2015 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 4-6, 2015 - NOVI, MICHIGAN

FUEL COMPENSATION SOLUTION FOR A MULTI-FUEL CAPABLE DIESEL ENGINE

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ABSTRACT

This paper describes the approach used to improve the fuel flexibility of a high power density diesel engine intended for tactical combat applications. The objective of this work was to demonstrate a technically feasible solution that mitigated the negative performance impacts encountered when commercial and military-grade aviation fuels are used in diesel engines that were calibrated with standard Type 2 diesel fuel. To accomplish this objective, modifications to the engine calibration and the implementation of a fuel compensation algorithm, which used cylinder pressure feedback, resulted in successful demonstration of meeting the program requirements of maintaining acceptable combustion quality and maximum power output to within ± 2 percent of the rated power target regardless of the fuel type supplied to the engine.

INTRODUCTION

As part of the military's overall goal of improving future warfighting capabilities, the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC) contracted Southwest Research Institute® (SwRI®) to address several powertrain improvement areas for tactical tracked vehicles in the 20 to 40 ton range under the Topic 24 Efficient Powertrain Technologies program [1]. These improvements included: 1) fuel efficiency in the form of improved cross-drive transmission and engine efficiency; 2) fuel flexibility to allow operation on a wide range of fuels without performance penalty or any need for operator input; 3) reduced drivetrain heat rejection to reduce cooling system demand and thermal signature; 4) tactical electrical power requirements to enable key battlespace operational capabilities; 5) high power density for reduced weight and improved packaging; and 6) lower noise for improved warfighter productivity and for acoustic signature suppression. This paper describes the approach used to improve the fuel flexibility of a higher power density diesel engine to allow operation on a variety of fuels without a performance penalty or operator input.

Extensive research has been performed over the last two decades to evaluate the performance, emissions and durability effects of using aviation fuels in diesel engines. Collectively, there is general agreement that the main engine performance-related impacts that aviation fuels can have on diesel engines are reduced power output due to lower volumetric heating values [2-4] and poor combustion quality at light loads due to low cetane numbers of some JP-8 fuels [4]. In most modern diesel engines, the injection volume is fixed so the lower density aviation fuel results in reduced energy delivery per injection event and subsequently, reduced power output. Power losses in the range of 3 to 10% have been observed when using lighter kerosene-based fuels. Cetane number is a measure of a fuel's ignitability, which is a key property for compression ignited engines, and typically varies from 40 to around 60 for standard Type 2 diesel fuel (DF-2). The higher the cetane number, the more easily the fuel is ignited. However, some JP-8 fuels have cetane numbers below 30 which can significantly impact the ignition behavior, especially at light loads where in-cylinder temperatures are low and high engine speeds where the available time for combustion is shortened. To address these performance issues, modifications to the engine calibration and implementation of a fuel compensation algorithm, which used cylinder pressure feedback, were performed on a high power density, heavy-duty diesel engine. The specific program objectives were to maintain acceptable combustion quality over the engine operating range and to successfully demonstrate the fuel compensator's ability to correct the power output to within ± 2 percent of the rated power target within five minutes after a fuel change.

FUEL COMPENSATION APPROACH

Cylinder pressure feedback has been used in production light-duty diesel engines (Volkswagen Jetta TDI) and in alternative combustion research such as homogeneous charge compression ignition (HCCI) and pre-mixed compression ignition (PCI). The most common functions of cylinder pressure feedback is injection quantity balancing between cylinders, compensation of injector aging, fuel cetane number variation compensation, and combustion control during transient operation [5]. For the fuel compensator developed in this program, cylinder pressure feedback was used to compute net indicated mean effective pressure (nIMEP) since this a direct measurement of the work done by the cylinder. The term net indicates that the calculation is done over the whole 720 degree crank angle cycle which includes the gas exchange portion. For a given engine speed, nIMEP correlates well with the rate of work done, or power, as shown in Figure 1, which was taken with standard DF-2 on the test engine used in this program.

