

# Influence of High Fuel Rail Pressure and Urea Selective Catalytic Reduction on PM Formation in an Off-Highway Heavy-Duty Diesel Engine

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## ABSTRACT

The influence of fuel rail pressure (FRP) and urea-selective catalytic reduction (SCR) on particulate matter (PM) formation is investigated in this paper along with notes regarding the NO<sub>x</sub> and other emissions. Increasing FRP was shown to reduce the overall soot and total PM mass for four operating conditions. These conditions included two high speed conditions (2400 rpm at 540 and 270 Nm of torque) and two moderated speed conditions (1400 rpm at 488 and 325 Nm). The concentrations of CO<sub>2</sub> and NO<sub>x</sub> increased with fuel rail pressure and this is attributed to improved fuel-air mixing. Interestingly, the level of unburned hydrocarbons remained constant (or increased slightly) with increased FRP. PM concentration was measured using an AVL smoke meter and scanning mobility particle sizer (SMPS); and total PM was collected using standard gravimetric techniques. These results showed that the smoke number and particulate concentrations decrease with increasing FRP. However the decrease becomes more gradual as very high rail pressures. Additionally, the total PM decreased with increasing FRP; however, the soluble organic fraction (SOF) reaches a maximum after which it declines with higher rail pressure. The total PM was collected for the two 1400 rpm conditions downstream of the engine, diesel oxidation catalyst, and a urea-SCR catalyst. The results show that significant PM reduction occurs in the SCR catalyst even during high rates of urea dosage. Analysis of the PM indicates that residual SOF is burned up in the SCR catalyst.

## INTRODUCTION

The diesel combustion engine is the most energy-efficient powertrain for on and off-highway vehicles. However, diesel engines contribute significantly to the emissions of certain pollutants, particularly oxides of nitrogen, or NO<sub>x</sub>, and particulate matter (PM) (1). The generation of NO<sub>x</sub> has been shown to lead to the formation of tropospheric

formation of tropospheric ozone (and hence, urban smog), while PM is considered a health hazard. Because of these considerations, the U. S. Environmental Protection Agency (EPA) has been regulating exhaust emissions from on-highway diesels since 1988. Due to their greater efficiency and historically low fuel costs, diesel engines are the primary power units for off-highway applications, such as those used in agriculture, construction, logging, marine and rail transportation. As on-highway emissions become more reduced, the contribution to global NO<sub>x</sub> and PM emissions from off-highway sources becomes more pronounced. In 1996 the EPA began to regulate the off-highway sector. Both Tier 1 and Tier 2 emission levels were met without dramatic changes to the existing engine and exhaust hardware. Tier 3 standards may be met using cooled exhaust gas recirculation (EGR) in conjunction with advanced fuel delivery systems. However, it will be more challenging to meet Tier 4 emission levels for PM and NO<sub>x</sub> (beginning in 2011) without the application of advanced aftertreatment systems, such as urea-selective catalytic reduction (SCR) and lean-NO<sub>x</sub> traps (LNTs). Both SCR and LNT systems are used primarily to lower NO<sub>x</sub> emissions; they are not believed to contribute significantly to PM reduction. Many engine manufacturers are expected to employ a combination of advanced combustion (including high EGR and high rail pressures) and aftertreatment to meet Tier 4 limits for both NO<sub>x</sub> and PM (2).

## INFLUENCE OF FUEL INJECTION PRESSURE

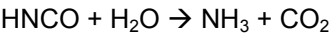
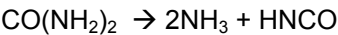
The influence of fuel pressure on fuel jet atomization and combustion has been studied by a number of researchers (3-5). Higher fuel injection pressures increase the degree of atomization of the fuel spray which results in smaller sized liquid droplets (3). This in turn results in better fuel evaporation and air entrainment and as a result improved oxidation of CO and nitrogen. Morgan et al, (3) have shown that fuel jet penetration increases with increasing

increases with increasing pressure up to a point threshold, after which penetration distance is constant.

Increasing fuel rail pressure has been shown to lower soot concentration in the exhaust (3). Studies have shown that the smoke number decreases in a nearly linear manner with increasing rail pressures. However, there is a corresponding rise in NOx emissions with increasing rail pressures. If the increase in NOx emissions associated with the high rail pressures can be mitigated using a aftertreatment device, then the overall emission reduction package for the engine will not necessitate a DPF to lower PM.

