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ACHIEVING 44% THERMAL EFFICIENCY in TODAY'S ENGINES "More for Less"

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ABSTRACT

The US Army is seeking improvements in the fuel efficiency of their military vehicles.. They have initiated a number of R&D projects aimed at advancing the state-of-the-art of powertrain efficiency including demonstration in a laboratory environment. This effort will set a benchmark for the vehicle integrators, allowing them to improve future vehicle offerings.

The SAIC, AVL, Badenoch, QinetiQ and Ker-Train Research team offered powertrain solutions from 7 Tons to 40 Tons that achieved the goal of 44% thermal efficiency and the stringent flexible fuel and emissions requirements. In each of these offerings the team was able to identify modifications to existing engines that allowed dramatic improvements in the thermal efficiency. These efficiency improvements were achieved through a combination of techniques, combustion cycle adjustments using in-cylinder pressure monitoring and precise control of fuel injector timing, and turbo-compounding.

For the R&D project, the fuel injector timing will be controlled using commercial engine development hardware and software. The high speed hardware emulates the engine control module but allows the developer to finely tune the fuel injection to maximize the 50% Maximum Fuel Burn point (MFB50) with only limited NOx production. This will be accomplished using a variety of fuels and maintaining the output power to within 2% of the engine's nominal rating.

This paper will describe the fundamental diesel combustion process that must be controlled and techniques for usable power extraction from the waste exhaust gases to provide this performance. It will describe the engine development tools that enable these controls changes to be realized within a vehicle development cycle and retain the baseline engine maturity.

INTRODUCTION

As part of the US Army efforts to reduce reliance on fossil fuels, there is a need to develop more efficient diesel engines. The SAIC team has offered to launch a four year program to advance the state of the art by developing new engine technologies which will improve overall efficiency by reducing fuel consumption and which run on a wide range of fuels. Under this effort, the team will utilize basic and applied research to develop specific hardware and algorithms. The project will provide electronically controlled powertrain, consisting of a diesel engine, a longitudinal transmission, and a high output optimized electrical generator device, which reduces fuel consumption, provides exportable electrical power, reduces noise, and is able to operate on a variety of fuel combinations and mixtures. Figure 1 describes the required characteristics for the powertrain operation is different vehicle weight classes. This paper will highlight our challenge and approach to solving the engine related development to accomplish these requirements. The other project team members are Badenoch LLC (trade studies and modeling support) and QinetiQ Inc (generator and converter used for power absorption and delivery) and SAIC (noise reduction) will support the non-engine development activities. (noise reduction) will support the non-engine development activities.

REQUIREMENTS

We will focus on compression ignition engine technology using a COTS engine as a baseline. Modern engines of this type typically have a high-pressure common fuel rail. To meet the conflicting demands of 44% thermal efficiency at 1998 EPA emission levels without any exhaust treatment, we will leverage advances in COTS high-performance diesel engine control technology, such as real-time sensing and measurement of in-cylinder pressure, control of cylinder combustion through precise metering, control, and injection timing. The goal is precise control of the combustion chamber heat release and pressure profiles to meet power, efficiency, emission, and fuel flexibility goals. A large portion of our work is made possible due to advances in the state-of-the-art modern high-speed digital controls. We will use a rapid prototype environment (e.g., MotoHawk, dSpace, or other control development environment) that will enable us to develop the control code for the engine and powertrain modules with an open interface that enables the customer to modify the code developed within these platforms.

Component/Capability	7 to 9 ton weight class	15 to 19 ton weight class	20 to 40 ton weight class
Engine			
Thermal Efficiency	44% or greater		
Heat rejection	.6 kW/kW or less		
Emissions	No Aftertreatment nor EGR; must conform to 1998 emissions		
Power	150 to 300 Hp	350 to 500 Hp	750 to 1,000 Hp
Fuel Compatibility	DF-2, ULSD, JP-8, JP-5, Jet-A, and mixture		
Transmission			
Configuration	Automatic Longitudinal		Automatic Cross-Drive
Ratio spread	Greater than 10.0		
Transmission Efficiency	90% or greater		
Generator			
Electrical Power Generation	85kW continuous	150 kW Continuous	
Generator Output Voltage	350 – 600 Volts DC	600 Volts DC	
Electronic Controller	Open source compatible buss capable of accepting prognostics and diagnostics in future		

