AIR MANAGEMENT FOR DIESEL ENGINES

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INTRODUCTION

Beginning in the 1970's, diesel engine manufacturers have developed technological approaches in response to increasingly stringent air quality regulations. The characteristics and performance requirements of heavy-duty diesel engines, however, have prevented them from achieving emission levels commensurate with light-duty gasoline vehicles. Despite the fact that diesel engines provide significant advantages in fuel efficiency, reliability and durability, control of PM and NO_x emissions have presented a conoid-enable challenge.

An advanced engine air enhancement device has been designed to meet these stringent egis-Zion standards while indicating performance increases not normally associated with emission reduction technologies. The technology improves air management within the internal combustion engine, which results in increased combustion efficiency and the resultant improvemeats in emissions, fuel economy and engine performance. The component, named the Electronic Demand Charger or TDC (trademark "Turbofan™"), is applicable to both naturally aspirated gasoline engines as well as diesel en-gins. The TDC works on the principle of adding air to the combustion chamber in order to im-prove the air/fuel ratio during combustion processes. This paper will focus on testing conducted with the TDC on heavy-duty diesel engine applications at Southwest Research Institute in San Antonio, Texas as well as tests conducted at Original Engine Manufacturer (OEM) transient test facilities. Test results indicate significant improvements that meet or exceed fuel management techniques designed to improve combustion efficiency, fuel economy, engine performance and emission reductions.

TRADITIONAL APPROACHES

Emission reduction approaches such as retarding injection timing have traditionally increased fuel consumption. Charge-air cooling, turbocharging and improved fuel injection seek to offset this penalty. Uncontrolled emissions of NO_x from heavy duty diesels range from 12 to 21 grams per kilowatt-hour (9 to 16 grams per brake horsepower hour) when measured using U.S. transient test cycles. PM emissions typically range from 1 to 5 g/kWh (0.75 - 3.7 g/bhp-hr). Engines that are tampered with or have been poorly maintained often emit higher PM emissions in the form of black smoke.

Moderate control of NO_x (8 g/kWhr or 6 g/bhphr) and PM (0.7 g/kWhr or 0.5 g/bhphr) requires further optimization of the overall combustion system. While traditional approaches such as variable fuel injection timing, high pressure fuel injection and charge air cooling are suitable approaches, it is combustion optimization that will correspond to U.S. Federal emission standards for PM and NO_x. This is particularly true for PM, with tighter U.S. standards (0.13 g/kwh or 0.10 g/bhphr) effective in 1994. Despite the requirement not to further limit PM in light of the NO_x requirements, in March of 1993 the EPA (Environmental Protection Agency) published a ruling reducing PM to 0.05 g/bhphr. In 1995 the EPA, California Air Resources Board (CARB) and automotive engine industry signed a Statement of Principles outlining their joint understanding of the actions required to meet a 2 g/bhphr NO_x limit by year 2004. This standard is expected to tighten once again upon further technological developments. In the U.S., urban buses are currently required to meet a 0.1 g/bhphr (0.13 g/kwh) PM standard under certification standards set by the EPA.

COMBUSTION AND EMISSIONS

Controlling NO_x and particulate emissions have proven a particularly difficult challenge for diesel engine manufacturers throughout the years. This is due to the effect of NO_x control approaches having the tendency to increase particulates, as well as particulate reduction technologies having an adverse effect on NO_x. This PM/NO_x tradeoff remains the subject of much research and debate.

Particulate matter, or black smoke, is the most visible pollutant attributable to diesels. These emissions are the combination of three phases: solids, liquids, and gases. The combination of solids and liquids comprise the Total Particulate Matter (TPM) or Particulate Matter (PM). PM is composed of dry carbon (soot), inorganic oxides (primarily as sulfates), and liquids. The liquids are composed of unburned fuel and lubricating oils, termed the soluble organic fractions (SOF) or volatile organic fractions (VOF). When diesel fuel is burned, a portion of the sulphur is oxidized to sulphate, which, when reacting with moisture in the exhaust, becomes H_2SO_4. The gas phase is composed of gaseous hydrocarbons, carbon monoxide, oxides of nitrogen, and sulfur dioxide. The dry soot comprises the insoluble fraction of the engine-out emissions.

The popularity of diesels is a result of their fuel efficiency relative to the gasoline engine. Diesels operate very lean with air-to-fuel ratios greater than approximately 22.

