Original Article

Institution of MECHANICAL ENGINEERS
Journal of AUTOMOBILE ENGINEERING

Proc IMechE Part D:
J Automobile Engineering
227(3) 400–408

DOI: 10.1177/0954407012457900
pid.sagepub.com
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Lean NO_x trap supplemental energy savings with a long breathing strategy

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Abstract

Current and upcoming diesel engine emission regulations in the USA and in Europe stipulate significant reductions of nitrogen oxide emissions. To satisfy these emission regulations and to maintain high fuel efficiency, energy efficient diesel after-treatment to remove nitrogen oxides is required. In this study, a long breathing (long adsorption) strategy was investigated for the reduction of supplemental energy consumption of a diesel lean nitrogen oxide trap. The long breathing strategy would be enabled by moderate exhaust gas recirculation to reduce the engine-out nitrogen oxide levels. With reduced feed gas nitrogen oxide levels, the adsorption time of the lean nitrogen oxide trap could be extended, leading to less frequent fuel-rich regeneration of the lean nitrogen oxide trap. Proof of concept studies were undertaken on a diesel engine to demonstrate the enabling of the long breathing lean nitrogen oxide trap strategy, while further tests were undertaken on a flow bench set-up to demonstrate the potential energy savings with the long breathing lean nitrogen oxide trap strategy. The test results indicated that, at the selected operating conditions, the long breathing strategy could be enabled by reducing the engine-out nitrogen oxide from 110 ppm to 50 ppm via moderate exhaust gas recirculation. The flow bench test results indicated that the adsorption time of the lean nitrogen oxide trap increased exponentially when the feed gas nitrogen oxide level was reduced. The longer adsorption led to supplemental energy savings in excess of 60% when the feed gas nitrogen oxide level was reduced from 110 ppm to 50 ppm. Furthermore, it was calculated that the long breathing lean nitrogen oxide trap strategy enabled a higher overall indicated efficiency of 36.4% compared to 35.9% with a conventional lean nitrogen oxide trap strategy.

Keywords

Long breathing, lean NO_x trap, diesel engine, after-treatment, exhaust flow control, NO_x reduction

Date received: 17 February 2012; accepted: 18 July 2012

Introduction

Lean burn diesel engines provide improved fuel efficiency compared to similarly-sized stoichiometric gasoline counterparts.[1] However, diesel engines tend to have higher tailpipe nitrogen oxide (NO_x) emissions than gasoline engines with three-way catalytic converters. Increasing concerns about the impacts of NO_x on human health and environmental sustainability have led governing bodies to impose continually stringent vehicle NO_x emission regulations.[2,3] For example, in the on-highway heavy duty diesel sector, the United States Environmental Protection Agency (EPA) has imposed 97% reductions in NO_x emissions from model year (MY) 1988 vehicles to MY 2010 vehicles.[4] To satisfy the current NO_x emission regulations on diesel vehicles, advanced in-cylinder combustion control strategies, such as exhaust gas recirculation (EGR)[5,6] and the use of alternate fuels,[7,8] have been developed and used in production engines. Nevertheless, after-treatment solutions[9–12] are inevitable to meet the EPA NO_x emission regulations for heavy duty on-highway diesel at all engine load levels.

The two leading de- NO_x after-treatment strategies are the lean NO_x trap (LNT) and selective catalytic reduction (SCR); both offer high NO_x conversion efficiencies over relatively wide exhaust temperature ranges.[13–15] SCR systems require the use of urea to generate ammonia on-board a vehicle to reduce NO_x.[16] Urea fluid is not traditionally found on-board a vehicle. Thus, SCR systems are faced with challenges related to on-board urea storage, urea distribution, and

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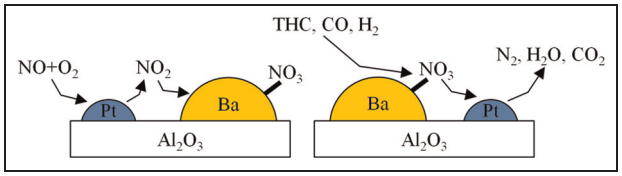

Figure 1. An example of NO_x adsorption (left) and reduction (right) mechanisms (adapted from Hachisuka et al.[19]).

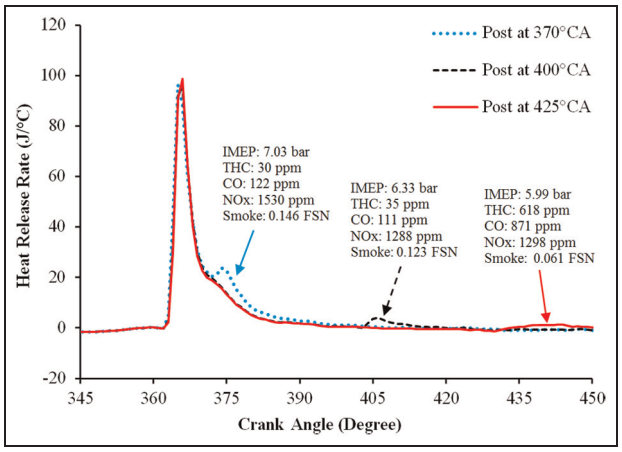

Figure 2. Post-injection heat release curves (see Table 1 for engine details).

implementation and control of urea dosing into the exhaust stream. On the other hand, LNTs offer simpler system design by utilizing the total hydrocarbons (THC), carbon monoxide (CO),and hydrogen to reduce NO_x. These three reductants are readily found in diesel exhaust or can be generated on-board the vehicle through supplemental fuel injection.

