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How to Deal with Fuel Found in Theater: CYPRESS-Cylinder Pressure Based Combustion Control for Consistent Performance with Varying Fuel Properties and Types

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ABSTRACT

Cylinder Pressure Monitoring (CYPRESS™). This technology provides closed-loop feedback to enable a real-time calculation of the apparent heat release rate (AHRR). This makes it possible to adapt to the fuel ignition quality (cetane number) by adjusting the pilot injection quantity and the placement of the pilot and main injection events. This enables the engine control system to detect fuel quality and adapt the ignition sequence accordingly.

This technology is also used 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 thermal efficiency as fuel properties vary which are implemented by controlling the fuel injection pulse widths and common rail injection pressure levels.

Key to the development of the control system and subsequent adaptation to a corresponding engine is the AVL analysis and simulation tool suite as follows:

- *BOOST—One-dimensional thermodynamic modeling of the engine system*
- *FIRE—Detailed fluid mechanics of compressible and incompressible fluid flows in the engine*
- *Engine Simulation Environment (ESE) Diesel— Simulation of the fluid mechanics and chemistry of the diesel combustion process.*

Through the use of a cylinder pressure sensor, the engine controller will be able to map the development of the AHRR and the mass fuel burn point (MFB50%), which provides good thermal efficiency correlation. The cylinder pressure map detects the start of combustion (SOC) and the feedback controller adjusts the start of injection (SOI) to maintain the SOC in the ideal 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.

MILITARY FUEL SPECIFICATIONS

The US Army encountered fuel waxing issues with NATO F-54 fuel (diesel fuel) during cold weather maneuvers in the early 1980s when the M1 battle tank was first introduced. Waxing refers to the formation of paraffinic crystals in the fuel at low temperatures as components of the fuel solidify. These crystals cause a non-Newtonian increase in fuel viscosity, affecting the pumpability of fuel in the vehicle's fuel delivery system and can ultimately plug fuel filtration systems. The interim solution to this issue was to blend F-54 with kerosene-like aviation fuels that have lower viscosity and lower wax formation temperatures when cold weather operating conditions were expected. This "M1 Fuel Mix", having 50:50 a proportion of F-54 and JP5 (NATO F-44) or JP8 (NATO F-34) is referred to as NATO F-65 fuel. While F-65 resolved the waxing issue, the logistics of supplying and blending two fuels for specific conditions complicated the supply chain [1].

To streamline fuel supply logistics in operation theaters while minimizing fuel waxing issues, the Department of Defense (DOD) sought alternatives to F-65 in ground vehicles. The US Army specified JP-8 as an acceptable alternative to DF-2 in 1986. Two years later the DOD issued the 'Single Fuel Forward' directive which designated JP-8 as the primary fuel for all land and air forces.

JP-8 is a kerosene like 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: a fuel system icing inhibitor (FSII), a corrosion inhibitor/lubricity enhancer (CI/LE), and a static dissipater additive (SDA). Jet A, another similar fuel, has a higher freeze point (the temperature at which the wax crystal begin to form, causing the fuel to appear cloudy) 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 on ship storage safety reasons.

Engine performance and durability depend on the fuel used, primarily due to differences in viscosity, heat content, density and ignition characteristics (cetane number and cetane index). The specifications for the fuels of interest to this study 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 (corr. to 40°C, mm^2/s)	1.0 – 1.7	1.9 – 4.1	1.6	1.5
Freeze Point (°C)	<-47	<-12	<-47	<-46
Density (kg/L)	.745 - .840			.788 - .845
Flash Point (°C)	>38	>60	>38	>60
Cetane Index (-)	Report	47	Report	Report
Sulfur Content (ppm)	<3000	<15	—	—
Heat Content (MJ/L)	34.3	36.6	34.5	34.9

Table 1: Typical Military Fuel Properties [2]

Aviation fuels 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.

There are some fuel property differences between aviation fuels such as JP8 and JP5 and diesel fuel. Of particular importance are the specifications (or lack of) for Cetane Index, viscosity, and Heat Content.

As shown in Table 1, unlike for diesel fuel there is no minimum Cetane Index specified for the aviation fuels, only the requirement to report the value for the batch of fuel delivered. Cetane Index is an indication of the auto-ignition characteristics of the fuel, based on the 50% distillation point and the fuel density (API gravity) [3]. For most diesel fuels it is a working surrogate for the actual (and expensive) engine test derived Cetane Number.

