Lean Burn Engine Control for Fuel Economy and Exhaust Aftertreatment

ZHENGMAO YE[1], ZHIJUN LI[2], HABIB MOHAMADIAN[1]
[1]College of Engineering, Southern University
Baton Rouge, LA 70813, USA

[2]State Key Laboratory of Engines, Tianjin University
Tianjin, 300072, P.R.China

Abstract: - **A novel catalyst system has been developed for NOx emission aftertreatment of a lean burn gasoline engine. The goal is to investigate its impact on emission characteristics and BSFC (Break Specific Fuel Consumption) across a broad engine speed and load operating region under various arrangement schemes for the new catalyst converter. It has been indicated from experimental results that the upstream placement of TWC (Three Way Catalyst) ahead of the NOx Adsorber Catalyst is the best solution, which gives rise to the highest converting efficiency to reduce the NOx emission level of the lean burn gasoline engine. The role of engine speed on exhaust emissions and BSFC is also reflected by the operating time of lean burn and rich burn as well as the time ratio between the two. Engine load is a major factor in affecting exhaust emission characteristics and BSFC of the lean burn gasoline engine. The heavier the engine load, the higher the NOx emission level, and the lower the BSFC.**

Key-Words: - **Lean Burn, Gasoline Engine, Adsorber-Reduction Catalyst, NOx Emission, BSFC**

1 Introduction

To meet more and more stringent engine emission regulations worldwide, it is hard to rely on some engine operation strategies exclusively to improve the quality. Instead, many countries have developed new exhaust emission after-treatment systems to reduce emission levels. In the mean time, some other aspects of engine performance are retained. Traditional TWC can be used to reduce CO, HC and NOx simultaneously and effectively when gasoline engines operate under the stoichiometric A/F ratio condition.

Lean burn is an internal combustion of lean air-fuel mixtures. Engine combustion is considered lean when excess air is introduced into the engine along with the fuel. It occurs at high A/F ratios which is good for fuel economy. The major drawback of lean burn is the relative large amount of NOx generated, complex catalytic converter system is thus required. Lean burn engines do not work well with TWC converters due to the lean A/F ratio. As a result, exhaust pollutant aftertreatment systems should be designed in order to implement both oxidation and reduction reactions. At present, the dominant technologies to reduce NOx emission of lean burn gasoline engine are EGR [1-4] and catalyzing [5-7]. Since a high EGR rate decreases the velocity of diffusion flame, obviously it can make the BSFC worse. Ricardo develops a variable tumble CCVS system [2] which can obtain a high EGR rate of 70% with good exhaust stratified combustion. The structure of this system is complicated and NOx emission is also hard to satisfy the request of stricter emission regulations. For other methods of NOx decomposing and selective catalyst reduction (SCR) for vehicle exhaust systems, both the NOx catalyst converting efficiency and the thermal stability of the catalyst are hard to satisfy the practical requirement. Compared with these two methods, the developed NOx adsorber reduction catalyst combined with TWC can cleanse the NOx efficiently within a wide temperature window. The BSFC of a lean burn gasoline engine might deteriorate slightly, while the catalyst converting efficiency can reach maximum in a short period of rich condition. A modified 16 valve EFI Quasi-Homogenous lean burn gasoline engine is currently studied on effects of different placement schemes of a NOx adsorber converter and TWC, engine load and engine speed on exhaust emissions and BSFC with a combination of the NOx adsorber catalyst and TWC.

2 Experimental Test Bench

The experimental study is conducted to indicate the effects of engine load, engine speed, TWC and adsorber catalysts on characteristics of the exhaust emission and BSFC. Combined with the traditional TWC, the research on NOx emission control in lean burn exhaust is carried out. Ahead of and after the lean burn NOx adsorber catalyst, devices for temperature and emission measuring are installed. During the testing, catalyst entrance exhaust gas temperature is changed between 300ºC and 600ºC using the temperature regulator. At different point of the exhaust pipeline, the gas temperature and NOx emission are measured to investigate the effects of catalyst arrangement schemes and catalyst entrance temperature on the NOx converting efficiency.

