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Consistent Performance With Fuel Found in Theater: Real-Time Fuel Adaptation With Cylinder Pressure Based Combustion Control

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ABSTRACT

Cylinder Pressure Monitoring (AVL CYPRESS™) is a technology which provides closed-loop feedback to enable real-time control of combustion in a compression ignition engine. This makes it possible to adapt to the fuel ignition quality and energy density by adjusting the main injection quantity and the placement of the injection events. The engine control system can thus detect fuel quality and adapt the combustion phasing quickly and robustly – and without any prior knowledge of fuel properties. By using a cylinder pressure sensor(s), the engine controller will be able to map the development of the apparent rate of heat release (ARHR) and the mass fuel burn curve - which provides good thermal efficiency correlation. The cylinder pressure map detects the combustion event and the feedback controller adjusts the start of injection to maintain the combustion event at the desired crank position. The cylinder pressure sensor allows for accurate measurement of the power produced. By varying the volume of fuel in each injection shot the controller actively manages the engine power and noise signature with different fuels (e.g. DF-2, JP-8, JP-5, etc.). The initial concept for this approach was derived from AVL's suite of hardware and software tools developed for base engine combustion research and development. This technology is now licensed to major OEMs and is in production vehicles in Europe. Results of AVL CYPRESS performance on military grade fuels is presented which demonstrate consistent torque performance within 1% regardless of varying fuel properties.

INTRODUCTION

Cylinder Pressure Monitoring (AVL CYPRESS™) is a technology which provides closed-loop feedback to enable real-time control of combustion in a compression ignition engine. This makes it possible to adapt to the fuel ignition quality and energy density by adjusting the main injection quantity and the placement of the injection events. The engine control system can thus detect fuel quality and adapt the ignition sequence quickly and robustly – and without any prior knowledge of fuel properties. By using a cylinder pressure sensor(s), the engine controller will be able to map the development of the AHRR and the mass fuel burn curve - which provides good thermal efficiency correlation. The cylinder pressure map detects the combustion event and the feedback controller adjusts the start of injection to maintain the combustion event at the desired crank position. The cylinder pressure sensor allows for accurate measurement of the power produced. By varying the volume of fuel in each injection shot the controller actively manages the engine power and noise signature with different fuels (e.g. DF-2, JP-8, JP-5, etc.). The initial concept for this approach was derived from AVL's suite of hardware and software tools developed for base engine combustion research and development. This technology is now licensed to major OEMs and is in production vehicles in Europe.

CHALLENGE OF USING MILITARY FUELS

In an effort to simplify in-theater logistics and reduce costs, the United States Army needs all equipment to operate on a single fuel. The Single Fuel Forward Concept (SFFC) specifies that Jet Propulsion Fuel 8 (JP-8) should be that fuel since it will allow for the operation of all equipment – although with reduced performance for Commercial Off-The Shelf (COTS) internal combustion piston engines originally designed for Diesel Fuel (DF-2). When vehicles are operated in peace time operations or near exiting fuel distribution infrastructure, however, it may be desirable to operate on DF-2. Therefore the effective application of compression ignition engines for military use requires that the engines operate on both fuels equally well with minimal operator intervention.

There are three primary challenges to using military grade fuels such as JP-8 in these COTS engines: fuel lubricity, cetane number variability, and energy density. The fuel lubricity issue relates to mechanical wear in the fuel system (especially high pressure common rail pumps) and can be effectively addressed with fuel additives as described in References [1-3]. The second two issues, however, cannot be solved with fuel additives and require special controls to maintain consistent engine performance on all fuels.

Cetane Effects

To illustrate the effect of cetane variability, Figure 1 shows the variability of cetane index in JP-8 and JP-5 compared to Ultra Low Sulfur Diesel (ULSD) (see Reference [4]). Although the distributions generally overlap within the ULSD specification range, there are several outliers below a cetane index of 40 that present special challenges for combustion in a piston engine. The resulting increase in ignition delay for these fuels would be excessive, and it would result in reduced efficiency or even misfire.

