

On the Availability of Commercial Off-the-Shelf (COTS) Heavy-Duty Diesel Engines for Military Ground Vehicle Use

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ABSTRACT

The continual reduction of diesel engine heavy-duty nitrous oxides and particulate matter emissions due to Environmental Protection Agency (EPA) regulations has resulted in significant changes to engine hardware since 1998. Such changes have included use of cooled exhaust gas recirculation, clean gas induction, oxidation catalysts, variable geometry turbochargers, lean nitrous oxide traps, urea selective catalytic reduction, passive and catalyzed particulate matter filters, and engine design changes to reduce oil consumption while allowing use of low sulfur diesel fuel (DF-2) and maintaining oil change intervals and subsystem durability levels of previous model years. The net result from a propulsion system perspective is increased heat rejection, additional induction and exhaust system volume, increased system weight, and less tolerance to military fuels and lubricants. Such changes are detrimental to the performance of military vehicles that are required to operate in both desert and artic-like conditions while meeting stringent mission dependent mobility and cooling requirements. To partially address this issue, the U.S. Army obtained National Security Exemptions that effectively allow use of non-compliant engines for tactical vehicles with permanent armor and use of 1998 compliant on-road and Tier III off-road engines for non-armored tactical vehicles. Nevertheless, there still exists the practicality of introducing current and future commercial engines into military applications through necessary engine system modifications that allow vehicles to meet mobility, cooling, and survivability requirements while either meeting 1998 standards or not complying with any particular standard. Such a scenario may result in the development of military aftermarket opportunities and the utilization of export markets for

engine manufacturers and selected partners given the typical low volume military engine production rates. This submission will address this key topic and also provide background concerning the U.S. Army's emission compliance strategy.

INTRODUCTION

Throughout the 1970's, 1980's, 1990's, and earlier in this current decade, the military has benefited from the increasingly stringent emission standards. Engine manufacturers have met the challenge of more stringent nitrous oxides (NOx) and particulate matter (PM) standards during this thirty-year period through significant advancements in fuel injection equipment, wider range and higher pressure ratio turbocharging, efficient air-to-air charge air cooling, and overall engine component and combustion system design improvements. The only major military issue during this time period occurred in the late 1980's when the U.S. Army adopted the one fuel forward policy of operating military vehicles on JP-8 in order to reduce the logistical burden associated with bringing multiple fuels to the battlefield. In most cases, engine manufacturers responded to fuel lubricity and lower volumetric energy content issues with necessary engine system modifications to ensure reasonable engine reliability and performance under military operating conditions.

The introduction of the 2007 heavy-duty on-road emission standards presented another major issue for military vehicles due to the technology solutions required to meet both the PM and NOx standards. Heavy use of cooled EGR (exhaust gas recirculation) and aftertreatment devices are major challenges for commercial applications let alone military applications.

Cooled EGR or clean gas induction (CGI) along with additional charge air cooling requirements for reducing intake manifold temperatures have led to heat rejection rates that generally are 50% higher than a model year 1998 military application. The additional required fan power and heat exchanger surface area presents both mobility and survivability issues for the U.S. Army. Furthermore, sulfur, ash, and phosphorus sensitive aftertreatment is an issue for the military since such systems are designed to tolerate both low sulfur diesel fuel (< 15 ppm) and commercial engine lubricants. In comparison, the military uses JP-8, high sulfur diesel fuel, and MILSPEC (Military Specification) oils that may or may not be remanufactured for field use. The performance degradation and potential reliability and durability issues of such systems under these military constraints is further compounded by the use of engine system closed loop control strategy for ensuring low tailpipe emissions that may dramatically impact the performance of Army vehicles. It is clear that such emission control technology approaches are not plausible for military use and thus the EPA granted the U.S. Army a National Security Exemption (NSE) from the

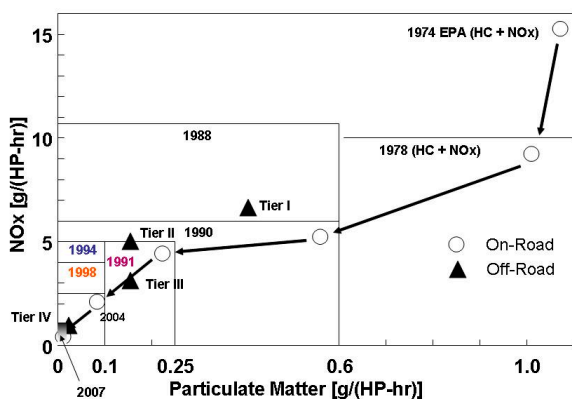


Figure 1: Evolution of the United States Heavy-Duty Emission Standards from the 220 to 450 kW Rated Power Range.