Lean NO_x traps operate on alternating cycles of fuel-lean and fuel-rich exhaust gas conditions. The typical lean cycle duration is of the order of one minute while the rich cycle is of the order of about ten seconds.[17,18] During typical diesel fuel-lean exhaust gas conditions, the LNT functions as a NO_x adsorber. Under lean conditions, nitric oxide (NO) must first be oxidized to nitrogen dioxide (NO_2), as shown in equation (1) and Figure 1, while exhaust nitrogen dioxide can be directly adsorbed onto the LNT catalyst surface by reacting with an alkaline oxide, such as barium oxide (BaO), to form a nitrate, as indicated by equation (2). Initially, the NO_x storage efficiency is high but with time the NO_x storage efficiency declines due to the saturation of available BaO sites with nitrates. Thus, there is a need to purge the nitrates out of the LNT by decomposing and reducing them to substances such as nitrogen or by-products such as nitrous oxide (N_2O) or ammonia (NH_3)

$$2NO + O_2 \xrightarrow{Pt} 2NO_2 \quad (1)$$

$$3NO_2 + BaO \rightarrow Ba(NO_3)_2 + NO \quad (2)$$

The LNT purge is generally accomplished by temporarily providing a fuel-rich exhaust stream. Under fuel-rich conditions, the nitrates are released from the storage sites and converted to nitrogen. LNT regeneration is a complex chemical process consisting of numerous reactions but the main reactions are shown in equations (3) to (6) using propene (C_3H_6) as a representative hydrocarbon.[20] More detailed NO_x storage and purge kinetic models are available.[20,21] The fuel-rich exhaust stream is generated either through late in-cylinder post-injection or through supplemental fuel injection directly into the exhaust stream.[17,18] Late in-cylinder post-injections can generate high exhaust hydrocarbon and carbon monoxide levels suitable for LNT regeneration but generate less useful work than if the same fuel was injected closer to top dead center, as indicated by the heat release curves in Figure 2. Supplemental fuel injection into the exhaust stream increases the exhaust hydrocarbon concentration but it does not contribute to any power production. Thus, with fuel-rich regeneration, the LNT consumes fuel which contributes very little or not at all to power production and can be considered as a fuel consumption penalty

$$C_3H_6 + 3H_2O \rightarrow 3CO + 6H_2 \quad (3)$$

$$9Ba(NO_3)_2 + 5C_3H_6 \rightarrow 9N_2 + 15CO_2 + 15H_2O + 9BaO \quad (4)$$

$$Ba(NO_3)_2 + 5CO \rightarrow N_2 + 5CO_2 + BaO \quad (5)$$

$$Ba(NO_3)_2 + 5H_2 \rightarrow N_2 + 5H_2O + BaO \quad (6)$$

In addition to hydrocarbons, hydrogen and carbon monoxide can be used as NO_x reductants. Several studies have investigated the effects of hydrogen and carbon monoxide on the LNT regeneration and desulfation processes.[22,23] It was found[22] that the LNT desulfation process benefited from the use of exhaust hydrogen. It was noticed[22] that desulfation was most effective when either water or hydrogen were present; water being capable of generating hydrogen via the water gas shift reaction. Other studies[23] showed that the LNT region with the highest hydrogen depletion coincided with the LNT region with the highest NO_x reduction. The effects of carbon monoxide and hydrogen on NO_x reduction were studied by Choi et al.[24] It was observed that at a temperature of 300°C the NO_x conversion efficiency was nearly the same regardless of the reductant used (hydrogen, carbon monoxide, or a hydrogen/carbon monoxide mixture). Thus, carbon monoxide was shown to be a relatively potent NO_x reduction agent. However, when the temperature was reduced to 200°C, hydrogen was observed to be the superior reductant. Although carbon monoxide and hydrogen are generally considered as good NO_x reductants, the concentration of each in the oxygen-rich exhaust of traditional diesel combustion engines are not high enough for complete

LNT regeneration. Thus, additional fuel must be injected through late post-injection or directly into the exhaust stream to provide additional hydrocarbons. The supplemental fuel can be used as a source of hydrocarbons or for fuel reforming to produce carbon monoxide and hydrogen via reaction mechanisms such as partial oxidation or steam reforming.[25]

The purpose of this study was to investigate, as a proof of concept, the potential LNT supplemental energy reduction by utilizing a long breathing adsorption strategy. Compared to conventional LNTs, a long breathing lean NO_x trap utilizes longer adsorption (breathing) cycles, thereby reducing the frequency of the fuel-rich regeneration cycle and decreasing the fuel consumption penalty of the LNT. Thus, flow bench studies were done to investigate and quantify the potential energy savings of the long breathing strategy. The motivation for this work originated from the reality that modern diesel engines typically incur fuel penalties due to the application of emission reduction techniques[18,26] and are thus less fuel efficient than traditional diesel engines, which could be calibrated to run at optimum efficiency without concern for emission reduction.

