

Ammonia Generation over TWC for Passive SCR NO_x Control for Lean Gasoline Engines

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ABSTRACT

A commercial three-way catalyst (TWC) was evaluated for ammonia (NH₃) generation on a 2.0-liter BMW lean burn gasoline direct injection engine as a component in a passive ammonia selective catalytic reduction (SCR) system. The passive NH₃ SCR system is a potential low cost approach for controlling nitrogen oxides (NO_x) emissions from lean burn gasoline engines. In this system, NH₃ is generated over a close-coupled TWC during periodic slightly rich engine operation and subsequently stored on an underfloor SCR catalyst. Upon switching to lean, NO_x passes through the TWC and is reduced by the stored NH₃ on the SCR catalyst.

NH₃ generation was evaluated at different air-fuel equivalence ratios at multiple engine speed and load conditions. Near complete conversion of NO_x to NH₃ was achieved at $\lambda=0.96$ for nearly all conditions studied. At the $\lambda=0.96$ condition, HC emissions were relatively minimal, but CO emissions were significant. Operation at AFRs richer than $\lambda=0.96$ did not provide more NH₃ yield and led to higher HC and CO emissions. Results of the reductant conversion and consumption processes were used to calculate a representative fuel consumption of the engine operating with an "ideal" passive SCR system. The results show a 1-7% fuel economy benefit at various steady-state engine speed and load points relative to a stoichiometric engine operation.

CITATION: Prikhodko, V., Parks, J., Pihl, J., and Toops, T., "Ammonia Generation over TWC for Passive SCR NO_x Control for Lean Gasoline Engines," *SAE Int. J. Engines* 7(3):2014, doi:10.4271/2014-01-1505.

INTRODUCTION

Gasoline vehicles dominate the light duty vehicle fleet in the United States, which is also the largest sector of petroleum consumption in the U.S. [1]. Implementing fuel efficient technologies for gasoline vehicles can significantly reduce U.S. petroleum consumption and greenhouse gas emissions (CO₂). Recent advancements in fuel injection technologies in spark ignited (SI) gasoline engines have enabled gasoline engines to operate in a lean stratified charge combustion mode over extended engine operating range showing significant fuel economy gains compared to an engine operating at a stoichiometric air-to-fuel (AFR) ratio [2, 3]. Control of nitrogen oxides (NO_x) emissions in oxygen rich exhaust, however, is challenging and requires a different exhaust aftertreatment technology than the three-way catalyst (TWC) commonly found on a gasoline engine operating at stoichiometric AFR.

Two lean NO_x control catalyst technologies have been successfully employed in diesel vehicles in the U.S to meet stringent NO_x regulations: urea selective catalytic reduction (SCR) and lean NO_x trap (LNT) catalysts. Urea SCR relies on the selective reaction of NO_x with NH₃ under lean environment where NH₃ is generated from a rapid hydrolysis of on-board stored urea directly injected into the hot exhaust stream [4]. In

contrast, LNT requires periodic lean and rich operation. During lean operation (30-60 s), NO_x is stored on the catalyst in the form of nitrites and nitrates on an alkali or alkali earth components (e.g. Ba, K). As storage components become saturated, a short (3-5 s) rich excursion is employed to regenerate the NO_x storage components and reduce NO_x to N₂ [5]. Both of these technologies add significant cost and complexity to a vehicle. The urea SCR system, for example, requires a secondary tank for urea storage and an urea injection system. Although the LNT utilizes fuel from the vehicle instead of a secondary tank, the catalyst contains high precious metal loading resulting in high catalyst cost. In addition, LNTs are susceptible to sulfur poisoning that requires periodic high temperature regeneration leading to thermal degradation and additional fuel penalty. Despite these difficulties, urea SCR and LNTs have been commercialized to control NO_x from diesel vehicles.

Higher NO_x concentrations and exhaust temperatures in gasoline engines make adapting urea SCR and LNT technologies for NO_x control in lean gasoline applications challenging. For example, higher NO_x concentrations will require more frequent LNT regenerations resulting in increased fuel penalty. With urea SCR, higher NO_x concentrations will

require increased urea dosing, increasing the cost of operation of the system. An alternative approach, termed passive SCR, controls NO_x emissions from a gasoline engine operating in a fuel lean regime uses a close-coupled TWC and an underfloor SCR catalyst [6, 7, 8]. Ammonia is generated over the TWC during periodic slightly rich engine operation and subsequently stored on the SCR catalyst. Upon switching to lean combustion, NO_x passes through the TWC and is reduced by the stored NH_3 on the SCR catalyst. This approach eliminates or greatly reduces the need for urea dosing and avoids the addition of high cost, precious metal based catalysts. Thus, the approach is an attractive, low-cost and urea free option for controlling nitrogen oxide emissions from lean burn gasoline engines.

