</sub> sensor to detect pre catalyst NO<sub>x</sub>. The second was a feedforward plus feedback algorithm which used a pre and post catalyst ceramic NO<sub>x</sub> sensor to generate feedforward and feedback signals, respectively.

The feedforward control algorithm was inaccurate following space velocity transients, because the ceramic NO<sub>x</sub> sensor was not pressure compensated. This led to overfeeding of ammonia at high space velocities and underfeeding of ammonia at low space velocities.

The feedforward plus feedback algorithm used an algorithm that minimized the post catalyst ceramic NO<sub>x</sub> sensor signal. This feedback technique controlled the molar ratio set point. Minimization of the post catalyst ceramic NO<sub>x</sub> sensor signal is a new approach for utilizing ceramic NO<sub>x</sub> sensors that is independent of sensor calibration. This approach capitalizes on NO<sub>x</sub> sensor ammonia interference to improve SCR control. Two decision times were tested, a 15 min decision time and a 5 min decision time. The 15 min decision time algorithm was able to approach appropriate ammonia feed, a 40% correction, in about 4 hours at steady state feedforward conditions. The 5 min decision time algorithm was robust and operated fast enough to account for sensor drift in stationary engine applications. The 15 min decision time algorithm stabilized much faster, in about 1.5 hours, but was less robust.

## 5. Acknowledgements

This work was funded by the Pipeline Research Council International.

## 6. References

- [1] M. Chen and S. Williams, "Modeling and Optimization of SCR-Exhaust Aftertreatment Systems," SAE International, 2005, Article No. 2005-01-0969.
- [2] C. M. Schär, C. H. Onder and H. P. Geering, "Control of an SCR Catalytic Converter System for a Mobile Heavy-Duty Application," *IEEE Transactions on Control Systems Technology*, Vol. 14, No. 4, 2006, pp. 641-653. [doi:10.1109/TCST.2006.876634](https://doi.org/10.1109/TCST.2006.876634)
- [3] C. M. Schär, "Control of a Selective Catalytic Reduction Process," IMRT Press c/o Institut für Messund Regeltechnik, ETH Zentrum, 2003.
- [4] D. Simpson, "Precombustion Chamber Design for Emissions Reduction from Industrial Natural Gas Engines," Master's Thesis, Colorado State University, Fort Collins, 2009.
- [5] J. Lisowski, "Diagnostic Techniques for Precombustion Chambers in Large Bore Lean Burn Natural Gas Engines," Master's Thesis, Colorado State University, Fort Collins, 2007.
- [6] K. Ivaturi, "Experimental and CFD Investigation of Re-agent Mixing in an SCR System," Master's Thesis, Colorado State University, Fort Collins, 2007.
- [7] T. Moosman, "FTIR Spectroscopy for 2-Stroke, Lean Burn Gas Engines Emphasizing Low-Level Detection of HAPs," Master's Thesis, Colorado State University, Fort Collins, 2005.