

Engines in 1988. Since then, the  $\text{NO}_x$  and particulate matter trade-off characteristic became the Achilles heel of heavy-duty diesel engines. Most  $\text{NO}_x$  reduction measures invariably lead to higher particulate matter emissions. In 1998,  $\text{NO}_x$  emissions from heavy-duty diesel engines will not be allowed to exceed 4.0 gm/bhp-hr while particulate matter will still be regulated at 0.1 g/bhp-hr. Post-1998  $\text{NO}_x$ /PM emissions standards are expected to be drastically tighter. Ultra-Low Emission Vehicle (ULEV) standards are proposing a combined  $\text{NO}_x$  and HC standard not to exceed 2.5 g/bhp-hr with particulate matter regulated at 0.10 g/bhp-hr.

This paper also considers the impact of exhaust gas recirculation on particulate matter composition. In addition, the potential of combining both exhaust gas recirculation and passive trap aftertreatment is demonstrated as a potential solution for simultaneous control of these two emissions species.

## INTRODUCTION

The diesel engine has long been the most energy efficient power plant for transportation. Moreover, diesels emit extremely low levels of hydrocarbon and carbon monoxide that do not require aftertreatment to comply with current and projected standards. However, it is admittedly difficult for this power plant to simultaneously meet  $\text{NO}_x$  and particulate matter projected standards. Traditionally, design changes aimed at reducing one of these two exhaust gas species have led to an increase in the other. This physical characteristic, which is known as  $\text{NO}_x$ /PM tradeoff remains the subject of an intense research effort.

As mentioned in the abstract, future emissions standards are proposing extremely low  $\text{NO}_x$  and particulate matter limits. A reasonable objective for  $\text{NO}_x$  control is 2.0 g/bhp-hr (2.7g/kWh) in order to meet the  $\text{NO}_x$  + HC limits of 2.5g/bhp-hr (3.4g/kWh) proposed in the Statement of Principles (SOP) agreed to by the North American Engine Manufacturers.

## TECHNOLOGIES FOR LOW $\text{NO}_x$ IN DIESEL ENGINES - A REVIEW

Many technologies for  $\text{NO}_x$  reduction have been considered over the last two decades. Some of these technologies are:

- Pilot injection and injection rate shaping
- Intake charge air cooling
- Injection timing retard
- Water emulsion/injection
- Exhaust aftertreatment
- Exhaust gas recirculation

by 50 percent from that of the conventional injection systems.<sup>(1)</sup> This ignition delay reduction allowed more injection timing retard with good combustion stability. Significant reductions in flame temperature, NO<sub>x</sub>, and fuel consumption were also reported by the same researchers. These improvements were attributed to a slower rate of combustion pressure rise resulting in better mechanical efficiency and lower cooling loss. Their work, however, documented an increase in smoke emissions and pointed to the need for flexible control of pilot injection timing and quantity as a function of engine speed and load. Similar results were reported earlier by researchers from the ACE Institute Co., Ltd. and JARI, Inc. in Japan<sup>(2)</sup> These researchers achieved 35 percent NO<sub>x</sub> reduction and 60-80 percent smoke reduction simultaneously without fuel consumption penalty. They have achieved these results by combining pilot injection with high injection pressures.

Pilot or staged injection research and development results indicated that an optimum injection strategy would be a slow injection rate (small pilot) for NO<sub>x</sub> control. The latter portion of the injection would be characterized with a fast injection rate for particulate control where most of the fuel would be injected at the highest combustion temperature near TDC. Work by researchers at the University of Wisconsin, Madison<sup>(3)</sup>, using multiple injections (more than two), generally supported the above conclusions. Figures 1a and 1b were adapted from reference<sup>(3)</sup> to illustrate the effects of low injection rate on NO<sub>x</sub> reduction and the adverse impact of higher rates after the bulk of the fuel had released its heat, respectively.

#### **EFFECT OF INTAKE CHARGE AIR COOLING**

Most if not all published data agree that for high specific output diesel engines (high BMEP), there is a beneficial effect for lower temperature charge air.<sup>(4,5,6)</sup> Many engine manufacturers replaced their water-jacket with air-to-air intercooled systems.<sup>(4,7)</sup> For a typical North American 7.5 liter turbocharged diesel engine a fuel consumption improvement of 2.49 percent was seen when intake charge air temperature was reduced from 200°F to 120°F (93°C to 49°C).<sup>(7)</sup> Meanwhile, a NO<sub>x</sub> reduction of 17.5 percent was reported at the same injection timing.<sup>(7)</sup> Figure 2 was adapted from reference 7 and gives the effect of rated speed intake manifold temperature on EPA heavy-duty transient test NO<sub>x</sub> emissions.