The developed 16 valves EFI Quasi-Homogenous lean burn gasoline engine system has been used. The structure of this exhaust system is shown in Fig. 1, with the new design of lean burn NOx adsorber catalysts. Locations of component 2 and component 3 along with the tailpipe system can be swapped. There are three schemes of component arrangement for the exhaust tailpipe. At Scheme 1, the sequence order is 1-5-2-4 with NOx adsorber and no TWC. The sequence order is 1-5-2-3-4 at scheme 2, where the NOx adsorber is placed ahead of TWC. On the other hand, in scheme 3, the NOx adsorber is placed downstream after the TWC with a sequence order of 1-5-3-2-4.

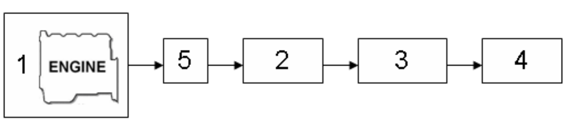

Fig. 1 Schematic of Engine Exhaust Systems
1. Engine, 2. Lean NOx Adsorber Catalyst, 3. TWC, 4. Muffler, 5. Temperature Regulator

Scheme 3 is found to be the best scheme for NOx conversion. From theoretical point of view, when the TWC is placed ahead of the NOx adsorber-reduction catalyst, the exhaust gases flow through TWC at first before these gases react with the reducing agent rhodium. Accordingly, even though oxygen is rich among the exhaust gases, the converting process of NOx is restricted and the NOx converting efficiency is reduced. This arrangement can reduce the concentration of O_2, HC and CO as well as the absolute inlet NOx emission level for the lean burn NOx adsorber-reduction catalyst, so as to reduce the level of oxygen adsorbed, alleviate the load of the lean burn NOx adsorber-reduction catalyst and prolong the saturation time of the catalyst. When the time ratio t_{lean}/ t_{rich} is fixed, as the absolute time of t_{lean} and t_{rich} drops, the absolute NOx emission level is low, so there is little possibility of NOx overflow within a short period of time. In the mean time, there is a NOx reduction process in each short period, making the chance of NOx overflow even smaller. During the rich process of NOx reduction, the NOx adsorbed is almost deoxidized. When the gasoline engine switches to lean burn mode, the adsorber capacity of catalyst is enhanced again. Thus, the NOx emission level consequentially decreases. In other words, as the absolute time of t_{lean} and t_{rich} drops, the emission level of NOx in this system also decreases.

3 Electronic Throttle Control Systems and Baseline Engine Maps

Using the same set of sensors and wires, the original ECU is substituted by one more flexible to regulate the A/F ratio for lean burn control. The electronic controlled throttle and the linear A/F sensor are also used for special demands of the NOx adsorber-reduction catalyst and lean burn operation. The A/F ratio and the operating time are set beforehand according to requirements of experiments. Throttle angle and injection pulse width can be adjusted by the current ECU to ensure the required A/F ratio and the steady power output. The linear A/F ratio sensor keeps the engine operating condition in a suitable range of A/F ratio via the feedback control signal.

When the engine operates at the lean mode, regular engine control parameters are selected. When the engine operates at the rich mode, the throttle position and spark timing will be adjusted. In order to keep the engine power output and torque output stable under an allowable range of engine speed fluctuation, the throttle opening is reduced and spark timing is retarded. At the same time, the spark advance angle retarding is helpful to avoid engine knock. For the optimization purpose, the step motor is used to adjust the throttle angle with priority, then a fine tuning is made by adjusting the spark advance angle. Base on intelligent control principles, a self-learning algorithm is used to determine both the increment and decrement offsets to the baseline engine maps. The baseline engine maps for the lean mode (A/F ratio =21) and rich mode (A/F ratio =12) in this research are shown in Fig. 2 and Fig. 3. For any specified throttle angle, the engine map can be made by the interpolation.

