**2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM**
**Power and Energy Mini-Symposium**
**AUGUST 17-19 DEARBORN, MICHIGAN**

# Diverging Requirements: Solving Future Challenges for COTS Engine Conversion from USEPA 2010 to Military Specification

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**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 as funded by Broad Agency Announcement (BAA) Topic 15.*

## 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 BAA Topic 15 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 3 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 2001.

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.

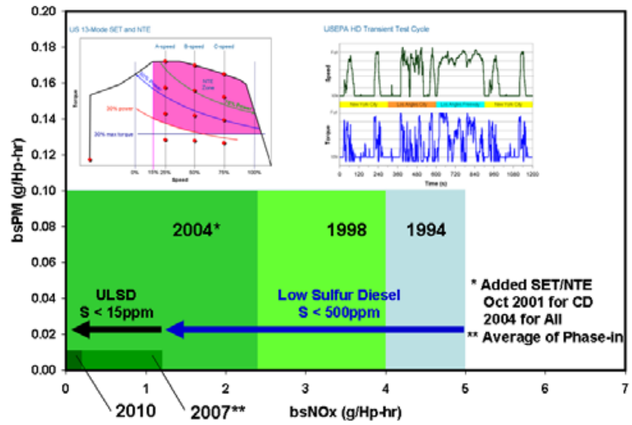


**Figure 1 - US Heavy Duty Emissions History**

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.

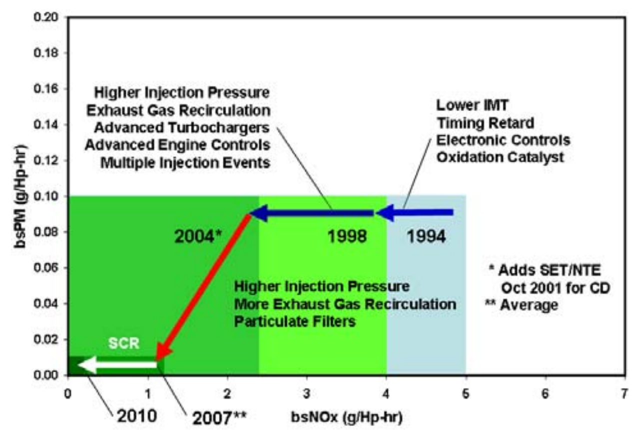


**Figure 2 - Emission Control Technology Solutions**

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 3 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.

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 NOx and the faster mixing rates available from high injection pressures to control PM yielded a path to lower NOx 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 NOx levels required along with higher injection pressures and multiple injection events to mitigate the impact to engine out PM levels.

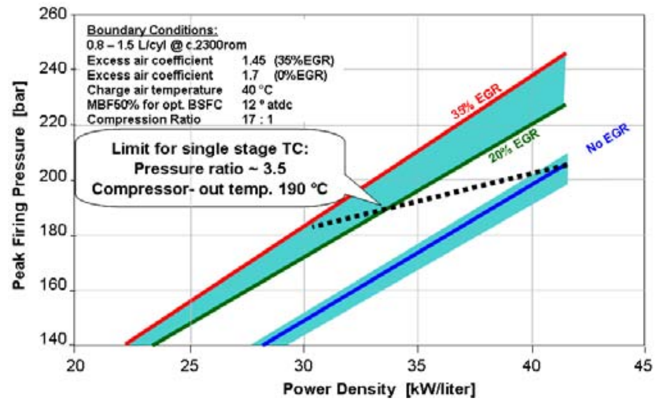


**Figure 3 - Impact of EGR on Peak Firing Pressure**

Although EGR is an effective and efficient means of reducing NOx, 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.

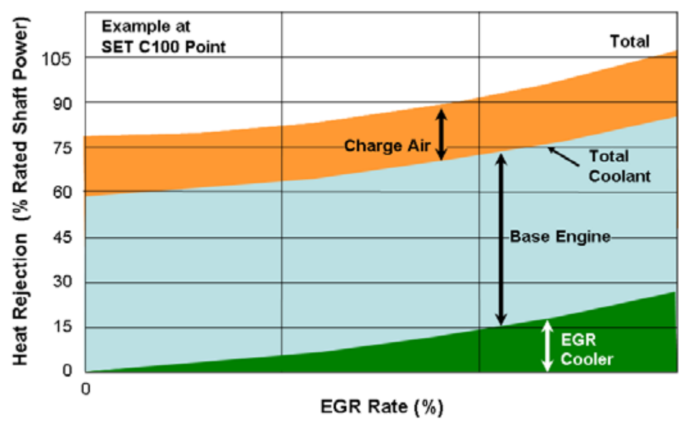


**Figure 4 - Impact of EGR on System Heat Rejection**

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 $SO_2$ 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.

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 $NO_2$ formed by the DOC. $NO_2$ 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 NOx levels dictated by the USEPA 2010 standards, most manufacturers have adopted a combination of in-cylinder NOx control using EGR and NOx aftertreatment based on Selective Catalytic Reduction (SCR). SCR systems utilize a reductant compound mixed with the NOx containing exhaust gas. This reductant reacts with the NOx on a catalytic surface, typically an iron zeolyte or copper zeolyte, to convert the NOx and reductant to $N_2$, $O_2$ 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 NOx production rate of the engine and the NOx and ammonia storage and utilization capacity of the SCR catalyst. If not carefully controlled, either not enough NOx 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.

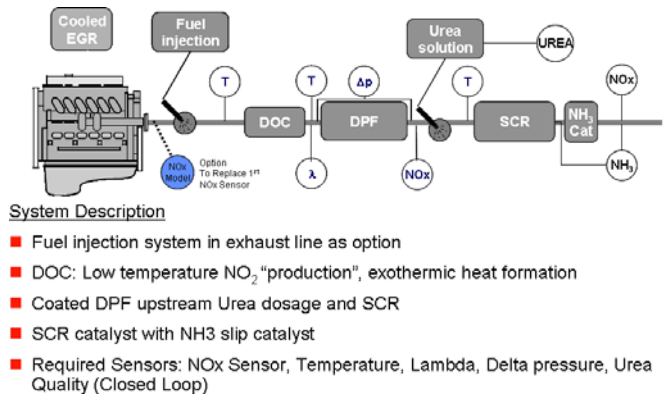


**Figure 5 - Typical MY2010 COTS Emission Solution**

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 NOx, were reduced, breaking the classic NOx-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 NOx levels dictated for 2007 from 2004 to be achieved without further fuel consumption penalty. Fuel consumption is again improving for 2010, even though the NOx 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.