#### **EFFECT OF INJECTION TIMING RETARD**

The effect of retarding injection timing on NO<sub>x</sub> emission in diesel engines has been well documented.<sup>(5,6,7)</sup> Retarding injection timing by 8-10° crank angle was found to help most heavy-duty DI diesel engines to meet the 1991 NO<sub>x</sub> standards of 5.0g/bhp-hr (6.8g/kWh) from their pre-1991 calibrations of 9-10.5 g/bhp-hr (14.3g/kWh). Adverse NO<sub>x</sub> emission behavior was noted however where injection timing was extended beyond this margin.<sup>(6)</sup> This phenomenon was attributed to an increase in the premixed fuel fraction due to a significant increase in ignition delay. Figure 3 which was adapted from reference 7, ties the influence of both injection timing retard and intake charge air cooling on NO<sub>x</sub> emissions.

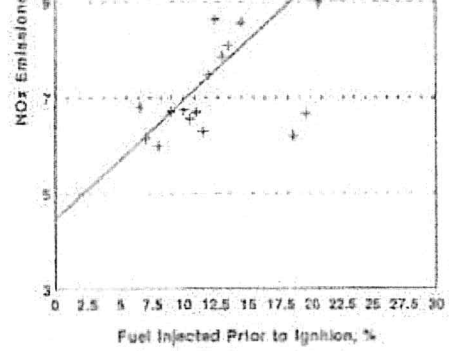


Figure 1a. Relationship Between NOx and Fuel Injected Prior to Ignition at 75% Engine Load

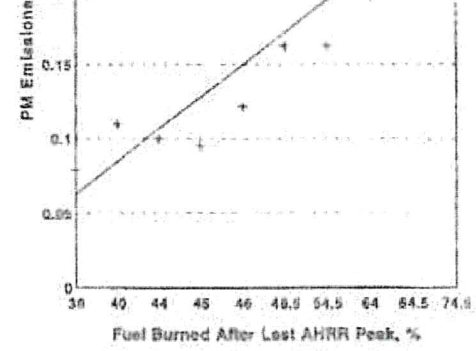


Figure 1b. Relationship Between PM and Fuel Injected After Peak Apparent Heat Release Rate

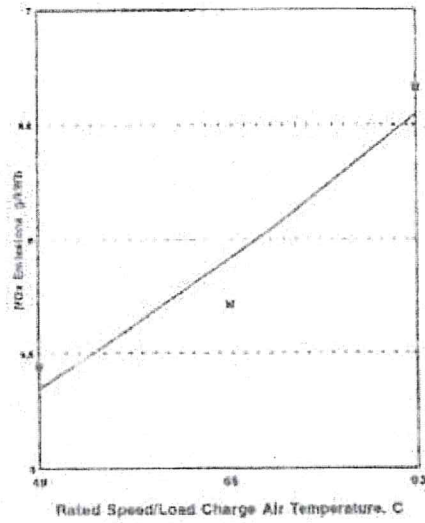


Figure 2. Relationship Between Charge Air Temperature and EPA Heavy-Duty Transient NOx Emissions

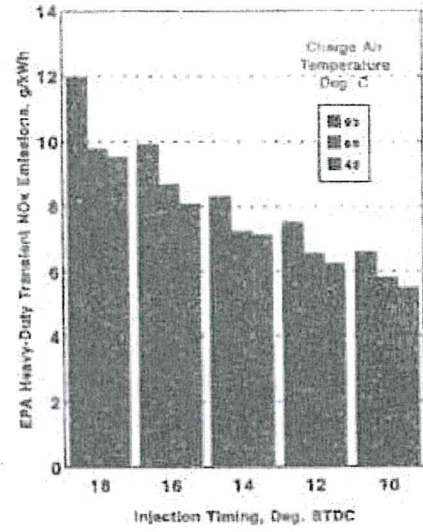


Figure 3. Combined Effect of Charge Air Temperature and Injection Timing Retard



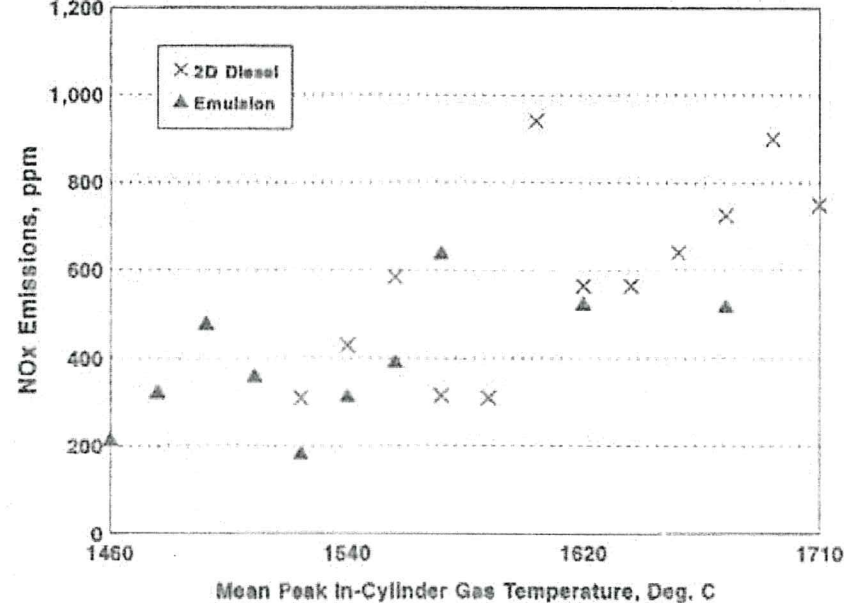


Figure 4. Effect of Water Emulsion on NO<sub>x</sub> Emissions at Various Timing and Compression Ratios