Figure 1 Project Objectives – Powertrains shall be able to maintain engine thermal efficiency, NOx emissions and power using a variety of fuels

APPROACH

The smaller engines in the 150–300 hp power range will typically be designed at 1 liter/cylinder and a total displacement of 4 -7.5 liters. As shown in Figure 2, a typical engine in this class with no Exhaust After treatment System (EAS) will produce close to 10 g/kW-hr of NOx and consume over 194 g/kW-hr of fuel. To meet the emission and thermal efficiency we must modify the engine to consume less than 190 g/kW-hr BSFC (corresponding to 44% peak brake thermal efficiency). The team estimates that the NOx must remain at or below 7.2 g/kW-hr at the peak thermal efficiency point (minimum BSFC). Analysis has shown that reaching this NOx point will allow the engine average NOx to be at or below the EPA 1998 level over the HDT (Heavy Duty Transient) duty cycle.

As stated previously, we will use a COTS engine as our baseline and make the following modifications:

- Remove the EGR and EAS systems, which will have a negative impact on emissions but a positive impact on efficiency
- Modify the intake valve closing, thus reducing emissions while maintaining efficiency
- Replace the open-loop engine controller with a closed-loop in-cylinder pressure-based controller, which provides multi-fuel capability, improves efficiency, and reduces emissions
- Add a turbo-compounding unit, which increases overall thermal efficiency.

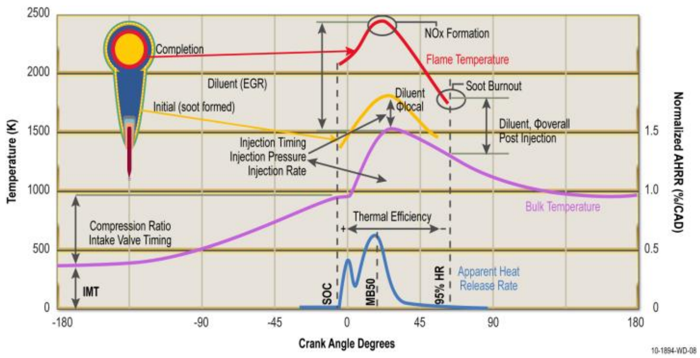

Figure 3 Combustion Physics –Managing the Flame Temperature and keeping the MFB50 close to start of combustion is critical

Combustion processes in diesel engines occur in distinct phases (SOC, rich phase and completion). During initial (pilot) injection, the fuel mixes with the hot gasses in the combustion chamber. When, due to compression, the fuel air mixture reaches 825°K, the fuel-rich mixture (meaning less than stoichiometric oxygen) begins to combust. This is shown as start of combustion (SOC) in Figure 3. Because there is not enough oxygen to fully react with the fuel, fragments of the original fuel molecules, CO, and soot and soot precursor molecules are produced (Figure 3 Upper left corner). The relative low-temperature products)1200K – 1700K) from the rich phase continue penetrating the combustion chamber, where they are consumed during the completion phase of combustion, which occurs around the periphery of the plume as the flame and fuel are exposed to additional oxygen. The high temperatures and the availability of oxygen and nitrogen produce NOx.

Figure 3 depicts the histories of the three temperature regions that affect the emission formation processes. The bulk gas temperature (magenta) indicates the mean temperature of the gasses in the combustion chamber. This represents the temperature of the combustion chamber gasses reacting with the diesel plume. The orange line represents the temperature history of a location in the rich phase reaction zone. Managing the reactions in this region controls the soot formation processes. The red line represents the flame temperature history at the periphery of the diffusion flame where the combustion processes are completed, most of the CO and soot formed during the rich phase combustion are consumed and NOx formation occurs. As this is where NOx forms, controlling this temperature history is crucial to managing the NOx formation process in a diesel engine.