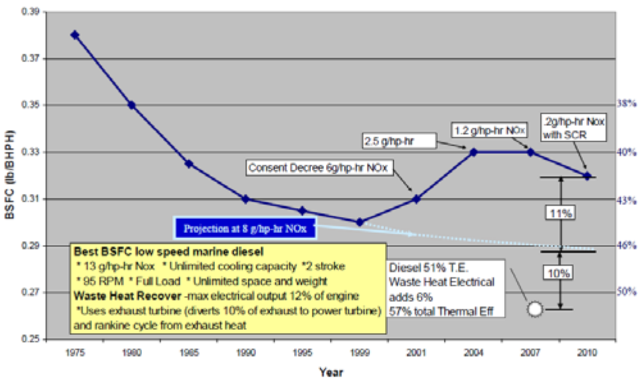


**Figure 6 – Impact of Emission Regulations on Heavy–Duty Engine Minimum BSFC Levels [2]**

**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 3 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.

| Fuel type | JP-8 | DF-2 | Jet A-1 | JP-5 |
|---|---|---|---|---|
| NATO Designation | F-34 | F-54 | F-35 | F-44 |
| Viscosity (@ 40°C, $mm^2/s$) | 1.0 – 1.7 | 1.9 – 4.1 | 1.6 | 1.5 |
| Freeze Point (°C) | -47 | -12 | -47 | -46 |
| Flash Point (°C) | 38 | 60 | 38 | 60 |
| Cetane Number (-) | 45 | 47 | — | 42 |
| Sulfur Content (ppm) | 3000 | 15 | — | — |
| Heat Content (MJ/L) | 34.3 | 36.6 | 34.5 | 34.9 |

**Table 1 – Typical Military Fuel Properties [3]**

Aviation fuels actually offer several potential benefits over DF-2. Because of their higher solvency properties, there is reduced injector nozzle fouling issues and increased fuel filter replacement intervals. Oil change intervals are also increased and there is a potential for reduced engine wear relating to combustion by products. Aviation fuels also offer improved performance at low ambient temperatures due to a significantly lower freeze point.

One crucial consideration to be made in the adaptation of modern COTS engines to defense applications is the level of fuel sulfur in available military fuels and the potential impact fuel sulfur can have on engine and exhaust aftertreatment system operation and durability.

**OVERALL APPROACH TO ENGINE CONVERSION**

As described earlier, modern state of the art COTS engines reflect design and development processes driven by the need to meet stringent emission requirements and provide optimum commercial desirability. When adapting these engines to defense purposes, it is highly desirable to maintain as much commonality with the base engine hardware as possible, both from the perspective of taking as much advantage as feasible from the base engine technology, and to maintain the accessibility to high volume production components the COTS engine hardware presents.

Engines developed for military applications should conform to applicable U.S. emissions standards when tested with certification grade DF-2 fuel and be robust to the affects of the low viscosity, high sulfur content JP-8 fuels available in military theaters of operation. Owing to tactical fuel availability and costs, engine fuel efficiency is a crucial optimization goal. Another concern is the amount of heat that is rejected to the vehicle cooling system. The configuration and duty cycle of many defense vehicles precludes the use of large capacity cooling systems and 'ram-air' cooling strategies available to commercial vehicles. This concern is compounded by the use of ballistic grills which further inhibit air flow through the vehicle's engine cooling system.

For non-tactical vehicles, the applicable emission target is the USEPA 1998 model year standard for on-highway diesel engines, tested using certification grade DF-2 fuel. No exhaust aftertreatment system is needed to attain the required levels. This eliminates potential issues the high sulfur levels possible with military fuels can cause with modern COTS exhaust PM aftertreatment systems. High sulfur can lead to de-activation of the DOC, inhibiting the continuous regeneration of the DPF leading to higher soot loading, and difficulties with initiation of forced regeneration of the DPF, leading to mission disabling exhaust back pressure levels. Packaging constraints, the severe nature of the vehicle applications, and the need for periodic maintenance make the use of PM and NOx aftertreatment systems in military vehicles undesirable.

Similarly, the required NOx levels, as with the MY1998 COTS engines, can be met without the use of EGR. This has multiple benefits, including reducing the heat rejected to the vehicle cooling system and improving engine life. The high fuel sulfur levels and exhaust sulfate concentrations are also an issue when using a COTS engine EGR system. The high concentration of sulfates in the recirculated exhaust can cause rapid corrosion based deterioration and wear of the intake system, cylinder liners, piston rings and lands, and result in rapid oil deterioration. For these reasons, it is highly advantageous to remove the exhaust aftertreatment and EGR systems when adapting COTS engines to military use.

Removing the COTS engine EAS (Exhaust Aftertreatment Systems) and EGR systems requires careful re-optimization and technology application to achieve the 1998 emission levels while taking advantage of the other engine system technologies and capability to maintain or improve engine thermal efficiency and performance. Engine efficiency and heat rejection reduction can be met with minimal changes to the remaining base engine hardware in order to maintain commonality between the COTS diesel engine and the defense configuration developed. The overall technology path to adapt MY2010 and later COTS engines to defense applications is shown in Figure 7.

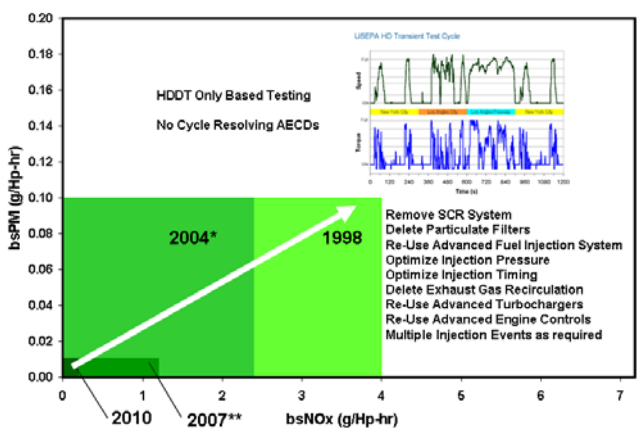


**Figure 7 - Technology path for defense applications using JP-8**

Removing the exhaust aftertreatment and EGR systems positively affects the air handling system. The air handling system affects brake thermal efficiency through the gas exchange processes and the energy required to push exhaust gas out of and pull fresh air into the cylinder. Removing the EGR system and the EAS improves the air handling system efficiencies by reducing the overall back pressure (i.e., removing the EAS) and facilitates a more favorable turbocharger work balance (i.e., removing the EGR system).

