Passive SCR performance under pseudo-transient cycle: challenges and opportunities for meeting Tier 3 emissions

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Abstract

The passive ammonia (NH_3) selective catalytic reduction (SCR) system is a potential approach for controlling nitrogen oxides (NOx) emissions from lean burn gasoline engines based on utilizing NH_3 generated by a three-way catalyst (TWC) during brief periods of fuel-rich engine operation. NH_3 generated by the TWC is stored and available to reduce NOx on a downstream SCR catalyst during subsequent periods of lean engine operation. Control of the overall passive SCR process can be more challenging than current urea-based approach because it depends explicitly on fuel-rich engine operation, which must be implemented in the context of transient engine operation. Under transient engine operation, significant variation in SCR temperatures are also to be expected. With NH_3 storage capacity highly dependent on exhaust temperatures, proper system architecture and engine operating strategy are needed for effective NH_3 utilization over the SCR catalyst. In this study, the performance of a passive SCR system was evaluated on a 2.0-liter BMW lean burn gasoline direct injection engine under 6-mode pseudo-transient cycle. The aim of this work is to understand how various engine operating strategies change the dynamics of NH_3 generation and utilization, and NOx reduction in the passive SCR system. A 5.9 % fuel economy improvement relative to stoichiometric-only operation with 0.018 g/mi of NOx + NMHC emissions were demonstrated over 6-mode pseudo-transient cycle; however, CO emissions were twice the emission standard. The results of this work reveal challenges and opportunities for meeting Tier 3 emissions and improving fuel savings benefits.

Keywords

Passive SCR; TWC; lean NOx; NH_3 formation; lean gasoline;

1. Introduction

In the U.S., the light duty vehicle fleet is dominated by gasoline engines operating at stoichiometric air-to-fuel ratios (AFR) and accounts for 63 % of the transportation petroleum use [1]. Implementing fuel-efficient technologies in this sector can significantly reduce U.S. petroleum consumption and greenhouse gas emissions. Fuel consumption of a gasoline engine can be improved by as much as 10-20 % by operating the engine in lean combustion [2], [3]. Reduction of NOx emission in fuel-lean (oxygen-rich) exhaust, however, is challenging with currently available technology. The most widely used post-engine emissions control device for gasoline vehicles is the three-way catalyst (TWC). While the TWC is highly effective for stoichiometric engine exhaust, it is ineffective in reducing NOx in the oxygen-rich exhaust of lean-burn gasoline engines.

One of the newly proposed technical approaches for adapting TWCs to lean-burn engines is the so-called passive selective catalyst reduction (SCR) system. This consists of a close-coupled TWC combined with an under-floor SCR catalyst that utilizes ammonia (NH_3) generated over the TWC to reduce residual NOx in the exhaust [4], [5]. Ammonia is formed over the TWC during occasional fuel-rich excursions and subsequently stored on the downstream SCR catalyst. When the engine returns to lean combustion, NOx passes through the TWC and is reduced by the stored NH_3 on the SCR catalyst. This approach is particularly attractive for lean gasoline engine application because it utilizes a TWC that is already onboard and can potentially control lean NOx at a lower cost compared to urea-based SCR systems by eliminating the need for urea storage and delivery components.

Unlike the urea system where continuous NH_3 supply is available from the urea tank, the passive SCR process depends explicitly on fuel-rich engine operation to generate NH_3, which must be implemented in the context of transient operation. A key challenge is to develop engine fueling strategies for exploiting the NH_3 generation process such that the consumption of excess fuel is minimized while still meeting NOx reduction targets. The potential of the passive SCR approach to achieve high NOx conversion efficiency with minimal fuel penalty has previously been demonstrated under simple engine lean/rich cycling conditions [6]. To further demonstrate the fuel savings potential of lean gasoline engines and the effectiveness of the passive SCR system for meeting U.S. Tier 3 emissions regulations, the passive SCR approach was investigated over a pseudo-transient cycle representative of the conditions encountered during the Federal Test Procedure (FTP) drive cycle. The aim of this work is to understand how the engine fueling schedule can influence fuel consumption and emissions control performance.

2. Material and methods

2.1. Engine Platform

The lean gasoline engine research platform utilized in this study is a commercial lean gasoline engine removed from a European Model Year (MY) 2008 BMW 1-series 120i (E87) vehicle. It is a 4-cylinder 2.0-liter naturally aspirated direct injection gasoline engine that has a rated power of 125 kW at 6700 revolutions per minute (rpm) and a torque of 210 Nm at 4250 rpm. Table 2-1 summarizes engine specifications. The engine is installed in a test cell at Oak Ridge National Laboratory and is coupled to a motoring direct current dynamometer that controls the engine speed and load.

Table 2-1. BMW 2.0-liter lean direct injection engine specifications.

Engine Model Number	N43B20
Displaced volume	1995 cm^3
Number of cylinders	4
Stroke	90 mm
Bore	84 mm
Compression ratio	12.0:1
Rated Power	125 kW at 6700 rpm
Rated Torque	210 Nm at 4250 rpm

The engine was fueled with a EEE-lube certification gasoline fuel containing low sulfur levels. The fuel was acquired from Haltermann Solutions. Fuel properties are listed in Table 2-2.

Table 2-2. EEE-Lube Cert Gasoline fuel properties.