For an air-fuel mixture, stoichiometric conditions are often referred to as 100 percent theoretical air. Since actual oxidation reactions are incomplete, many combustion systems operate on excess air. For example, 150 percent theoretical air is equivalent to 50 percent excess air. A lean mixture ($\lambda>1$) contains more air; a rich mixture ($\lambda<1$) less air. The A/F ratio decisively affects the engine's operating characteristics. However, an insufficient quantity of excess air results in increased emissions of particulate matter, carbon monoxide, and hydrocarbons, as well as an increase in brake specific fuel consumption. Diesels generally produce good fuel economy and have an engine life approximately ten times that of a gasoline engine. For these reasons, much effort is placed on achieving PM/NO_x reductions.

The retrofitting of diesel engines with oxidation catalysts has been the most common approach to reducing the soluble fraction of diesel particulate emissions. The general idea surrounding diesel oxidation catalysts was for the catalyst to oxidize the SOF without oxidizing the SO_2 to sulphate. To function, the dry soot had to be further reduced to eliminate plugging of the system. The engine design parameters that had to be modified to allow for a reduction in the dry soot resulted in an increase in the SOF, which could then be oxidized by the catalyst. Catalysts containing precious metals such as Pt and Pd were the best candidates as they exhibited low-temperature activity for hydrocarbon conversions. Different catalysts provide different reductions for different engines. Some diesel engines exhibit a SOF fraction of 30 percent, whereas others are as high as 40 percent. It is necessary to further reduce the insoluble fraction to achieve the maximum benefit of the catalyst.

The Electronic Demand Charger, described more fully below, offers the opportunity to significantly reduce the insoluble fraction of the particulate matter formation. A brief understanding of the correlation between the A/F ratio and emissions formation is necessary in order to understand this effect. NO_x formation in diesels occurs due to a complex relationship of gas temperatures and non-uniform fuel distribution. The critical formation period exists when unburned gas temperatures are at a maximum between the start of combustion and just after peak cylinder pressure. Local NO_x concentrations rise to a maximum at $\lambda = 1$ and decrease as the mixture becomes leaner since formation becomes much slower as dilution occurs.

Particulate emissions (PM) are the solid and liquid particles resulting from the incomplete combastion of the fuel, wear particles, and dirt that escape the air filters and become airborne with the gaseous emission. Smoke consists primarily of visible particulate matter (the insoluble fraction) Most particulate material results from incomplete combustion of fuel hydrocarbons. The composition of the particulate material depends on the conditions in the engine exhaust and the existing reduction technology. The TDC addresses overall emission formation by increasing the A/F ratio at low-end operating conditions in order to decrease emissions of HC, CO, and PM. The system introduces additional air to the engine manifold via a simple valving mechanism. This additional air not only leans the A/F ratio, but provides additional boost to the engine, which also improves engine performance by eliminating turbolag.

THE ELECTRONIC DEMAND CHARGER

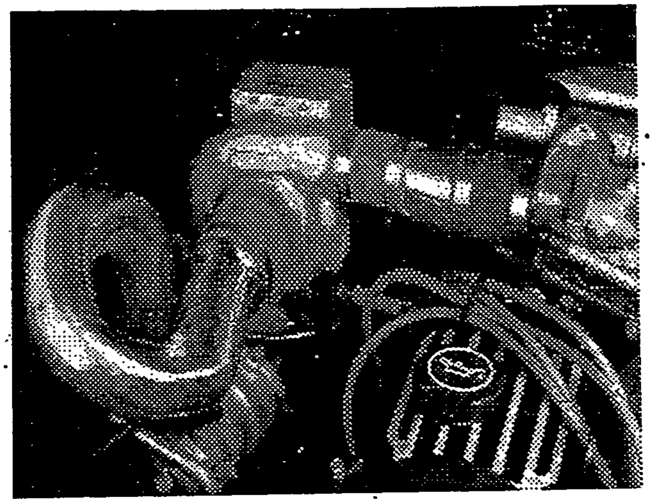
The application of a motor-assisted device, such as the electronically actuated TDC, provides a means of supplying air to the engine cylinder at low idle or low loads in preparation for the next acceleration of the engine before an increased amount of fuel is injected. When used in series with a standard turbocharger, the TDC supplies boost pressure to the engine until there is enough energy in the engine exhaust to accelerate the turbocharger. When the turbocharger is capable of supplying sufficient air, the unit is de-energized, thus eliminating the power drain from the vehicle batteries.