Issues with aviation fuel are mostly related to lower viscosity and lubricity. Fuel system component wear has proven to be the most prevalent problem in the past. In addition, hot start and hot idle capability is reduced in high ambient temperatures since the lower viscosity causes internal fuel pump leakage which ultimately reduces fuel pressure. The reduced volumetric energy content contributes to decreases in full load performance and volumetric fuel economy that must be compensated for in the fuel system calibration. The wide range of cetane number variation of JP-8 can decrease engine starting ability and part load performance, especially at low ambient temperatures or high altitudes. Passive fuel lubricity filters can be used to help minimize durability issues with the military fuels, but the use of other lubricity devices or fuel additives that require manual intervention or periodic replenishment is discouraged.

Although the lower boiling point of JP-8 and the lower molecular weight of the associated hydrocarbon emissions help to reduce engine out particulate levels, these benefits are offset by the increased sulfur content leading to higher sulfate based particulate emissions.
Switching between aviation fuel and DF-2 in a vehicle creates additional challenges. The increased solvency of the aviation fuel cleans the fuel system and requires frequent fuel filter replacement until the debris is completely removed. Also, repeated switching of fuels can cause increased issues with internal fuel system leakage due to less swelling of the fuel-wetted o-rings.

## EXAMPLE ADAPTATION OF A COTS ENGINE

The overall objective of BAA Topic 15 was to adapt two example state of the art MY2011 COTS engines to the use of military fuels, satisfy the performance, thermal efficiency, emissions and heat rejection goals of the program, and maximize the component commonality between the military and COTS versions of the engines selected.

One of the engines selected for conversion in this program was the recently introduced MY2011 Ford 6.7L V8 diesel. Two versions of this engine are being produced; a ‘chassis certified’ version generally applied to pick-up trucks less than 14000 lbm. GVWR, and a heavy-duty dyno certified version used in 14000 lbm. GVWR and heavier pick-up and chassis cab trucks. To provide a meaningful dyno certification level baseline comparison point, the later configuration was selected for adaptation to military applications. Table 2 shows the specification of this engine. Further information about the design and development of this engine is available in [4].

| Properties | COTS Baseline/ Prototype | Unit |
|---|---|---|
| Engine Type | 4-Stroke | - |
| Combustion System | Diesel | - |
| Charging System | Honeywell GT32 VNT | - |
| Fuel Injection System | BOSCH Common Rail - 2000 bar | - |
| Valve Configuration | 2 Intake – 2 Exhaust | - |
| Engine Configuration | V8 | - |
| Displacement | 6.65 | L |
| Bore | 99 | mm |
| Stroke | 108 | mm |
| Compression Ratio | 16.2:1 | - |
| Conn Rod Length | 177 | mm |
| Piston Pin Offset | 0.5 | mm |
| Valve Timing @ IVC | 568.3° ATDCF | Deg |
| Valve Timing @ EVO | 121.4° ATDCF | Deg |
| Rated Power | 300 | hp |
| Rated Speed | 2800/ 2600 | rpm |

**Table 2 - Ford 6.7L V8 Specifications**

The second engine utilized for BAA Topic 15 is a smaller V8, not released for production at the time this paper was authored. This engine represents state-of-the-art diesel engine technology for engines in the range of 4 to 5 liter displacement applied to heavy light-duty vehicles such as SUVs. The development of this engine for defense applications will be documented in a later report.

Based on AVL’s prior experience with JP-8 applications and the history described above, the focus of the development effort was two-fold; engine development and fuel system validation.

### Engine Focused Development:

The Ford 6.7L V8 Used for this example was installed in an AVL test cell in Plymouth, Michigan as shown in Figure 8. The engine was instrumented as listed below:

- Engine Speed and Load
- Emissions for Hydrocarbon (THC), Carbon Monoxide (CO) and oxides of Nitrogen (NOx)
- Fuel flow and thermal efficiency determination.
- Coolant flow and temperatures to quantify specific heat rejection.
- Cylinder pressure for determining peak firing pressure, start of combustion and heat release
- Additional temperatures and pressures per AVL’s standard procedures for engine development.

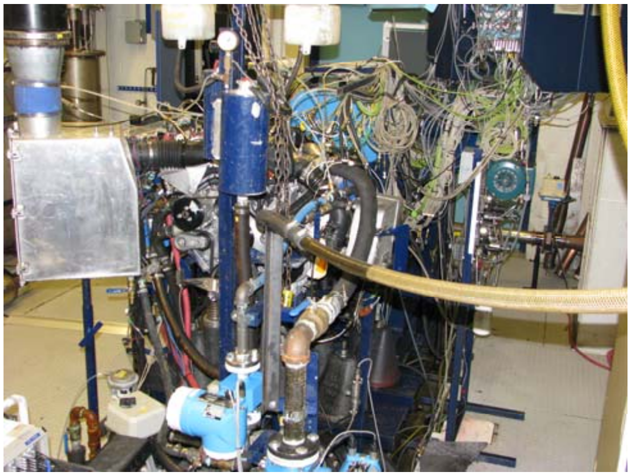

**Figure 8 - 6.7L Engine Installation in AVL Test Cell**

The engine was then run-in for 20 hours using conventional DF-2 to stabilize performance. Testing was then performed to establish the baseline engine performance and emission characteristics used for comparison to the engine after development for defense uses.

The properties of both the baseline DF-2 diesel fuel and the JP-8 fuel used emissions and performance measurements and development for this study are given in Table 3. The DF-2 properties represent a typical ultra-low sulfur diesel (ULSD) commercial fuel, while the JP-8 falls within the range of specifications for this fuel.

| Fuel | [-] | JP-8 | DF-2 (ULSD) |
|---|---|---|---|
| H/C Ratio | [-] | 1.93 | 1.79 |
| Density | [kg/L] | 0.79 | 0.85 |
| Net Heating Value | [MJ/kg] | 43.4 | 42.5 |
| Net Heating Value (Vol) | [MJ/L] | 34.5 | 36.2 |
| Viscosity @ 40C | mm^2/s | 1.21 | 2.44 |
| Cetane Index | [-] | 46.5 | 43.6 |
| Boiling Point | Deg F | 358-489 | 360-645 |
| Sulfur content | [ppm] | 190 | 10 |

**Table 3 - Properties of Fuels Used for Topic 15**

The COTS engine used for this work utilized a Bosch high pressure common rail (HPCR) fuel system with piezo injector actuation commonly found on current diesel engines in the 4 to 7 liter size range. Although this HPCR system is known to be less sensitive to lower fuel lubricity than prior rotary distributor pump systems, the durability of the high pressure pump was unknown. All engine testing using JP-8 was performed with a Fleetguard FA15700 lubricity fuel filter applied during all engine development and subsequent engine durability testing.

