

Engine Technologies for Clean and High Efficiency Heavy Duty Engines

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ABSTRACT

Diesel engine manufacturers have faced stringent emission regulations for oxides of nitrogen and particulate emissions for the last two decades. The emission challenges have been met with a host of technologies such as turbocharging, exhaust gas recirculation, high-pressure common rail fuel injection systems, diesel aftertreatment devices, and electronic engine controls. The next challenge for diesel engine manufacturers is fuel-economy regulations starting in 2014. As a prelude to this effort the department of energy (DOE) has funded the *Supertruck* project which intends to demonstrate 50% brake-thermal efficiency on the dynamometer while meeting US 2010 emission norms. In order to simultaneously meet the emission and engine efficiency goals in the cost effective manner engine manufacturer have adopted a systems approach, since individual fuel saving technologies can actually work against each other if fuel economy is not approached from a total vehicle perspective.

In this present work an optimization study was undertaken involving combustion improvements, aftertreatment and waste heat recovery technologies. The present paper summarizes experimental results of this effort around two typical driving cycle modal points. The selected engine architecture dictated the technology trade-off between the aftertreatment, combustion and waste recovery approaches. This paper examines the high and low temperature combustion systems associated with the high and low NO_x approaches respectively and the engine hardware for each configuration. Combustion improvements in the form of increasing the rail-pressure of injection and waste-heat recovery in the form of electrical turbo-compounding were examined for the high and low-NO_x combustion modes.

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INTRODUCTION

Diesel engines have changed dramatically in the last few decades in their emission, fuel economy, complexity and cost. These changes were initiated with the onset of emission regulations in 1988. In 1988, the required emission levels for oxides of nitrogen (NO_x) and soot were 10.7 g/bhp-hr and 0.6 g/bhp-hr respectively. These emission levels have been continuously reduced and the heavy duty diesel engines for 2010 are being regulated to have a tail-pipe NO_x and soot levels of 0.2 g/hp-hr and 0.01 g/hp-hr respectively. These emission norms have been met with improvement in all the major engine systems such as air, fuel, aftertreatment and engine controls. [Table 1](#) shows the typical system characteristics required to meet these emission levels.

The implementation of such an array technologies has enabled to make impressive strides in meeting these emissions; however these gains have come with a compromise in the brake thermal efficiency (BTE) as shown in [Figure 1](#). Combustion techniques such as retarding the

injection timing have limited the in-cylinder NO_x emissions but compromised the BTE as indicated in [Figure 1](#). Similarly, the use of aftertreatment devices such as diesel-particulate filter (DPF) has also led to increased engine back pressure and thereby negatively impacted the BTE.

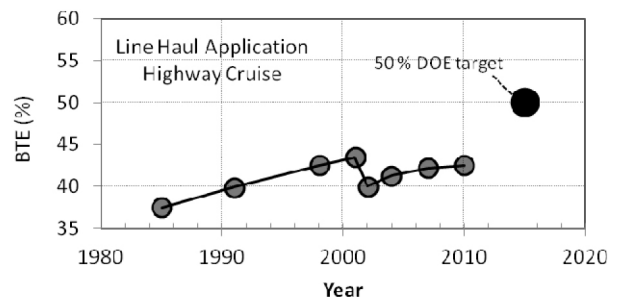


Figure 1. Historical brake-thermal efficiency trend [2]

The Department of Energy has recognized the need to maintain the BTE gains of the diesel engine while

Table 1. Comparison of engine emission levels and technology content for model year 1988 and 2010 engines [1]

	1998	2010
NOx (g/hp-hr)	10.7	0.20
Soot (g/hp-hr)	0.6	0.01
Fuel System	Mechanical Injection	Common-Rail up to 2500 bar Multiple Injections Piezo or solenoid injector
Air System	Single stage	Two fix-stage turbochargers Single stage vane turbocharger
Heat Exchangers	Charge-Air Cooler	Inter-stage cooler Charge-air cooler Advanced EGR cooler system
Aftertreatment system	None	Diesel oxidation catalyst Diesel particulate filter NOx after-treatment

Table 2. Technology matrix for the engine brake thermal efficiency improvement

	TECHNOLOGIES EVALUATED		TECHNOLOGIES TO BE EVALUATED
	High Temp Combustion	Low Temp Combustion	
COMBUSTION	Inj Press ~ 2500 bar Peak Cyl Press ~ 220 bar CR ~ 17-18	Inj Press ~ 3000bar Peak Cyl Press ~ 220bar CR ~ 16-17	
AIR MANAGEMENT SYSTEM	Two Stage Fix Geometry	Two Stage Variable Nozzle	Variable valve actuation
BASE ENGINE	Friction reduction Variable speed water pump Variable displacement oil pump		
WASTE HEAT RECOVERY	Electrical turbocompounding		Organic Rankine cycle

maintaining low emissions, and has therefore initiated the “Supertruck” project. Four original equipment manufacturers will be trying to demonstrate 50% brake- thermal efficiency on dynamometer and 50% improvement in vehicle freight efficiency (as measured in ton-miles/gallon). As part of the engine work, **Navistar** will implement combustion and aftertreatment improvements, base engine improvements and waste heat recovery as shown in [Table 2](#) to meet the BTE targets. [Table 2](#) also shows the list of technologies that will be evaluated in each of the categories. The paper discusses a [high](#) and [low temperature combustion approach](#), balancing the tradeoff between NOx emissions compliance with aftertreatment and in-cylinder and its impact on engine efficiency.