Figure 3 also depicts the Apparent Heat Release Rate (AHRR) (in blue) which is the computed value based on analysis of the cylinder pressure and volume history. Analyzing AHRR can indicate the start of combustion, the duration of combustion, infer the total net energy release from fuel combustion (by integrating the AHRR information), and infer the gross (closed cycle) efficiency of the engine. This computed rate represents the heat released and the integral of the value is work done by the fuel. The centroid of the AHRR or MBF50 point is the point that represents 50% of the necessary work has been completed. Moving the MFB50 closer to a crank angle of about 10 degrees improves the thermal efficiency but increases the NOx and heat losses to the combustion chamber surfaces.

Controlling this combustion process, discussed below, in real-time is critical to maintain efficiency and minimize the NOx creation, however this combustion control alone will not provide sufficient thermal efficiency to meet the project goal of 44%, especially in smaller engine classes.

We will also evaluate other air handling system-driven efficiency improvements, including turbocompounding, Atkinson Cycle (i.e., modified intake valve closing with high geometric expansion ratio), insulating exhaust ports and manifolds to preserve as much exhaust gas energy for the turbocharger turbine as possible, and reducing port flow losses. These engine technology configurations will be evaluated and analyzed during the program.

Turbocompounding, depicted in Figure 4, will be considered a means by which to recover some of the energy in the exhaust as it leaves the engine turbocharger. Demonstrated turbocompounding systems have used mechanical, electrical, and hydraulic systems to recover turbine mechanical power. Complications from the differences in operating speeds between the engine and power turbine as well as the issues caused by the torsional accelerations and fast engine speed changes complicate the development of the power turbine coupling system. In addition, previous turbocompounding systems have been successfully applied to larger engines, which may limit the availability of appropriate power turbine hardware for smaller engine applications.

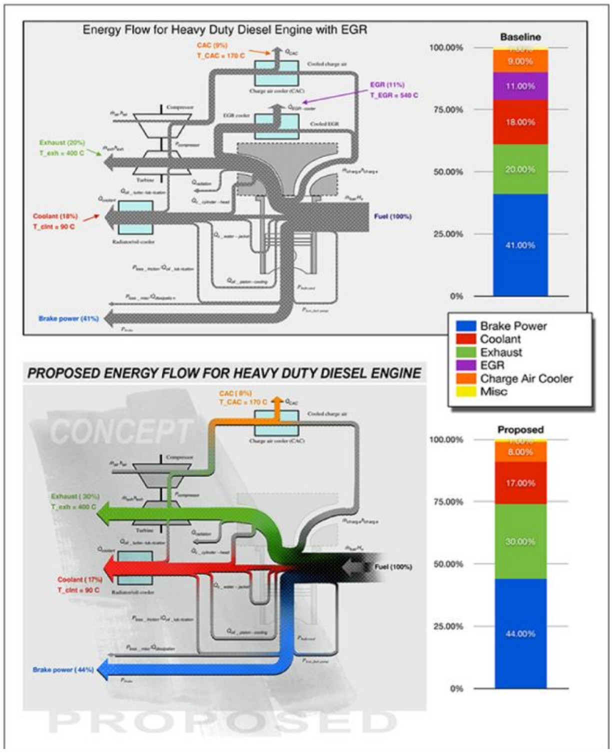

Figure 4 Turbocompounding – Using Turbocompounding can increase total power output

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- Turbo-coumponding
- Atkinson Cycle
- Insulating Exhaust ports
- Reducing port flow losses

Engine performance and durability depend on the fuel type and characteristics, primarily caused by differences in mass and volume energy density, ignition characteristics, viscosity, and the freeze and flash points. Maintaining a constant power (+/-2%) when operating over the range of fuel properties is a challenge we will meet by using closed loop control of cylinder pressure.

Because diesel fuel injection systems are primarily volume-metered devices, compensation for the variable volume specific energy content of different fuels must be implemented to maintain a relatively equivalent amount of injected fuel energy. However, merely detecting the fuel density and compensating the injected volume of fuel is not sufficient because of the viscosity and ignition characterisitics variations. Other control algorithms must be applied to vary both the Start Of Injection (SOI) and the injection volume to control the heat release timing and duration in order to maintain both power and efficiency over the specified range of fuels. Similarly, algorithms will be developed that compensate for the fuels' different ignition properties to prevent misfire and minimize issues with starting and light-load operation. Fuel chemistry attributes that affect diesel combustion include ignition quality (cetane index and number), component volatility, viscosity, density, and heat of combustion. Cetane and fuel volatility directly affect ignition delay, and the rate of pressure rises. Variations in these combustion cycle elements, in turn, have a direct effect on thermal efficiency, emissions, and noise. Viscosity and density affect injector droplet size, shape, and velocity, which can also affect ignition delay and rate of pressure rise. The fuel properties that have the greatest impact on engine power output and engine efficiency are summarized in Figure 5.