Enabling the long breathing strategy

The operation of a long breathing LNT has to be enabled by in-cylinder strategies to lower the exhaust gas concentration of NO_x. It was hypothesized that reducing the exhaust gas NO_x concentration would allow a prolonged adsorption cycle of the LNT. Extending the adsorption cycle would lead to less frequent use of supplemental fuel for LNT regeneration, thereby reducing the fuel consumption of the LNT. This study investigated the relationship between NO_x exposure and LNT adsorption time, and attempted to quantify how long the lean adsorption period could be extended by applying a long breathing strategy.

To demonstrate an example of a suitable condition for long breathing lean NO_x trap application, engine tests were undertaken at the Clean Diesel Engine Laboratory (University of Windsor, Ontario). The specifications of the engine are given in Table 1. An EGR sweep was done at a constant indicated mean effective pressure (IMEP) of 4.3 bar, a constant engine speed of 1500 r/min, a constant intake pressure and a constant fuel injection pressure. The test results are shown in Figures 3 and 4. The results showed that EGR was an effective method for reducing engine-out NO_x emissions. Utilizing EGR to reduce the intake oxygen concentration to less than 14% reduced the NO_x emissions below the EPA's on-highway heavy duty NO_x emission requirement. However, it was also noticed that hydrocarbon emissions increased rapidly when the intake oxygen concentration was reduced below 14%, indicating deteriorating fuel efficiency.

Suitable zones for the existing NO_x reduction strategies, low temperature combustion (LTC) and conventional LNT after-treatment, are indicated in Figures 3 and 4. In the LTC zone, both the NO_x and the smoke emissions were below the EPA heavy duty limits, but the THC emissions were at their peak, indicating relatively poor fuel efficiency. In the conventional after-treatment zone, Figures 3 and 4 show that the THC and smoke emissions were at a minimum. However, additional fuel would be frequently consumed to regenerate the LNT due to a relatively short adsorption cycle, because the NO_x emissions were at their highest

Table 1. Characteristics of the test engine.

Engine specifications	
Engine model	Four-stroke four-cylinder diesel
Compression ratio	18.2:1
Bore	86 mm
Stroke	86 mm
Fuel injection system	Diesel common-rail direct injection
Maximum fuel injection pressure	160 MPa

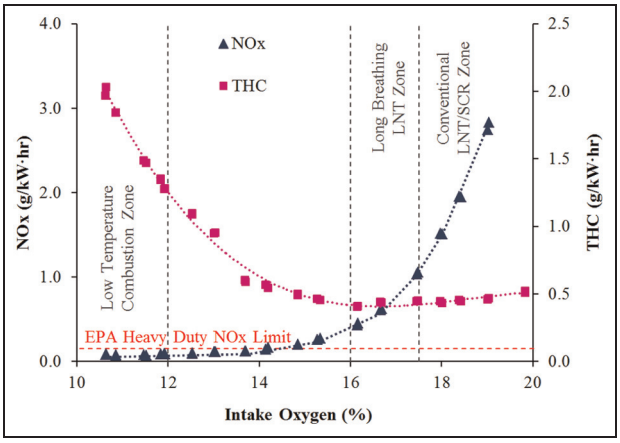

Figure 3. Effect of EGR on NO_x and THC engine-out emissions.

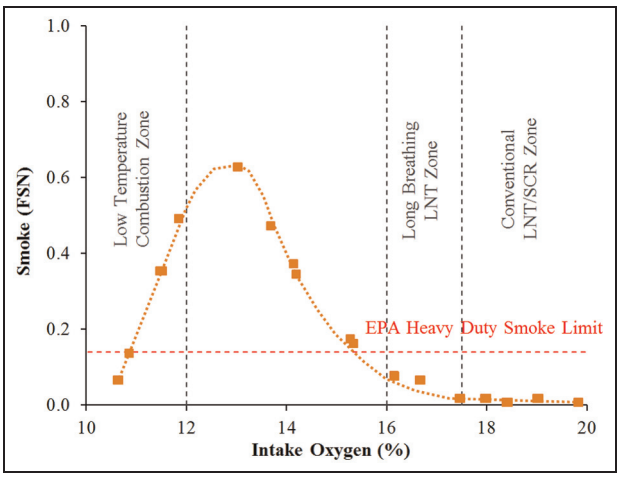

Figure 4. Effect of EGR on smoke engine-out emissions.

