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IMPACT OF MON ON ENGINE PERFORMANCE

Final Report

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COORDINATING RESEARCH COUNCIL, INC.

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FEV North America Inc.

Impact of MON on Engine Performance

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Introduction

Effects of fuel characteristics on knock resistance have been studied very well and are usually expressed in terms of Research Octane Number (RON) and Motor Octane Number (MON). The RON and MON of fuels are determined on a Cooperative Fuels Research (CFR) engine. With the significant development in Spark Ignition (SI) engines since the test was established, there was a need to re-evaluate the significance of RON and MON on knock resistance, especially with the vastly different modern engine technologies. The concept of Octane Index was introduced by Kalghatgi (2001) to express knock resistance in terms of RON and MON combined, and it is defined as,

$$\mathrm{OI} = \mathrm{RON} - \mathrm{K} \times \mathrm{S} \qquad \text{Eq. 1}$$

Here S is the sensitivity of fuel ($\mathrm{S} = \mathrm{RON} - \mathrm{MON}$), and K is a correlation constant which is a function of engine architecture and operating conditions.

Historically the K value has always been positive, but with the change in technologies on modern engines, in Kalghatgi (2001), it is suggested that today's high efficiency engines differ vastly from the CFR engine used for the RON test. Modern engines convert more of the fuel energy into useful mechanical energy instead of waste heat, and hence are more efficient. A modern engine compared to an older engine of similar architecture at similar operating conditions, has improvements in multiple areas including charge preparation, air flow, and thermal management. The improvements in these categories can lead to lower unburnt gas temperatures. In Kalghatgi (2001) it is suggested that the lower unburnt gas temperatures lead to a negative K value at the mostly knock limited regions i.e., low speed high load. From Eq 1, a negative value of K would suggest that an increased sensitivity leads to increased knock tolerance in knock limited regions, compared to fuels with lower sensitivity. Two recent studies on turbocharged engines Gopujkar (2020) and Zhou (2020) show negative K at low-speed high load, and positive K at high engine speed and/or high air temperature.

The primary objective of this study is to investigate the impact of fuel MON on engine performance for large bore naturally aspirated engines. Testing a variety of engine architectures will help establish the relevance of fuel MON for modern engines. As higher RON fuels, potentially with higher S, are discussed as enablers for improved vehicle fuel economy, it is important to ensure there are no unintended consequences of the reduced MON on engine operation.

Experimental Cell Setup

a. Test Engine:

The testing was conducted on two engines, GM L86 and Ford 7.3L. Both engines are large bore naturally aspirated V8 engines. The recommended fuel for the GM L86 engine is Premium Unleaded Gasoline (93 AKI), and Regular Unleaded Gasoline (87 AKI) for the Ford 7.3L engine. Detailed engine specifications are listed in Table 1.

For both engines, the cylinder heads were machined to accept in-cylinder pressure transducers. For both engines, the intake manifolds were modified to accept pressure transducers for pegging in the cylinder 1 intake runner. The oil pans on both engines were modified into deep sump oil pans to allow for higher oil volume and better temperature stability with the conditioning system. The oil pickup tubes were extended to work with the deep sump oil pans.

Both engines used development ECUs to facilitate dialing of engine control parameters like spark timing, injection timing, air-fuel ratio, etc. The development ECUs also facilitate easy flashing and communication with the test cell Data Acquisition (DAQ) software, through commercial DAQ software e.g., ETAS INCA, ATI Vision etc.

Table 1: Engine Specifications

Engine Specifications		
Engine	GM L86	Ford 7.3L
Engine Type	NA Premium Fuel V8	NA Regular Fuel V8
Injection System	Side DI	PFI
Ignition System	Coil Near Plug	Coil Near Plug
Gas Exchange	4 Valves/Cylinder, Dual Equal Cam Phaser	2 Valves/Cylinder, Dual Equal Cam Phaser
Firing Order	1-8-7-2-6-5-4-3	1-5-4-8-6-3-7-2
Displacement	6.2L	7.3L
Bore	103.25 mm	107.2 mm
Stroke	92 mm	101 mm
Stroke/Bore	0.89	0.94
Wrist Pin Offset	0.6 mm	0.8 mm
Crank Offset	0 mm	0 mm
Compression Ratio	11.5:1	10.5:1
Rated Torque	559 Nm @ 4250 rpm	636 Nm @ 3930 rpm
Rated Power	282 kW @ 5600 rpm	262 kW @ 3930 rpm

b. Test Setup:

The test engines were setup in an FEV test cell, attached to an AC dynamometer. The test setup used multiple conditioners to maintain combustion air, coolant, fuel, and oil boundary conditions. The boundary controls include inlet air pressure, humidity, intake manifold temperature (referred to as Air Charge Temperature or ACT in this report), engine coolant temperature, oil pan temperature, exhaust backpressure, and fuel temperature. The inlet air pressure is controlled by an air conditioner and is a closed loop system with feedback from pressure instrumentation upstream of the airbox. The humidity is controlled by an Electrode-Steam humidifier. The intake manifold temperature is controlled by a water to air heat exchanger, with feedback control. Engine coolant temperature is conditioned with a water-to-water heat exchanger and coolant conditioner with feedback control. Oil pan temperature is controlled directly through a lubricant conditioner, with external feedback to oil pan temperature. Fuel temperature is controlled indirectly by a conditioner which is routed to a water-to-water heat exchanger, with external feedback to the fuel inlet temperature. Exhaust back pressure is controlled by a butterfly valve, with external feedback to exhaust tailpipe pressure. The boundary conditions for the different test procedures are shown in Appendix E.

The positive crankcase ventilation (PCV) system was disabled to prevent intake air contamination. Blowby and crankcase fumes were routed out of the engine through a blowby meter to an external catch can where the gases were then vented. The test cell setup diagrams for the GM and Ford engines are shown 0 and Appendix C, respectively.

The engines were instrumented with water cooled piezoelectric pressure transducers (Kistler 6041); the transducers were flush mounted to prevent passage resonance. The transducers were pegged to the intake runner of cylinder 1 and averaged absolute pressure over 10 crank angle degrees, starting at -180 crank angle degrees after the top dead center of combustion (°CAaTDCF). The in-cylinder pressure transducer is located next to the spark plug, and between the intake and exhaust valves. The in-cylinder pressures were sampled at 0.2 CAD resolution (1800 samples per crank revolution). The ignition and fuel injection signals were measured using Fluke 80i-110s current clamps, at 0.2 CAD resolution.

The air flow rate was recorded using an ABB Sensyflow FMT700-P, flow meter. Fuel flow rate was measured using a Micromotion CMF025 flow meter. The blow-by gases were measured using an AVL 442 blow-by meter. Engine speed was measured using a magnetic pickup mounted on the engine flywheel. Engine torque was measured using an HBM T-40B inline torque meter. Coolant flow rate was measured using a Flow Technology FT-32 flow meter. All critical temperature and pressure measurements were instrumented on the setup using the appropriate thermocouples and pressure transducers.

Experimental Procedure

a. Health Measures:

Health checks were performed regularly during testing to ensure that engine health was maintained throughout the test program. The health measures consisted of different tests to track engine health through reference points.

Reference Points: Reference points help ensure both the engine health and the test cell instrumentation accuracy. Two different operating points, 2000 RPM/2bar BMEP and 2000 RPM/5bar BMEP were used as the reference points. Data at each of these reference points was collected at both Start of Test (SOT) and End of Test (EOT). The data was used to track the variation in different parameters i.e., spark timing, air fuel ratio, crankcase pressure, friction work etc.

b. Oil flush and Shearing Procedure:

Oil flush and shearing procedures were performed when switching fuels to prevent fuel properties from carrying over from the previous fuel.

The oil flush and oil shearing procedures were performed together, with the oil being flushed first and replaced with new oil, then the oil shearing procedure was conducted at 3000 RPM/5 bar BMEP for 5 minutes. This procedure was repeated 2 more times, for a total of 3 times, and was done before testing on each fuel. The boundary conditions maintained during the oil shearing procedure are shown in Appendix E.

c. Knock Mapping

The knock mapping procedure was developed to implement a consistent method to collect data under knock limited conditions, as data is collected with different fuels and operating temperatures. Throughout the test matrix in Table 2, at the same operating point, only the air/fuel ratio and spark timing were varied to either achieve maximum brake torque (MBT) or knock limit. All fuel comparisons were performed based on spark timing and air/fuel ratio, and direct results of these controls such as the burn parameters. The list of modified engine control parameters is shown in Table 3.

Table 2: Test matrix chosen for fuels testing.

Test Run	GM L86	Ford 7.3L
1	Fuel 4 High ACT Map	Fuel 4 Normal ACT Map
2	Fuel 4 Normal ACT Map	Fuel 4 High ACT Map
3	Fuel 5 Normal ACT Map	Fuel 1 Normal ACT Map

4	Fuel 5 High ACT Map	Fuel 1 High ACT Map
5	Fuel 6 Normal ACT Map	Fuel 2 Normal ACT Map
6	Fuel 6 High ACT Map	Fuel 2 High ACT Map
7	Fuel 7 Normal ACT Map	Fuel 3 Normal ACT Map
8	Fuel 7 High ACT Map	Fuel 3 High ACT Map

Table 3: Knock mapping control parameters and methods.

Knock Mapping Control Parameters		
Engine	GM L86	Ford 7.3L
Spark Timing	Spark advanced to find MBT or Knock Limit	Spark advanced to find MBT or Knock Limit
Injection Timing	Fixed for each operating point	Not controlled
DI Pump Pressure	Fixed for each operating point	N/A
Air Fuel Ratio	Fixed at stoichiometric or leaned to the least achievable enrichment at each point	Fixed at stoichiometric or leaned to the least achievable enrichment at each point
Cam Phasers	Fixed for each operating point	Fixed for each operating point

Test Development

a. Knock Characterization

To ensure that knock characterization and detection were kept the same for both engines, the OEM knock control strategies were disabled to prevent interference in moderate knocking conditions. A knock characterization method developed inhouse at FEV was used to detect knock, provide real-time feedback from the combustion analyzer, and serve as the basis for knock limit setting.