Modern common rail diesel engines use sophisticated electronic fuel control systems to regulate fuel injection timing, quantity, and pressure, often injecting multiple fuel pulses during a single combustion cycle to tailor the shape of the heat release and cylinder pressure throughout the combustion cycle. These control capabilities minimize fuel consumption, reduce exhaust emissions and noise. The conventional control system accounts for these variations using open-loop schedules based on measured operating parameters such as mass air flow, exhaust gas temperature and ambient temperature.

Fuel Type	JP-8 Spec	JP-8 Sample (US)	JP-8 Sample (Greece)	U.S. Hwy. No. 2 Diesel Spec.	No. 2 Diesel Sample (U.S.)	Europe Diesel Spec.	Europe Diesel Sample (Greece)	JP-5 Spec.	Jet A Spec.
NATO Designation	F-34	F-34	F-34	F-54	F-54	F-54	F-54	F-44	F-35
Cetane Index	Report	39	47	> 40	47	> 51	54.8	report	report
Lower Heating Value (MJ/kg)	> 42.8	43.2	42	-	42.8	-	42.5	> 42.6	43.0
Heat Content (MJ/L)		34.3			36.6			34.9	34.5
Density @ 15°C (kg/m^3)	774–840	812	790	-	847	820–845	830	788–845	820
Freeze Point (°C)	-47			-12				-46	-47
Flash Point (°C)	38			60				60	38
Kinematic Viscosity (cSt @40°C)	1.0–1.7	1.4 (est)	1.65	1.9–4.1	2.86	2–4.5	3	1.5	1.6
Sulfur Content (ppm)	3,000			15					
Source	[1]	[2]	[3]	[4]	[2]	[5]	[3]	[6]	[7]

Figure 5 Fuel Characteristics – Control will provide required performance across a variety of fuels

Fuels with different chemical properties (notably cetane number) produce significantly different ignition delays. Improper compensation of ignition delay can lead to incorrect fuel injection timing and lower efficiency and power losses.

The SAIC Team will use direct cylinder pressure measurement and feedback control to meet the conflicting engine technology objectives of efficiency, multifuel capability, and emissions without EGR and exhaust after-treatment systems. We will use AVL CYlinder PRESSure-based closed-loop combustion (CYPRESS™), Figure 6, to measure, digitize, and extrapolate Apparent Heat Release Rate (AHRR) that will be crucial to controlling both the start of injection and the amount of fuel on each of the multishot injections. The AHRR characterization allows the CYPRESS™ to determine the MFB50, another key control parameter indicative of thermal efficiency and NOx production. The second key parameter is SOC, which is calculated by the CYPRESS™ analysis of cylinder pressure. The SOC can be controlled by advancing or retarding the SOI to ensure that SOC occurs at the most desirable point in the cycle. As such, feedback control regulating measured ignition delay to a desired value will compensate for variations in actual ignition delay caused by fuel property changes (such as cetane number). The integral of the AHRR over the crank angle is a calculation of total fuel energy released during combustion, which is directly proportional to the amount of fuel energy converted to work per cycle: In this way engine power is maintained when the engine is run on different fuels. By controlling MFB50 and SOC, the control system can adapt to the differences in power and efficiency that occur when operating on the different specified fuels. Production-grade cylinder pressure sensors are available, and Volkswagen recently introduced cylinder-pressure–based control on the 2009 Jetta TDI, demonstrating the feasibility of the recommended control approach.

SOLUTION

Control system modifications alone will not enable us to meet all the engine emission and efficiency requirements, so we may use a bottoming cycle (turbo compounding) to extract additional mechanical energy from the exhaust stream and modified diesel cycles to increase engine efficiency. The following section elaborates on these issues and describes the theory behind our approach to meet all the engine-related requirements of the BAA.