Lower Heating Value, kJ/kg	42715
Density, kg/liter	0.742
C, weight fraction	0.8598
H, weight fraction	0.1314
Oxygen, weight %	<0.01
Sulfur, mg/kg	4
Aromatics, volume %	27.4
Olefins, volume %	0.9

Saturates, volume %	71.8
Research Octane Number (RON)	96.4
Motor Octane Number (MON)	88.4

The BMW lean gasoline engine uses a spray guided combustion system design. In this design, a piezoelectric injector is located at the top center of the combustion chamber, with a spark plug in close proximity to the injector. This geometry allows ignition of the fuel as it is injected, which results in shorter mixture formation time compared to wall guided and air guided combustion systems [2]. With shorter mixture formation time, lean engine operation can be extended to higher speeds and loads, resulting in additional fuel savings. The overall air-fuel equivalence ratio, or λ (ratio of actual AFR to stoichiometric AFR), during lean operation ranges between 1.4 and 2.2. Up to 20 % reduction in fuel consumption can be achieved with lean operation relative to stoichiometric; however, the engine only operates lean over a portion of the engine's speed and load range (up to 4500 rpm and 75 % load) as shown in Figure 2.1. At higher engine speeds (>4500 rpm) and loads (>75 %), the engine operates in the stoichiometric combustion mode. The engine is also designed to operate in the stoichiometric mode over its entire operating range. In this study it was necessary to operate the engine fuel-rich ($\lambda<1$), and this was achieved by manual fuel injection adjustments to achieve the desired λ. Details on an additional rich combustion strategy available on this engine can be found in a previous publication [7].

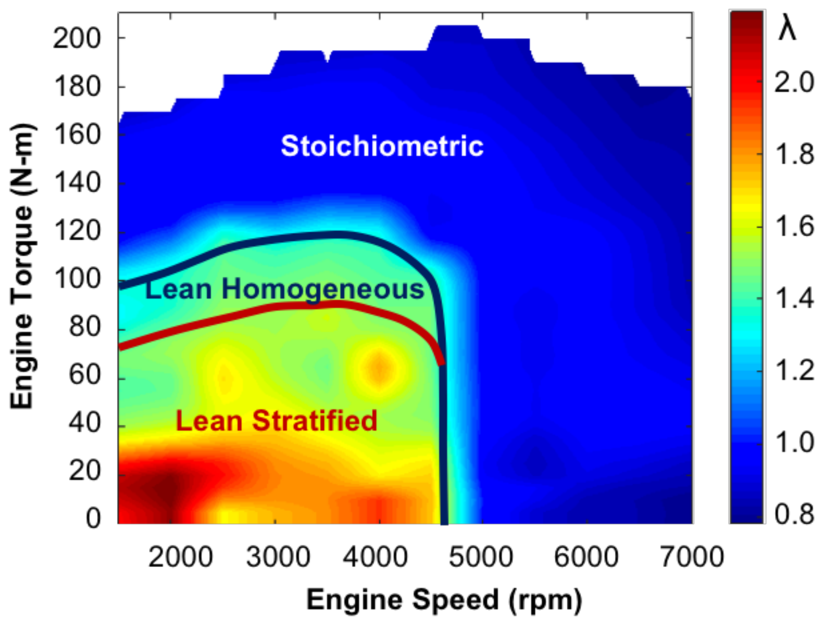

Figure 2.1 Air-fuel equivalence ratio, λ, as a function of engine speed and load. Also shown three main combustion modes employed by the engine: lean stratified, lean homogeneous with additional stratification and homogeneous stoichiometric.

To achieve the necessary engine control, the factory engine control unit was replaced with a custom full-pass control system developed by National Instruments - Powertrain Controls Group. The controller algorithms were implemented using LabVIEW to mimics the original equipment manufacturer (OEM) combustion strategies and also enable full control of all engine parameters including fuel injection quantity and timing, and spark timing. Additional information on the engine setup, performance and emissions can be found elsewhere [3], [7]–[9].

2.2. Catalysts

The passive SCR system evaluated in this work consisted of a 1.3 L close-coupled TWC and a 2.5 L Cu-zeolite SCR installed downstream of the TWC. The location of the SCR catalyst is representative of an underfloor position, which allows for lower temperatures and higher NH_3 storage. To mimic the underfloor catalyst temperatures observed on the BMW 120i during the hot start Federal Test Procedure (FTP) drive cycle, the length of the exhaust pipe between the TWC and SCR catalysts was adjusted such that the SCR inlet temperature was 200-450 C° [8].

The engine and the exhaust configuration are shown in Figure 2.2. The TWC is a Pd-based formulation containing 7.33 g/L of Pd and without a dedicated oxygen storage component (OSC). This catalyst is the front half of a commercial dual zone TWC used in a 2009 PZEV (Partial Zero Emissions Vehicle) Chevrolet Malibu. For this study, the front portions of three Chevrolet Malibu TWCs were sectioned, mounted in series in a stainless steel can, and installed in the engine exhaust to provide the 1.3 L necessary for the experiments. The SCR catalyst was provided by Umicore. It is a small pore Cu-zeolite catalyst on a 400 cpsi substrate.

The catalysts were degreened in the engine exhaust for approximately 20 hours at inlet temperatures ranging between 650 °C - 850 °C and 550 °C - 700 °C for TWC and SCR catalysts, respectively. Prior to this study, both of the catalysts had been used in other studies on the same engine where they were exposed to the engine exhaust for approximately 100 hours with maximum inlet temperatures of 850 °C and 700 °C for the TWC and SCR, respectively.