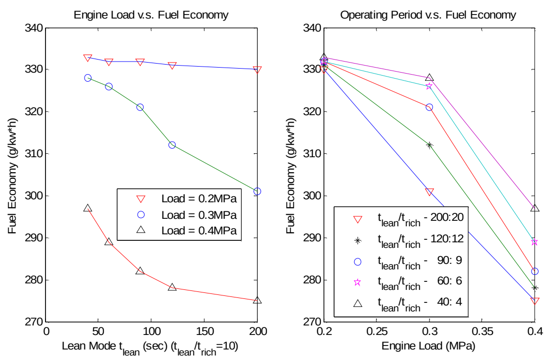

Fig. 2 Baseline Engine Map #1 (Rich and Lean)

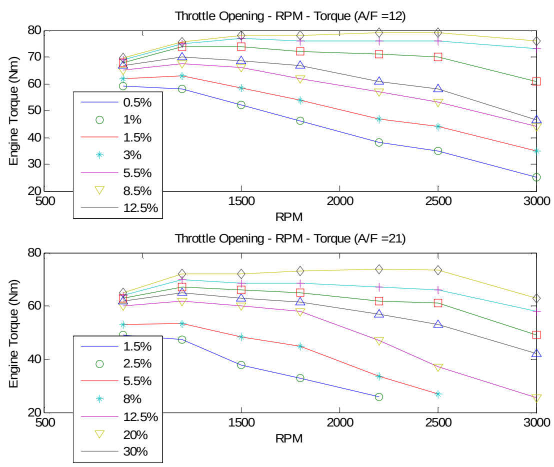

Fig. 3 Baseline Engine Map #2 (Rich and Lean)

4 Effects of Engine Speed on BSFC and Exhaust Emissions

With regarding to the scheme 3, effects of engine operations on exhaust emission characteristics and BSFC are both investigated. Fig. 4 and Fig. 5 show effects of exhaust emission and the NOx converting efficiency under different engine speed (1500, 1800, 2500 rpm) with the fixed engine load in scheme 3. The x-axis denotes the ratio of absolute lean burn operating time t_{lean} and absolute rich condition operating time t_{rich}. The y-axis denotes the concentrations of exhaust emissions of CO, HC, NOx, the NOx converting efficiency and BSFC, respectively. Operating conditions of the lean burn engine are; engine load is selected to be 0.2MPa; engine speed is 1500, 1800 and 2500 rpm, respectively; A/F ratio is 21 in lean burn and 12 in rich burn; time ratio t_{lean}/t_{rich}=10.

