

COTS Engine Conversion

2011-01-0122

Published
04/12/2011Gary L. Hunter
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doi:10.4271/2011-01-0122

ABSTRACT

Modern heavy duty Commercial Off The Shelf (COTS) diesel engines represent the state of the art in engine performance and design features, control architecture, and the use of light weight high strength materials. These engines, with appropriate adaptation for operation on military fuels, make excellent choices for defense applications.

This paper reviews the selection and modification of a COTS engine suitable for potential defense applications. Considerations for robust operation of the engine on JP8, engine system modifications appropriate for military vehicle emission requirements, reduction of engine system heat rejection, and optimization of engine efficiency will be discussed using example data from converting a 2011 model year COTS engine for defense applications.

This work was funded by the Tank Automotive Research, Development and Engineering Center (TARDEC) from Broad Agency Announcement (BAA) Topic 15, awarded in 2009.

INTRODUCTION

Modern heavy-duty on-highway diesel engines have evolved based on regulatory demands for lower emissions and commercial pressures to improve fuel efficiency, life cycle costs, and various performance criteria. To take advantage of the capabilities these state of the art commercial off-the-shelf (COTS) diesel engines offer, defense system providers seek solutions to adapt these products to military applications. Goals for this adaptation include maintaining or improving the high thermal efficiency of these engines, reducing the amount of heat rejection relative to the baseline COTS product, and meeting applicable emissions expectations for defense uses.

These defense applications also require compatibility with the fuels such as Jet A, JP-8, JP-5, and high sulfur diesel fuel available in military operation theaters. Such fuels can have markedly different properties than the ultra-low sulfur diesel (ULSD) fuel COTS engines are developed to utilize. These differences in fuel properties must be considered in the hardware and calibration adaptation to defense applications.

Once these considerations have been successfully addressed, the adapted COTS diesel engines can then be considered for application in defense related ground vehicle and power system applications.

This paper first gives a brief history of the emission boundary conditions and technology solutions applied to COTS heavy duty diesel engines over the last 15 years, followed by a description of current military fuel and emission requirements. The generic technical approach to adapting a modern COTS engine to defense use is then described. A specific example of adapting a model year (MY) 2011 state of the art heavy-duty diesel engine from COTS configuration to defense application needs, performed as part of the program, is then detailed.

COMMERCIAL ENGINE BOUNDARY CONDITIONS

Much of the development effort applied to COTS heavy-duty on-highway diesel engines over the past three decades has focused on providing commercially viable engine system solutions while satisfying increasingly stringent emission requirements, especially for oxides of nitrogen (NOx) and particulate matter (PM) emissions. These emission requirements have not only driven engine system changes, but changes to the fuel specification as well. These changes have had particular impact on engine system selection and development since 1994.

Figure 1 depicts the history of NOx and PM emissions legislation for US heavy duty on-highway products from 1994 to the current 2010 standards [1]. While noting that the 1994 levels already represented an approximately 60-75% reduction from pre-regulated (c.1970) NOx and PM levels, the current 2010 requirements yield a further 95% reduction in NOx and 90% reduction in PM levels compared to those of 1994.

It should also be noted that due to a Consent Decree settlement with the Department of Justice, many of the US engine manufacturers agreed to implement the 2004 emission limits early, taking effect October 2002.

The progression of emission test cycles used for certification and the fuel sulfur levels allowed for US on-highway diesel fuel are also shown in Figure 1. Enhancements to the emission test process were made commencing with implementation of the 2004 requirements. These additional test cycles were implemented to better ascertain the impact of various emission control features during both urban (transient) and rural (more steady-state) operating regimes. These additional tests were an artifact of the development and resolution resulting in the Consent Decree.

The maximum allowed sulfur content of on-highway diesel fuel has also been reduced with time, as shown in Figure 1. These reductions were implemented both to reduce the contribution of sulfate emissions and to enable utilization of more advanced emission control technology as described below.