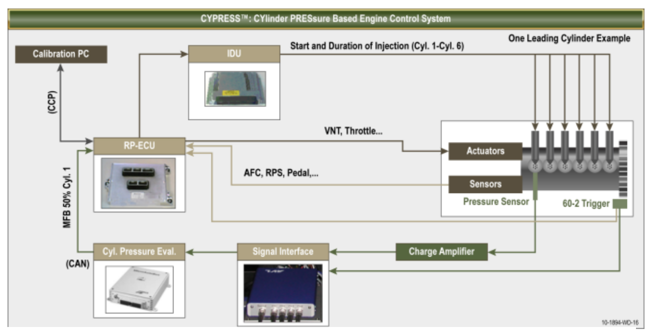

Figure 6 CYPRESS™ Operation – AVL's control approach uses a single in-cylinder pressure sensor to infer engine combustion characteristics

Direct in-cylinder pressure measurement and closed-loop feedback control offers the best solution to simultaneously meet the multifuel, efficiency, emissions, and heat loss requirements of this project. We will implement and calibrate a multi-input and multi-output closed-loop control system to regulate ignition delay and AHRR by suitably adjusting fuel injection timing and fuel injection amount. This is in contrast to existing methodologies, such as shown in Figure 7, that use indirect measures such as exhaust gas temperature and intake manifold temperature to infer in-cylinder pressure profiles. By directly measuring in-cylinder pressure we can more accurately infer performance measures such as AHRR and, as a consequence, better control ignition delay and injected fuel quantity.

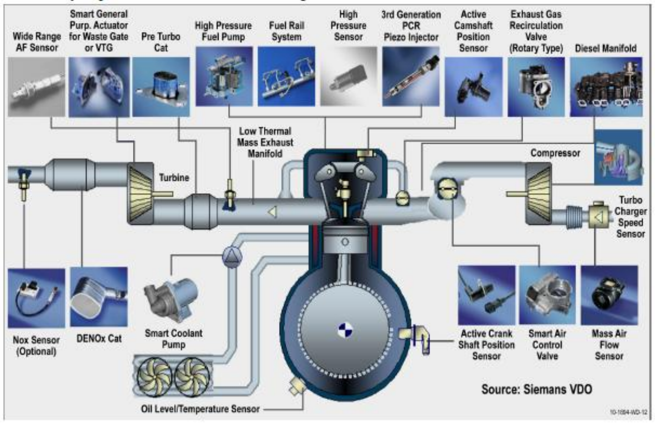

Figure 7 Existing Engine Controls – Conventional Controls use numerous sensors to infer engine operation

By regulating these two characteristics of engine performance, the control system will be able to adapt to the differences in power and efficiency that occur when operating on the different fuels in the specification. The team has selected AVL's CYPRESS tool suite, which supports high-frequency (14 bit/800 kHz per channel) data acquisition of a high precision instrument-grade GaPO4 crystal in-cylinder pressure transducers.

In traditional engine control systems steady-state, response maps are critical to maintaining engine efficiency. As such, careful engine mapping is required to obtain appropriate values and validate models. Because of the multidimensionality of these maps, the team will apply model-reduction methods based on mathematical models of engine physics to reduce calibration efforts typical of the traditional engine mapping approach.

Maximizing an engine's thermal efficiency requires fine-tuning many engine and fuel system parameters, including intake manifold temperature, compression history, injection events, and pressure. Many of these parameter decisions are also affected by the properties of the fuel being used. Traditional engine development methods have focused on detailed characterization of the engine intake air, recirculation air, exhaust, and fuel delivery paths. This characterization typically takes place at several key engine operational points identified as modes or states that have local maps for optimized engine operation. While steady-state operation at these specific points can be optimized to a high degree, transient engine operation often results in discontinuous, nonoptimal engine operation as the controller interpolates between the points of local optimization.