UREA-SELECTIVE CATALYTIC REDUCTION

Urea selective catalytic reduction is a process used to reduce NOx emissions in diesel engines (6-8). In the urea-SCR process an aqueous solution of urea, typically 32.5 wt% urea, is injected into the exhaust upstream of the catalyst. The injected solution becomes partially gaseous and the urea decomposition undergoes two reaction steps to produce ammonia (which is the actual reducing agent):



The ammonia formed from these hydrolysis reactions reacts with NOx to form elemental nitrogen (6). The process is highly temperature dependent. Poor conversion efficiencies are typically observed for temperatures below 300°C (9). As a result, urea-SCR cannot be employed during low load operations (such as idle). Several different catalyst materials have shown potential for urea-SCR systems and for each, the performance varies as a function of temperature. One commonly-used catalyst contains vanadia-titania (V-T) and has an optimum temperature operating window between 300 and 400°C.

For V-T catalyst systems the conversion of NOx to elemental nitrogen has been shown to be highly influenced by the NO2/NO ratio; peak conversion efficiency usually occurs near a NO2/NO ratio of 1 (10). Since over 90% of NOx emissions are NO, diesel oxidation catalysts (DOCs) are usually installed upstream of the urea-SCR system to convert a portion of the NO to NO2, thereby improving the NOx conversion performance of the catalyst. The presence of other exhaust products such as sulfur compound and unburned hydrocarbons (HC) may also negatively impact many catalyst based aftertreatment systems (11); however V-T based catalysts have demonstrated remarkable resistance to sulfur loading. The influence of HC on the urea-SCR process is less understood. However, with the advent of high EGR and high rail pressures on newer diesel engines, the influence of unburned HC on urea-SCR performance needs to be examined.

In this project a 2004 John Deere 4.5 Liter 4045H was installed with an open controller that enabled rail pressure and injection timing manipulation. The engine was mounted to a General Electric DC dynamometer capable of adsorbing and motoring 300 and 250 horsepower, respectively. The project goal was to investigate the feasibility of an approach whereby the PM emissions were reduced by raising the fuel rail pressure. To mitigate the high NOx emissions resulting from increased rail pressure, a urea-SCR system was mounted to the engine exhaust. The rationale for this approach is that only one aftertreatment device (urea-SCR) is needed to meet Tier 3 and potentially Tier 4 emissions. The utilization of urea-SCR also means that the fuel efficiency of the engine is not significantly impacted. However, in order for this approach to be considered acceptable, it is necessary to show that the urea-SCR process, itself, does not contribute significantly to the overall PM mass. Understanding how the urea, ammonia, and catalyst interact with the exhaust particles will help engine manufacturers assess the feasibility of combining high rail pressures with urea-SCR to meet emissions targets for PM and NOx.

EXPERIMENTAL METHOD

A 4.5L John Deere engine (Powertech 4045H) was used as the experimental powertrain for this study. This engine is equipped with a common rail fuel system and a control package capable of controlling key fuel injection parameters (timing, duration, fuel rail pressure, and injection frequency). This engine does not contain EGR. Performance data and engine specifications are shown in Table 1.

Table 1. General engine specifications and performance.

| Specification/Performance     | Value            |
|-------------------------------|------------------|
| Number of Cylinders           | 4                |
| Number of valves per cylinder | 4                |
| Compression Ratio             | 17.0:1           |
| Engine Type                   | In-line, 4-cycle |
| Rated Power @ 2400rpm         |                  |
| Intermittent, kW              | 129              |
| Continuous, kW                | 116              |
| Peak Torque, Nm               | 645              |

The intake air was conditioned to maintain air and dewpoint temperatures around 23°C and 13°C, respectively.

The engine exhaust was configured to incorporate a diesel oxidation catalyst (DOC), urea injector, and a urea-SCR catalyst as shown in the Fig. 1 schematic. The DOC and SCR catalysts were provided by Johnson-Matthey. The primary purpose of the DOC is to oxidize a portion of NO to NO<sub>2</sub>, but the DOC also effectively oxidizes unburned HC and CO as well. The SCR catalyst formulation is based on a vanadia-titania composition. An ultra-low sulfur diesel fuel (BP-15) was used during the experimental evaluations. Urea was injected into the exhaust using an air assisted Bosch (AdBlue) urea metering system developed for commercial vehicle applications. The unit is controlled through an integrated electronic control module (ECM) capable of precise metering of urea under stationary and transient operation.