Successful implementation of the passive SCR approach highly depends on the selective generation of NH_3 over the TWC. Ammonia generation over a precious metal containing catalyst is well documented in the literature [9, 10, 11, 12]; however, for a typical gasoline vehicle operating in a stoichiometric mode the focus was to minimize ammonia production. A recent bench flow reactor study by Pihl et al. details the dependence of NH_3 production over a TWC on air-to-fuel ratio, temperature and catalyst formulation [13, 14]. This study builds on the bench flow work by Pihl et al. and focuses on evaluation of a commercial TWC for ammonia generation under realistic exhaust conditions from a 2.0-liter BMW lean burn gasoline direct injection engine.

EXPERIMENTAL SETUP

Engine Platform

The lean burn gasoline direct injection engine used in this study is from a European Model Year (MY) 2008 BMW 1-series 120i (E87) vehicle. The model N43B20 4-cylinder 2.0-liter direct injection gasoline engine is naturally aspirated. The engine has a rated power of 125 kW at 6700 rpm and a torque of 210 Nm at 4250 rpm. Table 1 summarizes engine specifications. The engine was coupled to a motoring direct current (DC) dynamometer to control engine speed and load.

Table 1. BMW 2.0-liter lean burn gasoline direct injection engine configuration.

Displaced volume	1995 cc
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 uses a spray guided combustion system design. In this design, the piezoelectric injector is located at the top center of the combustion chamber with a spark plug in a close proximity to the injector allowing fuel ignition as the fuel being injected which, unlike the other two combustion systems (wall directed and air directed combustion systems), results in shorter mixture formation time [2]. With shorter mixture formation time, lean engine operation time can be extended to higher speeds and loads resulting in additional fuel savings.

In this engine, lean stratified operation is calibrated to operate up to 4500 rpm and 55% load as shown in Figure 1. In the adjacent region (55-75% load), the engine operates in a lean homogeneous with additional stratification (referred to as lean homogeneous in this manuscript) combustion mode. Outside the lean operation range, at high engine speeds and loads, the engine operates in a stoichiometric homogeneous combustion mode. However, when desirable, the engine can also operate in the stoichiometric mode over the entire operating range. In addition to these three main combustion modes, the engine has a calibration for homogeneous rich operation that is employed for regeneration of the LNT in the European BMW 120i vehicle to meet EURO V NO_x emission standards.

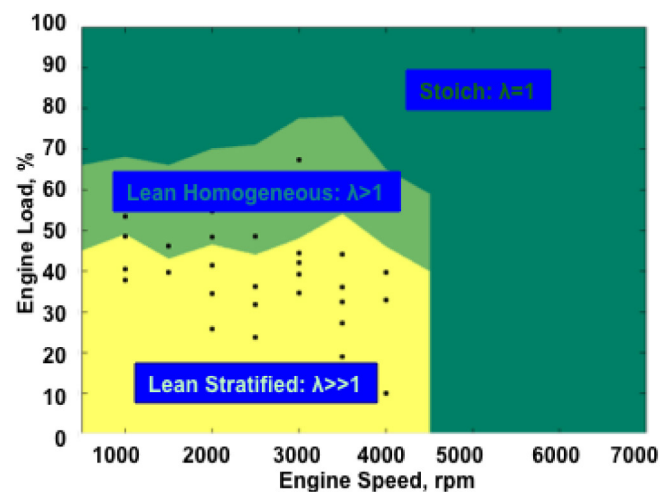


Figure 1. BMW engine main operation modes: lean stratified, lean homogeneous with addition stratification and homogeneous stoichiometric.

Combustion Mode Characteristics

Lean Stratified

In the lean stratified combustion mode, the fuel is injected late in the compression stroke close to top dead center (TDC), as shown in Figure 2, creating an ignitable mixture at the tip of the spark plug, the rest of the combustion chamber is very lean, non ignitable. The injections are followed by multiple spark events likely to insure ignition. The overall air-fuel equivalence ratio (λ , ratio of actual to stoichiometric air-to-fuel ratio) in the lean stratified mode ranges from 1.9 to 2.2.