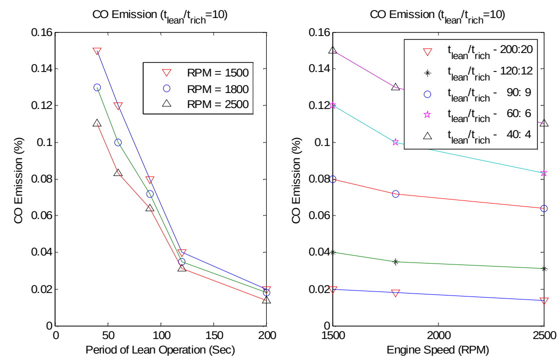

Fig. 4 Effects of Engine Speed on CO emission

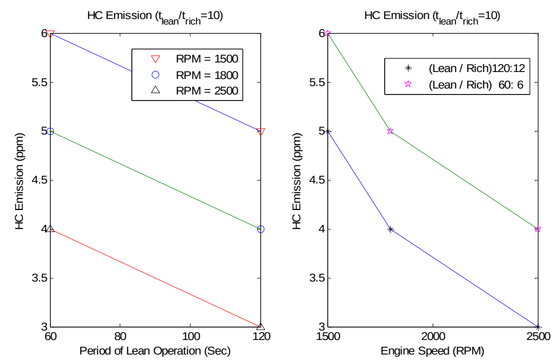

Fig. 5 Effects of Engine Speed on HC emission

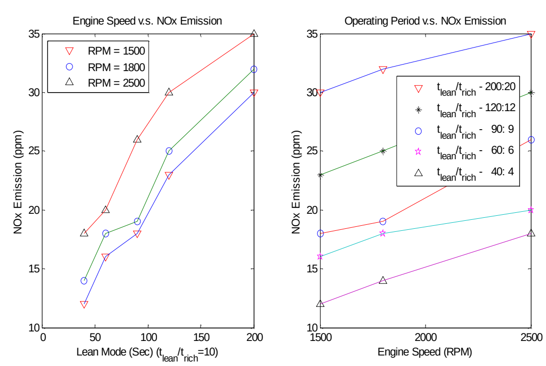

Fig. 6 Effects of Engine Speed on NOx emission

In Fig. 4 to Fig. 6, when the time ratio of t_{lean}/ t_{rich} and the absolute time of t_{lean} and t_{rich} keep the same, and engine load is set to be 0.2Mpa, as engine speed increases (1500, 1800, 2500 rpm), exhaust emissions of CO and HC decrease while the NOx level increases slightly. But with the absolute time of t_{lean} and t_{rich} decreased, the emissions of CO and HC increase while the NOx level decreases slightly. This is because the increased engine speed leads to the oxidation condition sufficiently to oxidize CO and HC, therefore the CO and HC emissions of the lean burn gasoline engine decrease. Owing to the setup of the NOx adsorber-reduction catalyst, concentrations of CO and HC in the exhaust system is slightly higher than that of pure lean burn gasoline engines.

As engine speed increases, engine operation cycle turns out to be a shorter period, making incylinder temperature slightly higher with the increased NOx concentration. On the other hand, with the absolute time of t_{lean} and t_{rich} decreased, the A/F ratio transient processes occur more frequently, so CO and HC emissions increase. Since the shortening of t_{lean} and t_{rich} improves the converting efficiency in the adsorber-reduction catalyst system, the NOx emission will decrease in this circumstance.

The shortening of the absolute time reduces the leakage of NOx through adsorber-reduction catalyst systems and enhances the absorbance of the NOx emission. The NOx level thus increases slightly. Under the fixed absolute time of t_{lean} and t_{rich}, the converting efficiency decreases slightly with the increasing engine speed, and vice versa. It indicates that extra NOx emission due to high speed can be improved by shorter absolute time of t_{lean} and t_{rich}.

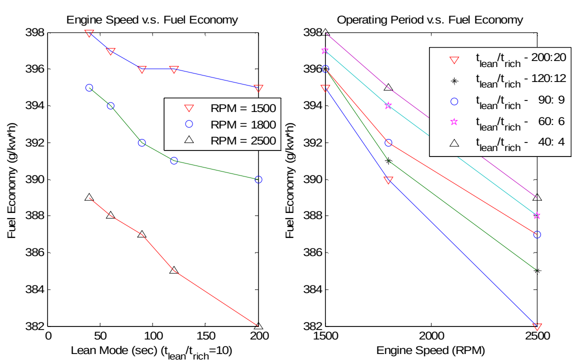

Fig. 7 Effects of Engine Speed on BSFC

In Fig. 7, when t_{lean}/ t_{rich} and the absolute time of t_{lean} and t_{rich} are fixed, if engine speed increases from 1500 to 2500 rpm, BSFC is slightly improved. Analyzing this phenomenon, when absolute time of t_{lean} and t_{rich} keeps the same, the in-cylinder turbulence intensity is enlarged so that combustion is improved which leads to the smaller BSFC. But if the engine speed is very high, the BSFC increment will be bigger because the strengthened incylinder air motion results in the heat loss. For low and medium range of engine speed, the increment of engine speed will lead to the BSFC decrement. As the absolute time of t_{lean} and t_{rich} decreases with a fixed time ratio t_{lean}/ t_{rich}, the A/F ratio transient process occurs more frequently, the BSFC increases very slightly.

The impact of engine speed on the exhaust emission and BSFC is related to the time ratio and absolute time t_{lean} and t_{rich}. For fixed t_{lean} and t_{rich} condition, the CO and HC emission level decrease and the NOx emission level increases with the increasing speed, while the converting efficiency in adsorber-reduction catalyst system decreases and its BSFC is improved. If the absolute time of t_{lean} and t_{rich} decreases, the CO and HC emission levels increase and the NOx emission level decreases, both the BSFC and converting efficiency increase.

5 Effects of Engine Load on Exhaust Emissions and BSFC

Using scheme 3, Fig. 8 to Fig. 10 show the effects of different engine load (Pe=0.2, 0.3 and 0.4 MPa) on exhaust emission CO, HC and NOx, the converting efficiency and BSFC, when engine speed is 1800 rpm, the time ratio t_{lean}/ t_{rich} is 10, A/F ratio of lean burn is 21 and A/F ratio of rich burn is 12.