The first step in the conversion process was to remove the COTS exhaust aftertreatment system and EGR cooler, and block the EGR flow (Figure 9). The COTS turbocharger and fuel injection system was preserved to take advantage of these state of the art systems and preserve the integrity and original engine configuration as much as possible.

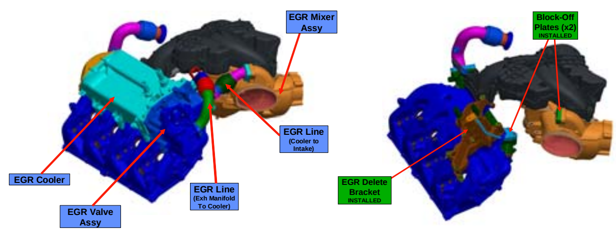


**Figure 9 - Removal of the COTS EGR system**

The development process utilized AVL CAMEO to provide optimized calibration for the engine fuel and air system calibration parameters. AVL CAMEO allows for efficient multi-variate optimization of the complex systems prevalent in today's diesel engines. The subsequent engine data presented in this paper represent results taken from testing performed using the final, optimized calibration and development configuration without exhaust aftertreatment or EGR performed to provide the highest possible fuel efficiency while meeting the program performance goals for reducing maximum heat rejection by 20% compared to the COTS engine, meeting USEPA 1998 emission requirements, and maintaining the remaining COTS engine components.

Removal of the exhaust aftertreatment system significantly reduced the turbine outlet pressure ('back pressure') as shown as 'P41' in Figure 10. This reduction in back pressure yielded an increased expansion ratio across the turbocharger turbine at speeds above 2000rpm, also shown in Figure 10 (exp_r_turbo). This trend was observed even though the final calibration resulted in calling for maximum turbine area from the variable geometry turbine.

The effects of deleting EGR on the COTS turbocharger are also apparent in Figure 10. Without the diluent effect of EGR, less intake manifold pressure (P21) is needed to provide sufficient air to manage PM and smoke emissions, especially at high engine speeds.

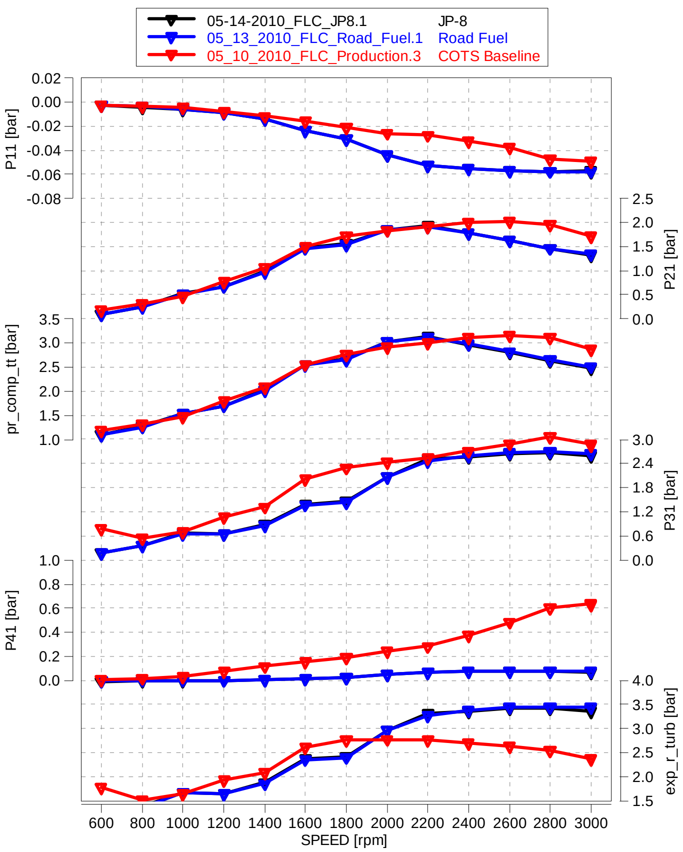


**Figure 10 - Effect of removing COTS Exhaust Aftertreatment System on Air Handling System**

Without EGR, all of the exhaust is used to drive the turbocharger turbine as opposed to the COTS engine case where a significant fraction of the exhaust is diverted back to the intake manifold as EGR. The final, optimized air system calibration takes this into account. Figure 11 shows the resulting commanded turbine position of the variable geometry turbocharger.

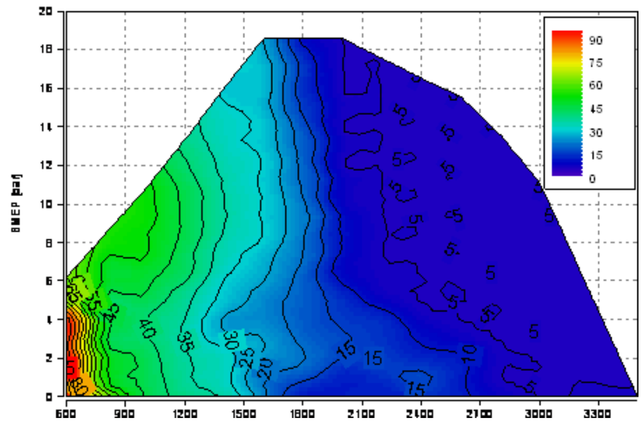

**Figure 11 - VGT Commanded Position, Final Calibration (5=fully open)**

Commanded VGT position values of 5 represent fully open vane positions, reflecting the attempt to minimize airflow as much as feasible for this COTS hardware at speeds above 2000rpm.

Another critical aspect of deleting the EGR system is reflected in the turbocharger compressor breathing lines as shown in Figure 12. The COTS baseline condition full load curve breathing line shown

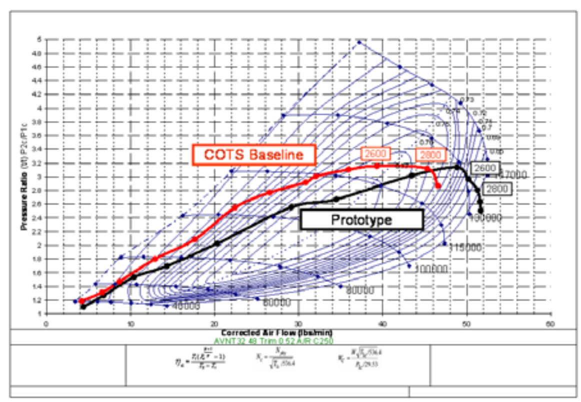


**Figure 12 - Compressor Map**

reflects the use of EGR in the production calibration. When EGR is turned off for the prototype development engine, the full load breathing line is shifted to the right, towards the choke line. At high engine speeds, this shift puts the breathing line in a region of the compressor map where efficiencies are rapidly dropping off. This lower efficiency results in increased compressor discharge temperatures, and when charge air cooling is applied to attain lower intake manifolds the combination of higher compressor discharge temperature and airflow of the adapted engine results in significantly higher charge air cooler heat rejection compared to the COTS baseline engine. This increased charge air cooler heat rejection partially offsets the elimination of the EGR system and its related heat rejection.