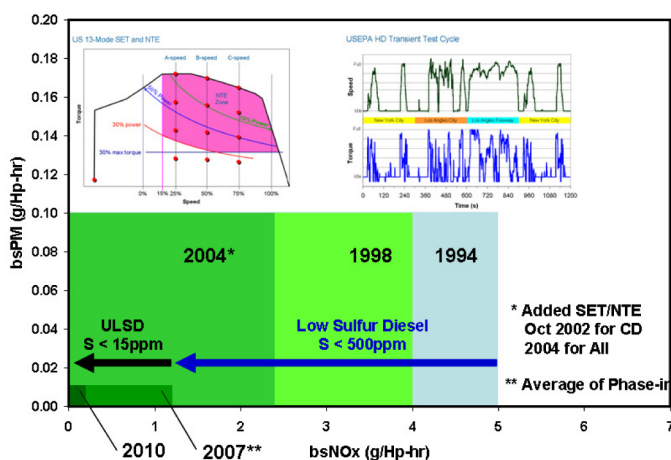


Figure 1. US Heavy Duty Emissions History

For a given engine hardware configuration, reducing engine out NOx generally results in increases to both engine out PM and fuel consumption. Enhancements to engine sub-system capabilities are required to realize the legislated simultaneous reductions in NOx and PM. Examples of how these

technologies were applied to reduce NOx and PM emissions from 1994 through 2010 are depicted in Figure 2.

Prior to 2007, emphasis was placed on in-cylinder control of NOx and PM. The primary engine particulate control mechanisms employed was to utilize more capable fuel injection systems having both higher injection pressure and in some cases capable of delivering multiple injection events within an engine cycle, thus enhancing the mixing of fuel and air resulting in lower soot formation. Application of increased fuel system capability continues to be the primary path used to reduce the engine out particulate levels, with current fuel injection systems typically capable of delivering 2000bar and three or more injection events.

The control of engine out NOx emissions is focused on management of the peak temperatures realized during the combustion event. Prior to the 2004 emission requirements, retarding the injection event and using improved charge air cooling systems to lower the intake manifold air temperature provided sufficient NOx reduction and was widely used. Retarding the injection event causes the combustion event to occur later in the expansion process, negatively affecting the gross efficiency of the engine. The Atkinson or Miller cycle (asymmetric compression / expansion using late intake valve closing (LIVC)) was also used on a limited number of products. However, these technologies were ultimately limited in the amount of NOx reduction that could be realized without serious impacts on engine efficiency, durability or the maximum power and/or torque capability of the engine.

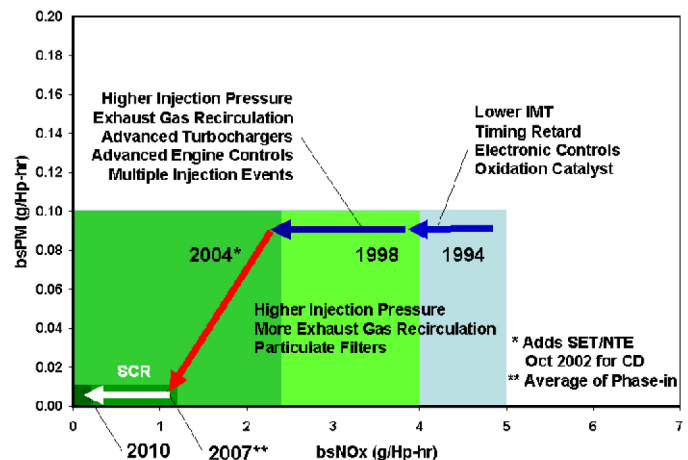


Figure 2. Emission Control Technology Solutions

Cooled Exhaust Gas Recirculation (EGR) was widely employed to meet the NOx levels dictated by the 2004 standards. The advent of cooled EGR also drove the application of more capable turbomachinery and higher peak firing pressure capability through improved design and materials to maintain power density, as shown in Figure 3. EGR also drove a need for advanced engine controls and the

need for more capable fuel injection systems to utilize the now diluted oxygen content of the air and EGR mixture. The synergies between the dilution of oxygen available for combustion afforded by EGR to control NO_x and the faster mixing rates available from high injection pressures to control PM yielded a path to lower NO_x while minimizing adverse effects on PM and fuel consumption. This trend continued through the development for the 2007 emission standards; higher EGR rates to achieve the NO_x levels required along with higher injection pressures and multiple injection events to mitigate the impact to engine out PM levels.