Multiple knock characterization methods were compared prior to selecting one for characterizing knock and ensuring consistency in knock detection. The knock metrics were compared based on consistency at different operating conditions, to ensure a universal comparison metric. The different knock characterization metrics are discussed in detail, along with a comparison to show differences between them.

1- Knock Intensity – Knock intensity is defined as the integral of the rectified knock signal over the defined integration window. The integration window is a moving window with its center -2 °CA from the peak pressure location, and a with a width of 30 °CA on either side. As the location of peak pressure varies, the location of the integration window also varies. The knock signal is calculated by applying a Savitzky-Golay filter on the pressure trace and then subtracting the resulting “smoothed” trace from the original trace. The resulting “noise” in the signal is the knock signal. An example knocking trace and the resulting integration window and knock signal is shown in Figure 1.
2- Knock Intensity Squared – Knock intensity squared is defined as the integral of the squared rectified knock signal over the defined integration window. The integration window is the same as what is used for the knock intensity definition. The filtering used for knock intensity square is the same as the knock intensity definition.
3- Knock Peak to Peak – Knock peak to peak is defined as the delta between the maximum and minimum values of the knock signal. The filtering used to extract the knock signal is the same as the knock intensity signal.

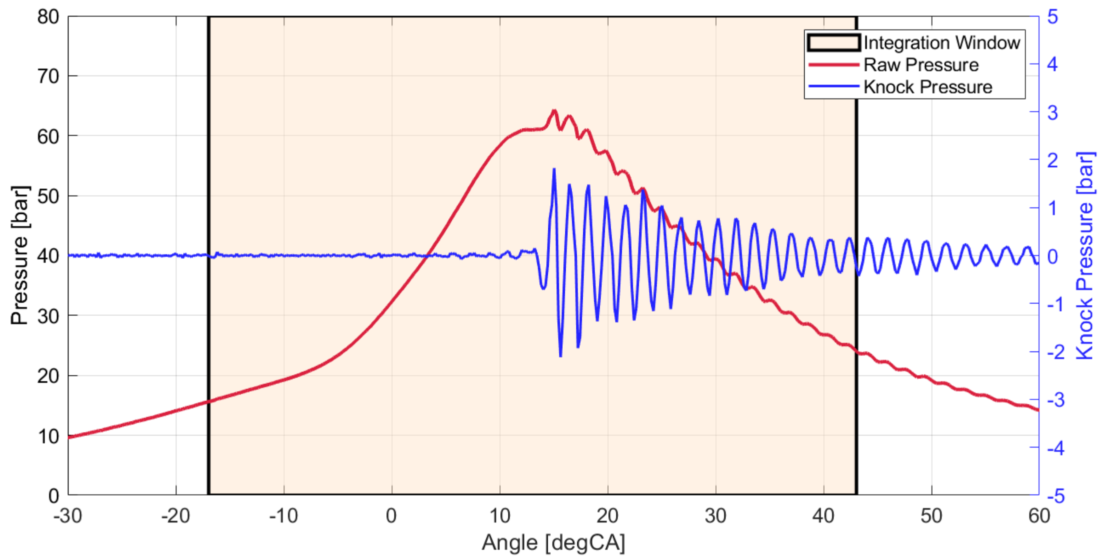

Figure 1: Knocking pressure cycle and integration window.

4- Knock Ratio – Knock Ratio is the ratio of knock intensities determined over two integration windows 30 °CA window on each side of -2 °CA of the peak pressure location. The knock ratio is calculated based on the formula where Base Offset is used to nullify any zero values in the denominator and knock intensity 1 and 2 are the knock intensities over window 1 and 2, respectively. A Base Offset of 1.5 has been found to be sufficient considering the knock intensity magnitudes generally seen. The knock integration windows for knock ratio calculation are shown in Figure 2.

$$\text{Knock Ratio} = \frac{\text{Knock Intensity 2} + \text{Base Offset}}{\text{Knock Intensity 1} + \text{Base Offset}}$$

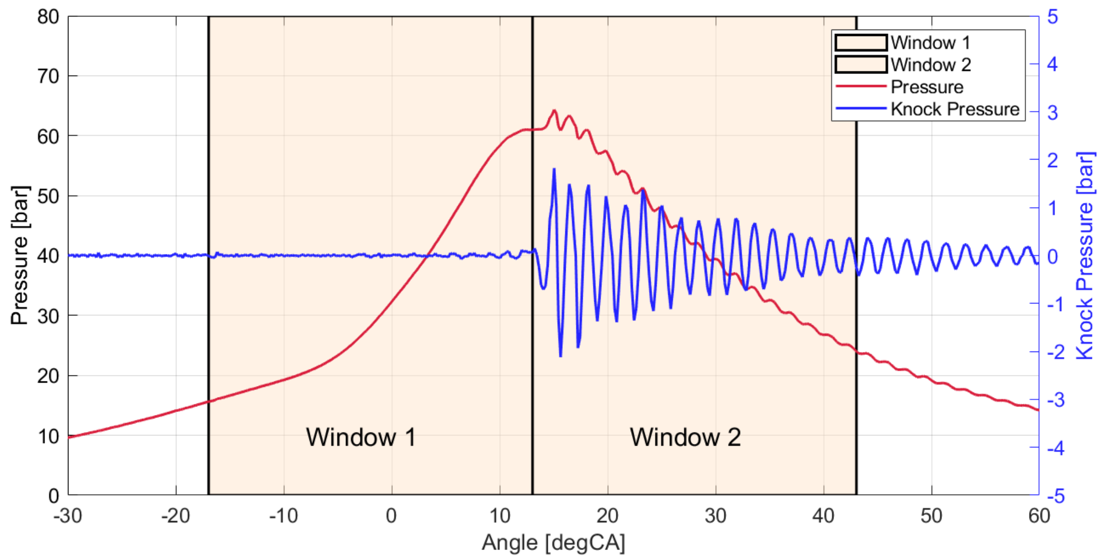

Figure 2: Knock Ratio calculation integration windows.

Figure 3a to Figure 3d show comparison of individual knock metrics vs spark timing advance, the right Y-axis shows the percentage of knock events above different thresholds (which are indicated in the legend) over 4000 cycles, and the left Y-axis shows the maximum magnitude of knock at each spark timing advance. All figures show event counts at different threshold levels. All knock metrics compare well, showing the same hockey stick style curve as the spark timing advance increases, which suggest that with a well-defined threshold, all metrics would be successful in detecting knock onset.

