

Lean Gasoline Engine Reductant Chemistry During Lean NO_x Trap Regeneration

2010-01-2267

Published
10/25/2010

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ABSTRACT

Lean NO_x Trap (LNT) catalysts can effectively reduce NO_x from lean engine exhaust. Significant research for LNTs in diesel engine applications has been performed and has led to commercialization of the technology. For lean gasoline engine applications, advanced direct injection engines have led to a renewed interest in the potential for lean gasoline vehicles and, thereby, a renewed demand for lean NO_x control. To understand the gasoline-based reductant chemistry during regeneration, a BMW lean gasoline vehicle has been studied on a chassis dynamometer. Exhaust samples were collected and analyzed for key reductant species such as H₂, CO, NH₃, and hydrocarbons during transient drive cycles. The relation of the reductant species to LNT performance will be discussed. Furthermore, the challenges of NO_x storage in the lean gasoline application are reviewed.

INTRODUCTION

Engines that operate at lean air-to-fuel ratios ("lean engines") offer the potential to reduce fuel consumption and, thereby, lower greenhouse gas emissions.[1] A difficult problem to address when commercializing vehicles with lean engines is the control of oxides of nitrogen (NO_x) emissions. For stoichiometric combustion, the three-way catalyst technology commonly found on gasoline-engine vehicles controls emissions of NO_x as well as carbon monoxide (CO) and hydrocarbon (HC) emissions; however, the three-way function is only effective in the low-oxygen exhaust conditions associated with stoichiometric combustion. Lean combustion results in oxygen-rich exhaust where the reduction of NO_x is difficult.

Recently, diesel engine vehicles have been commercialized for the U.S. market that meet NO_x emissions regulations by employing catalysts for lean NO_x control.[2] Two catalytic approaches have been used: urea-based selective catalytic reduction (urea-SCR) and lean NO_x trap (LNT) catalysts. The urea-SCR approach requires the on-board storage of urea which is introduced into the exhaust upstream of the SCR catalyst, converted to NH₃ via hydrolysis reactions, and interacts with NO_x on the SCR catalyst. In contrast, the LNT technology utilizes fuel from the vehicle and advanced engine controls to enable periodic operation of the engine at rich air-to-fuel ratios which produces oxygen-depleted exhaust suitable for reducing NO_x stored on the LNT catalyst surface. Both technical approaches have been proven effective in controlling NO_x from diesel engines.

Despite the commercialization of diesel vehicles in the U.S. with lean NO_x control, the U.S. passenger market is dominated by gasoline-engine vehicles. Gasoline engines can be operated lean, and direct injection gasoline engines show promise for significant fuel economy gains from lean operation. However, gasoline engines do not typically operate as lean as diesel engines, and portions of the load and speed map would likely be handled with stoichiometric operation. Thus, NO_x control for lean gasoline engines would be required for both lean and stoichiometric conditions. The ability to operate gasoline engines with a wide range of air-to-fuel ratios offers advantages for the LNT catalyst approach for controlling NO_x emissions since LNTs require rich air-to-fuel operation for reducing the NO_x stored during lean operation. In this study, a lean gasoline engine in a BMW vehicle has been studied on a chassis dynamometer to evaluate the exhaust conditions during lean and rich air-to-fuel operation to better understand the chemistry of lean gasoline engine exhaust as related to the LNT technology.

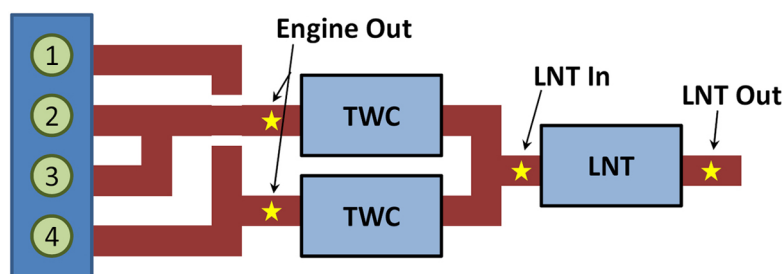


Figure 1. Schematic of BMW 120i exhaust system; yellow stars note exhaust sample positions.