2007 emission standards.

Additionally, after careful consideration of emission control technology employed to meet the 2004 heavy-duty on-road emission standards, the U.S. Army concluded an NSE was necessary for these particular emission standards. In particular, cooled EGR presents an issue for the Army due to the significant increase in engine system heat rejection that makes introduction of such engines into existing vehicles for re-power purposes nearly impossible without significant cooling system modifications that may negatively impact both vehicle mobility and survivability. Furthermore, military use of both JP-8 that includes sulfur content as high as 3000 ppm and worldwide DF-2 that has been measured as high as 10,000 ppm in certain regions present additional engine system reliability and durability challenges that are compounded by the use of MILSPEC

oils. In particular, these high sulfur fuels lead to a higher rate of sulfuric acid formation in the EGR loop and induction system that can lead to engine system reliability issues after continual exposure exceeding an engine dependent period of time. Other non-EGR technologies do not have this latter issue, but certainly require an increase in cooling system capacity for reducing charge air temperature that in certain cases push already marginal vehicle thermal management systems beyond their capacity to meet stringent military cooling specifications without significant system modifications. In light of this situation, the EPA granted the U.S. Army a NSE from the 2004 emission standards for non-armored tactical vehicles and also a NSE from all emission standards for armored tactical vehicles.

EGR IMPACT

Chemical and thermal dilution of the reaction front in diesel combustion is one method for reducing nitrous oxide production. Currently, numerous engine manufacturers are using cooled EGR to meet the 2004 and 2007 on-road, heavy-duty nitrous oxide standards of 2.4 g/bhp-hr and 1.2 g/bhp-hr. Early issues with cooled

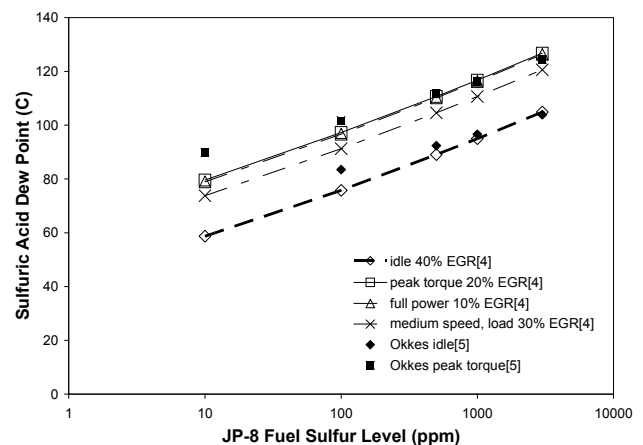


Figure 2: The Influence of JP-8 Sulfur Content on the Sulfuric Acid Point for Various Engine Operating Conditions. The assumed EGR levels are shown for each operating point for the models of Verhoff and Bachero[4] and Okkes[5].

EGR included more rapid oil degradation, accelerated valve seat and in-cylinder wear, unreliable EGR system components, and additional vehicle heat rejection management issues. Fuel sulfur concentration was the primary source of such reliability and durability issues since the EGR loop and induction system sulfuric acid dew point is affected by sulfur oxide concentration. Much effort was spent by engine manufacturers to improve EGR system component reliability by engineering solutions for the cooler and valve assembly that could withstand a specific time period of exposure to low levels of sulfur acid. This issue was further addressed with the reduction from 300 ppm to 15 ppm sulfur concentration in commercial on-road diesels during 2006. The additional heat rejection associated with such cooled EGR systems is a vehicle level issue that has been

addressed with approaches such as higher capacity water pumps, more efficient fans, additional heat exchanger surface area, etc. Engine manufacturers will likely continue to use larger quantities of cooled EGR as nitrous oxide standards become more stringent and thus vehicle thermal management will be an on-going issue.

Military requirements make utilization of cooled EGR engines nearly impossible to implement except for a few special cases where particular vehicles are non-deployable, will be exposed to low sulfur commercial diesel fuel on a steady basis, and will not be impacted by the additional heat rejection associated with cooled EGR. Current ground forces use both diesel fuel and JP-8 which are normally provided from regional sources. JP-8 in particular is a broad property specification fuel that by commercial standards is a multi-fuel. For example, the sulfur concentration is specified to be no higher than 3000 ppm and cetane number is currently not specified since the military aviation sector does not have a need for this particular fuel property requirement. Also, there are certain portions of the world that still produce diesel fuel with sulfur concentrations up to 1%. The issue with such highly variable sulfur levels is the dramatic impact on sulfuric acid dew point in EGR and induction systems. One researcher [1] has shown that an increase in sulfur concentration from 10 ppm to 1000

manufacturers address this reliability and durability issue through use of stainless steel EGR system components though oil change intervals are still shorter in comparison to the past which is an issue for operations in theatre where scheduled maintenance intervals are a real challenge for the U.S. Army.