In order to satisfy the program goal of reducing maximum heat rejection by 20% while maintaining the COTS engine turbocharger configuration and achieving USEPA 1998 emission levels, some modifications to the full load torque curve were implemented. The developed torque and power curve are shown in Figure 13, compared to the COTS engine levels. The speed at which peak power is attained was

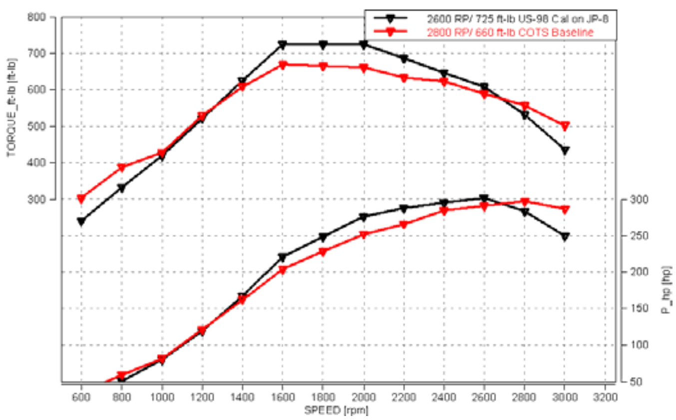


**Figure 13 - Full load Torque and Power Curves**

reduced slightly from 2800 to 2600 rpm while maintaining the original 300Hp peak power level. The overall speed range of the COTS engine was maintained. During calibration development it was also determined that the maximum torque level could be increased, owing to the reduced back pressure afforded by removal of the COTS exhaust aftertreatment system and the shift of the full load breathing line in this speed range to more efficient turbocharger compressor operation.

The resulting heat rejection characteristics of the modified engine compared to the baseline engine are shown in Figure 14, showing the attainment of reducing the total heat rejection with respect to the baseline COTS engine by 20%. The distribution of heat rejection, normalized to the total fuel energy available, is given in Table 4. As shown, the heat

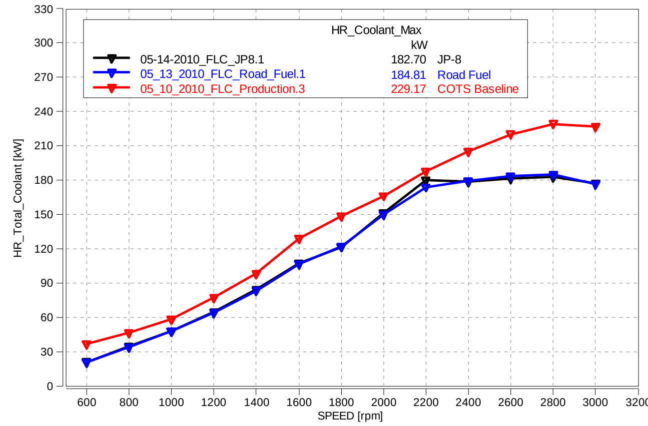


**Figure 14 - 20% Reduction in Total Heat Rejection**

| Engine Configuration | COTS | Prototype |
|---|---|---|
| Calibration | Production | AVL Developed |
| Fuel | ULSD | JP-8 |
| Rated Power [rpm] | 2800 | 2600 |
| Fuel Heat Input [%] | 100 | 100 |
| Output Power [%] | 34 | 36 |
| Engine Coolant (incl HT EGR cooler) [%] | 27 | 21 |
| CAC (LT) [%] | 7 | 8 |
| LT EGR Cooler [%] | 2 | 0 |
| Total Coolant [%] | 36 | 29 |
| Exhaust [%] | 29 | 32 |

**Table 4 – Normalized Heat Rejection Distribution at Rated Power**

rejected to the charge air cooler (CAC) was increased, but this increase was more than offset by the combined total coolant heat rejection comprised of (in the case of the baseline COTS engine), the engine coolant and the high and low temperature EGR coolers. Due to engine coolant passage structure, it was not possible to delineate the high temperature EGR cooler heat rejection from the balance of engine heat rejected to the coolant.