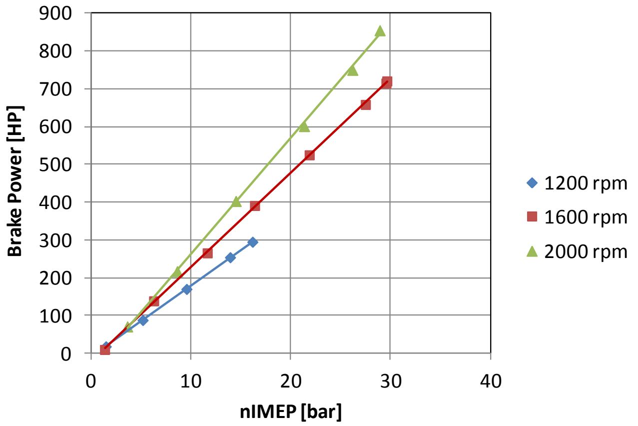

Figure 1: Correlation between IMEP and engine output power at various engine speeds.

Therefore, any change in engine power resulting from a fuel property change shows up in the nIMEP calculation. The fuel compensator essentially compares the current nIMEP to the desired nIMEP (based on the base DF-2 calibration) and makes fuel quantity adjustments to reduce the error between the two nIMEP values. The fueling adjustments were made by a fueling multiplier or fueling gain. It should be noted that the fueling gain was limited to 1.10 and 0.90 for the testing conducted in this program.

EXPERIMENTAL SETUP

The test engine and fuels used for this study are described in this section. In addition, the cylinder pressure measurement system details are provided.

Test Engine

The base engine for the program was a 2011 model year Cummins ISX15 with a 600 horsepower (HP) rating. However, the engine power rating was increased to 850 HP as part of this program in a separate design task. To accomplish the increased power rating, several engine hardware and calibration tables were changed. For example, higher flow injectors and a larger, fixed geometry turbocharger were used in place of the stock parts. The engine specifications of the base and up-rated engines are listed in Table 1. A picture of the up-rated engine installed in a development test cell at SwRI is shown in Figure 2.

Table 1: Engine specifications.

Parameter	**Base**	**Up-rated**
Displacement (L)	15.0	15.0
Bore x Stroke (mm)	137 x 169	137 x 169
Compression Ratio	17	17
Rated Power (HP/ RPM)	600/1800	850/2000
Peak Torque (lb-ft/RPM)	2050/1200	2360/1600
Fuel System	Common Rail	Common Rail
Turbocharger	Holset VGT	Holset Fixed Geometry
EGR System	High pressure	None

Figure 2: 850 HP Cummins ISX15 test engine.

Test Fuels

The up-rated engine calibration and target nIMEP table used by the fuel compensator were developed using a pump-grade DF-2. An extensive array of fuels was used for the fuel compensator tuning and demonstration and included the base DF-2, an emissions certification grade Ultra Low Sulfur Diesel (ULSD) with high energy density, two variations of JP-8, a JP-5 and a Jet A. For readability purposes, the fuel properties are listed in Tables 2 through 4 and are grouped by JP-8, DF-2 and JP-5 and Jet A, respectively. Because multiple batches of the same fuel type were used in this program, fuel codes were assigned to the test fuels. For example, "Fuel A" was used for the iso-paraffinic kerosene (IPK), "Fuel B" for the hydro-treated renewable jet (HRJ) JP-8, "Fuel C" for the base DF-2 and so on. These codes are used in the experimental results.

Table 2: JP-8 test fuel properties.

Fuel Type		**IPK JP-8**	**HRJ JP-8**
Fuel Code		**A**	**B**
Property	**Units**		
Density at 15°C	g/L	760	765
Viscosity at 40°C	cSt	1.13	1.57
Carbon Content	wt%	84.0	84.5
Hydrogen Content	wt%	15.2	15.2
Sulfur Content	ppm	13.6	2.1
Cetane Number	--	25.2	58.6
Heat of Combustion			
GROSS	BTU/lb	20306	20336
GROSS	MJ/kg	47.2	47.3
NET	BTU/lb	18914	18950
NET	MJ/kg	44.0	44.1
NET	MJ/L	33.4	33.7

Table 3: DF-2 test fuel properties.

Fuel Type		**Base DF-2**	**ULSD**
Fuel Code		**C**	**D**
Property	**Units**		
Density at 15°C	g/L	809	844
Viscosity at 40°C	cSt	2.50	2.72
Carbon Content	wt%	85.8	86.6
Hydrogen Content	wt%	14.3	13.4
Sulfur Content	ppm	12.7	9.1
Cetane Number	--	61.0	48.3
Heat of Combustion			
GROSS	BTU/lb	19934	19694
GROSS	MJ/kg	46.4	45.8
NET	BTU/lb	18626	18474
NET	MJ/kg	43.3	43.0
NET	MJ/L	35.1	36.3

Table 4: JP-5 and Jet A test fuel properties.