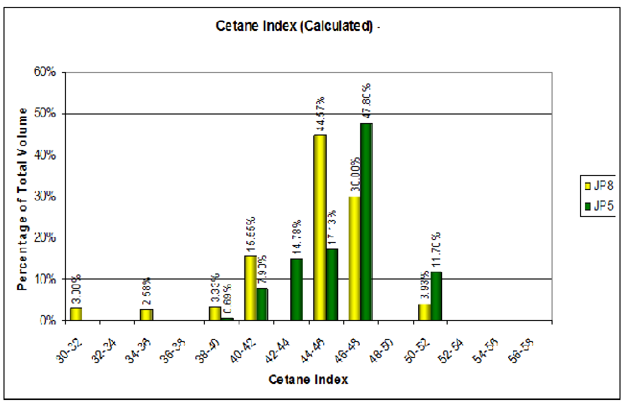

Figure 1: Cetane Index Variability of JP-8 & JP-5 vs. ULSD

Energy Density Effects

Figure 2 shows similar data for mass density of military grade jet fuels vs. ULSD. While mass density itself is not critical to combustion performance, it can be used a surrogate for energy density. All fuel injection systems in use on COTS engines meter fuel on a volume basis, and thus changes in energy density on a volume basis directly result in a difference in fuel energy delivered to the combustion chamber. Generally speaking military grade jet fuels have higher energy content on a mass basis (as a result of the higher hydrogen to carbon ratio), but lower energy density on a volume basis (see Figure 3). The effect of this difference is twofold: first less energy corresponds to less fuel, and second the rate of energy release tends to be less since the fuel is typically injected at a fixed rate during the injection event. Both of these phenomena result in reduced power and torque output when a COTS engine is operated on military grade jet fuels versus DF-2 on the order of 5%.

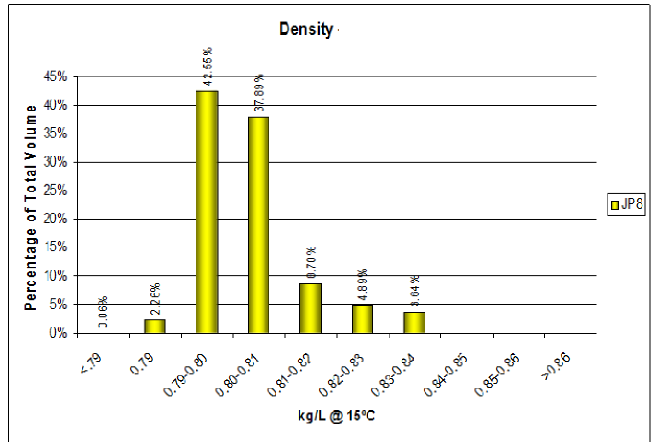

Figure 2: Density Variability of JP-8 & JP-5 vs. ULSD

Property	Units	Diesel	JP-8
Cetane Index	-	45 Typical (Min 40)	25 – 50+ Typical
Energy Density (Typical)	*MJ/kg*	42.5	43.4
	MJ/L	36.2	34.5
Density	*kg/L*	0.85	0.79
Lubricity	-	Nominal	Poor

Figure 3: Typical Properties of JP-8 vs. ULSD

CONTROL SYSTEM REQUIREMENTS

Actuator Selection

In order to address and overcome the challenges of cetane and energy density variability, special engine controls are required to respond to changes in fuel properties. To account for the effects of cetane variability, the fuel injection event must either be advanced or retarded with respect to crank angle to maintain combustion phasing a the desired point. The actuator to accomplish this phasing already exists on COTS engines in the form of electronically controlled injection timing. Similarly, to account for differences in total energy rate, the volume of fuel injected must be modified to keep total fuel energy constant. The duration of injection event is electronically controlled on modern COTS engines and can be used for this purpose. Finally, the rate of combustion can be controlled by adjusting the rate at which fuel is injected – which is electronically controlled on high pressure common rail (HPCR) fuel systems by modulating fuel rail pressure. Indeed these mechanisms are precisely the technologies that have allowed modern diesel engines to meet very stringent emissions and efficiency targets simultaneously (see Figure 4). They are traditionally, however calibrated in an "open-loop" manner that assumes a very narrow range of fuel properties – a valid assumption if the engine is only intended to burn DF-2 or ULSD. In order to run "closed-loop" on fuel properties requires the addition of a sensing mechanism provide feedback on actual fuel properties or engine performance.