Thermal management is also an issue for military tactical and combat vehicles. The additional engine heat rejection for such 2010 emission compliant EGR engines is projected to increase by at least 50% versus a 1998 model year engine which will result in much larger heat exchanger surface area and associated larger fan power requirements. Many military vehicles do not include ram air and thus additional cooling burden is predominately handled with increased forced air flow rates. Additionally, survivability is a major area of concern for such military vehicles and thus adding more heat exchangers to a vehicle frame is not an effective thermal management strategy for military tactical vehicles. This situation is further exacerbated by the continual need for ballistic grilles in ram air scenarios that further increase the required fan power. An illustrative example of how increased heat rejection affects fan power in a 45,000 kg combined vehicle weight application under North American ambient conditions is shown in figure 3 under the constraint that additional surface area is not

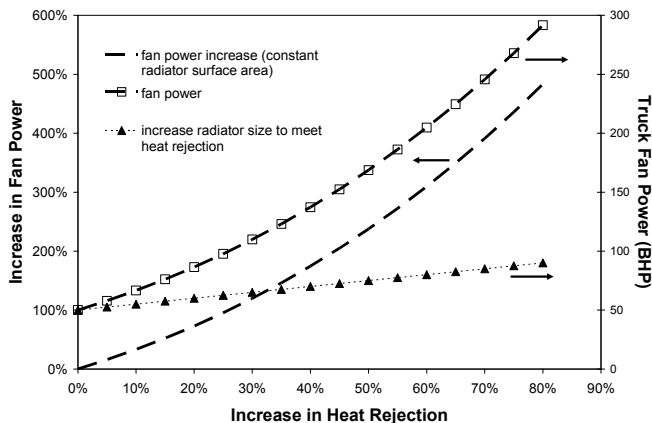


Figure 3: The Impact of Additional Heat Rejection on the Required Coolant System Fan Power in a Representative Military Medium Tactical Truck.

ppm in commercial DF-2 will increase the dew point by approximately 20 °C and further increases in sulfur concentration will lead to even further, but less pronounced increases in dew point. Figure 2 also highlights such dramatic shifts in sulfuric acid dew point with increasing fuel sulfur concentration at representative idle, high load, and medium load operating conditions based on the assumption of a 3% conversion of sulfur dioxide to sulfur trioxide [2,3]. Such large fluctuations in dew point result in a higher propensity to form sulfuric acid in the EGR loop and induction system which leads to component level reliability and durability issue such as accelerated valve seat and assembly wear, shorter oil change intervals, and accelerated in-cylinder corrosion. Some

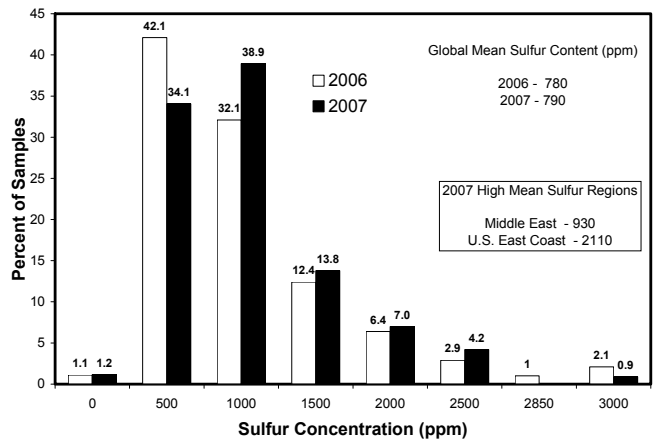


Figure 4: The Global Mean JP-8 Sulfur Concentration.

available on the vehicle due to the aforementioned survivability concern. This analysis shows that replacing an older model year non-EGR engine with a newer EGR engine would result in a two-fold increase in fan power which must be offset with a higher engine full load power curve or the potential loss of vehicle mobility and a deficiency in meeting the required Army high load cooling test point. This overall thermal management issue is further compounded by modern engine control strategies of de-rating the engine crankshaft power to maintain acceptable fluid temperatures under high load, high temperature duty cycles which present challenges to vehicle manufacturers in meeting Army high load, high temperature cooling requirements.