Fuel Type		**JP-5**	**Jet A**
Fuel Code		**F**	**G**
Property	**Units**		
Density at 15°C	g/L	809	787
Viscosity at 40°C	cSt	1.39	1.06
Carbon Content	wt%	85.6	85.6
Hydrogen Content	wt%	13.9	14.3
Sulfur Content	ppm	1353	80
Cetane Number	--	44.0	42.6
Heat of Combustion			
GROSS	BTU/lb	19774	20056
GROSS	MJ/kg	46.0	46.7
NET	BTU/lb	18504	18754
NET	MJ/kg	43.0	43.6
NET	MJ/L	34.8	34.3

A flush-mounted Kistler 6125B pressure transducer was installed in cylinder number one and was sampled at 0.5 degree crank-angle increments by a National Instruments compact RIO (NI cRIO). The NI cRIO performed real-time calculations on the measured cylinder pressure, such as peak pressure, location of peak pressure, and of course, nIMEP. The nIMEP values were sent by CAN to an ETAS FlexECU, which served as a supervisory controller. Within the FlexECU, the current nIMEP was compared to the target value at the current accelerator pedal position and engine speed and based on the error between these two values, fueling gain adjustments were sent to the customized Cummins ECM. A schematic of the fuel compensator data flow is shown in Figure 3.

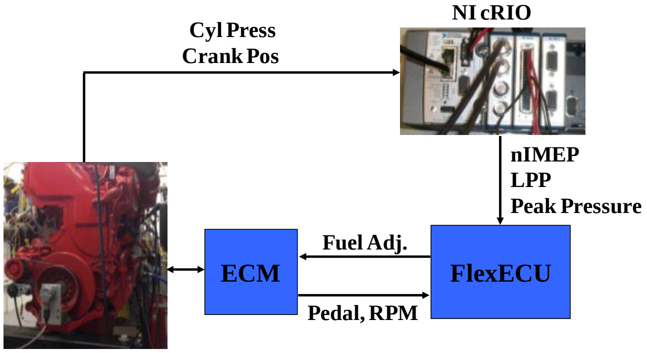

Figure 3: Fuel compensator control flow.

EXPERIMENTAL RESULTS

The experimental results are presented in two sections. The first section focuses on the combustion impact and improvement obtained at light load and high speed. The next section presents the fuel compensation test results obtained with various test fuels.

Light Load Combustion Improvement

As discussed earlier, cetane number is a measure of the ignition character of the fuel. Since compression ignition engines rely on auto-ignition of the fuel, low cetane number fuels can lead to excessively long ignition delays and poor combustion, especially at light loads and high engine speeds. To demonstrate this issue, cylinder pressure data (100 cycle average) obtained at 2000 rpm and 10% load with the base DF-2 (Fuel C) and the IPK JP-8 (Fuel A), both with the stock engine calibration settings is shown in Figure 4. Injector current traces are included in the plot to show that the injection timings were the same for both cases. As indicated by the late and small cylinder pressure rise, very poor combustion quality resulted with Fuel A due to its low cetane number and in fact, the target load could not be maintained during testing.

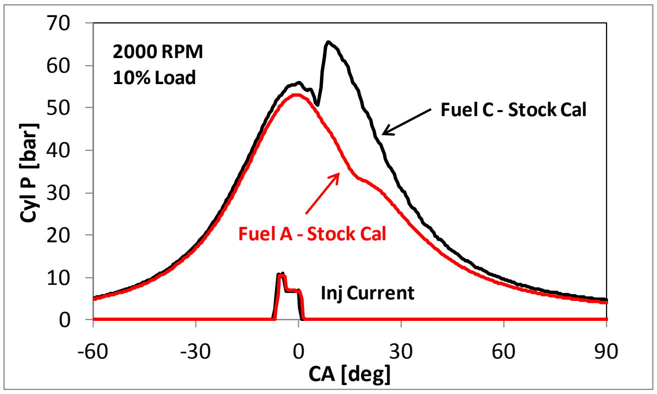

Figure 4: Combustion comparison with base DF-2 (Fuel C) and low cetane JP-8 (Fuel A) using stock engine calibration.