Figures 15 thru 18 depict the brake thermal efficiency,

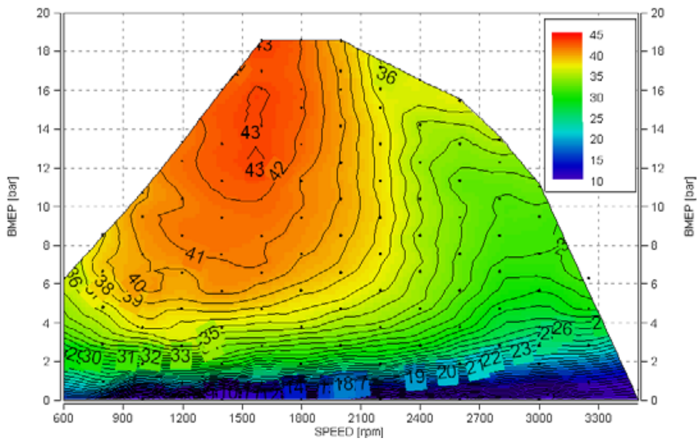


**Figure 15 – Brake Thermal Efficiency on JP-8**

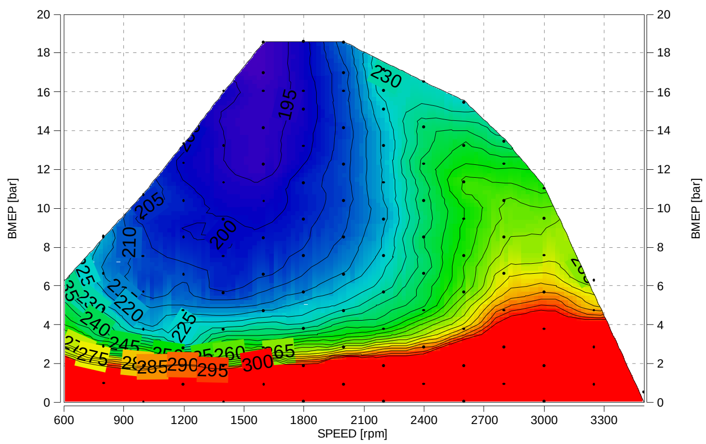


**Figure 16 – Brake Specific Fuel Consumption on JP-8 (g/kW-hr)**

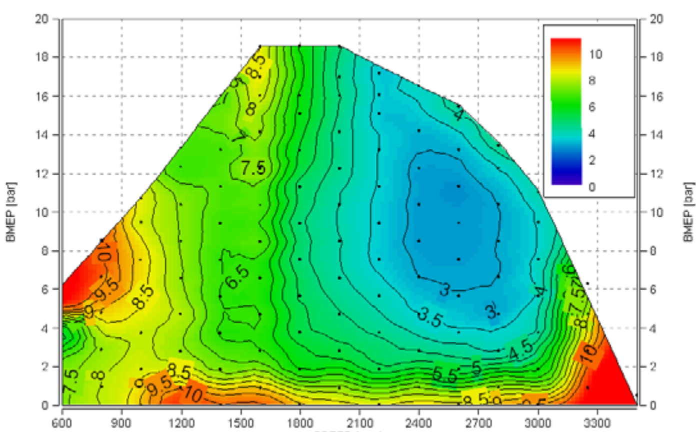


**Figure 17 – bsNOx (g/Hp-hr) on JP-8**

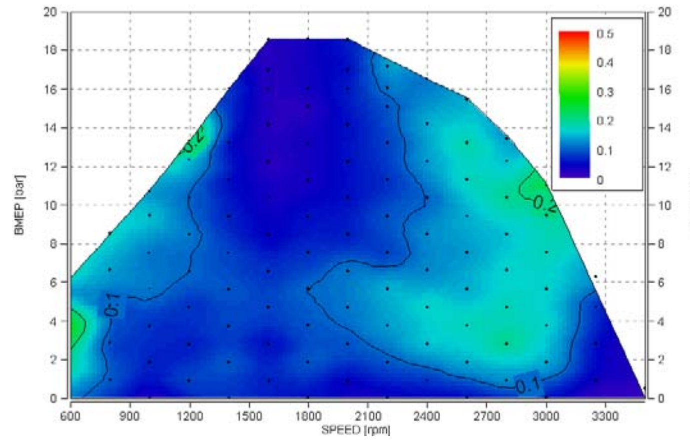


**Figure 18 – Exhaust Smoke (Bosch) on JP-8**

brake specific fuel consumption NOx, and exhaust smoke characteristics operating on JP-8 resulting from the development and calibration work performed by AVL as part of the Topic 15 program. This effort resulted in a peak brake thermal efficiency of slightly over 43%. The indicated thermal efficiency at this condition was determined to be 48%. The large area of brake thermal efficiencies above 41% is of particular advantage to the in-use fuel economy of many vehicle applications.

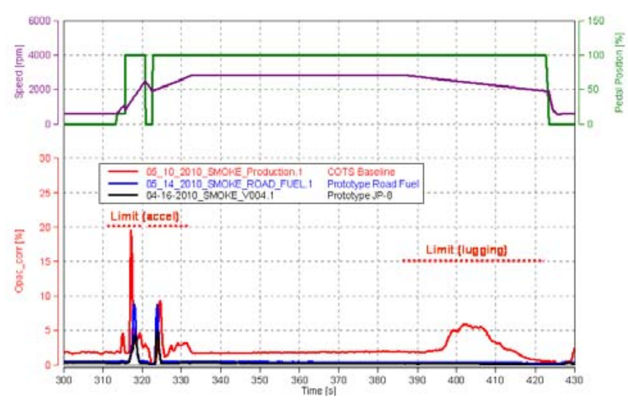


**Figure 19 – Federal Smoke Cycle Results**

Final federal smoke cycle and emission cycle confirmation testing using both DF-2 and JP-8 was then performed. Figure 19 compares the federal smoke cycle results from the modified engine operating on both JP-8 and ULSD DF-2. Although the MY2011 COTS engine did not need to be tested under these conditions, the engine out (before the COTS exhaust aftertreatment system) was also tested to provide a comparison point. The modified engine on both DF-2 and JP-8 presented very low smoke during this test. In this case, owing to the higher hydrogen to carbon ratio and the lower aromatic content of the JP-8 used for this study, the testing conducted with JP-8 resulted in lower smoke. Both fuels tested with the modified engine resulted in lower engine out smoke than the EGR equipped COTS engine.

The results of the heavy duty transient emission testing with the modified engine using JP-8 and DF-2 are shown on Table 5. All emission requirements for the program were achieved.

| | Target (Limit) | Prototype (JP-8) | Prototype (Road Fuel) |
|---|---|---|---|
| HDDT BSNOX [g/hph] | 4.00 | 3.96 | 3.92 |
| HDDT BSPM [g/hph] | 0.100 | 0.039 | 0.054 |
| HDDT BSHC [g/hph] | 1.30 | 0.22 | 0.23 |

**Table 5 – Heavy Duty Transient Emission Results**

The engine testing then proceeded to a durability demonstration using 50 hours of NATO cycle operation. The NATO cycle is described in Figure 20.

| Sub - Cycle | % Rated Speed | % Load | Duration (Hours) |
|---|---|---|---|
| 1 | IDLE (1) | 0 | ½ |
| 2 | 100 | 100 (5) | 2 |
| 3 | Governed (2) | 0 | ½ |
| 4 | 75 | 100 (5) | 1 |
| 5 | Idle to 100 (3) | 0[4min]-100[6min] | 2 |
| 6 | 60 | 100 (5) | ½ |
| 7 | Idle | 0 | ½ |
| 8 | Governed (4) | 70 (6) | ½ |
| 9 | Max Torque | 100 (5) | 2 |
| 10 | 60 | 50 (6) | ½ |

(1) Deviation from regulated coolant outlet temperature (96C+3C) is permitted.
(2) The speed shall be that obtained with the engine at full throttle and with minimum load. When the engine is not fitted with a governor, the throttle will be adjusted to obtain 110% of the rated speed.
(3) The moving of the command is shorter than 3 seconds.
(4) The speed shall be the steady speed of the engine at full throttle and 70 % load.
(5) One hundred percent load will be governed by full throttle.
(6) Part loads (70 and 50 %) shall be taken from the initial performance test.

**Figure 20 - NATO Durability Test Cycle**

The impact of the durability test on the fuel injection system (primarily the injection pump) and the engine was quantified by monitoring the time histories of the fuel system pressure control and volume control commands (Figure 21), the fueling error history during the test (Figure 22), and by comparison of the engine friction characteristics before and after the durability test was executed (Figure 23). None of these parameters indicated any issues or degradation had occurred during the 50 hours of NATO cycle durability testing. The minor variations in engine motoring torque measured before and after the durability test is attributed to the small change in oil temperature observed during the pre and post durability test conditions.