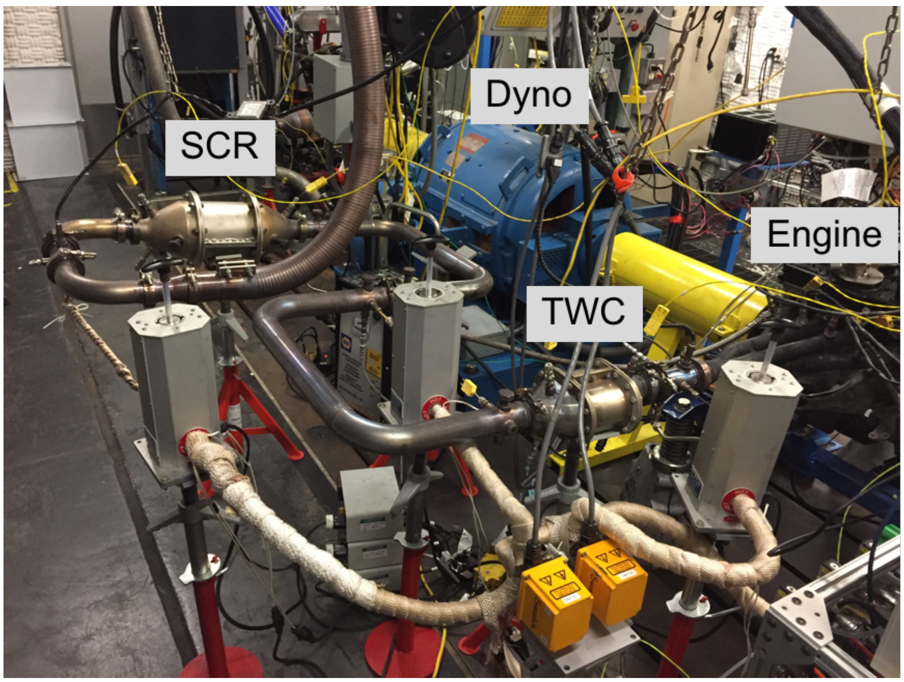

Figure 2.2 Lean gasoline engine with a close-couple TWC and an underfloor SCR.

2.3. Emission sampling

To characterize catalysts performance, raw exhaust gas was sampled at each catalyst entrance and exit locations and routed through heated stainless-steel lines to gas analyzers. The gas sample was passed through a heated filter to remove particulates to protect the gas analyzers. Multiple species concentrations were determined by an MKS MultiGas Model 2030 continuous gas analyzer. The MultiGas is a Fourier-Transform Infrared gas analyzer with a heated 5.11 m multi-pass gas cell capable of measuring multiple gases including NH_3, CO, CO_2, CH_4, NO and NO_2.

Total hydrocarbon (THC) emissions were measured with a California Analytical Instruments (CAI) heated flame ionization detector (HFID).

2.4. Experimental conditions

To enable emissions and fuel economy measurements under realistic operating conditions, a pseudo-transient drive cycle provided by General Motors R&D was employed [10]. The pseudo-transient cycle is a simplified modal engine test cycle intended to be representative of the engine operating conditions encountered during the Federal Test Procedure (FTP) driving cycle. The cycle was developed to conduct emission characterization tests, and to provide realistic exhaust emissions and temperature transients for full-scale catalyst system integration studies and control strategy development. It consists of a combination of six speed and load points listed in Table 2-3. The set points represent typical idle, acceleration and cruise events that the engine encounters during the FTP cycle. The pseudo-transient modal cycle is a compilation of these set points with constant acceleration during speed and load changes as shown in Figure 2.3.

Table 2-3. Speed and load operating points employed by the pseudo-transient drive cycle including the default combustion mode of operation.

Engine Speed (rpm)	Engine Load (bar BMEP)	Default Combustion Mode
1000	1.0	Lean Stratified
1500	2.0	Lean Stratified
1500	4.0	Lean Stratified
2000	3.0	Lean Stratified
2000	5.0	Lean Homogeneous
3000	8.0	Stoichiometric

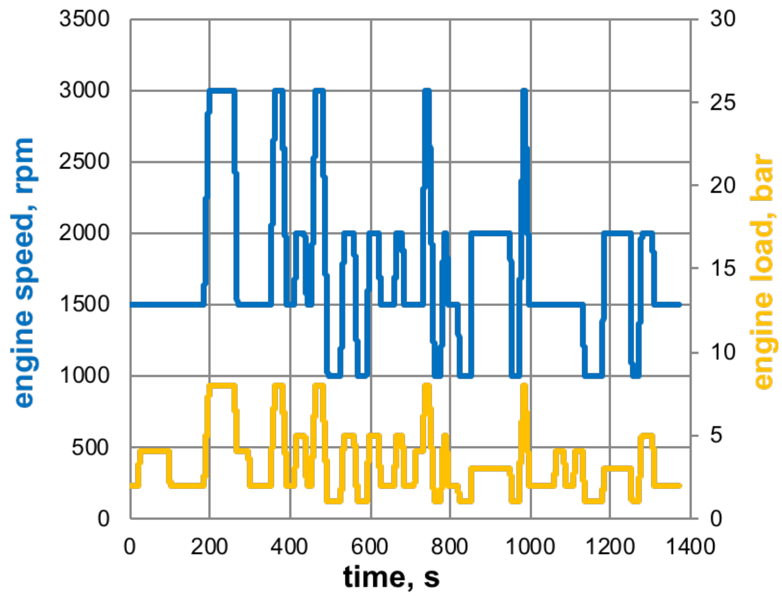

Figure 2.3 Pseudo-transient drive cycle used for engine studies of the passive SCR system.

3. Results and discussion

In the passive SCR approach, the engine is used to actively set the boundary conditions for the emissions control system. Unlike the urea system where continuous NH_3 supply is available from the urea tank, the passive SCR process depends explicitly on fuel-rich engine operation to generate NH_3, which must be implemented in the context of transient operation. The challenge is to be able to control the rich fueling events in sufficient quantities to meet NOx reduction requirements without consuming excessive amount of fuel. To exploit the potential opportunities and challenges of the passive SCR system, the performance of both the engine and catalysts as a combined system was evaluated over the pseudo-transient FTP cycle to assist in making better assessments of the passive SCR technology as a potential fuel-efficient solution for controlling NOx emissions from lean-burn gasoline engines. The work reported here is aimed at investigating how various engine operating strategies change the dynamics of NH_3 generation and utilization, and NOx reduction in the passive SCR system.