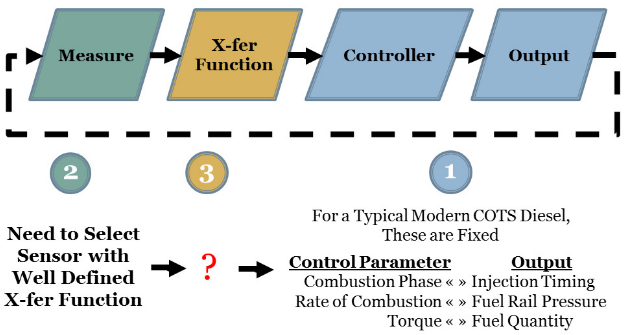

Figure 4: Fuel Sensing Control System Schematic

Sensor Selection

There are two general approaches to measuring fuel variations using existing sensing techniques. First, the properties of the fuel can be measured. Sensors exist that can measure viscosity, chemical composition, and exhaust composition. Secondly, the engine behavior can be measured through optical measurement of combustion, torque variation vs. crank angle, and cylinder pressure vs. crank angle. Since the actuators are fixed (preexisting hardware on the engine), the best criterion available to select the best sensor technology is to ask: which sensor technology has the most direct and robust transfer function from sensor signal to actuator signal? (See Figure 4). Figure 5 illustrates the relative strengths of several measurement techniques based on this metric. Both the transfer function between sensor signal and actuator signal is considered, as well as the overall system complexity in terms of hardware and computation.

Type	Sensor	Output	X-Fer Func.	Complexity
Engine Behavior Sensing	**Cylinder Pressure**	Pressure vs. CA	MFB, AHRR, CHR	Med
	Torsional Variation	Torque vs. CA	Phase & Mag of Torque Pulses	Med
	Combustion Luminosity	Combustion Brightness vs. CA	SOC, ~MFB	Very High
Fuel Property Sensing	**Viscosity Sensor**	Viscosity	?	?
	Optical Encoder	All Modeled Properties	?	Very High
	Fiber Optic	All Modeled Properties	?	Very High

Figure 5: Sensor Technology Evaluation

When examined this way, all sensors measuring fuel properties directly are at an inherent disadvantage. All of these sensors either classify the fuel type (such as DF-2, JP-8, etc.), or directly report a physical property of the fuel (such as viscosity or chemical composition). This information is insufficient to reliably and robustly decide what changes in fuel injection timing, duration and rate needed to maintain constant engine performance.

The class of sensors that measures engine performance directly greatly simplifies the task of specifying a sensor transfer function because the measurement is closely related to the actuator outputs. Measuring combustion with optical techniques is impractical outside of a laboratory setting due to the high cost for the sensing system as well as the requirement mounting a camera system into a COTS engine. Another possibility is to measure the torque pulsations that result from combustion events at the crankshaft. While instantaneous torque measurements vs. crank angle are possible, it is difficult to separate the effects of individual combustion events since the crankshaft torque is the sum of all cylinders. Using cylinder pressure versus crank angle to measure combustion is both practical and precise, and this is in fact the technique used during traditional engine development testing. Using commercially available sensors it is possible to directly measure when combustion occurs (50% mass burn fraction – MFB50), how much fuel energy is released (total apparent heat release - CHR), and the rate at which it is released (apparent heat release rate - AHRR) using well established techniques based on engine geometry. The most effective sensor technology for the required real-time combustion control should be based on cylinder pressure measurements.