Low Cetane Index values indicate fuels that are resistant to auto-ignition. As the diesel combustion process depends on auto-ignition for initiation, low Cetane Index fuels can result in difficulties with engine starting and light load operation, especially in cold temperatures. Low Cetane Index fuels can result in longer ignition delay (the time lag between when the fuel injection event starts and when combustion starts), delaying the combustion event and adversely affecting the engine efficiency.

Figure 1 shows the distribution of Cetane Index reported from fuel analysis performed on JP8 and JP5 fuels delivered to the military in 2008, the latest year for which data have been compiled and reported [2], compared to minimum, 25th percentile, median, 75th percentile and maximum for the range of Cetane Index of commercial diesel fuel as surveyed in 2007 [4].

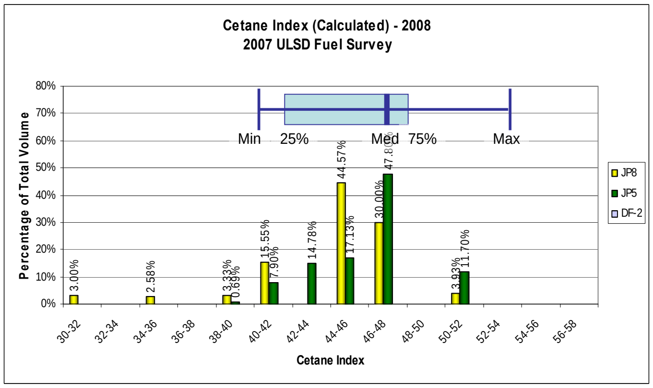


Figure 1: Variation of Cetane Index for JP8, JP5 and DF-2

Although most of the fuel samples analyzed for both of these fuels had Cetane Index levels consistent with the current specification for on-highway diesel fuels, nearly 10% of the volume of the JP8 delivered had Cetane Index values less than 40, and 3% of the samples had Cetane Index levels less than 34. The use of these fuels would be expected to result in delayed start of combustion, including the potential for no-starts or mis-fires, especially at lightly loaded operating conditions at low ambient temperatures and high altitude.

Figure 2 depicts the heating value of JP8 and JP5 fuels. As with most non-oxygenated hydrocarbon fuels, including diesel fuel, the heating values of all these fuels are fairly consistent. However, as shown in **Figure 3**, the densities of JP8 and commercial diesel fuel can cover a different and wide range of values. Given the consistent mass specific heating values, the variation in density is expected to result in a similar variation in the volume based energy content of these fuels. As most COTS fuels systems rely on some variant of volume based fuel injection metering, these energy density variations could result in, if uncompensated, unwanted variation in full load torque and power characteristics of the engine.

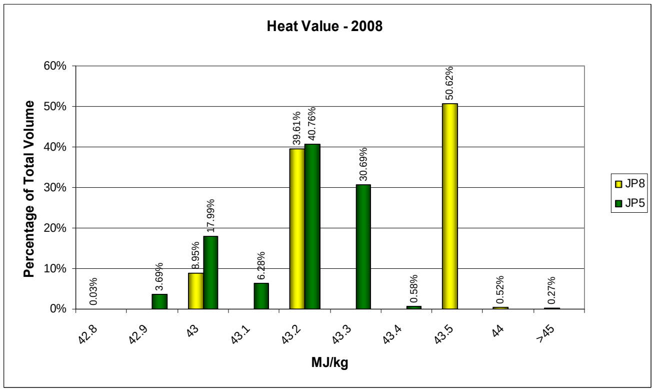


Figure 2: Mass specific Heating Values of JP8 and JP5 Fuels [2]

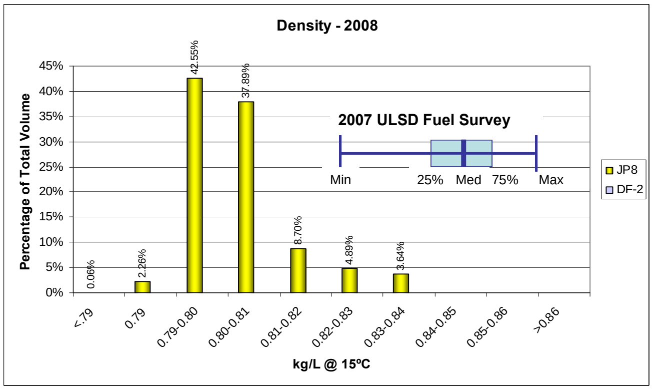


Figure 3: Density of JP8 and DF-2 fuels [2 and 4]