Table 2. Characteristics of different intake oxygen zones.

Oxygen concentration (%)	Zone	NO_x	THC	Smoke	After-treatment
> 17.5%	Conventional LNT	High	Low	Low	Yes
16–17.5%	Long breathing LNT	Moderate	Low	Moderate	Yes
12–16%	Transition	Low	Moderate	High	Yes
< 12%	Low temperature combustion	Low	High	Low	No

in the conventional after-treatment zone. Thus, a long breathing LNT zone was proposed, as shown in Figure 3.

In the long breathing zone, the NO_x emissions were much lower than in the conventional LNT zone but not quite low enough to meet the EPA heavy duty emission standard without after-treatment. The smoke emissions were relatively low, as shown in Figure 4. The hydrocarbon emissions were also quite low in the long breathing zone and although additional fuel would be required to regenerate the LNT, it was hypothesized that the additional fuel would be supplied less frequently than with conventional after-treatment due to the much lower engine-out NO_x emissions, as shown in Figure 3. A summary of the different NO_x reduction strategies is given in Table 2. Due to the potential for reduced supplemental fuel consumption, it was decided to investigate the effect of feed gas NO_x concentration on the LNT adsorption duration.

Experimental set-up

The long breathing LNT tests were done on the flow bench set-up shown in Figure 5. The feed gas constituents were provided from a compressed air supply available at the facility and various Praxair bottled cylinders. Various levels of NO_x, consisting of over 98% NO, were used in the feed gas to study the effects of NO_x concentration on the LNT adsorption time. In addition to NO_x, the feed gas was composed of 8.5% carbon dioxide, 6% water and balance air. The simulated exhaust in the flow bench tests did not include exhaust particulates. At this NO_x level at the corresponding engine conditions shown in Figure 4, the exhaust smoke level was relatively low, below the EPA's heavy duty limit, and it was assumed that a DPF upstream of the LNT would very likely filter out the exhaust particulates before they reach the LNT. However, the presence of particulates in the exhaust could be detrimental to the LNT NO_x storage capacity according to the study by Artioli et al.[27] During the regeneration, nitrogen gas and fuel were added to the feed gas to create the necessary fuel-rich conditions. A series of pressure regulators were used to provide a stable flow rate. The feed gas flow rate was measured, upstream of the flow bench heater, by a Bosch mass air flow sensor. The flow bench heater was capable of heating the feed gas to stable temperatures up to 450°C. Water and fuel were injected downstream of the flow bench heater at a 4 bar injection pressure. Upstream of the LNT, a diesel oxidation catalyst (DOC) was used to help oxidize NO to NO_2 during the fuel-lean NO_x storage cycle, and to help convert hydrocarbons to hydrogen and carbon monoxide, generally considered as more potent reductants than hydrocarbons, during the fuel-rich regeneration cycle. An NGK NTK 22010 oxygen sensor was installed upstream of the LNT to determine if the feed gas was rich or lean. The LNT was an Umicore LNT catalyst coated on an NGK honeycomb monolith substrate with 400 cpsi. The diameter of the LNT was 54 mm and the length was 152 mm. The LNT was coated with a combined platinum/rhodium catalyst. It should be mentioned that this LNT was designed for conventional after-treatment use and that the catalyst was not optimized for use in a long-breathing LNT.

Gas sampling was done upstream and downstream of the LNT via a set of California Analytical Instruments (CAI) analyzer benches. Upstream of the LNT, the NO_x, the carbon dioxide, and the oxygen concentrations were measured by CAI chemiluminescence (CLD) and non-dispersive infrared (NDIR) analyzers, respectively. Downstream of the LNT, the NO_x, carbon dioxide, carbon monoxide, oxygen and total hydrocarbons were measured by CAI CLD, NDIR and a flame ionization detector (FID), respectively. An MKS Fourier transform infrared spectroscopy (FTIR) analyzer was also used downstream of the LNT to measure the N_2O and NH_3 concentrations during LNT regeneration.

Data monitoring and recording was done with National Instruments (NI) hardware and software. An NI SXCI-1000 chassis was used along with NI SCXI-1302 and NI SCXI-1303 modules to collect the data from the mass air flow sensor, the oxygen sensor, and the thermocouples. An NI cRIO-9002 real-time controller and cRIO-9474 output module were used to control and to provide the injection command signals for the fuel and water injectors. Ultra low sulfur diesel fuel with a cetane number of 44.95 and a density of 0.8465 kg/L was used for the fuel injection. The water was injected into a heated evaporation tube to help prevent water condensation in the feed gas stream.