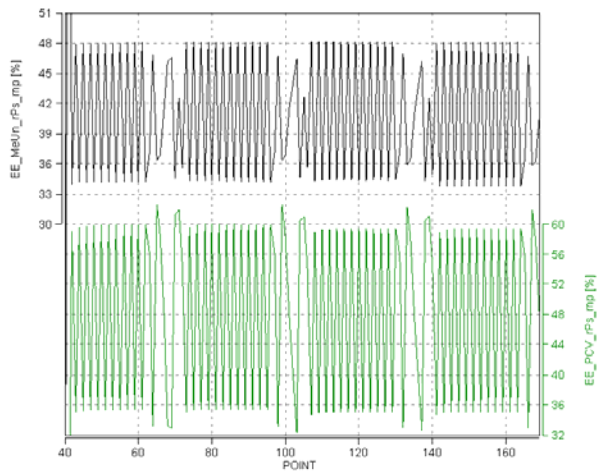


**Figure 21 – Fuel System Pressure and Volume Control Commands During NATO Cycle Test**

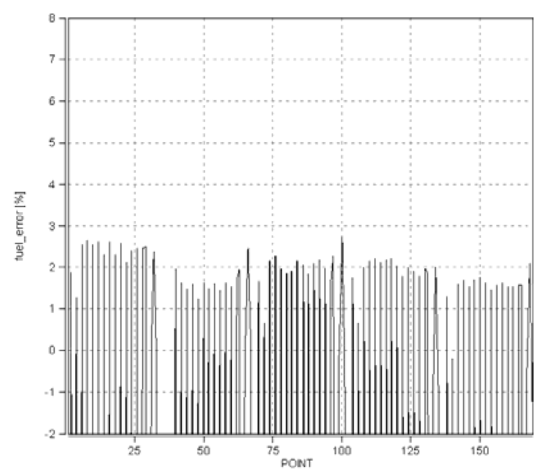


**Figure 22 - Engine Control Unit Fueling Error During NATO Cycle Test**

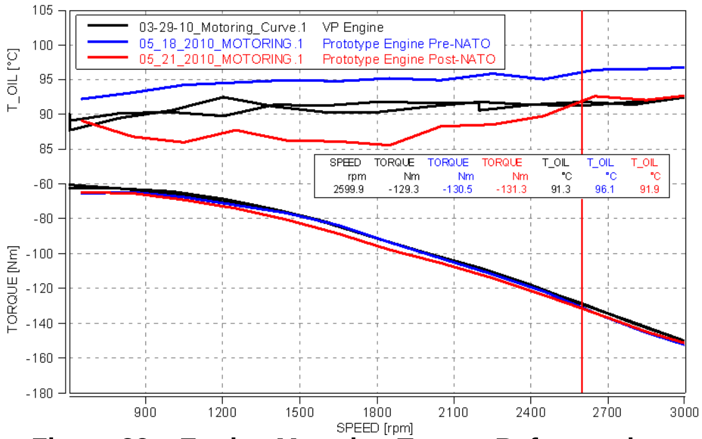


**Figure 23 – Engine Motoring Torque Before and After 50 Hour NATO Cycle Durability Testing**

The results realized from the adaptation of the MY2011 Ford 6.7L V8 diesel engine to a defense application configuration are summarized in Table 6. The BAA Topic 15 objectives for emissions, fuel efficiency and heat rejection reduction were all achieved for this engine.

| | Prototype (JP-8) | Prototype (Road Fuel) | Target (Limit) |
|---|---|---|---|
| Heavy Duty Diesel Transient BSNOX [g/hph] | 3.96 | 3.92 | 4.00 |
| Heavy Duty Diesel Transient BSPM [g/hph] | 0.039 | 0.054 | 0.100 |
| Heavy Duty Diesel Transient BSHC [g/hph] | 0.22 | 0.23 | 1.30 |
| Max. Thermal Eff [%] | 43.2 Brake | 43.5 Brake | 48.0 |
| | 48.5 Indicated | - | |
| Heat Rejection Decrease From Baseline [%] | 20.3 | 19.4 | 20.0 |
| Peak Torque [ft-lb] @ Speed [rpm] | 725 @ 1600 | - | 660 (min) |
| Rated Power [hp] @ Speed [rpm] | 300 @ 2600 | - | 300 (min) |

**Table 6 – Performance and Emission Summary for the Adaptation of a MY2011 Ford COTS Engine**

**Fuel System Validation:**

To provide an additional evaluation of the ability of a modern COTS fuel system to operate using military specification fuel, a sample of the baseline fuel system was bench tested for 400 hours to simulate the standard NATO durability test in parallel to the engine development work. By demonstrating Bosch HPCR system compatibility with JP-8, solutions generated during this program could then be applied to other COTS engines equipped with these types of fuel systems, potentially allowing the defense agencies more flexibility and program cost effectiveness in future engine purchase decisions.

In parallel to the engine development activities described earlier in this paper, AVL tested the common rail fuel system from a MY2011 Ford 6.7L V8 diesel for durability on the same JP-8 fuel described in Table 3. AVL focused on the durability of the high pressure pump, but the injectors, fuel rails, high pressure fuel lines, and associated control and sensing elements of the COTS fuel system were included in the test hardware set up.

The COTS fuel system was installed in the AVL fuel system test stand in Ann Arbor, MI. This stand uses an electric motor to drive the fuel pump at the test speed(s), a stand alone controller to control the fuel pump actuators and injector drivers, and injector drivers capable of actuating either solenoid or, as in the case of the fuel system evaluated for this study, piezo actuated injectors.

The fuel system components were mounted in a fixture emulating the layout of the COTS engine. The test configuration is shown in Figures 24 and 25.