Figure 4 shows the measured kinematic viscosity differences and field sample variation. For aviation fuels such as JP8 and JP5, the kinematic viscosity of the fuel at low temperatures is of importance as it affects flow and pumpability at the conditions attained in aircraft on-board fuel storage and delivery systems at high altitudes. For this reason, the kinematic viscosity of aviation fuels are reported at fuel temperatures of -20ºC and specified to be less than a maximum value of 8mm^2/s to ensure flow.

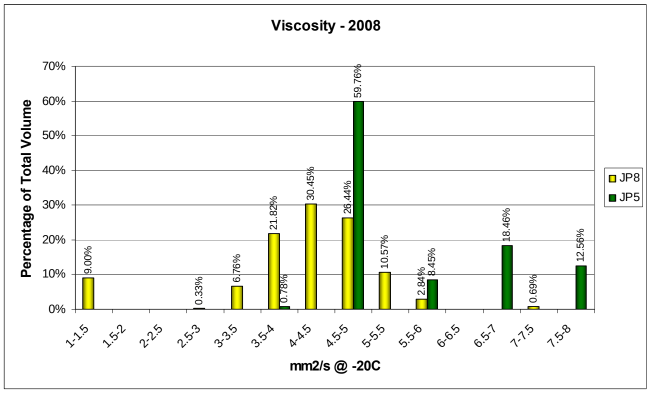


Figure 4: Variation in Kinematic Viscosity at -20ºC for JP8 and JP5 fuels [2]

For use in a diesel engine, the kinematic viscosity at high temperatures is of concern. Typical, modern COTS engine fuel systems rely on fuel to provide lubrication to the internal components subjected to high contact stresses and to control leakage past the injection pump plunger and barrel. A suitable minimum level of kinematic viscosity at conditions more representative of those realized in ground vehicle applications is required. For this reason, the kinematic viscosity for diesel fuel is specified at 40ºC. Fuels having low kinematic viscosity at high temperatures could adversely impact diesel fuel life due to low lubricity, and fuel system performance, as well as subsequent impacts on engine performance, due to higher leakage rates in the fuel system pressure generation elements affecting injection pressure and metering capacity.

A comparison of the kinematic viscosity characteristics of DF-2 and both JP8 and JP5 as corrected to 40ºC is shown in **Figure 5**. This chart was constructed using the data for JP8 and JP5 fuel samples shown in Figure 4, correcting the kinematic viscosity levels to 40ºC to provide comparison of these fuels to DF2. The correction was based on the ratio of kinematic viscosity measurements from a single sample of JP8 characterized at both -20ºC (4 mm2/s) and 40ºC (1.2 mm2/s). This technique compares well with typical trends in viscosity v. temperature as found in [5].

To provide consistent engine performance as various fuels are used or to compensate for batch to batch or region to region variations in fuel properties within a given type of fuel, some type of compensation, based on indicators of engine combustion and performance, needs to be applied.

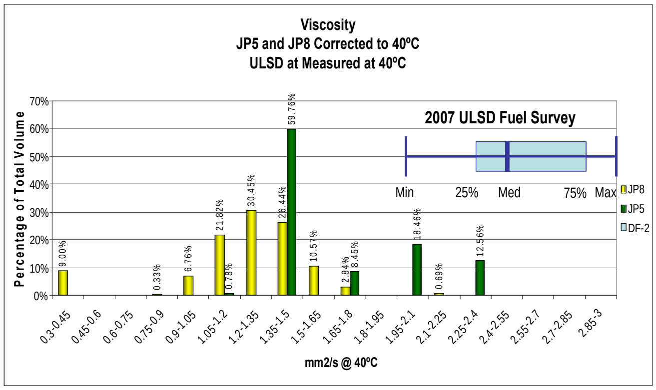
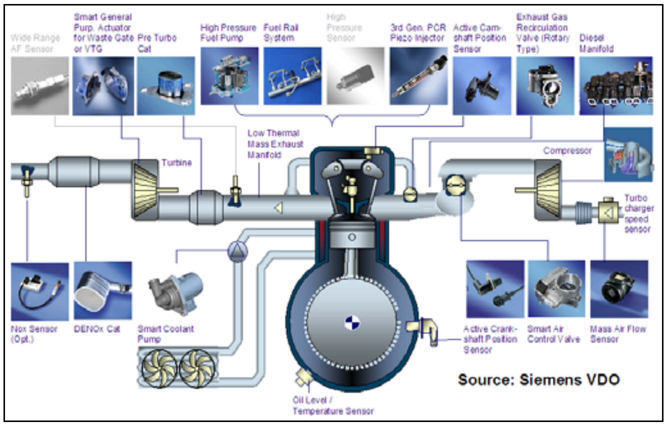