This paper focuses on **Navistar's** Supertruck program with its **MAXXFORCE13** engine. The paper shows results obtained to date with an *improved fuel injection system matched to the combustion chamber* for the high and low

temperature combustion approaches to raise the engine efficiency near 45%. It then proceeds to describe further improvement to the engine efficiency, near 46.5%, with the addition of a specially designed *electrical turbocompounding device*. The “Technologies to be evaluated” will be made available at a later date as the Supertruck project continues [3]. [Table 3](#) gives the base configuration of engine and when compared with [Table 2](#) shows the differences in specification of important systems as the fuel-injection system as the combustion approached the high- temperature or the low-temperature combustion.

EXPERIMENTAL SETUP

Test Engine and Test Conditions

The engine selected for the Supertruck project was the 2010 MY **MAXXFORCE13**. The base configuration is shown in [Table 3](#).



Table 3. Base configuration for the engine selected for the study.

Displaced volume	12.4 Liter
Stroke	166 mm
Bore	126 mm
Connecting Rod	251 mm
Compression Ratio	17.2
Fuel System	Common Rail Inj Pressure ~ 2200 bar
Air System	2-stage turbocharger Inter-stage cooler Charge-air cooler
After-treatment System	DOC + DPF

Table 4. Baseline efficiency and emissions

	Point A	Point B
N (rpm)	1215	1520
BMEP (bar)	17.3	11.5
BSNO_x (g/bhp-hr)	0.43	0.33
BSSoot (g/bhp-hr)	0.02	0.05
BTE (%)	41.4	37.8

The Supertruck requirement is that a BTE of 50% be demonstrated on the dynamometer at “load representative of level road at 65 miles per hour with a gross vehicle weight of 65,000 lbs”. Based on this requirement the **modal points** of **A** and **B** shown below in [Table 4](#) were selected for evaluating the merits of each engine technology. Points reflect the selection of various transmissions according to common drive cycles in the vehicle. The baseline emission levels and the efficiency are included in the table.

Test Setup

The system layout diagram for the engine is shown in [Figure 2](#). The **MAXXFOCE13** represents the state-of-the-art diesel platform. The engine is equipped with a common rail fuel injection system with a maximum rail pressure of 2900 bar. The air system consists of a two-stage turbocharger with a charge-air cooler after each compressor stage. A pneumatically actuated by-pass across the high-pressure turbine is used to reduce the back-pressure at high-speed and high-load conditions. For the [Low-Temp Combustion](#) diesel engine tests the turbocharger system was modified by incorporating variable nozzles for the high-pressure turbine. The system includes waste heat recovery in the form of electrical turbocompounding (ETUCO). An electrically actuated by-pass is provided across the ETUCO device to optimize the system performance. The engine uses a two-stage EGR cooler, where in the first stage the exhaust gas is cooled using engine coolant and in the second stage the exhaust gas is cooled by a secondary low temperature loop.

Conventional diesel fuel with a cetane index (ASTM D4737) of 43.1 was used for the testing. The gaseous pollutants in the exhaust were measured using a MEXA 7100

series emission analyzers from Horiba. The system included a heated flame ionized detector, non-dispersive infrared analyzer and chemiluminescence detector for total hydrocarbons, CO/CO₂ and oxides of nitrogen respectively. The CO₂ measurement probe was also included at the intake manifold. The EGR ratio at any operating condition was expressed as the ratio of the intake to the exhaust CO₂ concentration. The smoke was measured by means of a classical filter paper method with resolution of 0.01FSN or soot concentrations of 0.1mg/m³. The cylinder pressure was measured with a piezo type transducer and was used to calculate cycle indicated torque and the heat release trace.

Combustion Approaches

The baseline engine out NO_x emissions were approximately 0.35gNO_x/bhp-hr, higher than the 0.2 limit required for meeting the 2010 standards. Two distinct pathways were adopted to meet the 0.2g requirement representing high (or hot) temperature and low (or cold) temperature combustion.

[The high temperature combustion](#) represents conventional diesel combustion where the local equivalence ratio and local temperature yield in-cylinder NO_x with limited soot production. The engine out NO_x for the high temperature combustion is treated with a selective catalyst and ammonia as reductor to attain a tailpipe value below 0.2g/bhp-hr.

[The low temperature combustion](#) was implemented by means of charge dilution with EGR, appropriate combustion phasing, improved cooling, boosting system, enhanced combustion matching, and with a more capable higher injection pressure system. Conceptually, this is similar to the