3.1. Maximum lean operation strategy

Amid the fuel-rich operation requirement to meet NH_3 generation demands, the control algorithm must be adjusted to provide as much lean operation as possible for greatest fuel efficiency gains. The maximum fuel economy over the pseudo-transient FTP cycle was experimentally measured by operating the engine lean whenever possible and automatically transition to stoichiometric combustion when the demanded speed and load point fell outside the lean operating range. Relative to stoichiometric-only operation, this lean approach demonstrated 9.6 % improvement in cycle average fuel economy over the pseudo-transient FTP cycle. This is relatively close to the fuel economy improvement measured on a chassis dynamometer with the lean gasoline vehicle from which this engine was extracted [3].

Variation of the combustion modes employed by the engine during the pseudo-transient FTP cycle is shown in Figure 3.1. As shown in the figure, the engine switches to stoichiometric combustion during hard acceleration events when the engine transitions to 3000 rpm 8 bar BMEP (Brake Mean Effective Pressure, measure of engine load) modal point; the rest of the time (91% of the time) the engine operates lean. The resulting 9.6 % maximum fuel economy improvement serves as the baseline for comparing fuel penalties of the operating strategies investigated in this study.

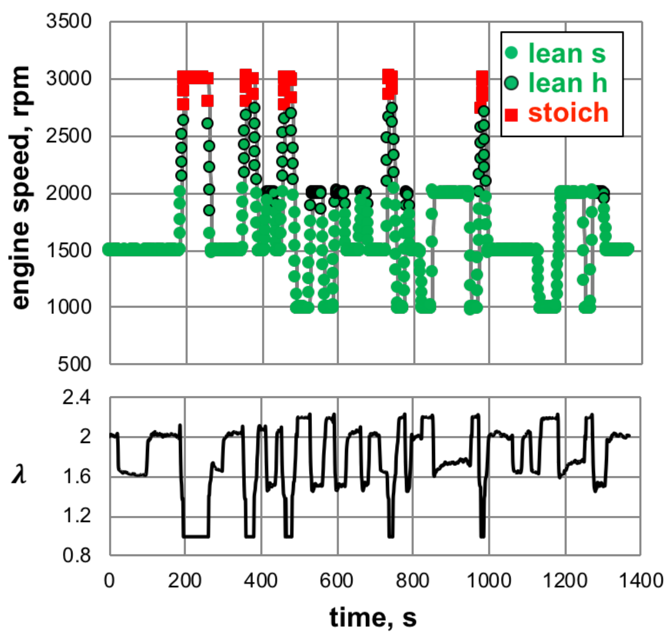

Figure 3.1 Engine speed trace overlaid with different combustion modes employed by the engine (multimode engine operation) during pseudo-transient FTP drive cycle. Also shown variation of λ during the cycle.

Initial operating strategy for passive SCR lean NOx control was based on the operating schedule shown in Figure 3.1 (referred to as the maximum lean operation strategy), but since occasional rich excursions were necessary to generate NH_3, the stoichiometric points were substituted with rich operating points. This initial simple strategy was implemented to assess NOx and NH_3 inventory, NH_3 utilization and NOx reduction processes in the passive SCR system. The results were subsequently used to determine how the engine fueling condition can be adjusted to meet NOx emissions targets while minimizing fuel consumption.

The temperature and emissions of NOx, NH_3, CO and THC were measured during the pseudo-transient FTP cycle at three different locations: engine out, TWC out, and SCR out (shown in Figure 3.2). To insure complete NOx to NH_3 conversion by the TWC catalyst, λ=0.96 was selected for the rich operation based on prior results showing complete NOx to NH_3 conversion on the same Pd-based TWC formulation [9]. The raw emissions presented in the figure illustrate the basic concept behind passive SCR, where NH_3 is generated in a post-engine TWC, stored and used in a downstream SCR catalyst to reduce NOx released by the engine.

Without stored NH_3 on the SCR in the beginning of the cycle, NOx passes through the catalyst system mostly unconverted during the first 200 seconds of lean operation. As the engine transitions to rich operation (shaded areas in Figure 3.2), NOx is instantaneously converted to NH_3 over the TWC. In the subsequent lean operation, the delay in NOx breakthrough over SCR catalyst indicates NOx reduction by stored NH_3, and as stored NH_3 gets depleted, NOx slip increases and eventually reaches engine out levels. Also during this lean operation, a significant amount of NH_3 slip is observed. The higher exhaust temperature that accompanies acceleration eventually increases the SCR temperature (~230 s), and with NH_3 storage highly dependent on temperature, the amount of stored NH_3 decreases. Thus, even though the long rich period coinciding with the first acceleration event (200 s) produces a lot of NH_3 over the TWC, increasing SCR temperature limits the availability of this NH_3 for lean NOx reduction. While acceleration events offer natural opportunities for fuel efficient NH_3 generation [9], NOx reduction can be limited due to low NH_3 storage at high temperatures and measures must be taken to account for these conditions.

The Pd-based TWC is effective in oxidizing CO during lean operation, but the onset of CO slip begins immediately on the transition from lean to rich and continues to slip for the duration of the rich operation. High THC conversion is observed during both lean and rich phases; however, during prolonged lean operation, as the catalyst gets oxidized, a slight increase in HC slip is observed. As expected, very little contribution to CO and HC conversion is observed from the SCR catalyst. This CO slip will be a major consideration in the implementation of this approach. A catalyst that can reduce CO levels under rich conditions, either through water-gas-shift (WGS) or with significant stored oxygen, will be necessary to bring the CO emissions into compliance.