Long breathing LNT energy savings

The flow bench tests investigated the response of an LNT to different levels of NO_x exposure. It was hypothesized that lower levels of NO_x would enable a

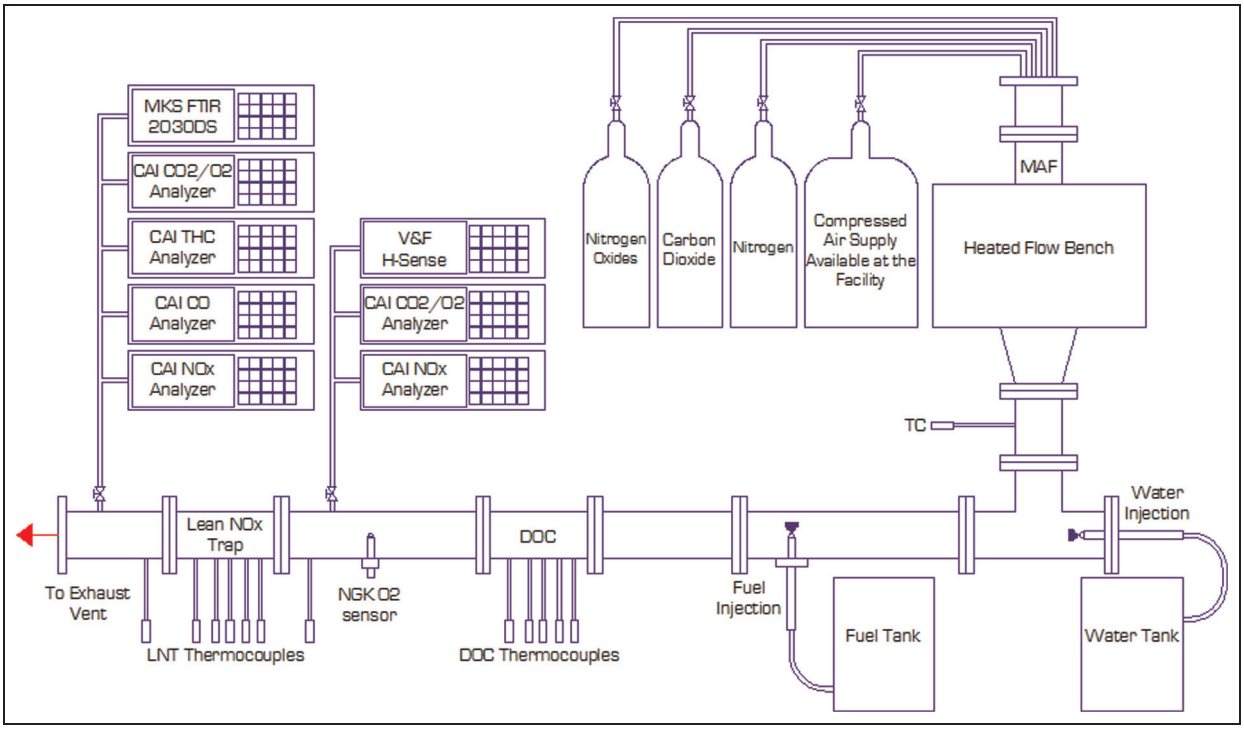

Figure 5. Schematic of the flow bench set-up.

longer adsorption time for the LNT. The tests were done at a constant LNT temperature of 300°C and an hourly space velocity of 75,000 h^{-1}. Three different levels of NO_x were utilized: 110 ppm, 70 ppm and 50 ppm. Correlating these levels with the engine test results shown in Figure 3, 110 ppm NO_x corresponded to the conventional LNT zone while the 70 ppm and 50 ppm NO_x levels corresponded to the long breathing zone. The adsorption time was measured as the time it took the LNT to reach a NO_x slip level of 20 ppm. The cut-off value of 20 ppm NO_x slip was derived from the engine tests shown in Figure 3; calculations based on the engine data indicated that a 20 ppm NO_x slip would allow the engine to meet the EPA's heavy duty on-highway NO_x emission standard with a conservative LNT NO_x conversion efficiency of 65%. This was a preliminary experimental proof of concept study; further tests are planned with a broader range of conditions. The response of an LNT exposed to 50 ppm and 110 ppm of NO_x is shown in Figure 6. The figure shows that the response of the LNT followed a similar trend in both instances. Initially, the NO_x slip from the LNT was very low, in the range of 0–1 ppm, indicating a high NO_x storage efficiency. As the LNT was continuously exposed to NO_x, it began to saturate and fewer sites remained for NO_x storage. Accordingly, the NO_x slip steadily increased with time until the targeted 20 ppm NO_x slip level was reached. The exact same pattern was observed for the 70 ppm NO_x exposure test.