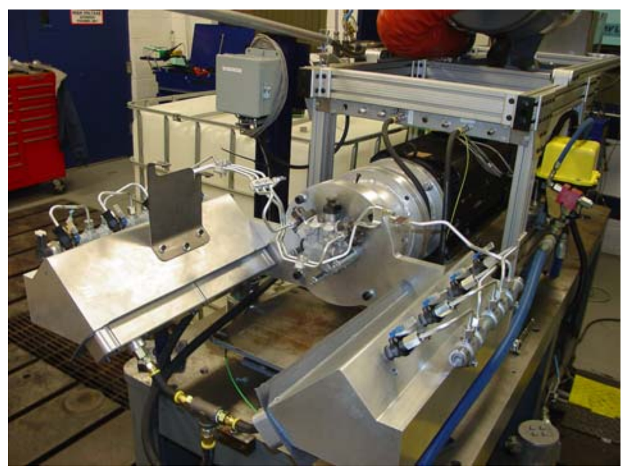

**Figure 24 - AVL Fuel System Durability Bench Rig**

The AVL Fuel System Durability Bench facility utilized 270 gallon batches of JP-8 stored in portable totes. As shown in Figure 25, fuel was taken from the supply tote, heated and pumped to the required fuel injection pump inlet pressure, the fuel rate measured, and run through the COTS fuel system. After being run through the injectors, the fuel was collected, cooled and collected in the return tote. After all the fuel in the supply tote was processed, the inlet connections were

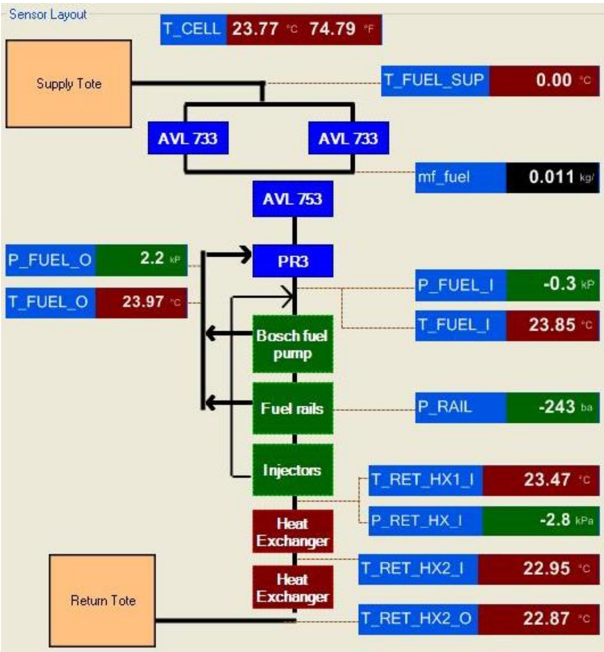


**Figure 25 - AVL Fuel System Bench Schematic**

switched and the fuel processing repeated. The fuel total acid number (TAN) of the fuel was monitored, and when the TAN, expressed in terms of mg KOH/g fuel reached 0.15 mg KOH/g fuel, the used fuel was switched out (to be consumed by the development engines) and a new batch of fuel was used. As shown in Figure 26, it was found that the fuel could be cycled through the fuel system 14 times before the TAN reached the allowed maximum TAN level.

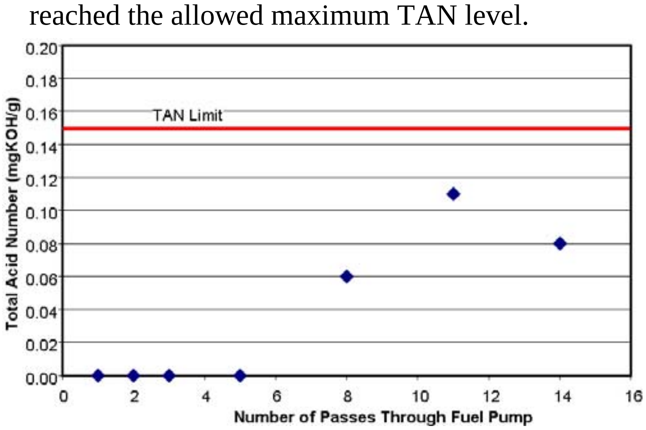


**Figure 26 - Typical TAN History**

The durability of the fuel system was evaluated over 400 hours of steady state operation under conditions represent the maximum amount of fuel injected per injection event as based on data from the full engine testing. This condition selected was 2400 engine rpm and a fuel rate of 52kg/hr (90.3 mg/injection). All fuel system durability work was conducted with fuel inlet temperature controlled to 70ºC to simulate as close as possible the expected elevated temperatures that could be seen in defense applications in high temperature environments.

The deterioration of the fuel system was evaluated by fixing the position of the fuel system high pressure common rail pressure control valve and tracking the required pulse command to the fuel pump volume control valve needed to maintain the fuel rate at that pressure. It was expected that if the fuel pump deteriorated, its effective capacity would decrease and the command to the volume control valve would need to be increased to maintain the pressure and flow set points. Fuel pump failure was defined as the point where the volume control valve could no longer be commanded to a high enough value to maintain the required fuel set point. The history of the volume metering valve position command over the 400 hour test duration is shown in Figure 27.

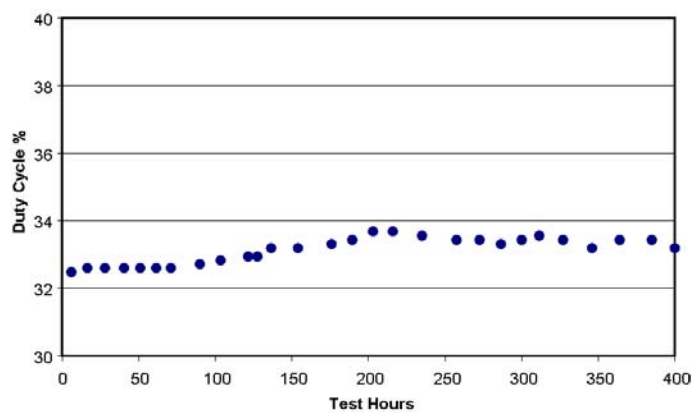


**Figure 27 - Volume Control Valve Signal Throughout Fuel System Durability Test**

After a slight increase in the required volume control command that occurred between 100 and 250 hours of testing, the fuel pump stabilized. No adverse effects of operating this fuel injection system on high temperature JP-8 were noted.

## CONCLUSIONS

Based on the findings presented in this paper the following conclusions can be made:

- ✓ Modern state of the art COTS engines provide an excellent framework for conversion to defense applications.
- ✓ Removal of the COTS exhaust aftertreatment and EGR systems can have substantial impacts on the turbocharger match, especially at high engine speeds.
- ✓ The COTS turbocharger can be maintained with clever calibration and some tuning of the full load curve to minimize the impact of compressor match behavior at high speeds.
- ✓ Excellent fuel efficiency, low smoke and low PM emissions can be achieved while meeting NOx emission limits.
- ✓ No engine or fuel system durability issues were encountered over the durability testing performed during this program.

## ACKNOWLEDGEMENTS

I would like to thank TARDEC for the sponsorship of this program, Ford Motor Company for the support they've provided, and AVL PEI for the resources applied in preparing this paper. I would particularly like to thank Brian Baldwin and the rest of my colleagues at AVL for their testing and development efforts in support of this program.

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