Advances in modern embedded controls have afforded a significant improvement in the amount of processing power available to support advanced mathematical functions, as well as increased processing speeds to allow crank-synchronous calculations. These advances have led to rapid growth in model-based engine controls development and have resulted in significant improvements in engine transient load response and average operational efficiency and significant reductions in engine emissions. These model-based approaches still need improvement, however, as they require a tremendous amount of engineering resource and testing infrastructure to support the required modeling, simulation, testing, verification, and correlation of each of the modeled components and/or subsystems. This complicates the model development in passenger cars and commercial trucks where an engine may be used for different vehicle and mated to different transmissions but our application will focus on a single drivetrain.

The specific modifications we will make to the COTS engine are discussed below.

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Cylinder Pressure Monitoring, providing closed-loop feedback to provide a real-time calculation of the Apparent Heat Release Rate (AHRR). This technology makes it possible to adapt to the fuel ignition quality (Cetane) by adjusting the pilot injection quantity and the placement of the pilot and main injection events. We also will use it to infer the total fuel energy injected by analyzing the AHRR, making it possible to vary the injected fuel volume quantity to achieve consistent (+/- 2%) full load power as the fuel energy density varies. Analysis of the position of AHRR with respect to the crank angle (CA) is dependent on the start of injection and subsequent fuel shots. The ability to control the position of the AHRR maintains high thermal efficiency as the fuel properties vary. These adaptations will be implemented by controlling the fuel injection pulse widths and common rail injection pressure levels.

Atkinson Cycle, provides reduction in combustion temperature and reduces NOx production. We will investigate the Atkinson cycle as a means for implementing a higher geometric compression ratio to increase gross thermal efficiency while controlling NOx via bulk gas temperature history management. The trade-off between the improvements in gross efficiency, NOx, and the impact on air-handling system gas exchange losses will determine if we further pursue this technology for the delivered engines.

Turbo-Compounding is technique to reducing the exhaust loss by reclaiming it and converting it into additional mechanical power, graphically described in Figure 4. Turbo-compounding will improve the fuel efficiency of the engine by recovering and using the energy contained in the exhaust gas exiting the turbocharger turbine. The exhaust leaving the turbocharger turbine contains a significant amount of energy. Turbo-compounding uses a secondary turbine, placed downstream of the turbocharger turbine to recover some of the exhaust energy normally lost to the environment. If turbo-compounding is selected as a delivery path, this study also will determine the most appropriate way to deliver this recovered energy back to the engine crankshaft (mechanical, hydraulic, or electrical) or for separate power generation to unburden any crankshaft driven generator.

Key to developing the engine and its corresponding control system are the AVL analysis and the simulation tool suite, as follows:

BOOST—1-dimensional thermodynamic modeling of the engine system

FIRE—Detailed fluid mechanics of compressible and incompressible fluid flows in the engine

ESE Diesel—Simulation of the fluid mechanics and chemistry of the diesel combustion process.

These modeling tools support the full range of engine modifications and are especially important in developing the injector control, which is a key part of all potential engine solutions. Using the cylinder pressure sensor the engine controller will be able to map the development of the AHRR and the MFB50, which will provide good thermal efficiency correlation. The cylinder pressure map can detect the SOC and the feedback controller can adjust the start of injection to maintain the SOC in the ideal crank position. The cylinder pressure enables accurate measurement of the power produced and by varying the volume of fuel in each of the injection shots the controller will maintain and accurately manage the engine power and noise signature with different fuels.

Our team member AVL has developed and validated unique strategies required to enable the robust and reliable realization of *CYPRESS*™ control. We will use this capability to modify the COTS engine. The following paragraphs summarize the key operational criteria, system structure, and mechanization as well as the benefits to be realized from implementing the *CYPRESS*™ system.

AVL *CYPRESS*™ is an integrated control system developed as a proof of concept of closed-loop combustion control using an in-cylinder pressure sensor. The initial concept for this approach was derived from the suite of hardware and software AVL developed for base engine combustion R&D. The indicating tool suite supports high-frequency (14-bit and 800kHz per channel) data acquisition of high-precision instrument-grade GaPO4-crystal in-cylinder pressure transducers. The data acquisition system comes with a suite of combustion and high-speed data analysis software capable of real-time combustion event–based calculation of key combustion metrics, including heat release, differential heat release, integral heat release, cylinder pressure, average cylinder pressure, and peak cylinder pressure. This tool chain provides the foundation for the detailed analysis required to identify control parameters and to define the sensor and calculation accuracy requirements.