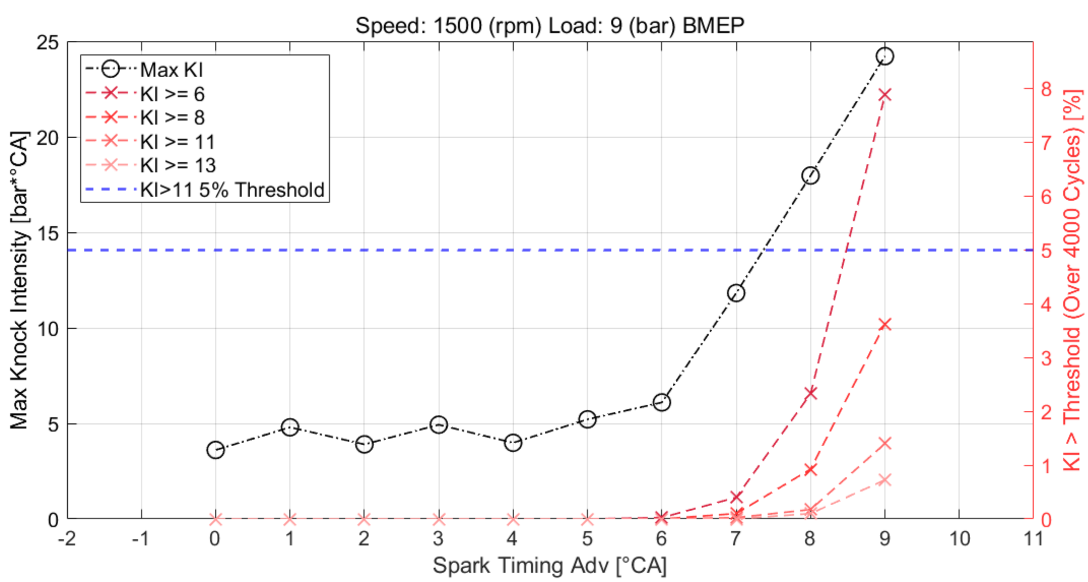

Figure 3a: Knock Intensity vs Spark Timing Advance

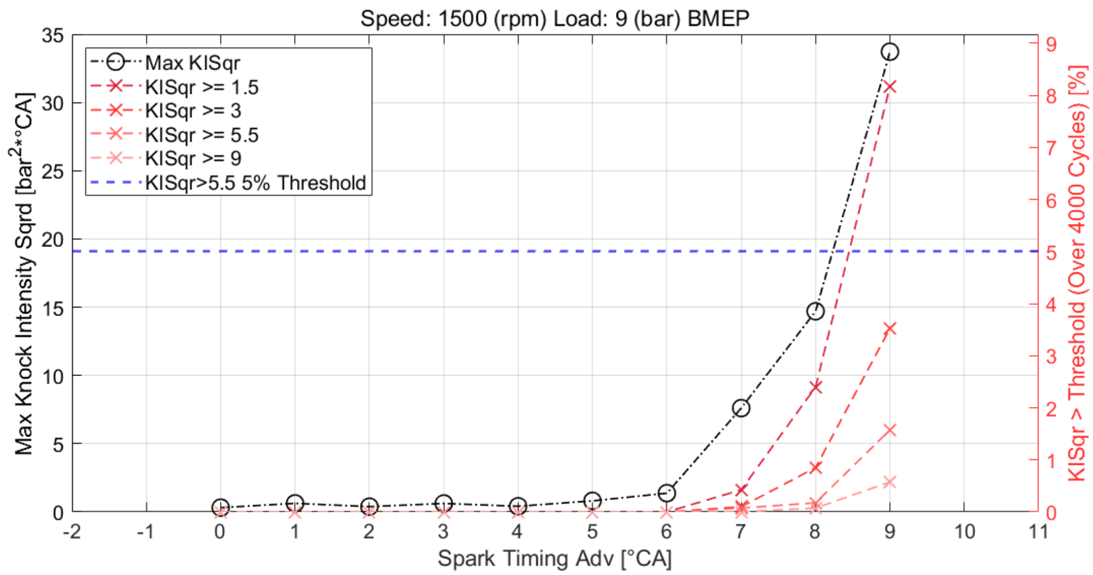

Figure 3b: Knock Intensity Squared vs Spark Timing Advance

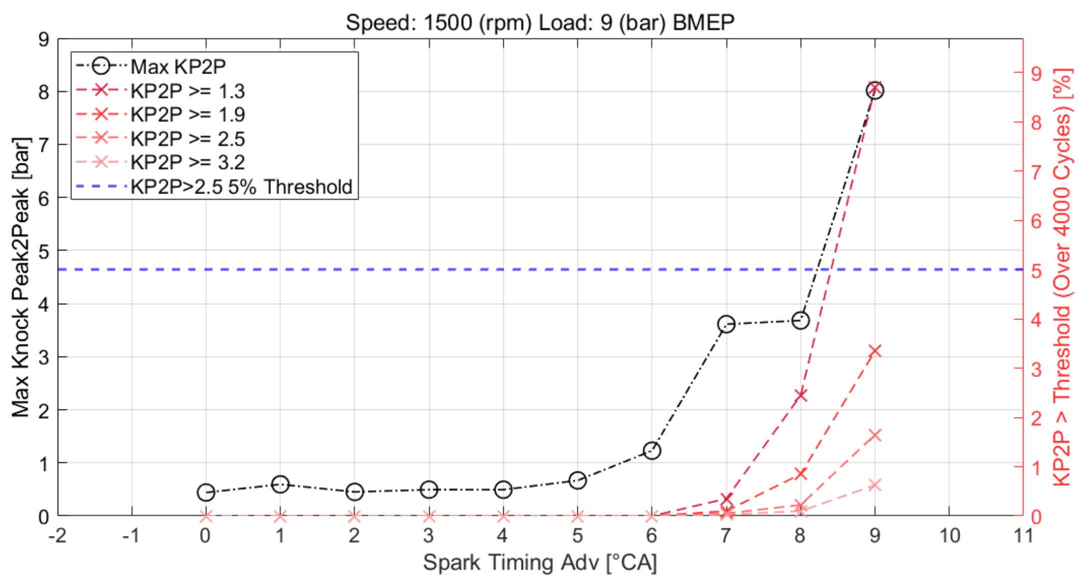

Figure 3c: Knock Peak to Peak vs Spark Timing Advance

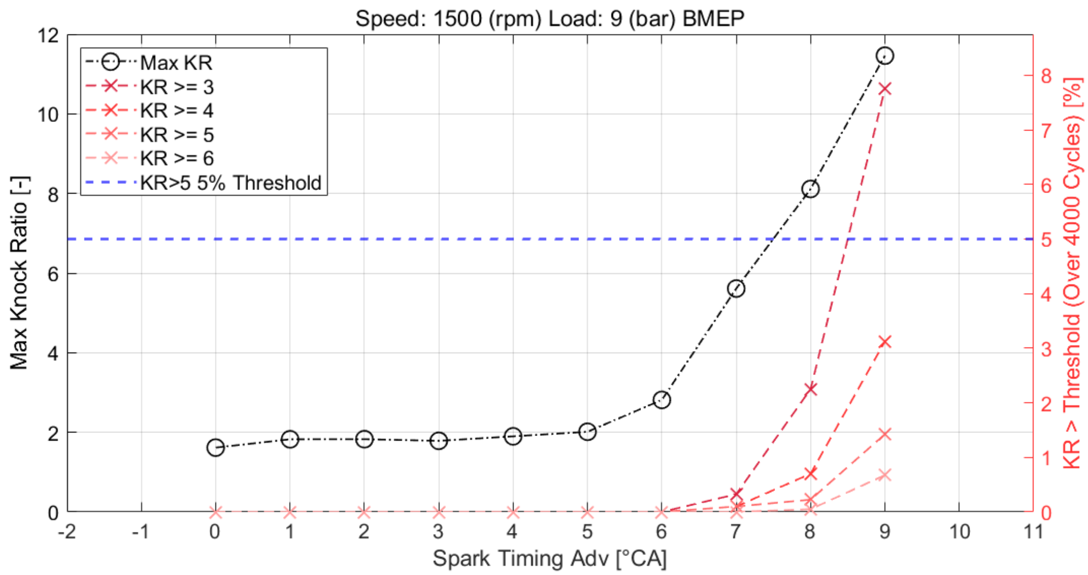

Figure 3d: Knock Ratio vs Spark Timing Advance

Figure 4a to Figure 4d show a comparison of the different knock metrics at several operating conditions. Knock Ratio and Knock Peak to Peak, show a distribution ranging from 0.6-2.6 and 0-2 respectively. As speed increases, Knock Ratio doesn't show any particular trends, but Knock Peak to Peak shows an increasing trend and spread, which shows some effect of increasing speed. Irrespective of the speed and load combination, knock ratio and knock peak to peak have a very narrow distribution, which indicates that changing speeds and loads has minimal effect. Knock Intensity shows a wider range than the other knock metrics, ranging between 0 and 12 Bar°CA. As the operating conditions change the distribution of knock intensity also becomes wider, indicating knock intensity is sensitive to changing speed and load. Knock Intensity Squared varies from 0-5 Bar^2°CA. Knock intensity squared is highly sensitive to changing speeds and loads, as seen with the high variation in distribution. Knock intensity, knock intensity squared and knock peak to peak have a direct correlation with engine speed. The mean ± standard deviation increases with increasing engine speeds. Knock ratio is less sensitive to change in engine speeds and hence shows a minimal variation in mean ± standard deviation with changing speeds. Knock Ratio is able to distinguish well between knocking and non-cycles well irrespective of engine speed, and although Knock Peak to Peak also does this distinction well, it shows slightly more sensitivity to speed, hence Knock Ratio was chosen as the knock metric for comparison between fuels.