To address this issue, the stock calibration was modified to advance injection timing and add a small pre-injection (pilot injection). Multiple injection capability is a benefit of the common rail fuel system on this engine. The combination of these two changes sufficiently improved the light load combustion quality as shown in Figure 5. In addition, the changes did not adversely affect the combustion with the base fuel.

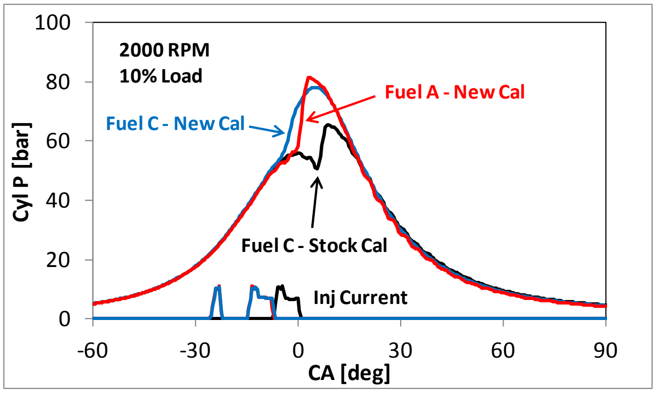

Figure 5: Combustion comparison with base DF-2 (Fuel C) and low cetane JP-8 (Fuel A) using modified engine calibration.

Fuel Compensation Test Results at Rated Power

The basic test procedure for fuel compensation testing was to operate on the base DF-2 with the fuel compensator active until stable operation was achieved, which was generally less than 5 minutes. After this stabilization period, a data logger was started and engine operation with the base fuel was recorded for around five minutes before changing the fuel supply. The fuel supply system was setup to allow fuel supply changes while the engine was running. From previous testing, it was determined that approximately ten minutes was required at rated power to completely consume the previous fuel in the supply system so fuel changes were made in twelve minute increments in order to capture the behavior completely on the current test fuel.

To demonstrate the worst case performance impact observed with the available test fuels and effectiveness of the final tuned fuel compensator, two back-to-back tests were conducted at the rated power condition using Fuel A, the low cetane IPK JP-8. The first test was conducted with the fuel compensator turned off (ie. fixed fueling gain of 1.0). The resulting engine power time history is shown in the top chart of Figure 6. As shown, a 6% power loss was observed at about 10 minutes after switching to Fuel A. However, when this test was repeated with the fuel compensator turned on, the power was maintained within the target window as shown in the bottom chart.