In diesel applications, the TDC is an inlet air compressor installed independently of the turbocharger between the air intake and the engine manifold. The system is comprised of a compressor housing, compressor wheel, a brushless electric motor, a motor controller, an engine interface controller, and simple valving mechanism (See Figure 1). This system can be installed on both gasoline and diesel applications. On turbocharged diesels it is installed in series with the turbocharger. In this instance, the assembly is comprised of a compressor assembly, a motor controller in a separate housing, a 5 inch (12.7 cm) diameter check valve, associated intake tubing and connecting sleeves, a manifold pressure shutoff switch, a throttle switch and bracket, a throttle switch actuation arm, and a wiring harness.

For the diesel, combustion processes inside the engine cylinder dictate engine power, efficiency and emissions. Following compression, burning proceeds as air and fuel mix to the composition necessary for combustion to take place. In the diesel engine, fuel is injected in the cylinder into high pressure and temperature air. The engine has less time to form the air-fuel mixture, which is less homogenous as a result. This creates periods during the combustion phase where the air to fuel relationship is non-optimized. This is particularly apparent during lowend operating cycles. Traditionally, efforts to reduce engine-out emissions have concentrated on fuel management. The TDC focuses instead on air management with the optimization of this relationship of air to fuel. In turbocharged diesel engines, the turbocharger provides the engine with more air than it can induce through natural aspiration. This increased air supply allows more fuel to be burned, thereby increasing power and torque obtainable from a given displacement engine.

In turbocharged engines, there is very little energy in the engine exhaust and this prevents the turbocharger from providing a significant level of boost in the engine intake air system. When the throttle is opened to accelerate the engine, there is a time lag before the exhaust energy level rises sufficiently to activate the turbocharger rotor. This time lag is traditionally termed "turbolag" and, over the years turbochargers have been made smaller and lighter in order to minimize this lag period.

The TDC can be installed on both turbocharged and non-turbocharged vehicles. In non-turbocharged vehicles it is installed between the air intake system and the engine manifold. In this application, the TDC provides benefits similar to retrofitting a turbocharger on the vehicle.



TDC INSTALLATION ON NONTURBO-CHARGED ENGINE

A standard passenger car (1.9L) will realize a thirty to forty percent increase in low-speed torque in addition to fuel economy benefits and reduced pollutants. For the purposes of this paper, however, these benefits will not be quantified and the focus will remain on turbocharged heavy duty diesel applications.

On diesel, turbocharged vehicles, the compressor and check valve are configured in parallel, and together they feed in series with the existing turbocharger inlet. The check valve is oriented so that intake air will be drawn through the valve and the TDC during periods of high intake air demand. During periods of low intake air flow, the check valve will close and the TDC will pressurize the turbo inlet. All components are designed to mount directly onto the engine, whereas the controller should be mounted on the vehicle body or chassis in a clean environment where temperatures will not exceed 150° F (65.5° C). For heavy duty diesel applications, the unit requires a 24V DC power supply capable of 250 amps for 1 second and 150 amps at a 50 percent duty cycle. The three sensor switches are connected in series and control the engagement and disengagement of the TDC.

The unit utilizes a high speed boughless electric motor and an electronic controller for the purpose of electronically commutating the D.C. electric power into a three-phase power supply and a feedback circuit. The motor is activated by remote sensors that monitor the demand for power and boost. Using remote sensors, the EDC interface controller constantly monitors engine parameters such as throttle position and boost pressure. In configurations which utilize a pre-existing electronic engine controller, the unit can be integrated into the existing controller system. The interface controller then activates the EDC during predefined engine operating modes indicated by the sensors. The electronic control module can also interface with engine management systems in similarly equipped vehicles.

ENGINE PERFORMANCE AND EMISSIONS

A number of bench, steady state, and transient dynamometer tests were performed on the EDC under a variety of conditions. The following presents results achieved on various engines under varying operating conditions.

BENCH TESTING

The EDC compressor must accelerate rapidly to effectively reduce turbolag and PM. This acceleration is accomplished by means of a brushless permanent magnet motor which produces high torque, accelerating the compressor shaft to over 100,000 revolutions per second. To further reduce the time lag, the compressor "idles" at 10,000 rpm, waiting for the command to accelerate to 40,000 rpm. To verify the rapid pressure rise, the compressor discharge pressure was monitored on a digital oscilloscope. The results indicated that the compressor was able to produce 80 percent of its final pressure in 250 milliseconds, corresponding to 2.5 engine revolutions at a 600 rpm engine idle speed.