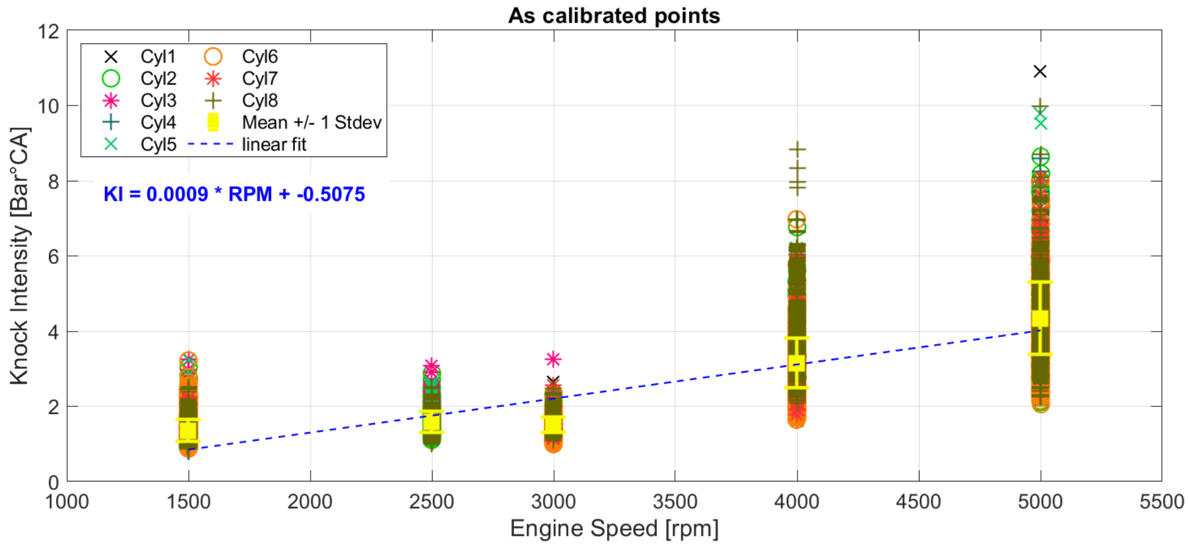

Figure 4a: Knock Intensity vs Engine Speed

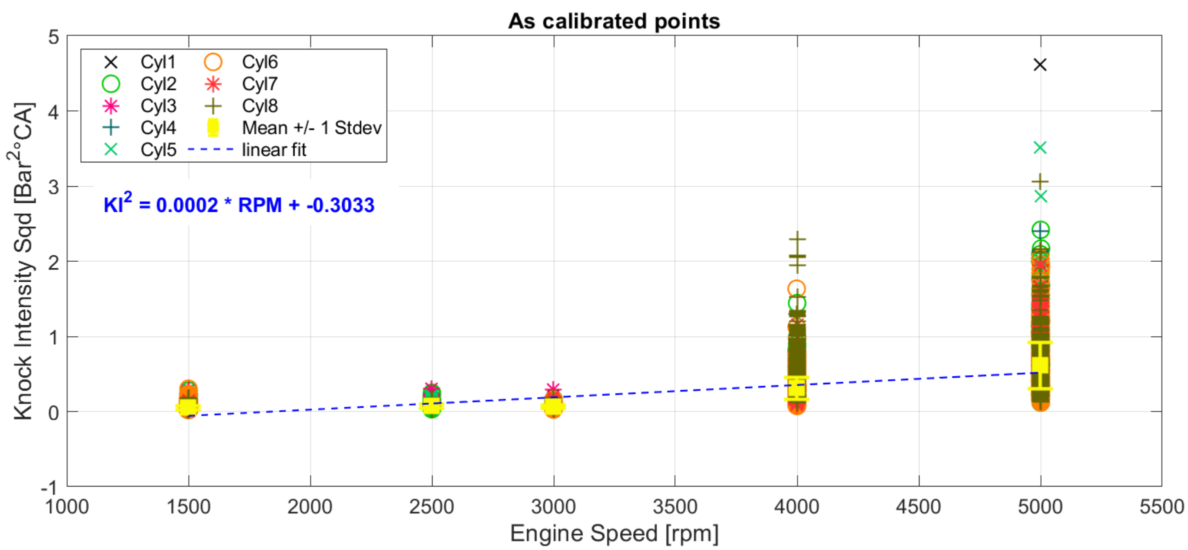

Figure 4b: Knock Intensity Squared vs Engine Speed

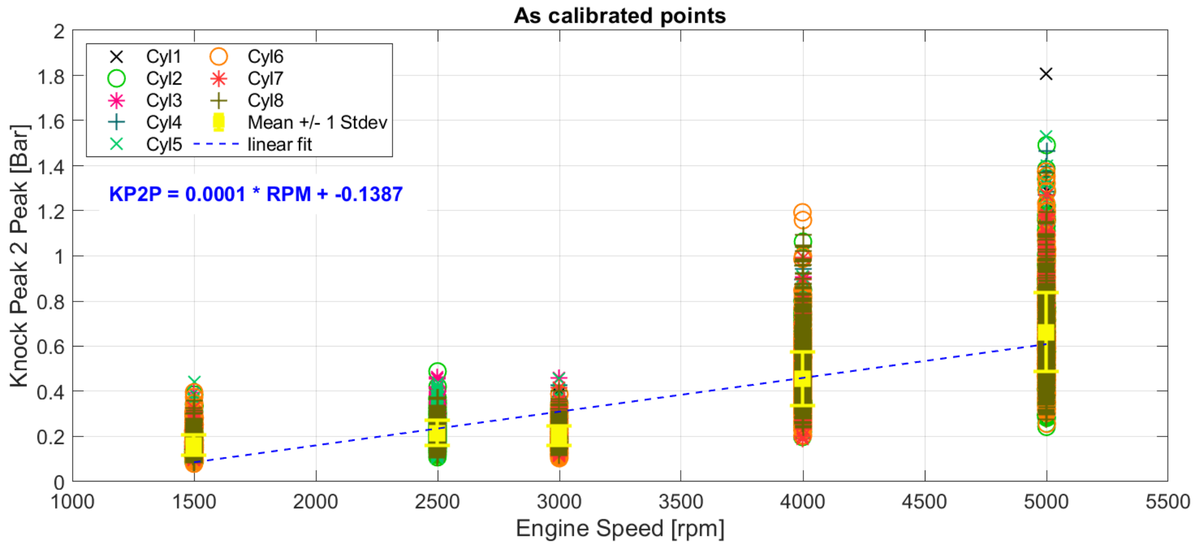

Figure 4c: Knock Peak to Peak vs Engine Speed

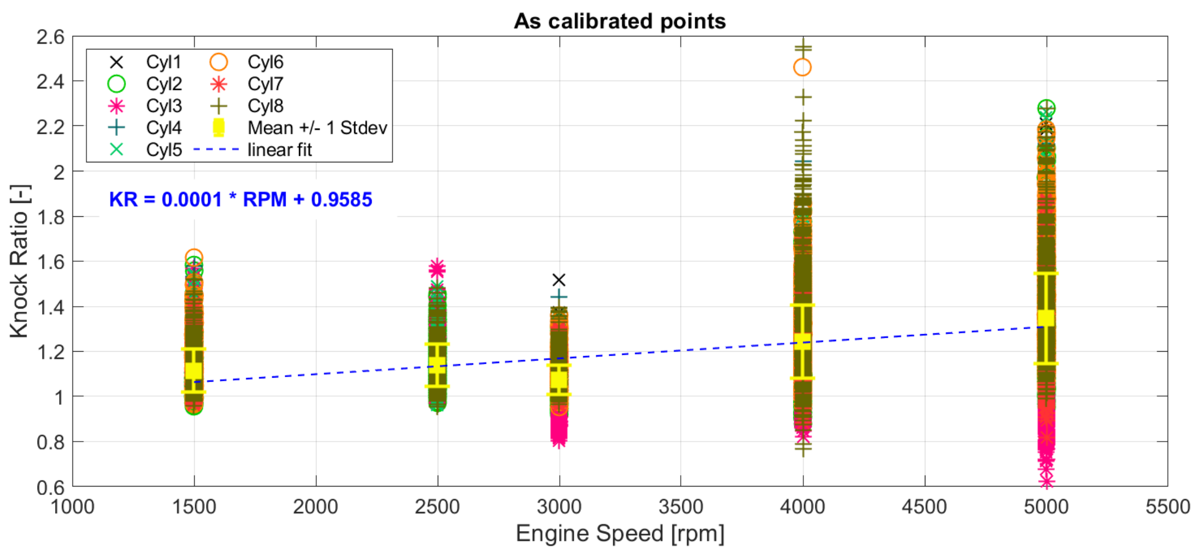

Figure 4d: Knock Ratio vs Engine Speed

b. Knock Mapping

For test development, on each engine calibration parameters were dialed in manually at multiple speed and load points to test the knocking characteristics of the engine. Based on these initial tests, knock limits were established that were safe but not overly cautious. Exhaust temperature limits were also determined from the engine mapping procedures and these temperatures were used as a baseline to limit the amount of enrichment the engine runs during testing.

The baseline calibration for the mapping exercise i.e., spark timing and enrichment was determined by a combination of thresholds relating to exhaust temperatures, burn characteristics, and knock characteristics.

1- Exhaust Temperature Limit – The exhaust temperature was limited for all operating points to ensure safe operation of the engine, especially at higher loads. The temperature limit was discussed with the OEMs, and the limits were set to 870 °C for the GM L86 engine, and 900 °C for the Ford 7.3L engine and was constant between the normal and high ACT maps. The exhaust temperature limit was set to the average of both banks before the catalyst (measured ~1" before the catalyst front face) on the GM L86 engine. On the Ford 7.3L engine, the catalysts were further downstream compared to the close-coupled catalysts of the GM L86 engine. The exhaust temperature was decided to be measured at the collector after the manifold, and the maximum of both banks was set as the limit. Specific measurement locations are shown in and. If the exhaust temperature was below the limit, aa stoichiometric air-fuel ratio (Lambda = 1) was used. When the exhaust temperature reached the limit, a fuel-enrichment strategy (Lambda < 1) was used. The Lambda was adjusted to the least-rich condition to maintain the exhaust temperature limit to the achieve the required load.
2- Burn Characteristic / CA50 – For both engines a CA50 of 7 °CAaTDCF was chosen as the limit for the maximum spark advance allowed at non-knock limited operating points.
3- Knock Limits – Knock limits were split into multi-cycle and single cycle knock limits, with a total of 3 limits.
    a. Knock Ratio > 5 – A multi-cycle limit was applied for knock ratio values greater than 5. When 5% out of 4000 cycles (500 cycles x 8 cylinders) exceeded a knock ratio of 5, the spark advance was stopped, and data collection was completed before returning to a safe operating condition.
    b. Knock Ratio > 15 – A single cycle knock limit was applied for knock ratio values greater than 15. During an operating point when a cycle in any cylinder exceeded a knock ratio of 15, a 500 cycle combustion data collection was started, and the spark advance was stopped at that point. The data collection was completed before the engine was returned to its safe operating condition. Examples of a knock ratio greater than 15 events are shown in Figure 5**,** Figure 6**,** and Figure 7**.**
    c. Knock Ratio > 20 – A single cycle knock limit was applied for knock ratio values greater than 20. During an operating point when a cycle in any cylinder exceeded a knock ratio of 20, all procedures were immediately stopped, and the point was returned to the safe operating condition. Under this limit, the point was returned to a safe operating condition irrespective of an ongoing data save, this was done to reduce chances of engine damage during high engine knock. Examples of knock ratio greater than 20 events are shown in Figure 8**,** Figure 9**,** and Figure 10**.**