CYLINDER PRESSUE BASED CONTROL

Three parameters must be controlled to maintain consistent engine performance with varying fuel properties: combustion phasing, total fuel energy released, and the rate at which fuel energy released. Figure 6 describes the importance of each parameter over different operating regimes of a COTS engine. All of the control parameters below are calculated based on the ARHR and CHR of a combustion event which is calculated using Equations (1-2). The inputs required are cylinder pressure vs. crank angle, combustion chamber volume vs. crank angle (engine geometry), and the ratio of specific heats for the gas in the combustion chamber. The cylinder pressure and crank angle can be easily measured in real time. The combustion chamber volume versus crank angle is fixed for a given engine geometry. The final component – the ratio of specific heats of the combustion gases – varies according to temperature, pressure, and chemical composition (none of which are constant during the combustion stroke). It is sufficient for the purposes of control, however, to assume a constant value for this parameter. The resulting loss of precision does not substantially alter the shape of the resulting CHR curve, and, since control parameters are based on this shape, control fidelity does not suffer as a result. Heat loss through the combustion chamber walls is also neglected during the combustion event. While this does introduce some error into the result, again it does not substantially alter the shape of the resulting CHR curve.

Regime	Control Importance			Notes
	Phasing	ARHR	Total HR	
At/Near Idle	Critical	Low	Low	Premixed Combustion, Idle Governor in Control
Light Load	Critical	Low	Normal	Premixed Combustion
Moderate Load	Normal	Normal	Normal	Balanced Combustion
Near Full Load	Low	Critical	Critical	Diffusion Combustion, Need Constant Full Load Curve

Figure 6: Control Characteristics vs. Engine Operating Regime

$$AHRR = \frac{1}{1-\gamma}\left[\gamma P \frac{\delta V}{\delta \alpha} + V \frac{\delta P}{\delta \alpha}\right] \quad (1)$$

Where,

γ = ratio of specific heats of combustion gasses
P = cylinder pressure as a function of crank angle
V = cylinder volume as a function of crank angle
α = crank angle

$$CHR = \int AHHR(\alpha)d\alpha \quad (2)$$

Combustion Phasing

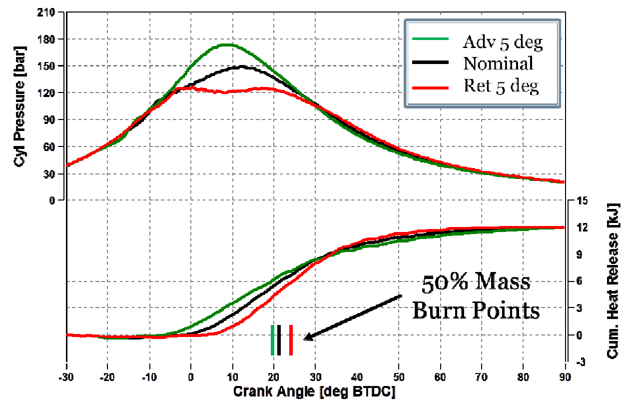

Figure 7: MFB50 vs. Combustion Phasing

Combustion phasing represents when a combustion event occurs with respect to engine crank angle. The variable selected to measure phasing is the 50% mass fraction burn (MFB50): the crank angle at which half of the fuel energy has been released. The choice of MFB50 to represent combustion phasing has two key benefits. First, it can be directly calculated from cylinder pressure and engine geometry with minimal computational resources. Secondly, the 50% mass burn point is not sensitive to cycle-to-cycle variability and is very repeatable as a result. The start and end of combustion, by contrast, are extremely sensitive to cycle-to-cycle variations and are thus produce very noisy outputs. Furthermore, this quantity can be reliable calculated at all engine operating conditions from idle to rated power. Figure 7 illustrates how MFB50 changes with combustion phasing. Given a target value for MFB50, a controller can adjust injection timing to achieve that target.

Total Fuel Energy

Total fuel energy released is represented by the maximum value of the CHR curve over the course of a combustion event. This value is calculated by integrating the ARHR curve as shown in Equation (2), and since integration is effectively an infinite impulse filter with equal weighting for all data points, it has excellent repeatability from cycle to cycle. Given a target value for total fuel energy, the duration of the injection event can be adjusted to achieve that target.