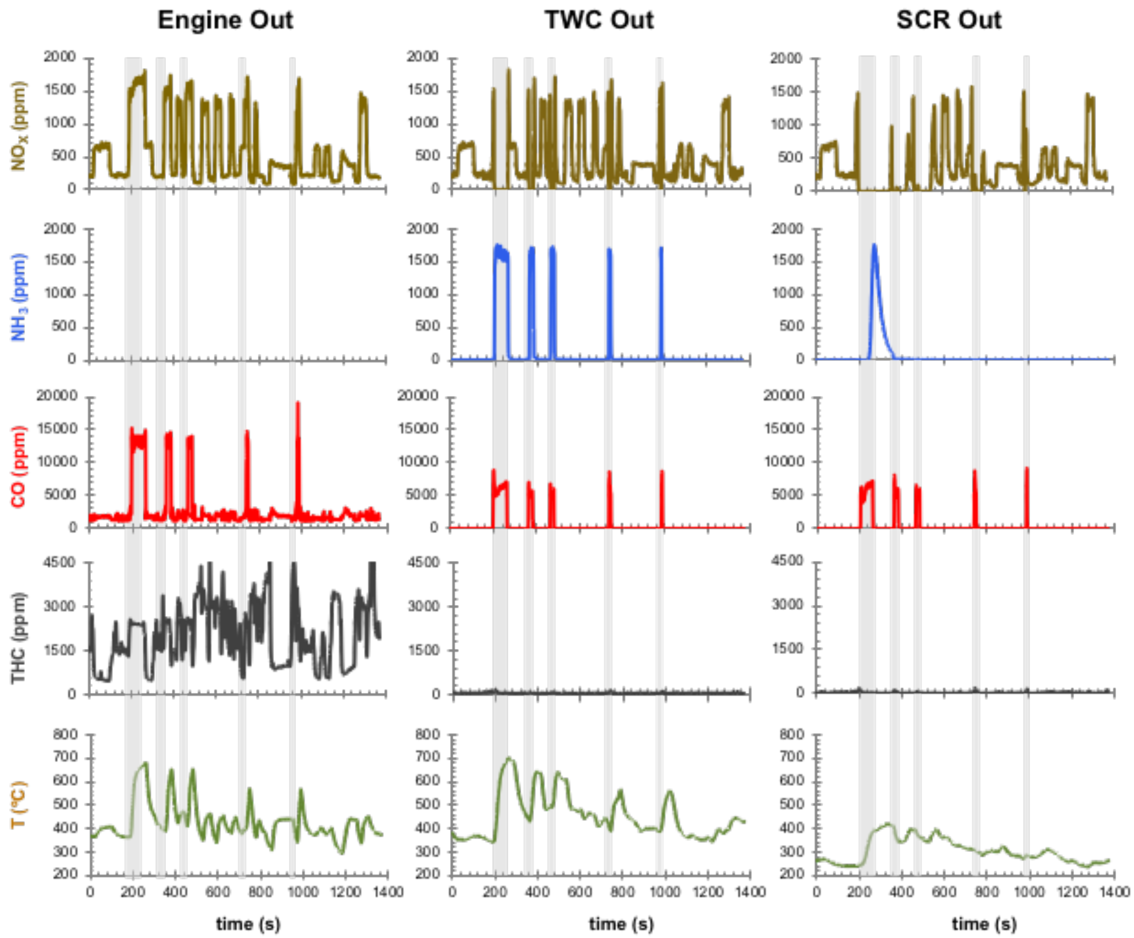

Figure 3.2 Emissions of NOx, NH_3, CO and THC at the engine, TWC and SCR outlet sampling locations along with the outlet temperatures during 6-mode pseudo-transient FTP cycle. Engine operated using maximum lean operating strategy with rich λ=0.96. Shaded areas correspond to rich operation.

For the SCR NOx reduction, a molar ratio of NH_3 to NOx of 1 at the SCR inlet represents a theoretical minimum NH_3 production requirement for complete NOx reduction due to the stoichiometry of the reaction. In practice, however, higher levels of NH_3 must be produced to account for NH_3 lost to oxidation [6]. The cumulative cycle molar ratio of NH_3 to NOx for the maximum lean operating strategy with rich λ=0.96 was 0.59 as shown in Figure 3.3, which clearly indicates that the approach of only substituting rich operation for stoichiometric points does not generate enough NH_3 to fully react with the incoming NOx. Insufficient NH_3 production and losses due to NH_3 slip resulted in an overall cycle NOx conversion of only 53.5 % with this simple strategy. The fuel efficiency benefit relative to stoichiometric-only operation was 8.6 %, which translates to 1 % fuel penalty associated for this modified approach, yet clearly further improvements are necessary.

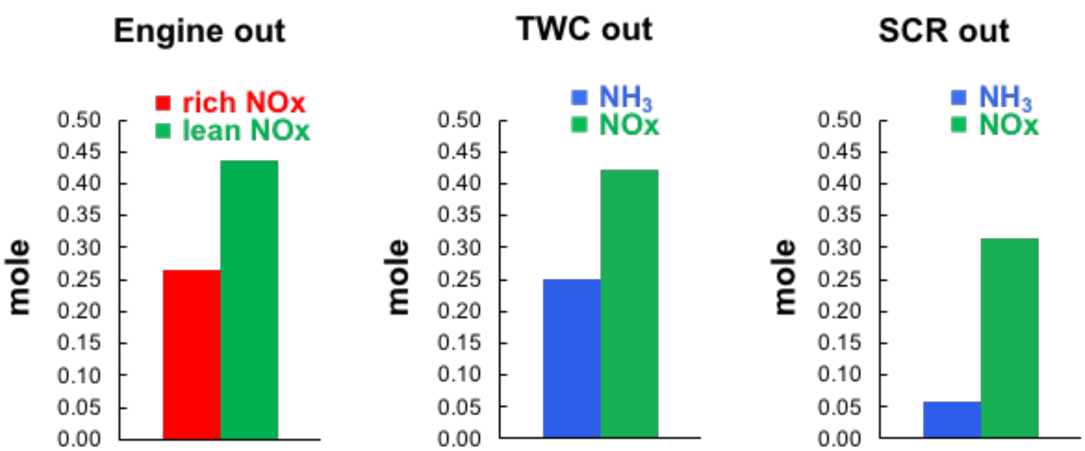

Figure 3.3 Cumulative NOx and NH_3 inventory during 6-mode pseudo-transient FTP cycle. Engine operated using maximum lean operating strategy with rich λ=0.96.