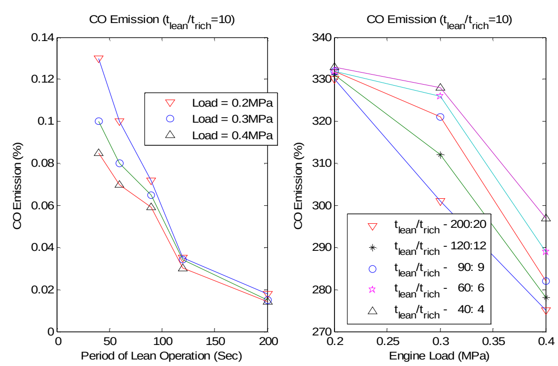

Fig. 8 Effects of Engine Load on CO emission

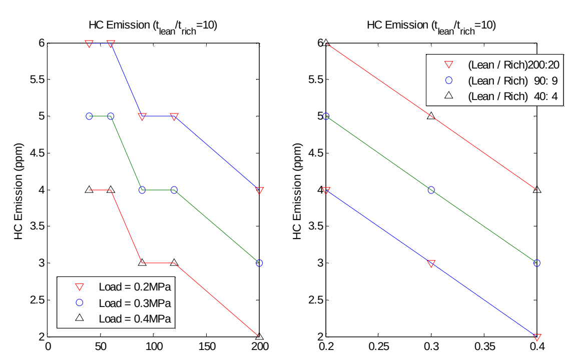

Fig. 9 Effects of Engine Load on HC emission

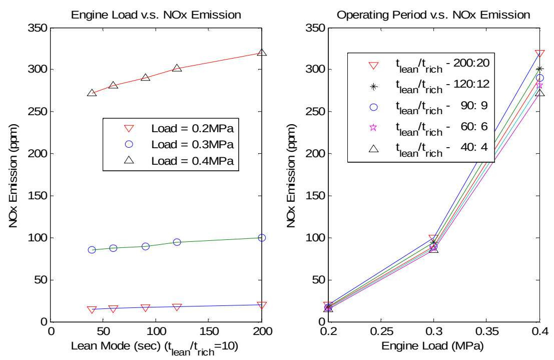

Fig. 10 Effects of Engine Load on NOx emission

In Fig. 8 to Fig. 10, engine speed is set to be 1800 rpm. When the time ratio t_{lean}/ t_{rich} keeps the same, if the absolute time of t_{lean} and t_{rich} is fixed, with the increasing engine load (0.2, 0.3, 0.4 MPa), emissions of CO and HC will decrease and that of NOx will increase. For shorter absolute time of t_{lean} and t_{rich}, emissions of CO and HC will increase and that of NOx will decrease slightly. This is mainly because that incylinder temperature rises due to additional engine load which enhances the fuel oxidation. Also the rise of cylinder wall temperature reduces the thickness of boundary layer attached, so HC level adsorbed by this layer decreases. At the same time, the amount of the unburned incylinder fuel mixture decreases. As a result, the levels of CO and HC decrease and that of NOx increases. In the mean time, for a fixed engine load, when the absolute time of t_{lean} and t_{rich} decrease, the levels of CO and HC increase and that of NOx decreases.

The shorter absolute time of t_{lean} and t_{rich} decreases the reaction time of lean burn before the restoration and regeneration process starts. The transient condition occurs more frequently during certain time period, making slightly larger concentrations of CO and HC. The NOx concentration becomes smaller due to the less absolute time t_{lean} and t_{rich}, where NOx created during lean burn is converted to N_2 during restoration in terms of reactions inside the alkaline earth of the catalyst system. These improve both the absorbance capability of the NOx catalyst and the converting efficiency.

In Fig. 11, engine speed is fixed (1800 rpm), engine load affects the BSFC remarkably. The heavier the engine load, the lower the BSFC. When engine load increases, incylinder temperature rises, from one aspect, the heavier load improves fuel pulverization and combustion conditions. From another aspect, the accumulation of engine load reduces the relative cooling loss and pumping loss of the engine, thus thermal efficiency increases. In addition, the engine load accumulation improves the engine mechanical efficiency and reduces BSFC.