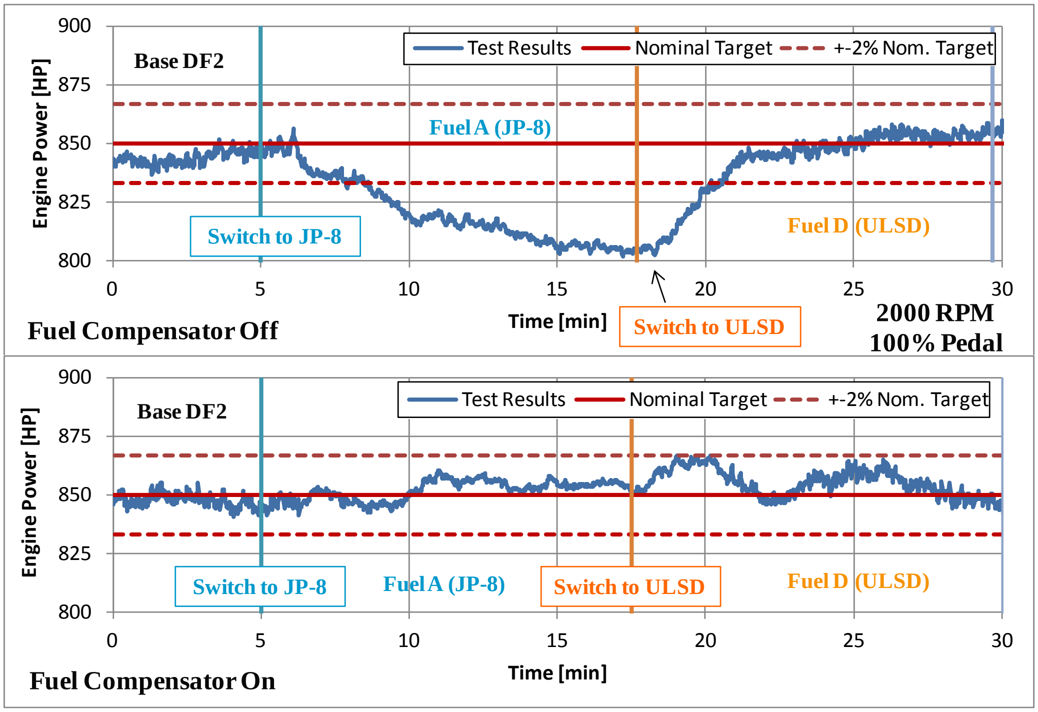

Figure 6: Effect of fuel changing at rated power without (top chart) and with (bottom chart) fuel compensator at rated power condition.

A more complete evaluation of the fuel compensator performance at the rated power condition was conducted by using a more extensive fuel changing matrix. As before, data logging was initiated after engine stabilization and was recorded for around 5 minutes before the first fuel change was made. Afterwards, fuel changes were made in 12 minute intervals and a total of five fuel changes were made. The obtained test results are presented in Figures 7 and 8. The timing and fuel type details are annotated in the figures.

As shown in the top charts of both figures, the fuel compensator was able to maintain the power within the target window for each fuel within the 5 minute requirement. The nIMEP calculated by the NI cRIO along with the target nIMEP at this engine speed and pedal are shown in the bottom figure of Figure 7. Generally, good tracking of nIMEP was observed. The actual fuel compensator gain is shown in the bottom chart of Figure 8 and shows that fairly high fueling gains of 1.05 and 1.06 were needed for Fuels G and A (Jet A and IPK JP-8), respectively.

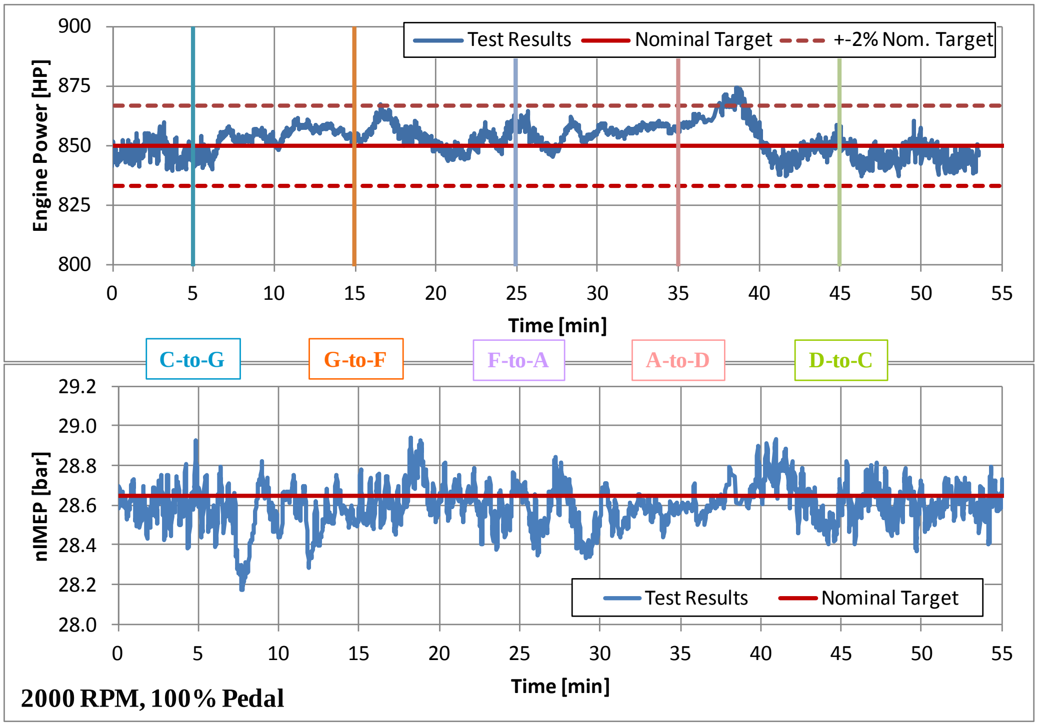

Figure 7: Engine power and IMEP results with fuel compensation at rated power with five fuel changes.