Figure 5: Variation in Kinematic Viscosity at 40ºC for JP8, JP5 and DF-2 fuels [2 and 3]

CYLINDER PRESSURE BASED SENSING AND CONTROL

Direct cylinder pressure measurement and feedback control offers the best solution to the multi-fuel problem. This approach suggests a two-input / two-output control system to regulate ignition delay and indicated mean-effective pressure (IMEP) by suitable adjustment of fuel injection timing and fuel injection amount.

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 support additional crank synchronous calculations. These advances have led to an explosion in the field of model based engine controls development and have led to a significant improvement in engine transient load response, average operational efficiency and significant reductions in engine out emissions. However, there is still a need for significant improvement in these model based approaches 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 sub-systems. This investment is often lost as design or architectural changes are made to the base engine system, requiring a re-execution of the complete model development & validation process.



Source: Siemens VDO

Figure 6: “Typical” HPCR Diesel Engine Control System Mechanization

There is a common issue among all of the integrated models. Each of the models is attempting to predict the amount of air and fuel introduced into the combustion chamber and the time domain of this mixing event to predict the resultant combustion efficiency, mechanical work, waste energy and emissions. The accuracy of these models is highly dependent on the accuracy of the sensors used to infer these air and fuel quantity metrics, and the ability of the mathematical models to predict what is physically occurring at the various speed and load operating points. **Figure 6** shows a typical mechanization of a high pressure common rail (HPCR) diesel engine. While many of the lower level pressure and temperature sensors required for air charge density approximation are not depicted, the figure does an accurate job of representing the complexities associated with the integration of the higher level sensor and actuators, each of which is required to meet the rigors of today’s modern day diesel engines.

One of the most critical factors to reference in this diagram is the relative position of the mass air flow (MAF) sensor relative to the intake valve. The air flow follows a lengthy and torturous path from the point of the measurement reference to the point of actual consumption. Under steady-state conditions the accuracy of this measurement is accomplished by the initial measurement of the fresh air charge mass and summed with a calculated approximation of the mass being recirculated from the exhaust gas to approximate the amount of combustion air charge entering the valve and consumed in the next combustion event. During transient operation, the accuracy of this approximated combustion air charge value is reduced by additional factors such as the mechanical inertia of the turbine and compressor wheel, the relative change in opening diameter of the air and egr control valves and the pressure pulsations associated with the change in combustion event frequency. Each of these variables results in a dilution of the accuracy of the metrics being targeted for control (air & fuel mass) and therefore results in degraded efficiency of engine operation.

The introduction of new industrial grade in-cylinder pressure transducers offers new opportunities for significant improvements in the accuracy of engine operation across all steady-state and transient operational conditions. The introduction of this sensor also results in a significant reduction in the required controls engineering effort, as well as accuracy requirements for the supporting pressure, temperature and flow sensors, as the measurement of the pressure at the final point of consumption enables simplification of all the models attempting to predict this quantity with inaccurate sensor inputs upstream of the point of actual consumption.

AVL has invested a significant amount of time and effort into the research, development, and validation of the unique strategies required to enable the robust and reliable realization of cylinder pressure based closed loop combustion (*CYPRESS*^{tm}) control.

The following summary describes some of the key operational criteria, system structure and mechanization, as well as the realized benefits from the implementation of the *CYPRESS*^{tm} system.