EXPERIMENTAL METHODS

Experiments were conducted on a MY2008 BMW 1-series 120i lean gasoline engine vehicle. The engine was a model N43B20 2.0-liter, 4-cylinder engine with direct injection. The vehicle was operated on a chassis dynamometer with ultra-low sulfur certification gasoline fuel. The vehicle had previously accumulated sufficient mileage during use to degreen the catalysts.

The vehicle's exhaust system is composed of two three-way catalysts (TWCs) which were located in two exhaust manifolds (one for each pair of cylinders: 1-4 and 2-3) close coupled to the engine. Downstream of the merge point for the two exhaust manifolds, the LNT was located in an underfloor position. The muffler was located downstream of the LNT, and the tailpipe was connected to the dilution system of the chassis dynamometer emissions measurement system.

Several transient drive cycles were driven with the vehicle; the drive cycles included: US Federal Test Procedure-75 (FTP), US06 Supplemental Federal Test Procedure (US06), and Highway Fuel Economy Test (HFET). In addition to the transient drive cycle operation, the vehicle was operated at various speed and load conditions at near steady-state conditions for the purpose of collecting emissions data. During the steady-state operation, the vehicle speed remained constant and the vehicle load was changed in a stepwise fashion.

Emissions from the engine and the subsequent catalytic-induced emissions changes were measured with a variety of analytical techniques. Two sets of emission analyzers were used to measure engine out emissions upstream of the TWCs from exhaust pulled from each manifold. The emission analyzers included: heated chemiluminescence for NO_x (California Analytical Instruments Model 400), non-dispersive infrared for CO and CO₂ and paramagnetic for O₂ (all three gases covered by California Analytical Instruments Model 300) on chilled exhaust, and heated flame ionization detector for hydrocarbons (California Analytical Instruments Model HFID). Another set of the same instruments (with different scale ranges) were used to characterize tailpipe emissions diluted by the dilution tunnel. Detailed

measurements relative to the LNT regeneration were made with a FTIR (MKS Multi Gas 2030HS) and a capillary-based magnetic-sector mass spectrometry technique called SpaciMS.[3] The FTIR and SpaciMS measurements were primarily made in exhaust downstream of the TWCs and upstream of the LNT; however, some measurements were also made at engine out and tailpipe positions. The FTIR allowed measurement of NO, NO₂, NH₃, N₂O, CO, CO₂, and hydrocarbons. To complement the FTIR data, the SpaciMS was configured to measure H₂ and O₂. In addition to the exhaust analyzers, thermocouples and universal exhaust gas oxygen (UEGO) sensors were mounted at various positions in the exhaust as well.

The average of the two UEGO sensors mounted in the engine out positions of both exhaust manifolds served as the master timing signal for aligning the data from the analyzers. Since various analyzers have different delay times in exhaust transfer and measurement, a common signal was needed to time align measurements of exhaust species from different analyzers. The UEGO air-to-fuel signal was converted to exhaust concentrations for O₂, CO₂, and H₂O using a simple model based on the fuel hydrogen to carbon ratio of 1.837. Then the O₂, CO₂, and H₂O signals were matched to appropriate signals for analyzers to achieve time alignment.

RESULTS AND DISCUSSION

DRIVE CYCLE FUEL ECONOMY AND EMISSIONS

The benefits of lean operation on vehicle fuel economy were characterized by comparing vehicle performance over drive cycles with stoichiometric only and lean plus stoichiometric operation. The default operation of the vehicle is to operate lean at low loads and speeds and operate with stoichiometric combustion at higher loads and speeds. There are also two other fuel savings technologies employed by the vehicle: start-stop operation and an intelligent alternator that allows for micro hybridization. Based on information from the OEM service manual, these fuel saving technologies were turned off for the experiments presented here by manually shorting or bypassing sensors that control those functionalities. Stoichiometric only operation was more challenging to