Figure 5: Knock Ratio > 15 event @ 2250 RPM 7 bar BMEP

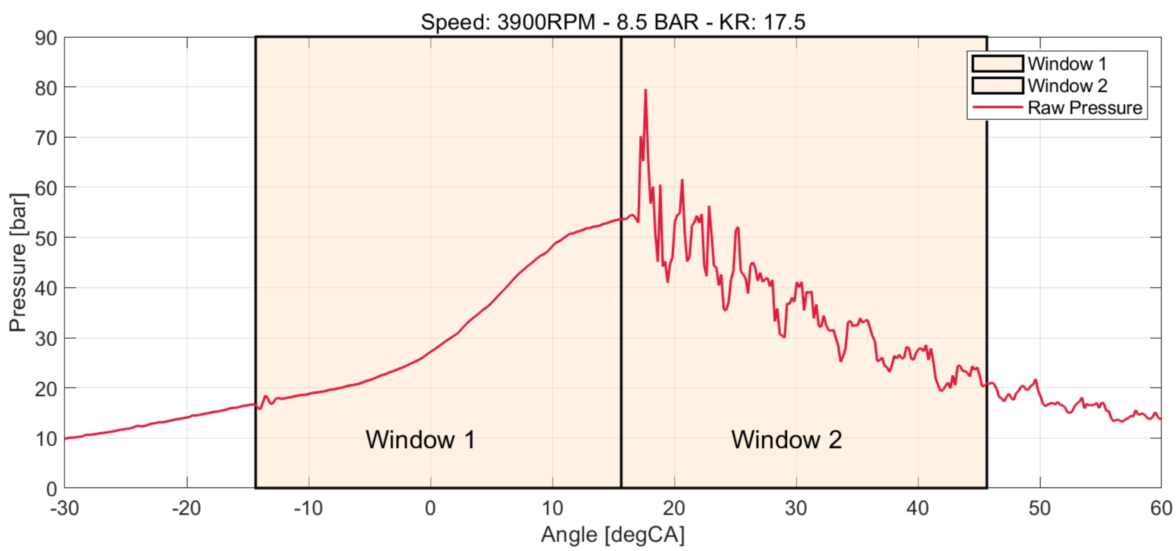

Figure 6: Knock Ratio > 15 event @ 3900 RPM @ 8.5 bar BMEP

Figure 7: Knock Ratio > 15 event @ 4500 RPM 9 bar BMEP

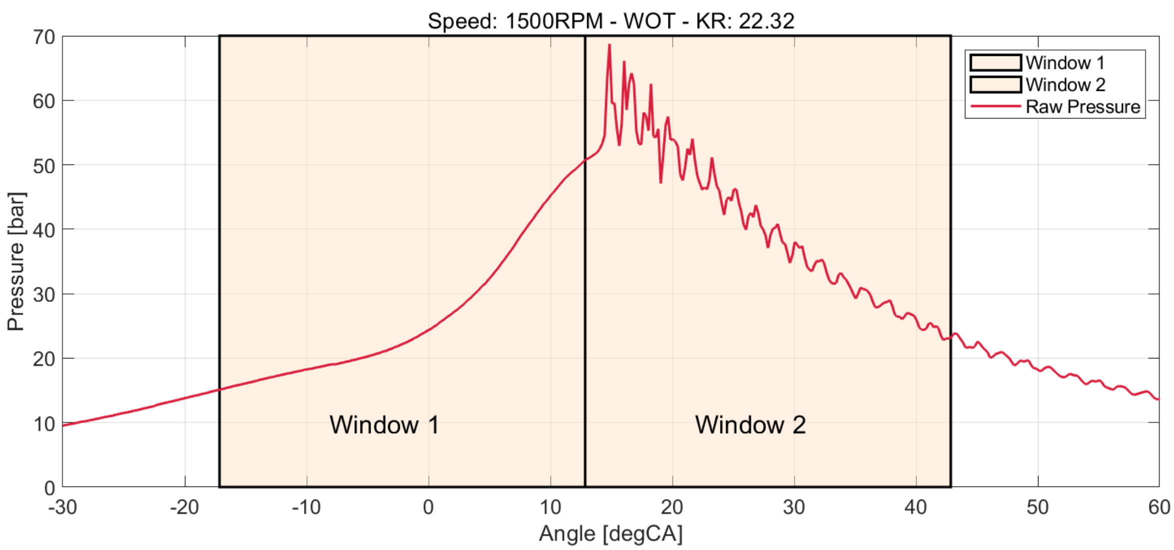

Figure 8: Knock Ratio > 20 event @ 1500 RPM WOT

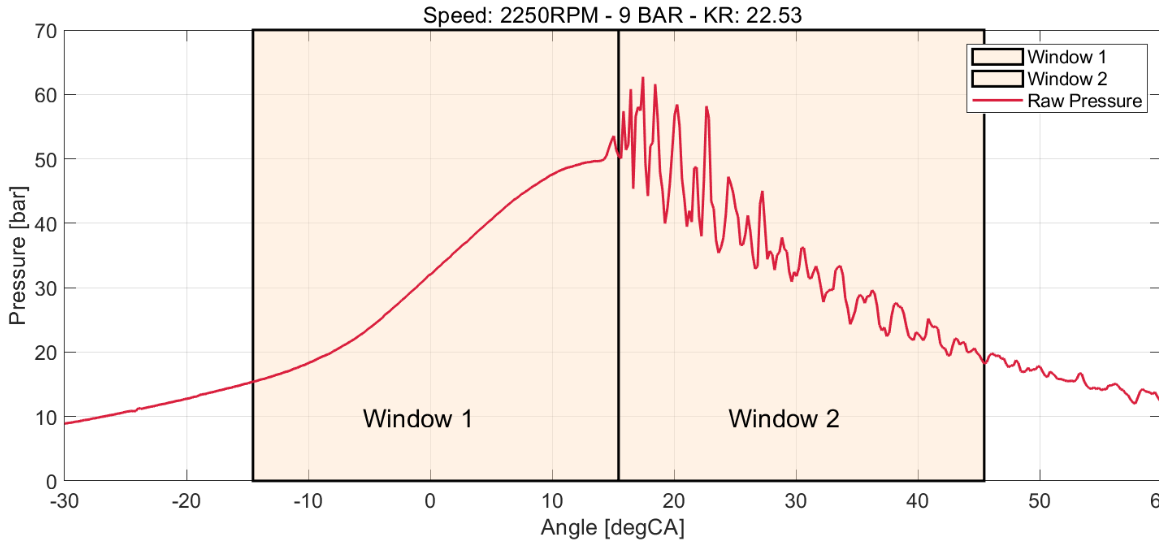

Figure 9: Knock Ratio > 20 event @ 2250 RPM 9 bar BMEP

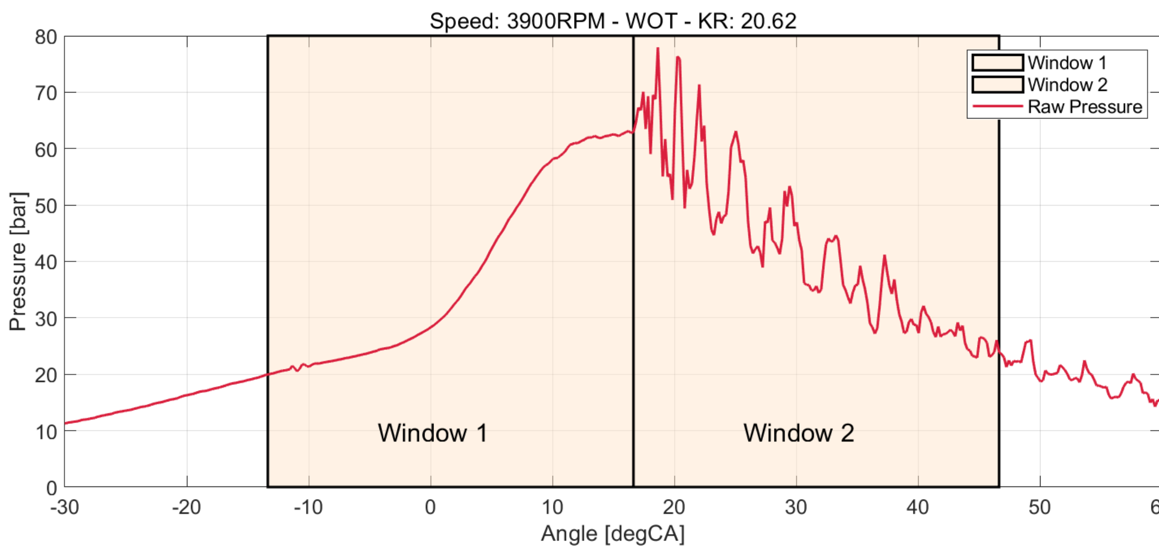

Figure 10: Knock Ratio > 20 event @ 3900 RPM WOT

For the knock mapping procedure, at the start of each operating point once BMEP has stabilized, engine control parameters are fixed to the base settings. Once the engine control parameters have been fixed a maximum 10-minute wait for boundary stabilization is enforced, with the minimum wait time being 1 minute. If the boundary conditions do not stabilize within the 10-minute period, the point is invalid. Once the boundaries stabilize, the knock mapping procedure is initialized.

c. Test Description

Two air charge temperatures (ACT) were selected to evaluate knock tolerance of fuels at normal and elevated temperatures:

- Normal ACT: Replicate the ideal and general operating temperatures (25 ^{o}C) for a vehicle.
- High ACT: Replicate operation under a high-power demand scenario such as vehicle towing at high load on a steep slope under hot ambient conditions i.e., a highly knock limited region with elevated ACT.

At each operating point, the spark was advanced until either MBT (CA50 + 7 CAaTDC) or Knock Limited Spark Advance (KLSA) was achieved. At lower engine speeds, where the production calibration was more retarded from knock limit, the spark timing was advanced by 2 degrees, until a single event of KR > 7 was seen, then spark timing advance was reduced to 1 degree. Stoichiometric Air Fuel Ratio (AFR) was maintained at all operating conditions unless exhaust gas temperatures were exceeded, at which point enrichment was applied.

The base operating points for the test matrix shown in Table 2 were set up as load sweeps at multiple speeds, encompassing the most frequent operating regions in different EPA drive cycles. Additional points at high speeds were included to account for different modes of operation of K, to better understand fuel knock tolerance. From the base operating points, points of interest were then chosen keeping in mind fuel consumption and fuel quantity. Apart from the speeds at which load sweeps were conducted, additional speeds were added for WOT operation for additional resolution in WOT regions. The base operating points for each engine and map are shown in Table 4, Table 5, Table 6, and Table 7. The maximum load achieved i.e., during wide open throttle operation, is dependent on the knock tolerance properties of each fuel and is discussed in more detail later.

To test fuel knock tolerance, a test was developed around spark timing advance and enrichment reduction. The test was automated to ensure repeatability between tests and for the ease of comparison between engines and fuels. The test procedure was developed around reaching either the MBT spark advance or the knock limit spark advance, at the least enrichment possible within the boundaries. The MBT spark advance was assumed to be a CA50 of 8 °CAaTDCF throughout the engine map. The test points were chosen based on a combination of test cycles like US06, HWFET and FTP to determine the most frequent operating points.

Engine mapping was conducted at each of the chosen operating points, at two temperature settings to determine the base engine operating parameters for spark timing, fuel timing, etc. For each fuel tested, apart from spark timing and air/fuel ratio all control parameters were kept fixed to narrow down variability and get easier comparison points between different fuels.

Table 4: GM L86 Normal ACT Operating Points

GM L86 Normal ACT Operating Points		
Point#	Speed (RPM)	BMEP (bar)

1	1000	Wide Open Throttle
2	1500	2
3	1500	4
4	1500	5.5
5	1500	6
6	1500	7
7	1500	7.75
8	1500	8.5
9	1500	9.25
10	1500	9.5
11	1500	Wide Open Throttle
12	3000	Wide Open Throttle
13	4250	4
14	4250	9
15	4250	10
16	4250	11
17	4250	Wide Open Throttle
18	5600	4
19	5600	8
20	5600	9.5
21	5600	Wide Open Throttle

Table 5: GM L86 High ACT Operating Points

<table>
<tr><th colspan="4">GM L86 High ACT Operating Points</th></tr>
<tr><th>Point#</th><th>Speed (RPM)</th><th>BMEP (bar)</th><th>Comments</th></tr>
<tr><td>1</td><td>1000</td><td>2</td><td rowspan="4">Only ran on Fuel 4</td></tr>
<tr><td>2</td><td>1000</td><td>4</td></tr>
<tr><td>3</td><td>1000</td><td>5.5</td></tr>
<tr><td>4</td><td>1000</td><td>7</td></tr>
<tr><td>5</td><td>1000</td><td>Wide Open Throttle</td><td></td></tr>
<tr><td>6</td><td>1500</td><td>2</td><td></td></tr>
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<tr><td>14</td><td>1500</td><td>Wide Open Throttle</td><td></td></tr>
<tr><td>15</td><td>2250</td><td>2</td><td rowspan="3">Only ran on Fuel 4</td></tr>
<tr><td>16</td><td>2250</td><td>4</td></tr>
<tr><td>17</td><td>2250</td><td>6</td></tr>
</table>