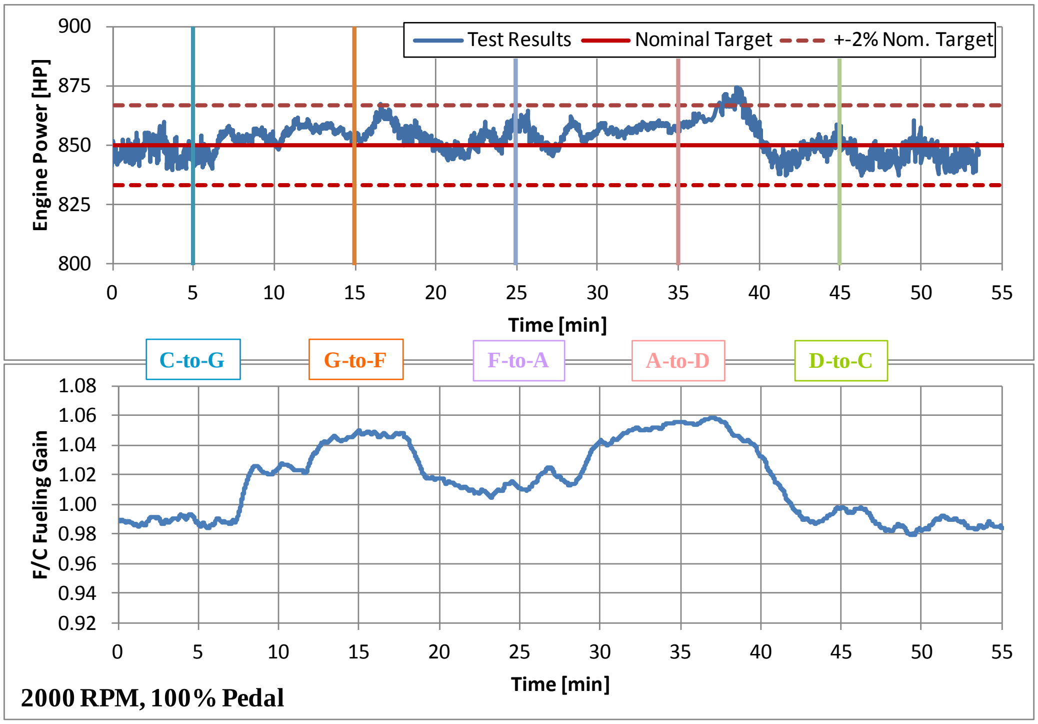

Figure 8: Engine power and fuel compensator fueling gain results at rated power with five fuel changes.

Fuel Compensation Test Results at Peak Torque and Part Load Conditions

The program requirement of fuel compensation demonstration was only at the rated power condition, namely 2000 RPM and 850 HP; however additional evaluations were conducted at several other engine conditions to better understand the potential of the approach. For this purpose, test results obtained at the peak torque condition, 1600 RPM and 2360 lb-ft or 720 HP, following a similar test procedure as before, with the exception of increasing the fuel change interval to 15 minutes, are presented in Figure 9. For this test, three fuels were used which included the base DF-2, HRJ JP-8 and JP-5. As shown, the fuel compensator performed quite well at this condition with power variation generally less than 1% from the nominal.

In addition to full load testing, the possibility of performing fuel compensation at part load conditions was explored. Since the fuel compensator determined target nIMEP values based on engine speed and pedal position inputs, there was no technical reason that would prevent operation at pedal positions below 100%. Therefore, testing was conducted at 2000 RPM and two different nominal loads, namely 65% and 25%. The obtained test results are presented in Figure 10 and 11 for these two cases.

As shown in the above part load test results, the engine power variation was a little higher than the full load tests in terms of percent variation from the nominal targets. However, in terms of absolute power, the variations were consistent or even lower than those observed at rated power. In addition, there was some general agreement in terms of fuel compensator (F/C) fueling gains for some of the fuels, such as Fuel G. These results suggest that fuel compensation may be possible under part load conditions.