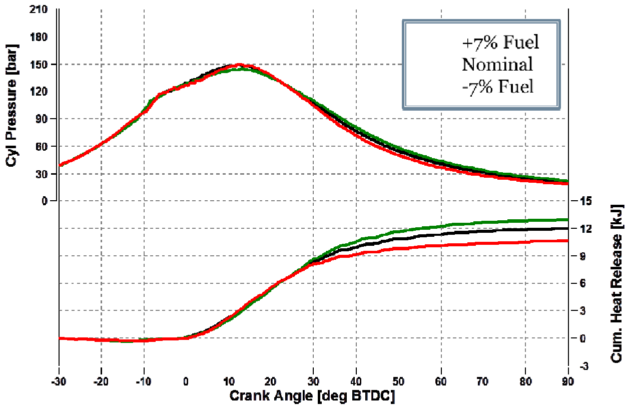

Figure 8: Max CHR vs. Total Fuel Energy

Rate of Energy Release

The rate of heat release varies over the combustion event, and it is generally divided into three phases. The first phase of combustion is known as premixed combustion and it is characterized as a small but rapid release of heat – which appears as a small hump at the beginning of the combustion event. The next phase is stable diffusion based combustion which ramps up to a roughly constant rate of heat release. Once the fuel injector stops injecting the remaining fuel continues to burn at decreasing rates with CHR asymptotically approaching its maximum value. For reasons similar to that of MFB50, the most stable and representative rate of heat release occurs near the middle of the combustion event. Although the point of maximum heat release rate does not necessarily occur at the same point as MFB50, it is usually close enough to be representative and is computationally simpler to calculate at that point. This parameter tends to be the most sensitive to noise in the pressure measurement signal, but that can be addressed with simple moving average filtering of the ARHR signal before calculation. Figure 9 illustrates the effect of rate of heat release on combustion. Given a target rate of heat release, the fuel rail pressure of an HPCR fuel system can be adjusted to achieve that target.

The AVL CYPRESS™ system is comprised of all three of these controllers acting simultaneously. If all three parameters are controlled to their respective targets, the ARHR and CHR curves will be identical regardless of the variation in fuel properties. With identical combustion events, the torque and power of the engine must be identical – so the system allows for the automatic adaptation to both cetane and energy density effects in various fuels. Of course there are inherent limits to the adjustments that can be made to injection timing, fuel rail pressure, and injection duration, but the changes required are generally well within the system limits.

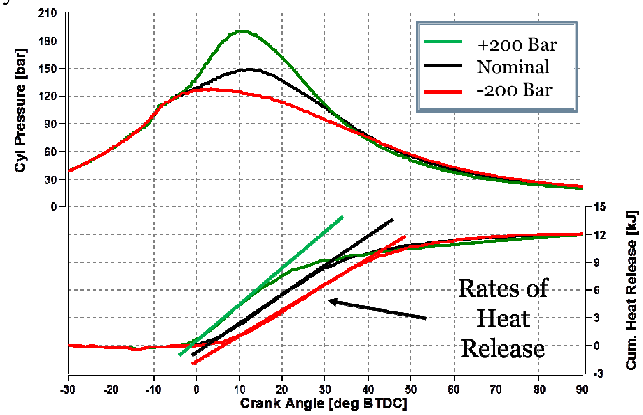

Figure 9: ARHR vs. Combustion Rate

ENGINE TEST RESULTS

BAA Topic 23 Engine

A 2012 model year Detroit Diesel 15 inline six engine was modified and recalibrated for use on military fuels under the BAA Topic 23 program funded by TARDEC. The base COTS engine was certified to the 2010 on road heavy duty emissions level. The objectives of the program were to achieve brake thermal efficiency of at least 44%, specific heat rejection to coolant less than 0.6 kW/kW, and torque variation less than 2% of full scale on all military grade fuels specified by TARDEC. The engine was required to meet US emissions standards for on road heavy duty engines for model year 1998. The engine was modified to remove EGR and exhaust aftertreatment systems. AVL CYPRESS was I nstalled to accomplish the torque consistency requirement. Figure 10 summarizes the configuration of the engine as tested.