#### EFFECT OF EXHAUST GAS AFTERTREATMENT

In spite of these design changes the basic NO<sub>x</sub>/PM tradeoff remained. Therefore, further NO<sub>x</sub> reductions, without increasing PM emissions, required new aftertreatment technologies. Normally, using a NO<sub>x</sub> decomposition catalyst in diesel exhaust environment would be preferable. However, diesel exhaust is typically oxygen-rich and characteristically low on HC and CO. Researchers<sup>(10,11,12)</sup> quickly realized that NO<sub>x</sub> decomposition in the oxidant-rich and reductant-lean environment was a formidable task. Even though the search for a NO<sub>x</sub> decomposition catalyst for diesel exhaust continues, current emphasis is on systems that rely on supplementing exhaust hydrocarbons.<sup>(11)</sup> This selective catalytic reduction (SCR) method is commercially applied in stationary installation using ammonia as a reductant.<sup>(12)</sup> Some work was carried out to adopt the use of ammonia in the mobile fleet<sup>(10)</sup>, but the impracticality of an on-board ammonia tank and the potential of reductant leakage were found to be detrimental. Therefore, experimentation using diesel fuel appeared to be favored over other reductants such as ammonia or urea<sup>(13,14)</sup>, even though it may not produce the highest possible NO<sub>x</sub> conversion.

Precious metal type catalysts such as Pt have typically given peak NO<sub>x</sub> conversion efficiencies at exhaust temperature levels of 200-250° C.<sup>(15)</sup> Base metal zeolite catalysts on the other hand, tend to provide peak NO<sub>x</sub> conversion efficiencies at 400° C.<sup>(15)</sup> In both precious metal

the catalytic converter. Although high conversion rates were possible at steady-state engine conditions associated with the narrow exhaust temperatures mentioned earlier, the overall EPA heavy-duty transient emission test resulted in about 15 percent NO<sub>x</sub> reduction, 25 percent particulate matter improvement, and 3 percent fuel consumption increase.<sup>(16)</sup>

The remainder of this paper will be devoted to EGR and particulate trap technology for the simultaneous reduction of NO<sub>x</sub> and particulate matter. Exhaust gas recirculation is certainly not a new technology for gasoline or light-duty diesel engines.<sup>(17)</sup> However, its application in heavy-duty diesels was not required. With the prospect of tighter NO<sub>x</sub> limits (2.0 g/bhp-hr or 2.7g/kWh), engine manufacturers are currently testing and developing sophisticated EGR systems for NO<sub>x</sub> control in direct-injected heavy-duty diesel engines.<sup>(18)</sup>

## EFFECT OF EXHAUST GAS RECIRCULATION ON NO<sub>x</sub> AND PM EMISSIONS

It has been shown that EGR is a very effective method for NO<sub>x</sub> reduction.<sup>(17)</sup> Two principles are believed to control the rate of NO<sub>x</sub> reduction when using EGR. The first premise is that of reducing peak combustion temperatures where EGR acts as a heat sink.<sup>(19)</sup> In this case, the heat absorbed by EGR is thought to be directly proportional to the product of EGR flowrate, the specific heat at constant pressure, and the temperature differential. Therefore, the absorbed heat (Q) can be expressed as follows:

$$Q = m^{\circ} \times p_{cp} \times (\Delta t) \quad (1)$$

The second and more important principle by which EGR reduces NO<sub>x</sub> emissions is displacing some of the oxygen induced with the fresh air charge. In a simplified way, thermal NO<sub>x</sub> is formed as a function of N<sub>2</sub>, O<sub>2</sub>, combustion temperature, and residence time in an environment of high NO<sub>x</sub> formation, modified by the dissociation of NO and NO<sub>2</sub>, i.e.

$$\frac{d(NO)}{dt} = K_1 (N_2, O_2) - K_2 (NO, NO_2) \quad (2)$$

where K<sub>1</sub> and K<sub>2</sub> are reaction rate constants that are strong functions of combustion temperature. Controlling any of the basic variables (N<sub>2</sub>, O<sub>2</sub>, T<sub>comb</sub>, and t<sub>r</sub>) would control the rate of NO<sub>x</sub> formation. Therefore, reducing the fresh charge air oxygen constant by means of EGR reduces NO<sub>x</sub> formation through reducing one of the four factors contributing to NO<sub>x</sub> formation. In addition, it can be concluded that EGR cooling would increase the temperature differential term in Equation 1, thus increasing the EGR heat absorbing capacity and further reducing NO<sub>x</sub>.

One of the negative consequences of using EGR is its adverse influence on particulate matter. A test conducted on a Series 60 11 L turbocharged and intercooled Detroit Diesel engine where EGR was systematically increased from Level A through D (given in Figure 5) shows the corresponding total particulate matter emission increase during a series of EPA heavy-duty transient tests. Analysis of the particulate samples indicated that the soluble organic fraction remained

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