Algorithms were written in Matlab and Simulink and implemented in an AVL IndiMicro to determine the control variables using the cylinder pressure curve and the crank sensor signal of a standard 60-2 tooth production engine. These algorithms, like their higher fidelity indicating counterparts, determine the Interim Mean Effective Pressure (IMEP), the crank angle at which 50% of the fuel is converted to work (MFB50), as well as the value and position of maximum pressure (Pmax) and maximum pressure rise rate (MPR). These metrics are critical in controlling emissions and thermal efficiency.

As shown in Figure 3, SOC depends on the start of injection and ignition delay. As discussed above, measuring cylinder pressure is the most effective feedback control to eliminate these many variables and Controlling the crank angle where the MFB50 occurs is the most promising control variable for combustion control. The team will use MFB50 as the primary control variable, but our recent experience using the MRP will enable us to use the MRP variable as well if early testing fails to provide adequate control. Both of these control variables have an advantage because they are relatively insensitive to a drift in the measurement of the absolute cylinder pressure, which occurs during the useful life of a sensor.

The signals of the in-cylinder pressure sensor are read into the AVL IndiMicro (Figure 6) using a signal interface developed specifically for this purpose. The signal interface design is flexible, which makes it possible to control combustion using indicating quartzes as well as pressure sensors integrated into the glow plug to ensure conditions are close to those of series production. The control variable MFB50 is determined in the AVL IndiMicro and transmitted to the combustion controller in the Rapid Prototype (RP)-ECU via CAN. Combustion control is performed in the RP-ECU, which controls the fuel injectors via the Injector Driver Unit (IDU). All other engine actuators are directly controlled via the RP-ECU. Both the parameters of combustion control and those in the serial controller can be calibrated using one common calibration computer.

For this project, we plan to vary the pilot injection shot quantity and timing to compensate for the varying ignition quality of the fuels. We also will compensate for the energy density of the fuel using analyses of the AHRR to determine appropriate modifications to the injected fuel quantity. We will use similar techniques to address the impacts of fuel properties on thermal efficiency. In all cases, the injection parameters (i.e., quantity, placement, and common rail pressures) will be manipulated based on analysis of the cylinder pressure waveform. Controlling combustion based on cylinder pressure reduces emissions scatter due to tolerances of the wear components throughout the life cycle of the engine. If combustion is controlled precisely, the accuracy of the open-loop control part of the engine can be reduced; subsequently, open-loop combustion control sensors can have larger tolerances or can be eliminated which will simplify calibration. Figure 8 shows some advantages of the closed-loop combustion control in the case of an error in the measured air mass. In the example, a test engine was kept on a constant operating point (80 Nm at 1,500 rpm) on the test bed. A simulated signal deterioration was introduced by using the EGR controller to feed a modified fresh air mass that did not correspond to the optimum for this operation point. The effect on combustion is identical to that of a measuring error in the air mass sensor.The left portion of Figure 8 shows the influence of this air mass error on combustion position MFB50. Without closed-loop combustion control (i.e., with open-loop control), the center of the combustion will change significantly; first, it will be too late and then as the air mass increases, it will be too early. With a closed-loop combustion controller, MFB50 will exactly follow the demand value (MFB50 – demand).

The right portion of the Figure 8 shows the effects of the air mass error on MFB50, noise, HC, and CO with and without closed-loop combustion control. From the figure, it is clearly visible that closed-loop combustion control not only considerably reduces the increase in combustion noise and HC but also that of NOx, CO, and soot

Due to the optimization of injection timing, cylinder pressure–based combustion control also yields considerable advantages at cold start, cold idling, warm up, and variable fuel quality. It is possible to stabilize engine operation to within +/-2% and to simplify calibration that usually is complex Figure 8. The combustion pressure sensor also can improve OBDs and calibration of the ideal injection quantity

CONCLUSIONS

Technology available today allows precise combustion control on most all common rail diesel engines. This control allows significant customization of engine performance to meet specific demands such as flexible fuel operation, high thermal efficiency and limited emissions. These characteristics can be modified to provide an optimal customer solution. The team will implement turbo-compounding and a modified Atkinson cycle to increase thermal efficiency as required.

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