18	2250	7	
19	2250	7.75	
20	2250	8.5	
21	2250	9	
22	2250	Wide Open Throttle	
23	3000	Wide Open Throttle	
24	3500	6	Only ran on Fuel 4
25	3500	7.75	
26	3500	8.5	
27	3500	9	
28	3500	Wide Open Throttle	
29	4250	4	
30	4250	9	
31	4250	10	
32	4250	10.5	
33	4250	11.4	
34	5000	9	Only ran on Fuel 4
35	5000	10	
36	5000	Wide Open Throttle	
37	5600	4	
38	5600	8	
39	5600	8.5	
40	5600	Wide Open Throttle	

Table 6: Ford 7.3L Normal ACT Operating Points

Ford 7.3L Normal ACT Operating Points		
Point#	Speed (RPM)	BMEP (bar)
1	1000	Wide Open Throttle
2	1500	2
3	1500	4
4	1500	5.5
5	1500	6
6	1500	7
7	1500	8
8	1500	8.25
9	1500	8.5
10	1500	Wide Open Throttle
11	2250	2
12	2250	4
13	2250	6
14	2250	7
15	2250	8

16	2250	9
17	2250	Wide Open Throttle
18	3000	Wide Open Throttle
19	3900	4
20	3900	6
21	3900	7.25
22	3900	8.5
23	3900	8.75
24	3900	10
25	3900	Wide Open Throttle
26	4500	4
27	4500	5
28	4500	6
29	4500	7.5
30	4500	8.5
31	4500	9
32	4500	10
33	4500	Wide Open Throttle

Table 7: Ford 7.3L High ACT Operating Points

Ford 7.3L High ACT Operating Points		
Point#	Speed (RPM)	BMEP (bar)
1	1000	Wide Open Throttle
2	1500	2
3	1500	4
4	1500	5.5
5	1500	6
6	1500	7
7	1500	7.75
8	1500	8.25
9	1500	Wide Open Throttle
10	2250	2
11	2250	4
12	2250	6
13	2250	7
14	2250	8.75
15	2250	Wide Open Throttle
16	3000	Wide Open Throttle
17	3900	4
18	3900	6
19	3900	7.5
20	3900	8.5

21	3900	9
22	3900	Wide Open Throttle
23	4500	4
24	4500	5
25	4500	6
26	4500	7.5
27	4500	8.5
28	4500	9
29	4500	Wide Open Throttle

Test Fluids

a. Test Oil:

The OEM recommended engine oils were used on both the GM L86 and Ford 7.3L engines. The GM L86 test oil was SAE 0W-20 (ACDelco PN# 19420054), and the Ford 7.3L test oil was SAE 5W-30 (Motorcraft PN# XO-5W30-Q1SP).

b. Base Fuel Properties:

Table 8: Base Fuel Properties

Property	Test Method	UOM	Premium E10	Regular E10
Research Octane Number	ASTM D2699	RON	98.5	92.4
Motor Octane Number	ASTMD2700	MON	88.3	82.4
Octane Rating	-	(R+M)/2	93.4	87.4
Octane Sensitivity	-	R-M	10.2	10
Aromatic Content	ASTM D6730mod	Vol%	-	23.7
Olefin Content	ASTM D6730mod	Vol%	-	8.8
Saturate Content	ASTM D6730mod	Vol%	-	-
Ethanol Content	ASTM D4815	Vol%	8.6	9.7
Specific Gravity @ 60.0 °F	ASTM D4052		0.745	0.746
Density @ 15.56 °C	ASTM D4052	g/cc	0.7451	0.7458
Sulfur Content	ASTM D5453	ppm	0	0
RVP @100 °F	ASTM D5191	kPa	70.3	63.43
Distillation, IBP	ASTM D86	Deg C	29.6	34.4
Distillation, 5%	ASTM D86	Deg C	41.1	45.4
Distillation, 10%	ASTM D86	Deg C	48.6	51.8
Distillation, 20%	ASTM D86	Deg C	58.8	58.2
Distillation, 30%	ASTM D86	Deg C	66.7	63
Distillation, 40%	ASTM D86	Deg C	75.2	67.4
Distillation, 50%	ASTM D86	Deg C	104.7	92.2
Distillation, 60%	ASTM D86	Deg C	113.7	113.6
Distillation, 70%	ASTM D86	Deg C	122.0	127.4
Distillation, 80%	ASTM D86	Deg C	135.8	141.6
Distillation, 90%	ASTM D86	Deg C	165.1	160

Distillation, 95%	ASTM D86	Deg C	182.6	170.6
Distillation, Dry Point	ASTM D86	Deg C	210.4	201.9
Recovery	ASTM D86	Vol%	95.9	95.5
Residue	ASTM D86	Vol%	1.1	1
Loss	ASTM D86	Vol%	3	3.5
Drivability Index	ASTM D4814 (Deg F)	Drive Index	-	
Carbon Content	ASTM D5291	Wt%	82.99	82.8
Hydrogen Content	ASTM D5291	Wt%	13.67	13.7
Oxygen Content	-	Wt%	3.34	3.57
C/H Ratio	-	mole/mole	-	-
H/C Ratio	-	mole/mole	1.963	1.967
O/C Ratio	-	mole/mole	0.030	0.032
Net Heat of Combustion	ASTM D240mod	MJ/kg	41.72	41.74

c. Test Fuel Properties, provided by CRC:

The test fuel properties for all fuels 1-7, are shown in Table 9, test results from 3 additional labs and the average fuel property results are shown in, Appendix J, Appendix K, Appendix L, and Appendix M.

Table 9: Test Fuel Properties

Property	Test Method	UOM	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7
Research Octane Number	ASTM D2699	RON	91.5	91.2	91.2	95.1	94.9	94.9	98.3
Motor Octane Number	ASTMD2700	MON	86.3	83.2	80.4	86.8	90.8	83	86.9
Octane Rating	-	(R+M)/2	88.9	87.2	85.8	91	92.8	89	92.6
Octane Sensitivity	-	R-M	5.2	8	10.8	8.3	4.1	11.9	11.4
Aromatic Content	ASTM D6730mod	Vol%	14.5	27.9	30.2	26.8	1.7	31.6	37
Olefin Content	ASTM D6730mod	Vol%	0.6	5.4	20.9	0.7	2.4	30.2	6.9
Saturate Content	ASTM D6730mod	Vol%	74.9	56.6	39	62.6	85.8	28	46.1
Ethanol Content	ASTM D4815	Vol%	10	10.1	9.9	9.9	10.1	10.2	10
Specific Gravity @ 60.0 °F	ASTM D4052		0.7237	0.747	0.757	0.7438	0.7024	0.756	0.7595
Density @ 15.56 °C	ASTM D4052	g/cc	0.723	0.7462	0.7563	0.7431	0.7017	0.7552	0.7587
Sulfur Content	ASTM D5453	ppm	0	0	0	0	0	0	0
RVP @100 °F	ASTM D5191	kPa	70.3	73	71	70.3	68.9	67.5	71
Distillation, IBP	ASTM D86	Deg C	32.6	28.7	31.9	30.9	35.1	35.8	31.6
Distillation, 5%	ASTM D86	Deg C	46.8	43.4	46.1	45.4	49.6	47.7	44.9
Distillation, 10%	ASTM D86	Deg C	51.7	48.7	51.5	50.8	54.6	53.4	50.3
Distillation, 20%	ASTM D86	Deg C	58.9	56.8	58.3	59.1	61.8	61.7	58.9
Distillation, 30%	ASTM D86	Deg C	64.9	64	63.7	66.1	66.7	66.9	66.1

Distillation, 40%	ASTM D86	Deg C	69.6	69.8	68.4	71.2	73.5	70.5	73
Distillation, 50%	ASTM D86	Deg C	96.5	105.2	106.8	106.1	99.6	105	112.4
Distillation, 60%	ASTM D86	Deg C	108.1	123.8	131.7	116.2	105	126.2	127.8
Distillation, 70%	ASTM D86	Deg C	116.4	134.3	140.1	123.7	109.6	146.4	140.4
Distillation, 80%	ASTM D86	Deg C	128.3	145.6	148.9	134.9	115.7	162.2	153.9
Distillation, 90%	ASTM D86	Deg C	155.5	152.5	163.2	156.2	132.9	178.7	167.5
Distillation, 95%	ASTM D86	Deg C	171.3	161.5	176.7	173.4	162.8	189.3	175.4
Distillation, Dry Point	ASTM D86	Deg C	186	190.1	189.8	189.7	194.2	198.2	189.8
Recovery	ASTM D86	Vol%	97.5	97.6	97.8	97.7	97.4	97.7	97.6
Residue	ASTM D86	Vol%	1.1	1	1	1.1	1	1.1	1
Loss	ASTM D86	Vol%	1.4	1.4	1.2	1.2	1.6	1.2	1.4
Drivability Index	ASTM D4814 (Deg F)	Drive Index	1141	1191	1209	1191	1125	1186	1244
Carbon Content	ASTM D5291	Wt%	81.76	82.94	83.36	82.76	80.46	83.4	83.54
Hydrogen Content	ASTM D5291	Wt%	14.43	13.35	13.04	13.58	15.6	12.87	12.84
Oxygen Content	-	Wt%	3.81	3.71	3.6	3.66	3.94	3.73	3.62
C/H Ratio	-	mole/mole	5.666	6.211	6.392	6.095	5.156	6.479	6.505
H/C Ratio	-	mole/mole	2.103	1.919	1.864	1.955	2.311	1.839	1.832
O/C Ratio	-	mole/mole	0.035	0.034	0.032	0.033	0.037	0.034	0.033
Net Heat of Combustion	ASTM D240mod	MJ/kg	42.13	41.64	41.57	41.61	42.66	41.37	41.18

Results and Discussions

The test results between different fuels were compared based on specific parameters to understand the fuel impact on knock characteristics. Parameters that were studied between fuels were spark advance, fuel enrichment, exhaust temperatures and CA50.