ENGINE PERFORMANCE RESULTS

An EDC was installed on a 225 kW turbocharged diesel engine to evaluate its effect on engine performance. The installation was discharging directly into the inlet of the turbocharger. A bypass check valve was used to prevent excessive inlet restriction at high engine speeds. BMEP improves up to 40 percent at low engine speeds. At 13 engine rpm and above, with the bypass valve opened, no improvement was indicated. The BMEP improvement is the result of additional airflow and a corresponding increase in fuel flow. Manifold Pressure Comparison indicates the intake manifold pressure for both baseline and EDC equipped engines. A portion of the increase in manifold pressure is a result of compounding the output of the EDC compressor and the turbocharger compressor. The additional pressure increase is the result of higher exhaust energy, thereby increasing turbocharger speed.

The EDC also improved brake specific fuel consumption by approximately 5 percent. The fuel consumption improvement can be accounted for by the increase in indicated torque, while the friction remains relatively constant, thus increasing the mechanical efficiency.

The low speed torque improvement is important to many truck and bus applications, permitting lower clutch engagement speeds, lower stall speed torque converters, and better throttle response. Future research will be conducted to evaluate the effect of the EDC as a cold start aid. The EDC increases inlet air temperature by 15° C due to compression heating. The effective compression ratio also increases by 20 percent. The cranking compression ratio of a nominal 17:1 compression ratio engine would increase to 20:1, thereby promoting faster startup. The increase in effective cranking compression ratio also allows a lower mechanical compression ratio and a means to lower NO_x emissions.

EFFECT ON EMISSIONS

An EDC was installed on a 206 kW Detroit Diesel 6V92TA engine with mechanical unit injectors. The engine was installed on an engine dynamometer at Southwest Research Institute and the engine was tested for emissions using the EPA Heavy Duty Engine Transient Test Procedure. No adjustments to the fuel control governor or injector timing were made.

The reduction in PM was a direct result of the enhanced air supply to the engine during low speed accelerations. It was notable that there was no increase in No_x. This is particularly relevant in light of the previous discussion on the PM/NO_x tradeoff inherent in many emission reduction strategies aimed at heavy duty diesel engines. Additional research is currently underway to further enhance this possible simultaneous reduction in PM and NO_x while utilizing the EDC in a "dual use" format.

The EDC provided 20 KPa intake manifold pressure within 0.25 seconds after the throttle moved from idle position. Without the EDC, the turbocharger required 2-3 seconds to provide the same boost level. The EDC was programmed to run at high speed for 8 seconds after the throttle was moved from idle position. This was sufficiently long for the engine exhaust driven turbocharger to spool up to provide the remainder of the air requirement.

POWER CONSUMPTION

The battery voltage and current were monitored during the FTP transient testing to determine the power and energy requirements of the EDC. It was determined that the EDC consumed 13.8 Amp hrs of battery energy at 24 volts during the 20 minute test. The energy consumption was 330 watt-hrs. The total energy requirement from the engine during the FTP was 14.8 kW-hr, thus the energy required to drive the EDC was 2.2 percent of the total engine power. If the vehicle alternator efficiency is assumed to be 60 percent, this would be the equivalent of 1.6 kW average mechanical power. Reducing the high speed time period from 8 seconds to 5 seconds will have a corresponding reduction on the EDC power consumption.

CONCLUSIONS

Enhancing the air supply to diesel engines has proven to result in significant improvements in engine low speed torque, efficiency, and exhaust emissions. An EDC has demonstrated that this improvement can be made in a device retrofitted to existing engine configurations and is an effective alternative to traditional approaches that are associated with decreased engine performance, turbolag, fuel penalties and PM/NO_x tradeoffs.

There is a definitive need for improved emission control systems in the diesel industry. The ability to improve the air/fuel ratio and subsequent emissions formation emphasizes the need for combustion optimization during certain operating conditions. This is especially true of low-end, fuel rich mixture conditions on turbocharged diesel engines. As combustion processes dictate engine power and efficiency, they also directly influence emission formation. Development and testing of the EDC/"Turbopac™" has resulted in a system that generates significant additional air and is capable of optimizing this air to fuel relationship under low-end operating conditions, thus enhancing combustion efficiency and engine operation.

The impact of enhanced air supply will also ultimately result in smaller engines, reduced vehicle weight, improved fuel economy and lower operating expenses. Future research and development are moving forward on these efforts.

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