CYLINDER PRESSURE BASED COMBUSTION CONTROL - CYPRESS^{tm}

AVL *CYPRESS*^{tm} is an integrated control system developed for the purposes of proving out the concept of closed loop combustion control using an in cylinder pressure sensor. The initial concept for this approach was derived from the suite of indicating hardware and software developed for the purposes of base engine combustion development. AVL's indicating tool suite supports high frequency (14 bit / 800kHz per channel) data acquisition of high precision instrument grade GaPO4 crystal in cylinder pressure transducers. The data acquisition system comes platformed with a suite of combustion and high speed data analysis software capable of real time combustion event based calculation of key combustion metric including heat release, differential heat release, integral heat release, cylinder pressure, average cylinder pressure, and peak cylinder pressure. This indicating tool-chain provided the foundation for the detailed analysis required for control parameter identification and sensor and calculation accuracy requirements definition.

DETERMINING THE SUITABLE CONTROL VARIABLES

For determining the control variables on the basis of the cylinder pressure curve and the crank sensor signal of a standard 60-2 tooth production engine, algorithms were written in Matlab/Simulink^{tm} and implemented in a dSpace^{tm} MicroAutoBox^{tm}. These algorithms, like their higher fidelity indicating counterparts determine the indicated mean effective pressure (IMEP), the crank angle at which 50% of the fuel is converted (MFB50% - Mass Fraction Burned 50%) as well as the value and position of peak pressure (Pmax) and maximum pressure rise (MPR).

During initial testing it was realized that ignition delay, which together with the start of injection, determines the start of combustion as shown in **Figure 7**, very critically depends on the state of charge in the cylinder, which is characterized by such variables as temperature, pressure, oxygen content and turbulence. Therefore, a first step consisted in determining suitable control variables on the basis of the signal from a cylinder pressure sensor.

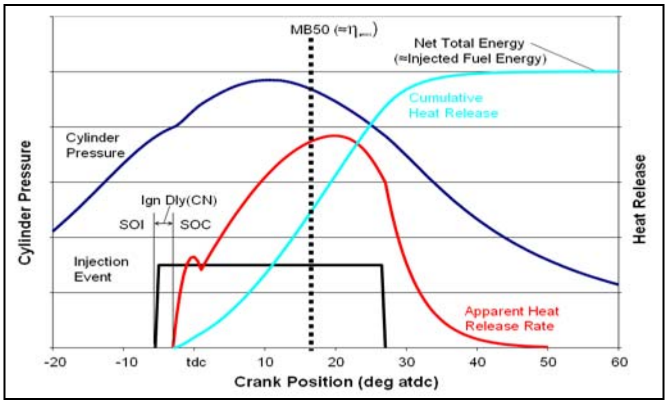


Figure 7: Sensed vs. Controlled Parameter Identification

After thorough analysis of all the available metrics, the MFB50% and MPR were identified as being the most promising control variables for combustion control. **Figure 8** graphically represents these variables. The use of MFB50% and MPR as control variables yields the particular advantage that these variables are relatively insensitive to a drift in the measurement of the absolute cylinder pressure which can occur during the useful life of a sensor.

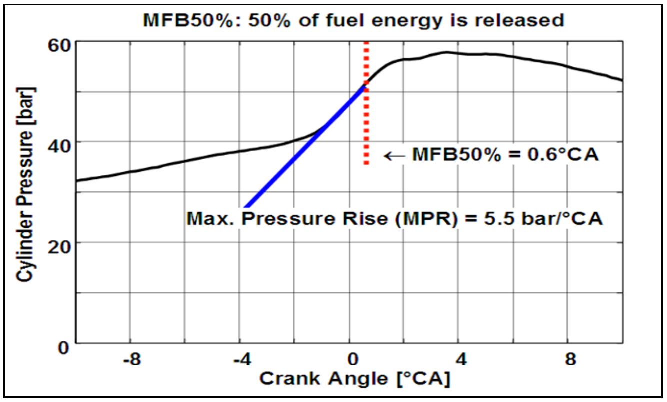


Figure 8: Cylinder Pressure Waveform Analysis for Control Parameter Identification