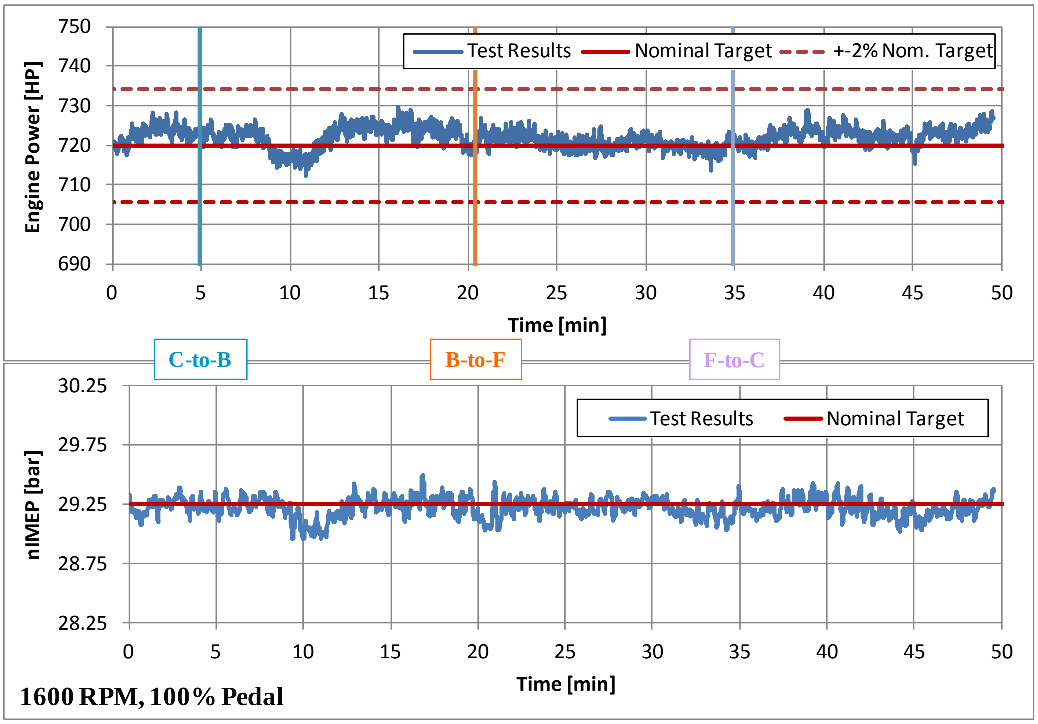

Figure 9: Engine power and IMEP results with fuel compensation at peak torque with three fuel changes.