Combustion phasing (CA50) is used to determine how knock prone a fuel is compared to other blends. At a particular operating point, a more retarded CA50 indicates that the fuel is more knock prone and similarly a more advanced CA50 indicates that the fuel is less knock prone. A fuel that is more knock prone can lead to a retarded spark timing, this increases exhaust gas temperatures due to a retarded combustion phasing. To maintain the exhaust temperature limit, fuel-enrichment is required to lower the exhaust gas temperature, due to the evaporative cooling effect. The lambda is enriched to the minimum required level, to maintain the exhaust temperature limit. Therefore, the level of enrichment can provide an insight into the knock tendencies of the fuel i.e., a fuel that is more prone to knock will require a higher amount of enrichment, and vice-versa. Finally, the fuels are also compared at WOT operation to understand the maximum loads achieved, CA50 at peak load, enrichment at peak load, and exhaust temperatures at peak load.

The legends in the plots have been ordered from the lowest to the highest MON, and the high RON fuel is placed last.

a. GM L86 Engine

Fuels 4-7 from Table 5 are premium blend fuels and were selected as the test fuels on the GM L86. This section discusses the results of fuel comparison for the GM L86 engine. All baseline data for the GM L86 engine was collected on a 98 RON Premium E10 fuel, where most test fuels are 95 RON E10 fuels.

i. Normal ACT Map

This section analyzes the results of fuels 4-7 on the GM L86 engine, for the Normal ACT map, i.e., engine coolant temperature at 90 °C, engine oil temperature at 90 °C, and manifold air temperature at 25 °C. Additional information regarding the knock mapping thresholds crossed at each operating point are listed in Appendix F.

Figure 11 shows the comparison between fuels for the engine average CA50, for the load sweep at 1500 RPM. From the plot it is seen that all the fuels are CA50 limited (i.e., they are not knock-limited) up to a load of 7.75 bar BMEP. However, as load increases the points are defined by KLSA as the engine/fuel combination becomes knock limited. For the higher loads it is generally seen that at constant RON the fuels with the lower MON can run a more advanced CA50, as they reach knock limits at a more advanced spark timing, indicating an increased S value is advantageous. Fuel 7, the 98 RON fuel can run a more advanced CA50 compared to the three 95 RON fuels. Note that a small change in RON (98 vs. 95 RON) affects knock limited CA50 more than a large change in MON (82 vs. 91 MON).

Figure 12 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 1500 RPM. It is seen from the data that all the fuels run stoichiometric for the complete load sweep at 1500 RPM. As all fuels can run stoichiometric, the differences in exhaust temperatures are due to different combustion phasing dependent on the knock limit of the fuels.

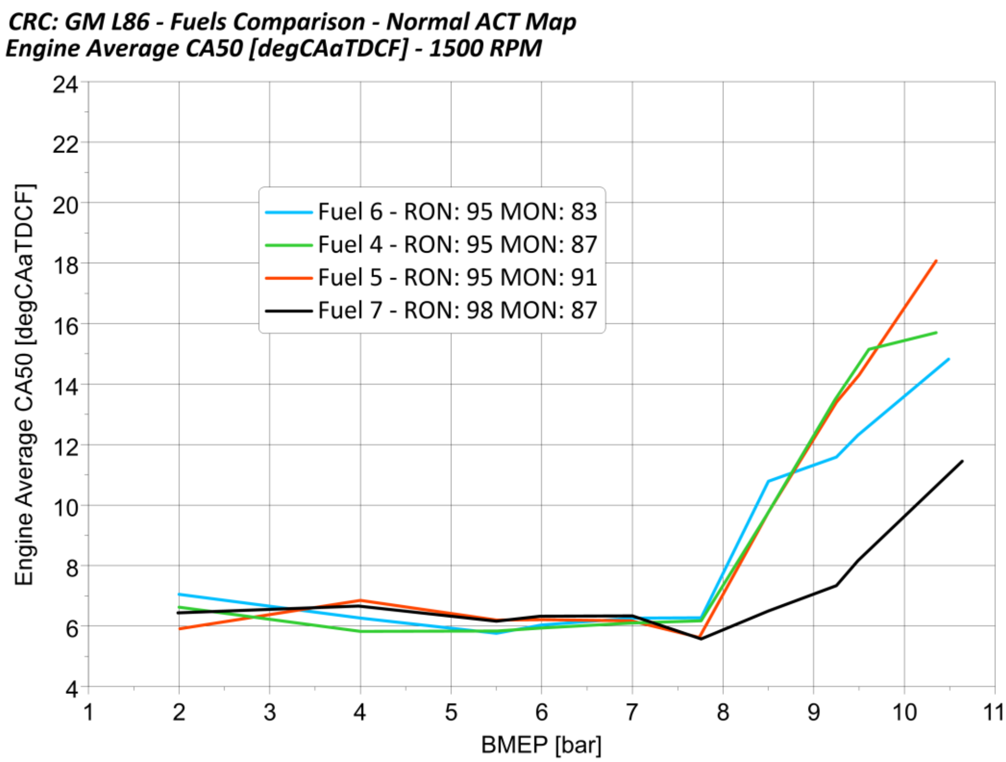

Figure 11: Comparison of Engine Average CA50 at 1500 RPM, Normal ACT map.

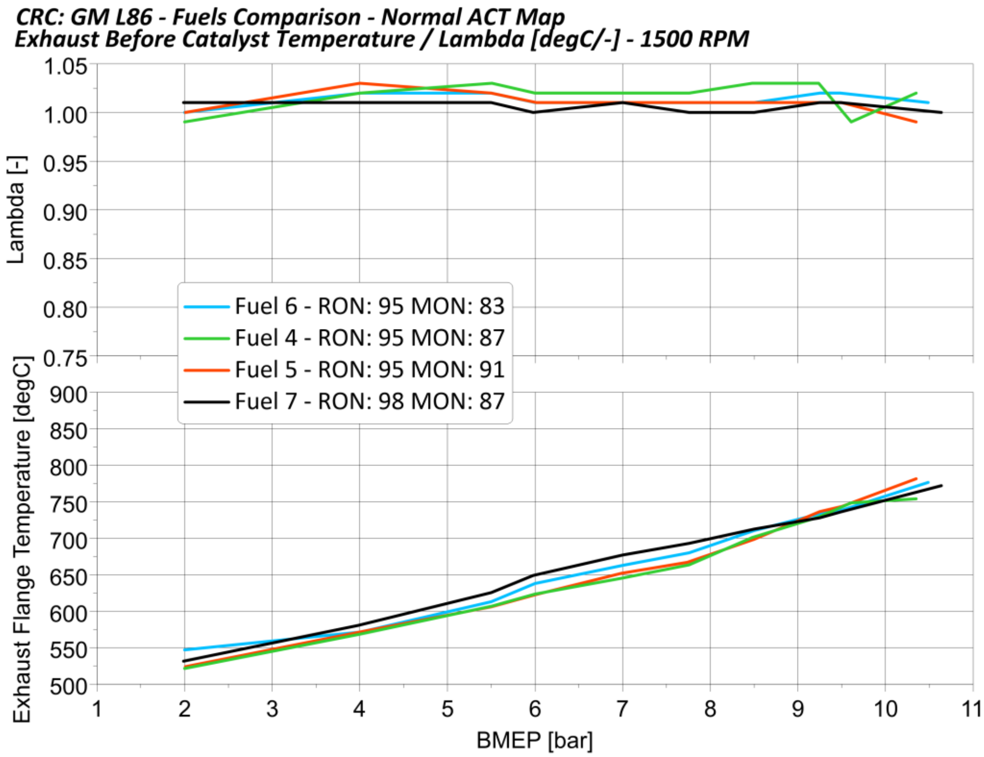

Figure 12: Comparison of enrichment and exhaust temperatures at 1500 RPM, Normal ACT map.

Figure 13 shows a comparison between fuels for the engine average CA50, for the load sweep at 4250 RPM. It is seen from the data that at 4 bar BMEP, all fuels are CA50 limited, with CA50s around 7 degCA. Above 9 bar BMEP, for the fuels with the same RON, fuels with a higher MON run more advanced CA50s throughout the load sweep, indicating a higher resistance to knock at this speed and a reversed trend from lower RPM testing. Fuels with increased AKI and lower S values are less knock limited. As at 1500 RPM, a small change in RON affects knock limited CA50 more than a large change in MON.

Figure 14 shows the comparison between fuels, for the enrichment and exhaust temperatures, for the load sweep at 4250 RPM. All fuels can run stoichiometric at 4 bar BMEP but require enrichment to maintain exhaust temperatures at the higher loads. As the load increases, for the same RON, the fuels with a lower MON require higher enrichment to maintain exhaust temperatures, as seen from fuel 6 which runs the most enrichment out of all fuels. Fuels with higher MON run a more advanced spark timing and maintain exhaust temperatures with lower enrichment.

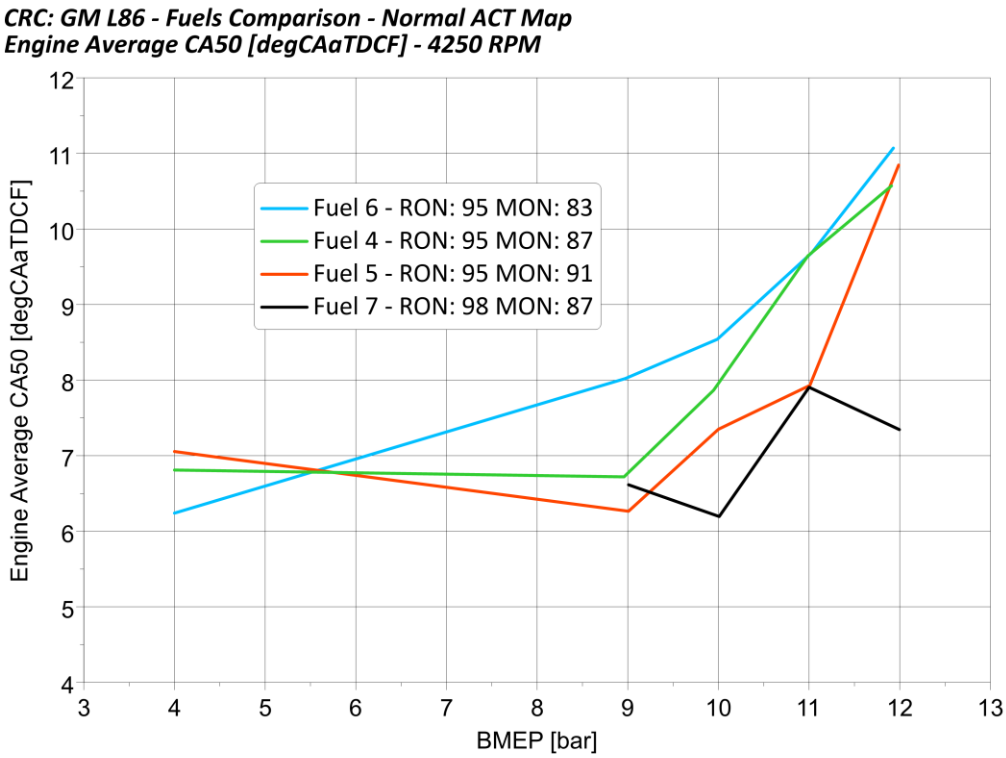

Figure 13: Comparison of Engine Average CA50 at 4250 RPM, Normal ACT map.