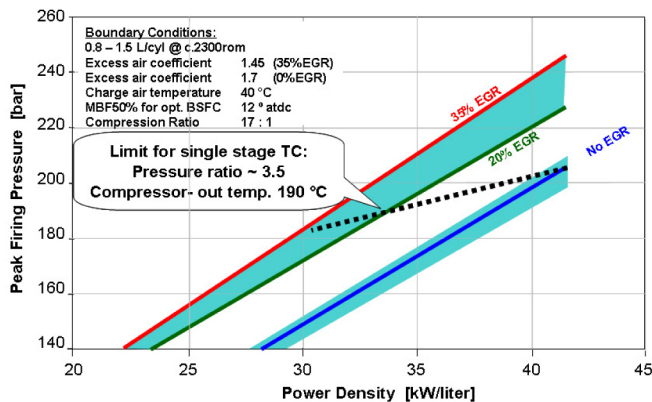


Figure 3. Impact of EGR on Peak Firing Pressure

Although EGR is an effective and efficient means of reducing NO_x, the increase in heat rejection due to the cooling of EGR is a significant vehicle application consideration. [Figure 4](#) shows the impact of increasing EGR rate on the heat rejection to the vehicle cooling system at rated power. Most of the increased cooling system load is from the EGR cooler, but some increase in the air intercooler heat load can occur, owing to the higher boost levels and resulting turbocharger compressor discharge temperatures associated with providing enough fresh air to control PM and smoke levels as EGR is increased.

[Figure 2](#) also depicts the implementation of exhaust aftertreatment devices, starting with the use of diesel oxidation catalysts (DOCs) in 1994. DOCs were first used to reduce the amount of soluble organic compounds (comprised of HC and lube oil emissions) that were measured as PM emissions. Usually, such catalysts are very effective at converting the SO₂ found in diesel exhaust from the oxidation of the sulfur compounds in the fuel, to sulfates. The reduction in fuel sulfur levels to 500ppm implemented in 1994 helped mitigate the unwanted increases in sulfate formation typically associated with such devices.

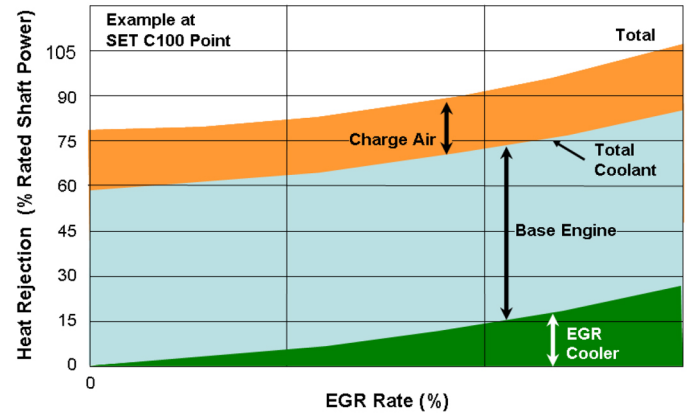


Figure 4. Impact of EGR on System Heat Rejection

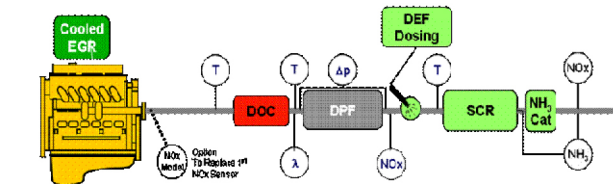
Diesel particulate filters (DPFs) used to trap and oxidize the agglomerated carbon particulate (commonly referred to as 'soot') became widely applied as part of the technical solution to meet the 0.01g PM/HP-hr standard first implemented in 2007. These devices first mechanically capture the particulates in the engine exhaust, and then oxidize them in a continuous reaction or, as required, a forced regeneration event. The continuous regeneration uses both the oxygen in the exhaust gas as well as the NO₂ formed by the DOC. NO₂ is a very effective oxidation agent for diesel soot, and the many DOCs have been formulated to provide feed gas to the DPF to maximize the continuous oxidation of soot in the DPF.

In the event that the continuous oxidation of soot collected in the DPF can not keep pace with the sustained soot production rate of the engine, a forced regeneration is required to oxidize the soot collected in the DPF. If the trapped mass of soot is allowed to build, the exhaust restriction of the DPF will continue to increase, adversely affecting engine operation and performance. A forced DPF regeneration can be initiated many ways, but the key result is that the temperature of the DPF is raised and managed to support a controlled oxidation of the collected soot, returning the DPF flow and restriction characteristics to nearly their 'new DPF' levels.

To attain the NO_x levels dictated by the USEPA 2010 standards, most manufacturers have adopted a combination of in-cylinder NO_x control using EGR and NO_x aftertreatment based on Selective Catalytic Reduction (SCR). SCR systems utilize a reductant compound mixed with the NO_x containing exhaust gas. This reductant reacts with the NO_x on a catalytic surface, typically an iron zeolyte or copper zeolyte, to convert the NO_x and reductant to N₂, O₂ and water. The source of the reductant used in the US is Diesel Emissions Fluid (DEF), which is a mixture of urea and water. When injected into the exhaust stream, the urea is hydrolyzed to form ammonia, which is ultimately the reductant used in the SCR catalyst. The dosing of DEF to the exhaust gas must be carefully

matched to the NO_x production rate of the engine and the NO_x and ammonia storage and utilization capacity of the SCR catalyst. If not carefully controlled, either not enough NO_x will be reduced (too little DEF dosed) or excess ammonia will be formed and released (ammonia slip).