The TWC is very effective in converting all of the rich NOx to NH_3 at λ=0.96 as depicted by nearly identical levels of engine-out rich NOx and TWC effluent NH_3 in Figure 3.3, which also indicates that NH_3 formation is limited by the NOx availability at the TWC inlet. These results indicate that the passive SCR NOx control would benefit from increased engine-out NOx emissions during rich operation to enable higher TWC NH_3 production. Equally important is the reduction of engine-out NOx during lean operation as it would preserve SCR catalyst NH_3 inventory and potentially reduce the need for NH_3 generation. This can be accomplished by manipulating specific engine parameters to change combustion characteristics and instantaneous emissions [9] and/or modifying the engine fueling shift schedule to achieve the desired NH_3 production and NOx reduction targets. The latter is discussed further below. Another option for extending lean operation is the addition of NOx storage to the TWC [11]; this approach is not explored here, but is the focus of future work.

3.2. Reduced lean NOx operating strategy

The BMW lean gasoline engine utilized in this study enables two lean combustion modes: lean stratified and lean homogeneous, both of which are encountered during the pseudo-transient FTP cycle as shown in Figure 3.1. Lean stratified combustion is the leanest of the two with λ ranging from 1.6 to 2.2, and it offers greater fuel efficiency than lean homogenous combustion. While the lean homogeneous combustion mode offers moderate fuel efficiency benefits, it generates much higher NOx emissions compared to lean stratified operation, which in the context of the passive SCR approach leads to high NH_3 consumption rates. In the maximum lean operating strategy discussed in Section 3.1, the engine operated in lean homogeneous combustion mode 15 % of the total lean time, but it generated 53 % of the engine-out lean NOx emissions.

With the aim to reduce lean NOx emissions, the operating schedule shown in Figure 3.1 was modified to substitute the lean homogeneous operating points to rich; referred to as the reduced lean NOx operating strategy. These modifications resulted in significant reduction in engine-out NOx emissions during lean operation, while also increasing engine-out rich NOx as shown in Figure 3.4. Higher availability of rich NOx enabled higher TWC NH_3 production, while reduced lean NOx emission preserved the NH_3 inventory on the SCR catalyst. This resulted in an overall cycle NOx conversion of 92.4 %, a significant improvement as compared to 53.5 % using the maximum lean operating strategy. Since the fuel penalty associated depends on the fraction of time that the engine is running rich rather than lean, both more frequent rich excursions and reduced operation time in lean combustion mode resulted in a reduction in fuel efficiency benefit. Even so, a fuel efficiency benefit of 6.0 % was achieved with this strategy, which translates to fuel penalty of 3.6 %.

These results clearly show the trade-off between various combustion regimes, engine-out NOx emissions, and the fuel consumption requirements for rich excursions necessary to generate sufficient levels of NH_3 in order to reduce NOx emissions, which must be considered when selecting the appropriate engine operating strategy.

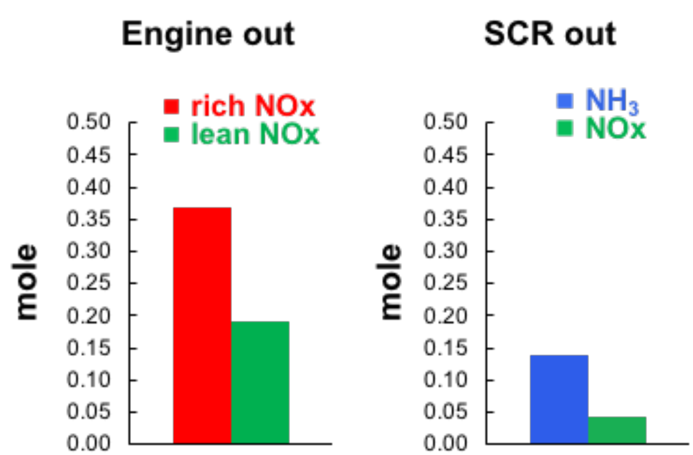

Figure 3.4 Cumulative NOx and NH_3 inventory during 6-mode pseudo-transient FTP cycle. Engine operated using reduced lean NOx operating strategy with rich λ=0.96.

3.3. Effects of rich λ on passive SCR performance

Air-fuel equivalence ratio (λ) and engine-out NOx emissions have a strong effect on NH_3 generation, with rich λ controlling how much of the engine-out NOx is converted to NH_3 in the TWC catalyst. The TWC converts the incoming NOx to a mixture of N_2 and NH_3, with higher selectivity to NH_3 with richer λs [7], but richer λs also increase CO and HC emissions and consume excess fuel, so a balance must be achieved to minimize emissions and maximize fuel economy.

To assess the effects of λ on the passive SCR emissions and fuel consumption, the reduced lean NOx operating strategy described in Section 3.2 was evaluated at different rich λs. As λ increases (less rich), NOx to NH_3 selectivity over the TWC decreases, thus less NH_3 is generated and available for NOx reduction by SCR, and higher tail-pipe NOx emissions and lower NH_3 slip results, as shown in Figure 3.5. As with other strategies, NH_3 slip occurs toward the end of the first acceleration event when the SCR temperature is too high and the NH_3 storage capacity decreases. As the amount of excess fuel decreases, CO and HC emissions also decrease with increasing λ, and, as expected, the fuel efficiency gain increases.