Steady State Results

To validate the AVL CYPRESS system's ability to maintain torque output within the program target of two percent of DF-2 baseline, the engine was tested on six fuels with varying properties. The engine is stabilized on DF-2 at sixteen operating points covering the entire engine operating envelope. The fuel is then instantaneously switched at the engine fuel inlet and data are recorded for a period of time sufficient for the residual DF-2 to be burned out of the engine fuel system and fully replaced by the new fuel. The remaining operating points and fuels were tested using the same procedure, and the results are summarized in Figure 11. The Figure shows the variability of each fuel tested with AVL CYPRESS active by plotting the total torque variation seen over the sixteen operating points as the dark blue line.

The light blue box corresponds to the average value plus or minus one standard deviation. Although each fuel was not tested without AVL CYPRESS active, in order to protect the engine from extreme combustion variations, the estimated loss of performance without CYPRESS is calculated based on the fuel system adjustments made by CYPRESS. For all fuels tested, AVL CYPRESS is able to maintain engine torque within less than one percent of the baseline torque measured on DF-2, and in many cases less than one half of one percent. Without AVL CYPRESS, these variations increase to as much as eight percent. It should also be noted that certain fuels like the JP-8 SASOL Low Cetane may not even run at all without CYPRESS compensation. See Figures 12 and 13 for detailed fuel properties for all fuels tested.

Properties	Value	Unit
Commercial Name	Detroit Diesel DD15 S/N 472903S0093541	-
Engine Type	4-Stroke	-
Combustion System	Direct Injection, Compression Ignition	-
Charging System	Holset HX55 VGT Turbocharger	-
Fuel Injection System	Bosch ACRS 900 Bar Max Rail 3x Max Amplification	-
Valve Config	2 Intake – 2 Exhaust	-
Engine Config	Inline 6	-
Displacement	14.8	L
Bore	139	mm
Stroke	163	mm
Comp Ratio	18.4	-
Rated Power	391	kW
Rated Speed	1,800	rpm
Peak Torque	2500	Nm
Speed @ Max Trq	1,200	rpm

Figure 10: ARHR vs. Combustion Rate

Transient Emissions Results

HDDT emissions cycles were also run with all fuels tested. Figure 14 summarizes the performance on the various fuels relative to specific performance targets to demonstrate that all program objectives are achieved on all fuels. These results confirm that even though emissions development was conducted exclusively on DF-2, the engine is capable of meeting US 1998 emissions standards on all fuels. AVL CYPRESS also reduces the variability in emissions results due to fuel energy density and ignition characteristics – although chemical differences still cause changes in emissions performance which cannot be eliminated entirely by AVL CYPRESS.