A key observation was made with respect to the adsorption length. Even though the NO_x slip pattern was the same in all three instances, the LNT exposed to 50 ppm of NO_x had a much longer adsorption time than the LNT exposed to 110 ppm of NO_x. For the 110 ppm NO_x exposure test, the LNT reached the cutoff NO_x slip level in 11.3 minutes, but for the 50 ppm NO_x exposure test, the LNT was able to adsorb NO_x for 51.5 minutes before it reached the targeted NO_x slip level. Plotting the relationship between adsorption time and NO_x exposure, shown in Figure 7, revealed that this relationship was not linear, as might have been expected. Instead, the adsorption time increased exponentially when the feed gas NO_x level was reduced. Further studies were done under similar test conditions and in all instances, an exponential relationship was observed. This was a key discovery because it validated the long breathing LNT concept. Consequently, Figure 7 shows that the LNT's supplemental energy consumption, normalized with respect to the fuel injection quantity, reduced significantly with lower feed gas NO_x levels. In these tests, reducing the NO_x exposure from 110 ppm to 50 ppm led to energy savings of 62%.

The exponential relationship was attributed to an improved NO_x storage efficiency. Figure 8 shows that for the whole adsorption length, the NO_x storage efficiency with a NO_x exposure of 50 ppm was 79.4%, but with 110 ppm NO_x, the NO_x storage efficiency was 90.5%. This seemed to suggest that the NO_x storage efficiency was better with a higher NO_x exposure. However, these values are misleading because of the different adsorption lengths. For a fair comparison, the NO_x storage efficiency should be compared with respect to a fixed time length. Taking this into consideration, when the LNT was exposed to 110 ppm NO_x, it had a NO_x storage efficiency of 90.5% for 11.3 minutes of operation, while when the LNT was exposed to 50 ppm

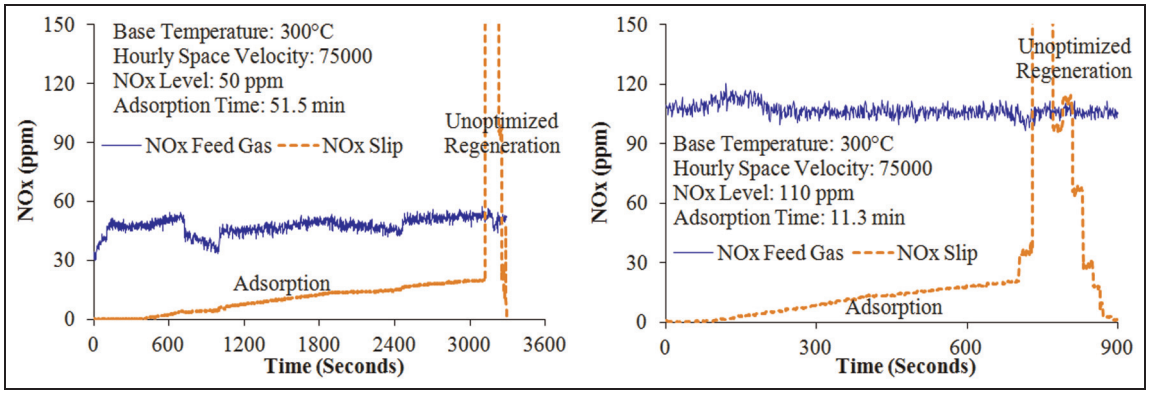

Figure 6. LNT response to 50 ppm of NO_x exposure (left) and to 110 ppm of NO_x exposure (right).

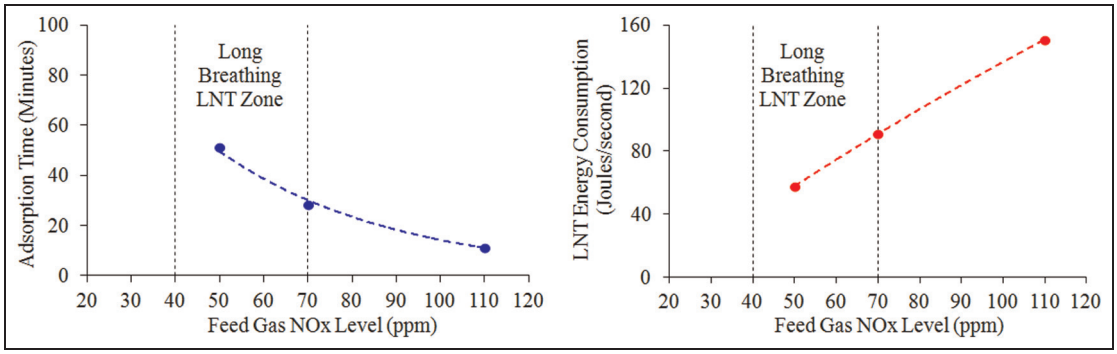

Figure 7. Relationship between NO_x exposure and LNT adsorption time (left) and between NO_x exposure and LNT supplemental energy consumption per gramme of supplemental fuel (right).