CLOSED LOOP COMBUSTION CONTROL SYSTEM ARCHITECTURE

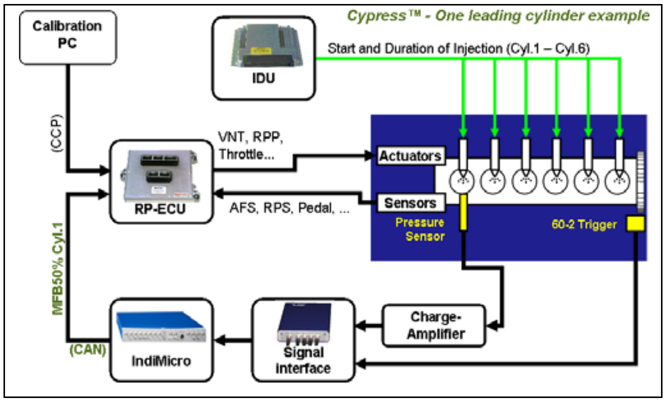


Figure 9: Overview of development environment with a single pressure transducer

Figure 9 shows the AVL CYPRESS™ hardware layout in a development environment. The signals of the cylinder pressure sensor – in this case, only one single guiding cylinder is shown – and of the engine speed sensor are amplified by a charge amplifier and adjusted to the 5V voltage level of the MicroAutoBox^{tm} by using a signal interface developed specifically for this purpose. The signal interface has such a flexible design that combustion control can be operated by using indicating quartzes as well as by using pressure sensors integrated in the glow plug to have conditions coming close to those of series production. As described above, the control variable MFB50% will be determined in the MicroAutoBox and transmitted to the combustion controller in the rapid prototype ECU via CAN. Combustion control is performed in the rapid prototype controller, which controls the fuel injectors via the injector driver unit (IDU). All other engine actuators are directly controlled via the rapid prototype engine controller. Both the parameters of combustion control and those in the serial controller can be calibrated using one common calibration computer.

Functional Benefits of Closed Loop Combustion Control

The following are some of the advantages for closed loop combustion control. Cylinder pressure based combustion control reduces scatter of emissions due to tolerances of the components throughout the life cycle of the engine. If emission limits continue to become more stringent, this topic will become even more critical – above all in the US. If combustion is controlled precisely, the quality of the open-loop control part of the engine can be reduced. Sensors providing measuring values for open-loop combustion control are allowed to have bigger tolerances or can be left out altogether. Furthermore, calibration can be simplified. Such sensors particularly include air mass and lambda sensors. **Figure 10** shows an example of advantages yielded by closed-loop combustion control in case of an error in the measured air mass. In this example, a test engine was kept on a constant operating point (80 Nm at 1,500 rpm) on the test bed. 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.

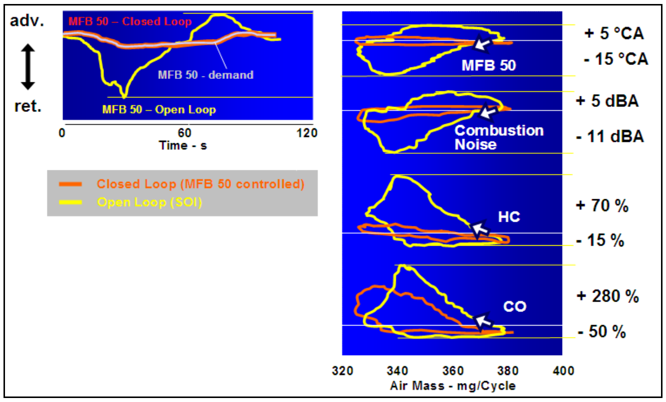


Figure 10: Closed-loop Combustion Control with Artificial Air Mass Error

The left portion of **Figure 10** shows the influence of this air mass error on combustion position MFB50%. Without closed-loop combustion control (open loop), the center of combustion will change significantly, first to late and, as the air mass increases, to early. With a closed-loop combustion controller, MFB50% will exactly follow the demand value (MFB50 – demand).

The right portion of **Figure 10** shows the effects of the air mass error on center of combustion, noise, HC and CO with and without closed-loop combustion control. What is clearly visible is that closed loop combustion control does not only considerably reduce the increase in combustion noise and HC but also that of NOx, CO and soot.

If a pressure sensor with a sufficiently low signal drift throughout the life cycle is used in each cylinder, the peak pressure can also be monitored and limited. This is why the safety margin to mechanical load limits of the engine structure can be reduced. This helps to increase performance of the engine even more. Furthermore, an efficient cylinder balancing with respect to torque is possible. Similarly, it then becomes possible to measure directly the torque as a central guiding variable of engine control. Last but not least, the combustion pressure sensor can also improve on-board diagnostics (OBD) and calibration of the minimum injection quantity.