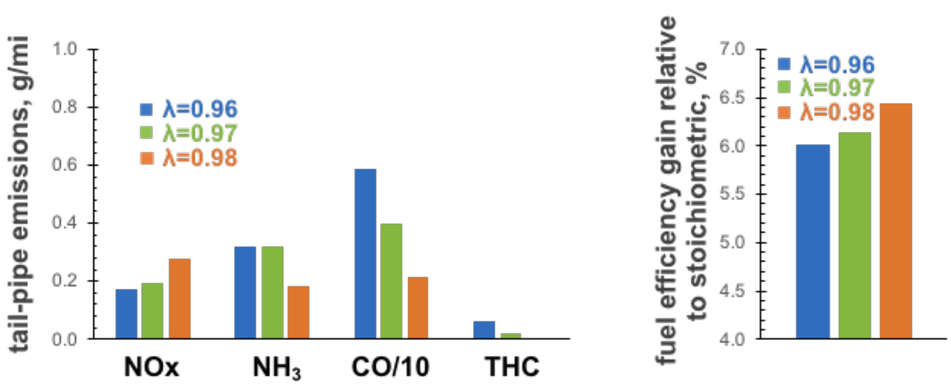

Figure 3.5 Effect of λ on emissions and fuel efficiency during 6-mode pseudo-transient FTP cycle. Engine operated using reduced lean NOx operating strategy.

The results shown in Figure 3.5 reveal the critical importance of rich λ in determining exhaust gas compositions. The observed trade-off between NH_3 selectivity, NOx reduction, CO and HC emissions, and fuel consumption can assist the development of the fueling shift schedule to provide high level of NOx reduction while also avoiding substantial amounts of CO, HC and NH_3 slip. The tail-pipe NOx emissions significantly exceeded the Tier 3 emissions target, 0.03 g/mi NOx+NMOG, when operating with a simple rich λ operating schedule. Based on the results presented thus far, a control strategy utilizing a direct feedback from the emissions and temperatures measurement was implemented on the engine controller to enable dynamic λ control to minimize NOx emissions. This strategy is discussed next.

3.4. Minimum NOx+HC strategy

A feedback control strategy with the dynamic λ control was implemented on the engine with the aim to maintain sufficient NH_3 coverage on the SCR catalyst to achieve high NOx reduction efficiency while minimizing NH_3 slip levels at the tail-pipe. This strategy, referred to as the minimum NOx+HC strategy, is based on the reduced lean NOx operating strategy and includes the following feedback control criteria:

- partially preload SCR to enable complete NOx reduction during the first 200 seconds of lean operation;
- operate $\lambda=0.97$ during rich phases of the cycle; but
- in order to minimize NH_3 slip, operate $\lambda=0.99$ during the first acceleration event when the SCR temperature becomes too high to store NH_3; and
- switch to rich operation if NOx slip at the tail-pipe exceeds the 10 ppm limit during the lean phase.

As shown in Figure 3.6, by employing the minimum NOx+HC strategy, NOx is essentially eliminated. Cycle average NOx conversion of 99.9 % is achieved with this strategy. The NH_3 slip is still observed but at much lower levels compared to other strategies. As with other strategies, NH_3 slip occurs toward the end of the first acceleration event when the SCR temperature is too high and the NH_3 storage capacity decreases, as shown in Figure 3.7. The NH_3 slip is an indication of a possible improvement in fuel efficiency and further optimization of the control strategy and catalyst system architecture requirements for effective NH_3 utilization over SCR catalyst.

The CO emission during rich operation are high and would still need to be addressed; one possible solution consists of a downstream clean-up catalyst with either significant oxygen storage/excellent WGS activity or secondary air injection to directly oxidize the CO. High THC conversion is observed during both lean and rich phases. The observed THC slip shown in Figure 3.7 primarily consists of methane (CH_4) and propane (C_3H_8) and occurs during prolonged lean operation. High THC reduction activity under rich operation suggest that the TWC formulation utilized in this study is very active for hydrocarbon steam reforming.

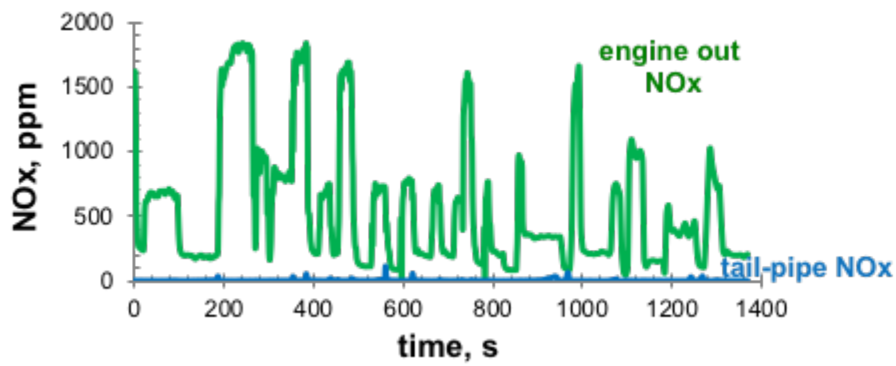

Figure 3.6 Emissions of NOx at the engine-out and tail-pipe (SCR outlet) sampling locations during 6-mode pseudo-transient FTP cycle with engine operating using minimum NOx+HC strategy.