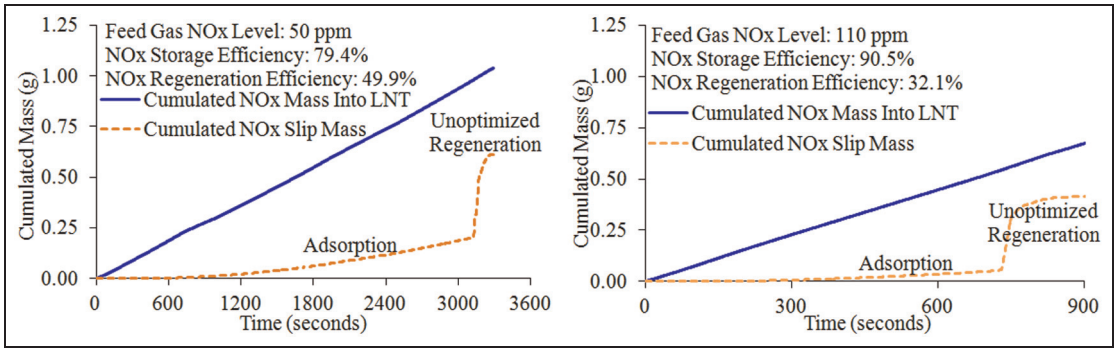

Figure 8. LNT NO_x storage and NO_x slip performance at 50 ppm NO_x exposure (left) and 110 ppm NO_x exposure (right).

NO_x, it had a NO_x storage efficiency of 98.3% for the first 11.3 minutes of its operation. Thus, a lower NO_x exposure led to an improved NO_x storage efficiency over a fixed time period.

At this point, the LNT was regenerated with an unoptimized and inefficient regeneration strategy. During adsorption the NO_x slip level had increased gradually, but when the LNT was regenerated a dramatic increase in NO_x slip was observed, of the order of several hundred parts per million. Thus, the overall LNT NO_x conversion efficiencies were quite low, below 50%, as shown in Figure 8, compared to levels exceeding 75% commonly reported in the literature.[9,18] However, this LNT catalyst composition was not optimized for long breathing application. Thus, for these tests, the goal of the fuel-rich regeneration was not to maximize the NO_x conversion but to purge the NO_x out of the LNT and free-up BaO NO_x storage sites for the next adsorption test. After regeneration, it was observed that the NO_x slip dropped back to the 0–1 ppm range, indicating that the stored NO_x had been purged out of the LNT. A low NO_x regeneration efficiency was

acceptable for these tests, since the focus was on the adsorption cycle, but more efficient regeneration strategies will be investigated in future work.

To determine the potential for NO_x reduction of the long-breathing LNT, further calculations were undertaken to compute the tailpipe NO_x emissions based on an assumed NO_x conversion efficiency for each of the three investigated NO_x exposure levels. To make this calculation, the results from the LNT flow bench tests shown in Figure 7 were combined with the results from the engine tests shown in Figure 3. A voluntary NO_x emission standard of 0.15 g/kw h was chosen as the benchmark to account for using indicated power instead of brake power to calculate the emission levels; the chosen value is moderately lower than the EPA's 2010 heavy duty NO_x emission standard of 0.2 g/hp h (0.267 g/kw h). The LNT NO_x conversion efficiency was varied from 0% to 100% while the LNT adsorption duration was held constant according to the values obtained from the flow bench tests. The results, shown in Figure 9, again highlight the advantage of the long breathing LNT. Under the investigated conditions, the long breathing LNT exposed to 50 ppm of NO_x would be able to achieve the voluntary NO_x emission standard with a 65% NO_x conversion efficiency while the conventional LNT exposed to 110 ppm NO_x required an 87% LNT conversion efficiency to meet the same target. It should be noted that in most cases, during these and similar tests, it was observed that a longer NO_x retention time in the LNT led to reduced NO_x regeneration efficiency. However, the figure below demonstrates that the EPA NO_x heavy duty limit can be satisfied with a long breathing LNT, even if it has a lower NO_x conversion efficiency than a conventional LNT.

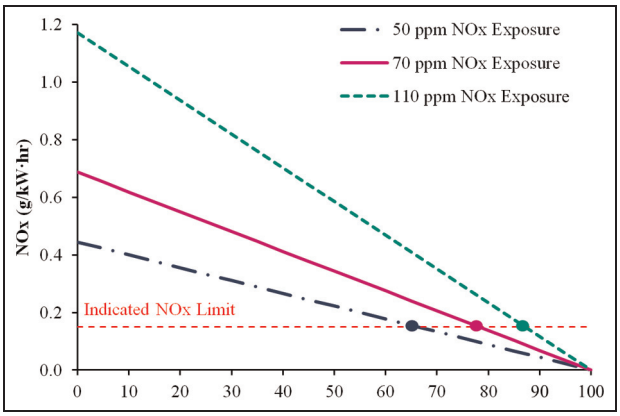

Figure 9. Calculated NO_x emission based on an assumed LNT conversion efficiency.