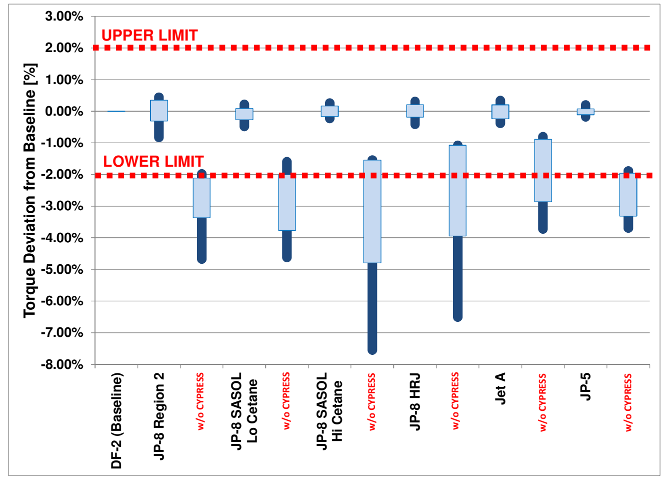

Figure 11: Steady State Torque Performance

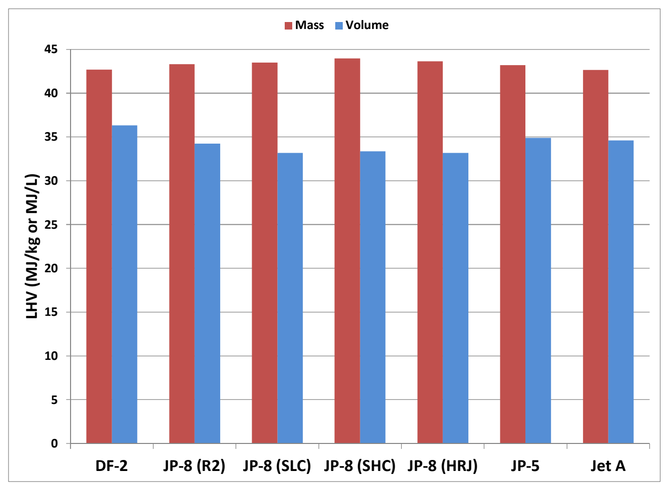

Figure 12: Fuel Energy Density as Tested

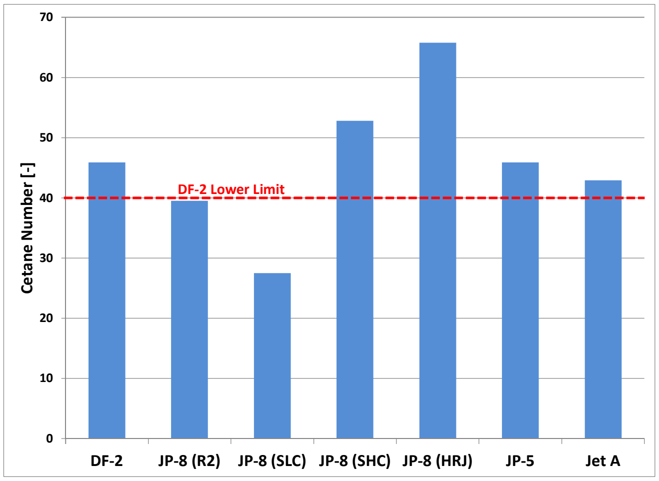

Figure 13: Fuel Cetane Number as Tested

Objective	Target	Units	DF-2	JP-8 Reg. 2	JP-8 S LC	JP-8 S HC	JP-8 HRJ	Jet A	JP-5
Therm. Eff.	≥44%	%	45.0%	45.7%	45.4%	45.0%	45.3%	45.1%	44.9%
Heat Rej.	≤0.60	kW/kW	0.56	0.56	0.56	0.56	0.56	0.56	0.56
NO_X	≤4.0	g/hp.h	3.77	3.74	3.60	3.64	3.83	3.95	3.30
HC	≤1.3	g/hp.h	0.25	0.30	0.36	0.50	0.24	0.30	0.21
CO	≤15.5	g/hp.h	1.18	1.12	1.51	1.67	0.85	1.17	0.76
PM	≤0.10	g/hp.h	0.067	0.039	0.040	0.040	0.031	0.044	0.054

Figure 14: Transient Performance Summary

ADDITIONAL BENEFITS

The AVL CYPRESS™ system responds to changes in combustion behavior and adjusts the fuel system accordingly to maintain consistent performance. While the discussion up to this point has dealt with combustion changes that occur as a result of changes in fuel properties, the system itself responds to all changes in combustion behavior regardless of source. That means automatic adjustments are made as a result of ambient temperature and pressure changes. The result is an engine control system that is not only capable of adapting to fuel property changes but also environmental conditions as well.

SUMMARY

AVL CYPRESS™ is a technology which provides closed-loop feedback to enable real-time control of combustion in a compression ignition engine. This technology allows an engine to respond to changes in fuel properties such as cetane number and energy density by adjusting combustion phasing, total fuel energy injected and rate of fuel energy injection to match calibrated targets based on cylinder pressure measurements vs. crank angle. The system operates automatically without the need for operator intervention, and is a key enabler to the successful implementation of the Single Fuel Forward Concept.

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