Table 1. Fuel Economy as a Function of Vehicle Mode and Drive Cycle

Drive Cycle	Stoichiometric Only Operation	Lean and Stoichiometric Operation	Fuel Economy Improvement from Lean Operation
FTP	26.8 mpg	29.5 mpg	10.0%
HFET	40.5 mpg	46.4 mpg	14.6%
US06	30.2 mpg	31.6 mpg	4.4%

Table 2. NO_x Emissions in g/mile as a Function of Vehicle Mode and Drive Cycle

Drive Cycle	Stoichiometric Only Operation	Lean and Stoichiometric Operation
FTP	0.03 g/mile NO _x	0.11 g/mile NO _x
HFET	0.00 g/mile NO _x	0.11 g/mile NO _x
US06	0.03 g/mile NO _x	0.35 g/mile NO _x

implement but was performed during cases where the vehicle was locked in stoichiometric mode. Thus, drive cycles were conducted with and without lean operation to define the benefit of lean combustion. Fuel economy results from three different drive cycles are shown in [Table 1](#). For all three drive cycles, the fuel economy with lean operation was better than for stoichiometric only operation; however, the amount of improvement was dependent on the drive cycle with the lowest improvement occurring for the most aggressive drive cycle (US06) which relied more on stoichiometric operation for the more aggressive accelerations. Overall, fuel economy improvements of 4-15% were observed.

While fuel economy improved with lean operation, the NO_x emissions became worse with the addition of lean operation. [Table 2](#) summarizes the tailpipe NO_x emissions on a g/mile basis for the same data shown in [Table 1](#). The increase in NO_x emissions is quite notable for lean operation with the highest NO_x emissions being observed for the most aggressive driving cycle (US06). All NO_x emissions from lean plus stoichiometric operation were found to be above the 0.05 g/mile NO_x level associated with the U.S. Tier II Bin 5 (at 50,000 miles) regulation. While this vehicle is not sold in the U.S. and was not designed to meet the U.S. emissions, the emissions relative to this regulation highlight the need for emissions reduction for the lean gasoline engine technology. Note that the values are rounded to the nearest hundredths of g/mile emissions.

LNT STORAGE AND REGENERATION CONDITIONS

During steady-state operation of the vehicle, data was acquired to understand the exhaust conditions experienced by

the LNT catalyst. At lower loads, the engine operated at lean air-to-fuel ratios (AFR) with periodic operation at rich AFR for the purpose of regenerating the LNT. At higher engine loads (>60%), the engine operated at stoichiometric AFR. [Figure 2](#) shows the average engine out AFR recorded by the two UEGO sensors in the exhaust manifold upstream of the TWC. The AFR plot is bifurcated with lean-rich cycling operation below 60% engine load and stoichiometric operation above 60% engine load. The engine speed did not affect the controlled AFR. LNT regeneration was performed at an AFR of 12 consistently over the load range; however, during lean operation the AFR varied with engine load and spanned from 19-28 with the lower AFRs occurring at higher loads.

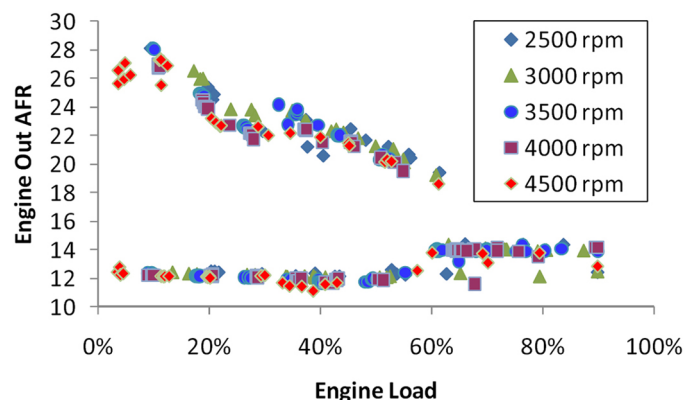


Figure 2. Air-to-fuel ratio as a function of load for different engine speeds.

Temperatures in the exhaust system varied as expected with AFR. Under lean conditions, the engine out exhaust generally