Figure 5 depicts the overall engine and exhaust system of a typical MY2010 COTS engine.



Typical 2010 COTS System Description

- Downstream Fuel Dosing for DPF Regeneration as Option
- DOC: Low Temperature NO₂ 'Production', Exothermic Heat Formation
- Coated DPF Upstream of DEF Doser and SCR
- SCR Catalyst with NH₃ Slip Catalyst
- Required Sensors: NO_x, Temperatures, Lambda, ΔP, DEF Quality

Figure 5. Typical MY2010 COTS Emission Solution

Figure 6 depicts the fuel efficiency impact that meeting the emission requirements have had on a typical heavy-duty diesel engine. The chart shows the minimum bsfc (best efficiency) actually improved through 1999 as emissions, especially NO_x, were reduced, breaking the classic NO_x-bsfc trade-off paradigm. This was because improved engine designs, implementation of modern high strength materials to deal with the higher thermal and mechanical loads, improved sub-system capabilities, and sophisticated engine control algorithms were applied. From 2000 through 2004 continued application of new technologies prevented the degradation in best fuel economy from being even greater than what was realized. Continued application of technologies allowed the 50% reduction in NO_x levels dictated for 2007 from 2004 to be achieved without further fuel consumption penalty. Fuel consumption is again improving for 2010, even though the NO_x level is reduced a further 80%.

Controlling emissions and engine efficiency are closely related and balanced during the engine development process. For modern COTS engines, advances in engine and exhaust after-treatment systems provided technologies that allow continued engine efficiency improvements. Taking maximum advantage of the appropriate engine technologies while adapting COTS engines to military fuels is key to providing readily available and efficient powertrains for use in defense applications.

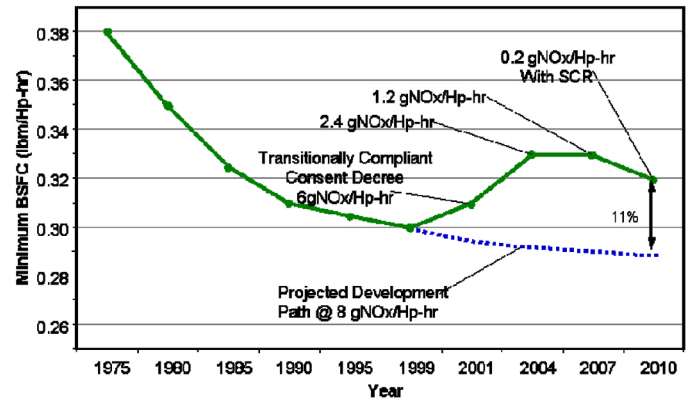


Figure 6. Impact of Emission Regulations on Heavy-Duty Engine Minimum BSFC Levels [2]

MILITARY FUELS AND SPECIFICATIONS

The US Army encountered winter fuel waxing issues with commercial diesel fuel (DF-2 or NATO F-54) in the early 1980s when the M1 battle tank was first introduced. The solution to the issue was to blend DF-2 with an aviation fuel, either JP-8 (NATO F-34) or JP-5 (NATO F-44) on a 50:50 proportion. This "M1 Fuel Mix" was widely accepted and referred to as NATO F-65 fuel. The US Army specified JP-8 as an acceptable alternative to DF-2 in 1986. Two years later the DOD issued a directive called the Single Fuel Forward Concept which designated JP-8 as the primary fuel for all land and air forces in order to improve logistics.

JP-8 is a kerosene blend fuel intended primarily for aviation turbine engines. JP-8 is similar to Jet A-1 fuel (NATO F-35), which is used worldwide except in the US, but has three additional additives: Fuel system icing inhibitor (FSII), corrosion inhibitor/lubricity enhancer (CI/LE), and static dissipater additive (SDA). Jet A, another similar fuel, has a higher freeze point than Jet A-1 and is used for commercial aviation. JP-5 is also similar to JP-8, but has a higher flash point and is used by the US Navy for safety reasons.

Engine performance and durability are somewhat dependant on the fuel used due to differences in viscosity, heat content, and freeze and flash points. The properties for the fuels of interest to this project are shown in [Table 1](#).