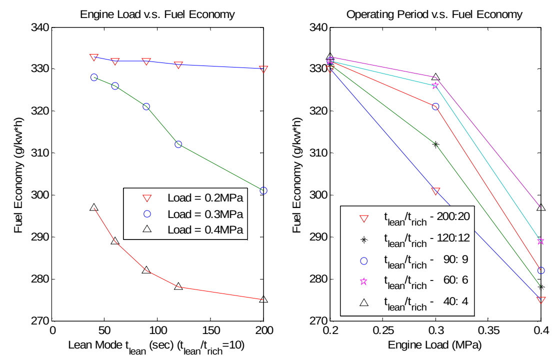

Fig. 11 Effects of Engine Load on BSFC

With a fixed time ratio t_{lean}/ t_{rich} and engine load, when absolute time of t_{lean} and t_{rich} decreases, BSFC is increased slightly since the shorter absolute time of t_{lean} and t_{rich} enlarges the total engine transient operating period for the same time period.

6 Conclusions

A new catalyst system has been used to investigate the impact of various schemes of the converter arrangements, engine speed and engine load on the BSFC and exhaust emission characteristics of a lean burn gasoline engine, which consists of a traditional TWC and a catalyst converter for NOx adsorber-reduction. These major conclusions are useful for potential engine control:

1. The arrangement scheme 3 can achieve the lowest NOx emission of $50*10^{-6}$ and the highest converting efficiency of 97.3%. Therefore, to reduce NOx emission level in lean burn gasoline engine via TWC and the lean burn adsorber catalyst, an upstream placement scheme of TWC ahead of the adsorber-reduction catalyst is the best solution.

2. For a fixed t_{lean}/t_{rich} ratio, if absolute time of t_{lean} and t_{rich} keeps the same, the emissions of CO, HC decrease and that of NOx increases slightly with the increasing engine speed, and its BSFC is improved as well. The change of NOx converting efficiency is negligible. With the absolute time of t_{lean} and t_{rich} decreasing, concentrations of CO and HC increase and that of NOx decreases slightly, the converting efficiency increases and the BSFC is improved.

3. For a fixed t_{lean}/t_{rich} ratio, if the absolute time of t_{lean} and t_{rich} keeps the same, the emissions of CO and HC decrease and that of NOx increases with the increased engine load. With the absolute time of t_{lean} and t_{rich} decreasing, concentrations of CO and HC increase and that of NOx decreases slightly, the converting efficiency increases, however the BSFC becomes worse.

References

[1] Grant Lumsden, David Eddleston and Richard Skyes, "Comparing Lean Burn and EGR", SAE Paper 970505,1997

[2] J. Stokes, T. Lake and M. Christle. "Improving the NOx/Fuel Economy tradeoff for gasoline engine with CCVS combustion system", SAE Paper 940482, 1994

[3] Hiromistu Ando and Kazunari Kuwahara, "A Keynote on Future Combustion Engines", SAE Paper 2001-01-0248, 2001

[4] Y. Iwamoto, K. Noma, O. Nakayama, T. Yamauchi, H. Ando, "Development of Gasoline Direct Injection", SAE Paper 970541, 1997

[5] W. Strehlau, J. Leyrer and E. Lox, "Lean NOx catalysis to Gasoline Fueled European Cars", Automotive Engineering, Vol.105, No.2, P133-135,1997

[6] D. Gregory, A. Marshall, B. Eves, M. Dearth, J. Hepburn, S. Brogan, D. Swallow, "Evolution of lean NOx-traps on PFI and DISI lean burn vehicles", SAE Paper 1999-01-3498, 1999

[7] M. Brogan, A. Clark and R. Brisley, "Recent progress in NOx-trap technology", SAE Paper 980933, 1998

[8] Z. Ye, "GDI Engine Exhaust Aftertreatment System Analysis and Oxygen Sensor Based Identification, Modeling and Control of Lean NOx Trap", Proceedings of the 2003 ASME Internal Combustion Engine Division Spring Technical Conference, pp. 713-719, May 11-14, 2003, Austria

[9] Zhengmao Ye, "Automotive Hybrid System Optimization Using Dynamic Programming", SAE Technical Paper 2003-01-0847, March 3-6, 2003, SAE World Congress, Detroit, USA

[10] Z. Li, G. Zhang and S. Liu, "An Electronic Control System Development of Reducing NOx Emission in a Quasi-Homogeneous Lean Burn Gasoline Engine", Journal of Combustion Science & Technology, Vol.10, No.5, PP. 400-404, 2004