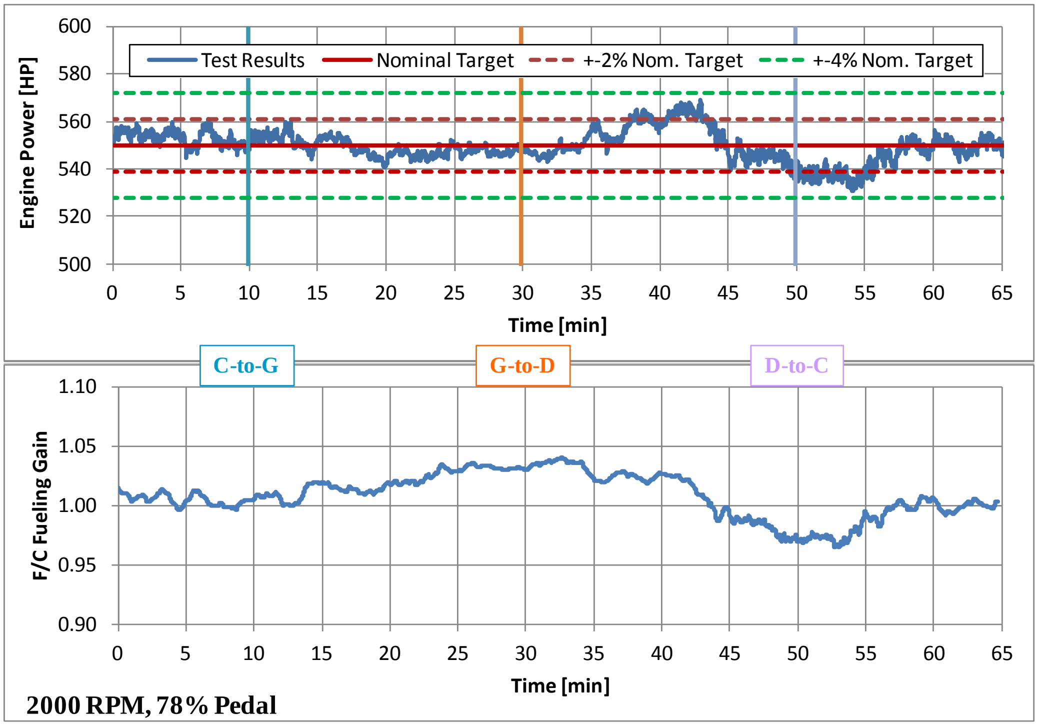

Figure 10: Fuel compensation testing at 2000 RPM and 65% nominal load.

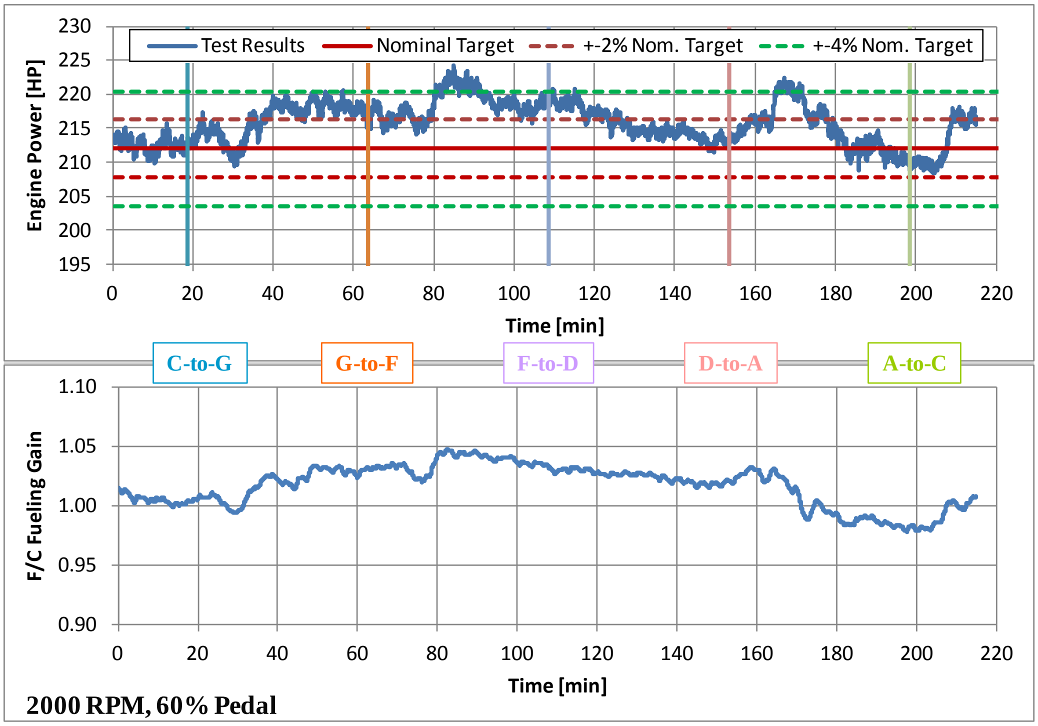

Figure 11: Fuel compensation testing at 2000 RPM and 25% nominal load.

SUMMARY AND CONCLUSION

As part of the TARDEC Topic 24 program, fuel flexibility improvement of a high power density diesel engine was successfully demonstrated. Specifically, a technically feasible solution that effectively utilized the capability of the engine's common rail fuel system and the development of a fuel compensation algorithm that used cylinder pressure feedback was employed to mitigate the negative performance impacts typically encountered when commercial and military-grade aviation fuels are used on diesel engines calibrated with standard Type 2 diesel fuel. This solution resulted in successful demonstration of the program requirements of maintaining acceptable combustion quality and maintaining maximum power output to within ± 2 percent of the rated power target regardless of the fuel type supplied to the engine. In addition, testing at peak torque and two part load conditions confirmed the potential of acceptable fuel compensation at other engine conditions.

ACKNOWLEDGEMENTS

The authors would like to thank TARDEC for funding this work and Cummins Inc. for engine hardware and controller support.

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