An analysis of the total fuel consumption of the combined engine and after-treatment system was carried out based on the engine test results shown in Figure 3 and the long breathing LNT test results. The total fuel consumption was calculated by adding the fuel consumption of the LNT regeneration and the fuel consumption of the engine at the corresponding NO_x level. The engine fuel consumption was calculated by the carbon balance method. The LNT fuel consumption was calculated according to the fuel required to produce slightly rich exhaust conditions, utilizing the exhaust oxygen data from the engine tests, for a period of 20 s for the long breathing strategy and for 8 s for the conventional LNT strategy. A shorter regeneration period was selected for the conventional LNT strategy because less NO_x was stored in the LNT, meaning less fuel was required for NO_x reduction, and the exhaust oxygen concentration was higher, requiring a higher concentration of fuel to be delivered to generate fuel rich exhaust conditions.

The results, shown in Table 3, indicated that the long breathing LNT strategy had the lowest total fuel consumption. The low temperature combustion strategy had a higher fuel consumption than the long breathing LNT strategy due to the higher fuel consumption of the engine, while the conventional LNT strategy had a higher total fuel consumption due to a higher after-treatment fuel consumption; the supplemental fuel penalty was reduced from 2.0% to 0.8% by utilizing a long breathing LNT instead of a conventional LNT. The calculations suggested that, at these conditions, the test engine operating in combination with a long breathing LNT strategy would have a fuel consumption rate 5.22 g/hr lower than the test engine in combination with a conventional LNT. Although it was estimated that the conventional LNT strategy allowed the engine to be run at a slightly higher indicated efficiency, as calculated by equation (7), it was calculated that the overall efficiency of the combined engine and after-treatment

Table 3. Comparison of combined fuel consumption between different NO_x reduction strategies.

EGR	Zone	Engine-out NO_x (ppm)	Fuel consumption			LNT fuel penalty (%)	Engine efficiency (%)	Overall efficiency (%)
			Engine test (g/h)	LNT (g/h)	Total (g/h)			
No/low	Conventional LNT	110	611.5	12.7	624.2	2.0	36.8	35.9
Medium	Long breathing LNT	50	614.2	4.8	619.0	0.8	36.6	36.4
High	LTC	15	656.4	0.0	656.4	–	32.7	32.7

system was 36.4% with the long breathing LNT strategy compared to 35.9% for the conventional LNT strategy. Thus, the energy saving advantage of utilizing a long breathing LNT strategy was validated at these operating conditions. Further analysis is required to confirm if this benefit is valid at different operating conditions

$$Indicated\,Efficiency = \frac{Indicated\,Power}{Fuel\,Consumption \cdot LHV} \quad (7)$$

Conclusions

A long breathing LNT was proposed as a method for reducing the LNT supplemental fuel consumption. With this strategy, the engine-out NO_x levels would be reduced via in-cylinder combustion control techniques, such as EGR, enabling a longer LNT adsorption cycle. A proof of concept study was undertaken on a flow bench set-up to determine the effects of different NO_x exposure levels on the adsorption duration of the LNT and to investigate if energy savings were possible with the long breathing LNT strategy compared to already-existing NO_x reduction strategies. The following trends were observed from the test results:

- Even with an unoptimized catalyst, the adsorption time of an LNT exposed to 50 ppm of NO_x was over four times longer than the adsorption length of an LNT exposed to 110 ppm of NO_x
- There was an exponential relationship between the LNT's adsorption time and the LNT's NO_x exposure with the adsorption time increasing exponentially as the NO_x exposure was reduced
- Reducing the NO_x exposure from 110 ppm to 50 ppm resulted in supplemental energy savings of 62%
- Calculations indicated that the long breathing strategy reduced the supplemental fuel penalty of the LNT from 2.0% to 0.8% at the selected operating conditions
- The overall indicated efficiency of the combined engine and after-treatment system was calculated to be 36.4% when the long breathing LNT strategy was used compared to 35.9% for the conventional LNT strategy
- Further testing and analysis are required to determine if energy savings are possible with the long breathing LNT strategy under different operating conditions

Funding

The research was sponsored by the Ontario Ministry of Training, Colleges and Universities, AUTO21, the Natural Sciences and Engineering Research Council of Canada, the Canada Research Chairs program, Canada Foundation for Innovation, Ontario Research Fund and other industrial sponsors and OEM companies.

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Appendix

Units

cpsi	cells per square inch
ppm	parts per million
r/min	revolutions per minute

Acronyms

CAI	California Analytical Instruments
CLD	chemiluminescence detector
DOC	diesel oxidation catalyst
EGR	exhaust gas recirculation
EPA	environmental protection agency
FID	flame ionization detector
FSN	filter smoke number
FTIR	Fourier transform infrared spectroscopy
IMEP	indicated mean effective pressure
LHV	lower heating value of fuel
LNT	lean NO_x trap
LTC	low temperature combustion
MY	model year
NDIR	non-dispersive infrared
NI	National Instruments
NO_x	nitrogen oxides
SCR	selective catalytic reduction
THC	total hydrocarbon