Due to the optimization of injection timing, cylinder pressure based combustion control also yields considerable advantages at cold start, cold idling and warm up as shown in **Figure 11**.

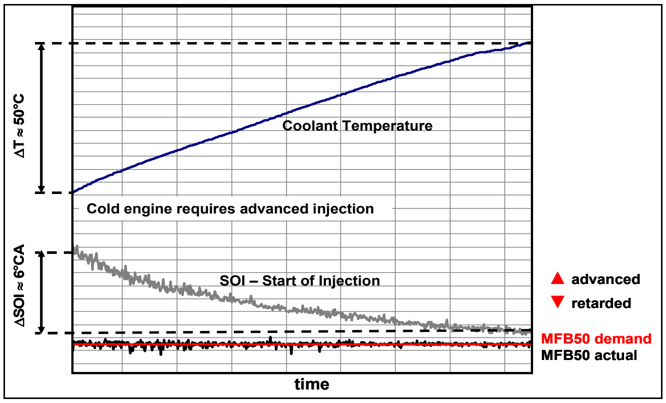


Figure 11: Engine Warm-up Combustion Control Compensation

In order to ensure smooth engine operation, optimized drivability and white smoke control the start of injection needs to be advanced in order to compensate for the longer ignition delay caused by cold air in the cylinder at the end of the compression stroke. Fuel injected in cold air needs a longer time to warm up and evaporate. Traditionally, the start of injection compensation is the result of a complicated software structure and a considerable calibration effort and time. A cylinder pressure controlled combustion system will automatically compensate for a cold engine by adjusting the start of injection to meet the calibrated MFB50% demand.

Engine operation and performance will vary with differences in fuel specifications and quality, like for example the cetane number. The ignition characteristics of diesel fuel are mainly determined by the cetane number or index. Diesel fuel with higher cetane levels will ignite easier than diesel fuel with a lower cetane value. In order to ensure smooth engine operation and compensate for the longer ignition delay when switching to a fuel with a lower cetane number, adjustments have to be made to the start of injection. **Figure 12** shows engine operation with different cetane numbers. AVL CYPRESS™ controls the start of injection to maintain MFB50% at the desired level. As a result, not only fuel compensation and NOX but also engine noise and soot levels will remain constant.

Here it is possible to stabilize engine operation and simplify calibration that usually is very complex.

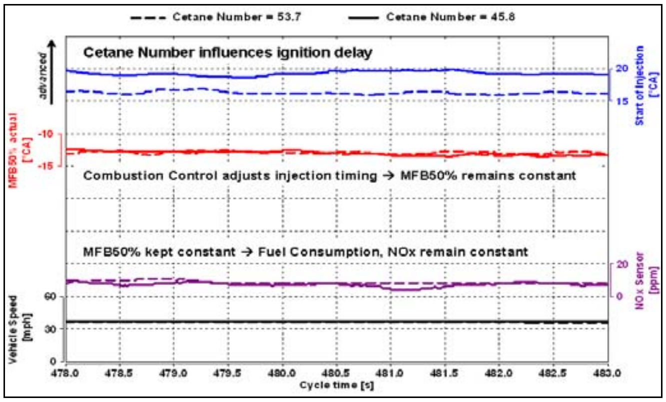


Figure 12: Combustion Control Compensation for Fuel Quality Variations

Summary

The AVL *CYPRESS*^{tm} system was developed to support the need for improved engine operation efficiency with additional constraints of optimized performance, fuel consumption and emissions. This complex and highly variable target was achieved through the integration of an in cylinder pressure transducer with the supporting control algorithms required to eliminate the high degree of variability seen in sensors placed remotely from the point of actual consumption. The implementation of this closed loop combustion control strategy has resulted in a number of significant improvements in the overall engine operation. These key improvements, as discussed in detail above are:

- High Fidelity Torque Control (measured IMEP)
- Optimized Engine Power Density (accurate control of peak firing pressure)
- Improved Cold Startability (automated injection timing compensation)
- Automatic Compensation for Fuel Quality Variability (cetane variability)
- Improved Engine Operation Diagnostics Capability
- Improved Engine Stability over the Useful Life
- Simplified Remote Sensing Requirements

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