The exhaust was sampled at the locations labeled A, B, and C in the diagram in order to ascertain the additional influences of a DOC and the urea-SCR catalysis on PM emissions. Total PM and gaseous emissions were measured at all three locations, but the smoke number and SMPS results were taken from the engine-out location (labeled A in the diagram) only.

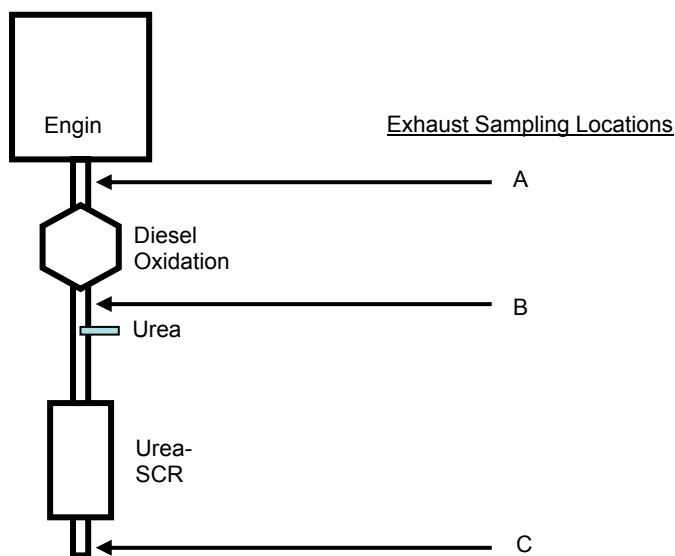


Fig. 1. Schematic showing exhaust configuration including sampling locations.

For each sampling location shown in Fig 1, the raw exhaust was sampled for particulate and gaseous analysis. For gaseous emission measurements the exhaust was filtered to remove exhaust particulates and sent to a standard emissions bench. The PM was measured using gravimetric filter collection, scanning mobility particle size (SMPS) analysis, and smoke meter methods. SMPS and gravimetric measurement required exhaust dilution, while the smoke meter sampled directly from the exhaust.

## GASEOUS EMISSION ANALYSIS

Standard heated chemiluminescence and flame ionization instruments were used for measuring the exhaust levels of NO<sub>x</sub> and unburned hydrocarbons, respectively, while the CO and CO<sub>2</sub> concentrations were measured using non-dispersive instruments. Exhaust oxygen was measured using a standard parametric detector. The exhaust sample entering the PMD and NDIR instruments was chilled to prevent moisture condensation in these instruments.

## PARTICULATE EMISSION ANALYSIS METHODOLOGY

The particulate emissions were evaluated using standard gravimetric, scanning mobility particle size (SMPS) analysis, and smoke number. The filtered smoke number (FSN) measurements were taken using an AVL smoke meter to assess soot concentration while the particulate concentration and size distribution were determined using the SMPS (TSI, Inc.). The smoke meter and SMPS were used to characterize the relationship between engine PM and fuel injection pressure, while the total PM mass was used solely to assess the impact of the urea-SCR system on the formation and chemistry of the total exhaust PM. The SMPS instrument required a dilute stream of exhaust for proper measurement. A micro-dilution tunnel was configured based on the Abdul-Khalek-Kittleson design (12) to provide an 8:1 dilution ratio for SMPS analysis. The temperature in the tunnel was maintained at 50°C and the residence time was estimated to be between 1 and 3 seconds. No attempt was made to control the relative humidity in the tunnel. However, the relative humidity is expected to be around 1% based on the calculated exhaust humidity and dilution air.

Total PM was determined using 70mm Pallflex membrane filters (type EMFAB TM0HI20-WW). Filter collection was accomplished using a BG-3 micro-dilution tunnel (Sierra Instruments). Typically, at least three filters were collected for each sampling location in the exhaust (see Fig. 1) and for each operating condition. After weighing each filter to determine total PM mass, the filters were extracted using supercritical CO<sub>2</sub> and a toluene co-solvent. The concentrates from were then analyzed on a HP 5890/5970 gas chromatograph-mass spectrometer (GC-MS) using a Restek RTX-5 30 meter column for the species separation.