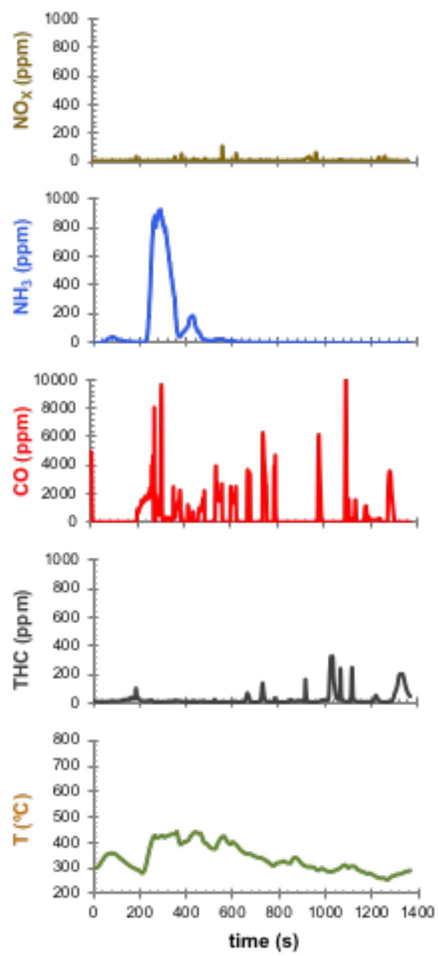

Figure 3.7 Emissions of NH_3, CO and THC at the tail-pipe (SCR outlet) sampling location along with the outlet temperatures during 6-mode pseudo-transient FTP cycle. Engine operated using minimum NOx+HC strategy.

To summarize the observed influence of the minimum NOx+HC strategy on the overall system performance, the cycle average emissions expressed in g/mi are plotted in Figure 3.8. The results demonstrate the ability to achieve cycle average NOx emissions of 0.003 g/mi (much lower than 0.03 g/mi NOx+NMOG Tier 3 Bin 30 standard) and a 5.9 % gain in fuel economy compared with the stoichiometric-only operation over the pseudo-transient FTP cycle. This is quite encouraging given that fact the control of NOx emissions from lean gasoline engines is a major technical barrier and is limiting introduction of fuel-efficient lean gasoline engines into the market. Furthermore, the combined NOx and non-methane hydrocarbons (NMHC) emissions are 0.018 g/mi, significantly below the 0.030 g/mi. Here, NMHC are calculated by subtracting methane measured by the FTIR from the THC measured by the HFID analyzer and assumed to approximately be similar in magnitude to the regulated non-methane organic gases (NMOG) [12]. Although methane does not count against hydrocarbon emissions, it is a greenhouse gas, and if its emissions levels are above 0.030 g/mi, it counts toward greenhouse gas emissions. The tail-pipe methane emissions were measured to be below the regulated cap at 0.014 g/mi at the tail-pipe. As noted above, CO emissions are considerably higher than is allowed, 2 g/mi or twice the EPA Tier 3 Bin 30 level, and thus more research is needed to further control CO emissions.

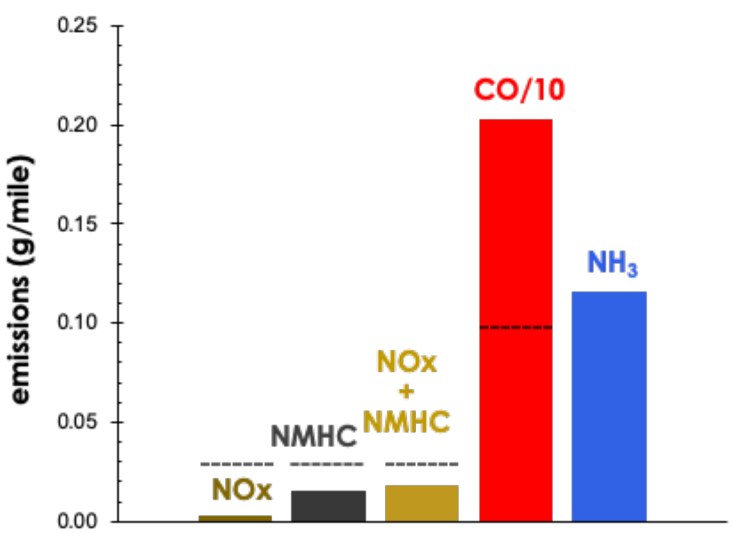

Figure 3.8 Cycle average emissions of NOx, CO, NMHC, NOx+NMHC and NH_3 at the tail-pipe (SCR outlet) sampling location during 6-mode pseudo-transient FTP cycle. Engine operated using minimum NOx+HC strategy. Tier 3 Bin 30 emissions limits are included for reference (dashed lines): 0.03 g/mi of NOx+NMOG and 1.0 g/mi of CO

4. Conclusions

This work has demonstrated that NOx emissions from a lean gasoline engine can effectively be controlled by a passive SCR approach utilizing NH_3 produced over a TWC to reduce NOx over a downstream SCR catalyst. Passive SCR enacted on a lean gasoline engine achieved 0.018 g/mi NOx + NMOG tailpipe emissions (below the EPA Tier 3 Bin 30 level of 0.030 g/mi) and a 6 % gain in fuel economy compared with the stoichiometric-only operation baseline over a pseudo-transient FTP drive cycle.

While a 5.9 % fuel economy benefit was observed for a lean gasoline engine employing passive SCR, more efficient NH_3 production can increase the fuel economy benefit. A potential approach to be considered is the addition of a NOx storage to the TWC. In the system studied here, TWC without NOx storage, the lean NOx and rich NOx, which is converted to NH_3, have to balance for the SCR reaction downstream. However, if NOx storage is included the lean timing can be extended, and by converting some of the stored NOx to NH_3 shorter rich times are needed to produce the required NH_3 levels. Both longer lean times and shorter rich times will potentially decrease the passive SCR fuel penalty [11]. This general approach is the focus of continuing research in this area.

Rich CO control and possibly lean HC remain challenging, but promising solutions are currently under investigation including a downstream clean-up catalyst with either significant oxygen storage, excellent WGS activity, or secondary air injection to directly oxidize the CO. The future work will focus on improving control strategies and utilizing additional catalyst technologies to maximize the fuel economy benefit of the lean gasoline engine while meeting EPA Tier 3 emission regulation levels.

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Conflict of Interest

On behalf of all authors the corresponding author states that there is no conflict of interest.

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