Lean Homogeneous

At higher loads (55-75%) more fuel is delivered to meet the torque requirement, putting stratified charge operation outside the combustion limits. In this case a lean homogeneous combustion mode with additional stratification is employed. In the lean homogeneous combustion mode, a portion of the fuel is injected during the intake stroke creating a well mixed lean homogeneous mixture. Additional fuel is injected late at the compression stroke followed by multiple spark events (Figure 2). The overall λ ratio in the lean homogeneous mode ranges from 1.3 to 1.7.

Stoichiometric Homogeneous

At higher speeds and loads, the engine operates in the stoichiometric combustion mode with $\lambda=1$. A portion of the fuel is injected during the intake stroke and a second smaller injection occurs early in the compression stroke creating a well mixed homogeneous mixture. A single spark event occurs close to TDC (Figure 2).

Rich Homogeneous

The calibration for the rich combustion mode on this engine is based on the original equipment manufacturer (OEM) strategy for LNT control of NO_x emission to meet EURO V NO_x emission standards. It is very similar to the stoichiometric mode but with an additional injection during the intake stroke, totaling to three injections: two during the intake stroke and one during the compression stroke, followed by a single spark event. The overall λ ratio ranges between 0.75 and 0.9.

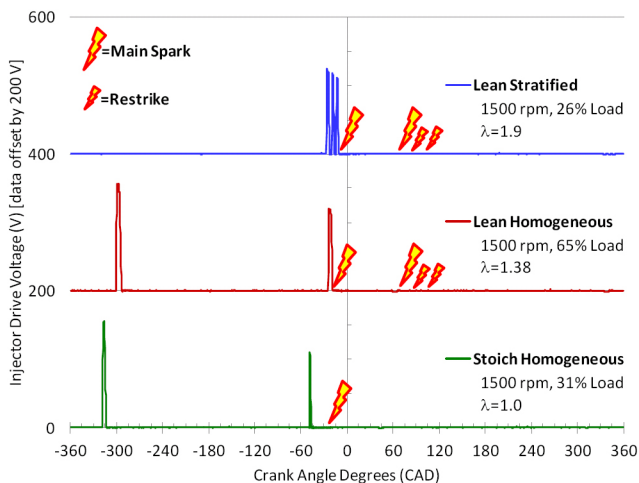


Figure 2. BMW engine injection and spark events for the three main operation modes: lean stratified, lean homogeneous with addition stratification and homogeneous stoichiometric.

Engine Controller

The factory engine control unit was replaced with a custom full-pass control system developed by National Instruments - Powertrain Controls Group. The controller mimics the OEM combustion strategies and, furthermore, enables full control of all engine parameters including manual control of injections, sparks, air-to-fuel ratio and combustion modes of operation.

The control of the air-fuel equivalence ratio was based on the feedback from the universal exhaust gas oxygen (UEGO) sensors that were mounted on the custom exhaust manifold at each of the cylinder exhaust runners. This control strategy allowed overcoming combustion instability issues that were present due to variation in injector calibrations.

Catalyst

A 1.3L commercial TWC catalyst was used in this study from a PZEV 2009 Chevy Malibu. It is a single monolith with a dual zone catalyst formulation as shown in Figure 3. The front 0.6-liter portion of the catalyst contained higher precious metal loading (7.33 g) compared to the rear portion (1.44 g). The catalyst properties are summarized in Table 2. The catalyst was degreened on the engine for at least twenty hours at temperatures ranging between 650 and 750°C prior to the evaluation.

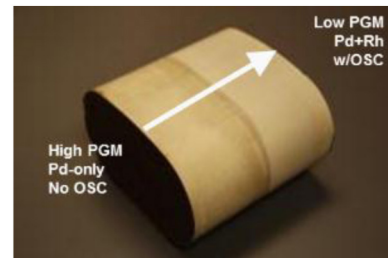


Figure 3. TWC with dual zone catalyst formulation

Table 2. TWC details

	Volume (liter)	Pt/Pd/Rh Loading (g/liter)	Oxygen Storage Component
Front Half	0.6	0.00/7.33/0.00	No
Back Half	0.7	0.00/1.14/0.30	Yes
Total	1.3	0.00/4.00/0.16	Yes

Fuel

The gasoline fuel used in the study was EEE-Lube Cert Gasoline containing no ethanol. Key fuel specifications are shown in Table 3.

Table 3. Fuel specifications for EEE-Lube Cert Gasoline Fuel

Lower Heating Value	42880 (kJ/kg)
Density	0.741 (kg/liter)
C	0.8632 (weight %)
H	0.1328 (weight %)
Oxygen	0.0 (weight %)
Sulfur	7 (mg/kg)
Research Octane Number (RON)	97.0
Motor Octane Number (MON)	88.7