## EXPERIMENTAL PROTOCOL

During the study period, no EPA-approved transient Federal Test Procedure existed for heavy-duty off-highway diesel engines. To properly assess emissions from these engines, the ISO 8178 steady-state test protocol was used as the standard. As shown in Table 1, there are 8 operating points; four at rated speed (2400 rpm), three at intermediate speed (1400 rpm) and idle. Weighting is highest at the high speed and load set points and at idle.

Table 1. Weighting factors of the ISO 8178 Type C1 test cycle.

| Mode | Torque, Nm | Speed, rpm | Weighting Factor |
|------|------------|------------|------------------|
| 1    | 540        | 2400       | 0.15             |
| 2    | 405        | 2400       | 0.15             |
| 3    | 270        | 2400       | 0.15             |
| 4    | 54         | 2400       | 0.10             |
| 5    | 650        | 1400       | 0.10             |
| 6    | 488        | 1400       | 0.10             |
| 7    | 325        | 1400       | 0.10             |
| 8    | Idle       | Idle       | 0.15             |

For the purposes of this study, two high speed modes (1 and 3) and two medium speed modes (6 and 7) were selected for evaluation. These points were selected since they provided a good opportunity to evaluate fuel-load and speed effects on combustion and subsequent NO<sub>x</sub> and PM formation. Also, during these four modes the SCR catalyst temperature was above the minimum temperature required for optimum performance.

## EXPERIMENTAL RESULTS

### ENGINE PERFORMANCE

One of the most important parameters in evaluating combustion chemistry is the air-fuel (A/F) ratio (1). The resulting bulk combustion and flame temperatures and the formation of the exhaust chemistry are highly influenced by the ratio of the mixture of air and fuel. For each test condition, the A/F ratio was observed to decrease slightly with increasing rail pressure, but not enough to be deemed significant. The exhaust temperature was also observed to drop between 5 to 10 degrees Celsius from the baseline setting to the maximum rail pressure values, depending on the test condition. Table 2 depicts the baseline A/F ratios for the four engine conditions investigated in this study.

Table 2. Baseline A/F ratios for each of the experimental modes investigated in this study.

| Mode | Torque, Nm | Speed, rpm | A/F Ratio   | Exhaust Temp. (°C) |
|------|------------|------------|-------------|--------------------|
| 1    | 540        | 2400       | 24.6 (0.11) | 425                |
| 3    | 270        | 2400       | 34.6 (0.20) | 329                |
| 6    | 488        | 1400       | 24.5 (0.31) | 500                |
| 7    | 325        | 1400       | 29.6 (0.38) | 409                |

For each speed setting the A/F ratio decreases with increasing torque due to the larger quantity of fuel required to reach the torque set point. (The standard deviation associated with the A/F ratio is shown in the parentheses.) Likewise the exhaust temperature rises as more fuel is injected into the cylinder to create the higher torque. Interestingly the A/F ratios for both modes 1 and 6 are nearly the same.

The Brake Specific Fuel Consumption (BSFC) was observed to decrease with increasing rail pressure for each of the four operating conditions as shown in Fig 2. Higher injection pressures increase fuel jet penetration and atomization of the fuel into smaller droplet sizes which improves the efficiency of combustion. At very high rail pressures the BSFC begins to level off for the 1400 rpm conditions. In contrast the 2400 rpm points show a steady drop in BSFC with rail pressure over the entire range.

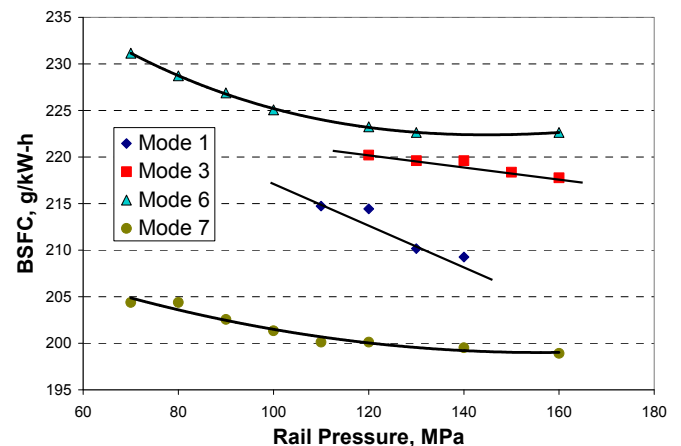


Fig. 2 BSFC results for each of the operating conditions as a function of rail pressure.