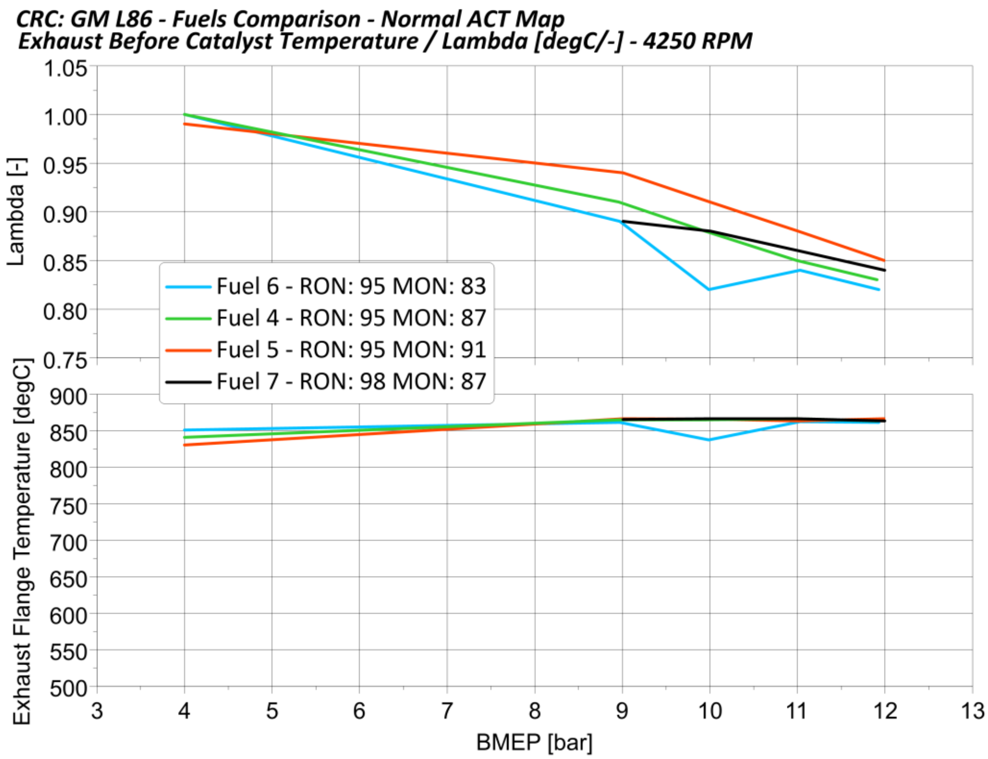

Figure 14: Comparison of enrichment and exhaust temperatures at 4250 RPM, Normal ACT map.

Figure 15 shows a comparison of the fuels for the engine average CA50, for the load sweep at 5600 RPM. It is seen from the data that, most of the points are CA50 limited at 5600 RPM, even if knock events were seen. At the higher loads, for the fuels with the same RON, the fuels with higher MON can run a more advanced CA50, as evidenced from fuel 5 which runs comparatively the most advanced CA50.

Figure 16 shows a comparison of the fuels for the enrichment and exhaust temperatures, for the load sweep at 5600 RPM. Enrichment is required at all the load points to maintain exhaust temperatures within limits. Following the trends seen with CA50, fuels with the higher MON run a more advanced spark timing and maintain exhaust temperatures with lower enrichment. Fuel 6, with the lowest MON of all fuels, needs the most enrichment to maintain exhaust temperatures.

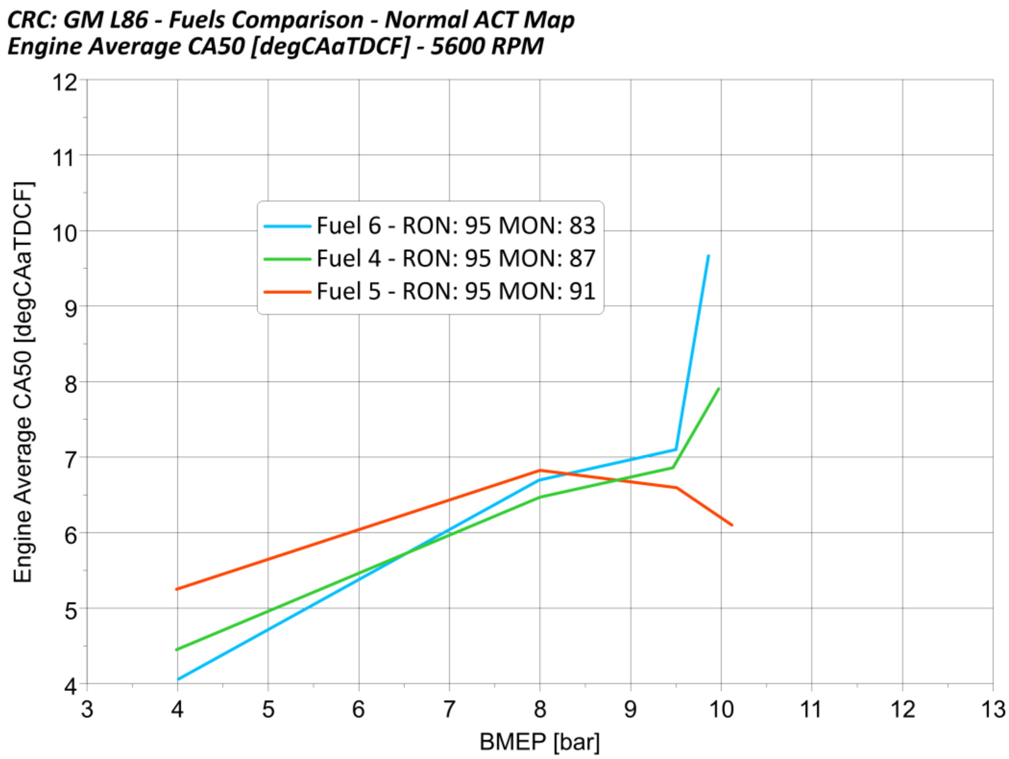

Figure 15: Comparison of the Engine Average CA50 at 5600 RPM, Normal ACT map.

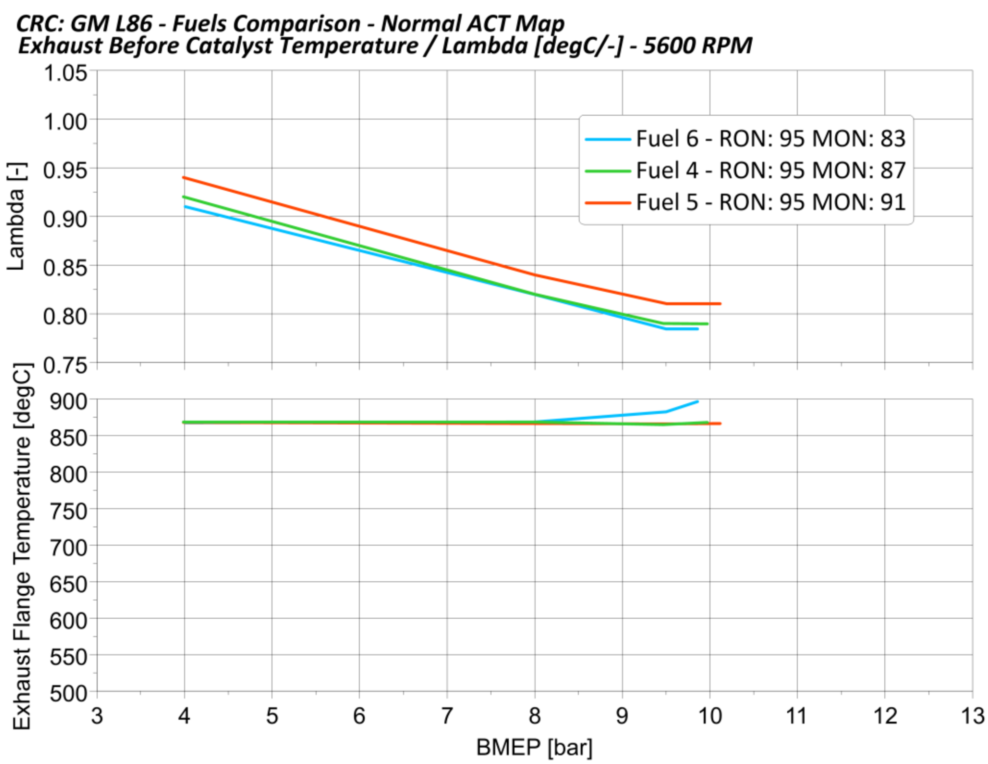

Figure 16: Comparison of enrichment and exhaust temperatures at 5600 RPM, Normal ACT map.

Figure 17 shows the comparison of fuels for the maximum load achieved at WOT operation. At low to mid speeds i.e., 1000 – 3000 RPM, from the constant RON fuels, the peak load achieved decreases as MON increases. As engine shifts to high-speed operation at 4250 and 5600 RPM, the trend reverses, and the peak load achieved increases with an increasing MON. At speeds where 98 RON data is available, it shows higher peak load than the 95 RON data. Also, a small change in RON (3 points) has a similar effect on peak load as a large change in MON (9 points).

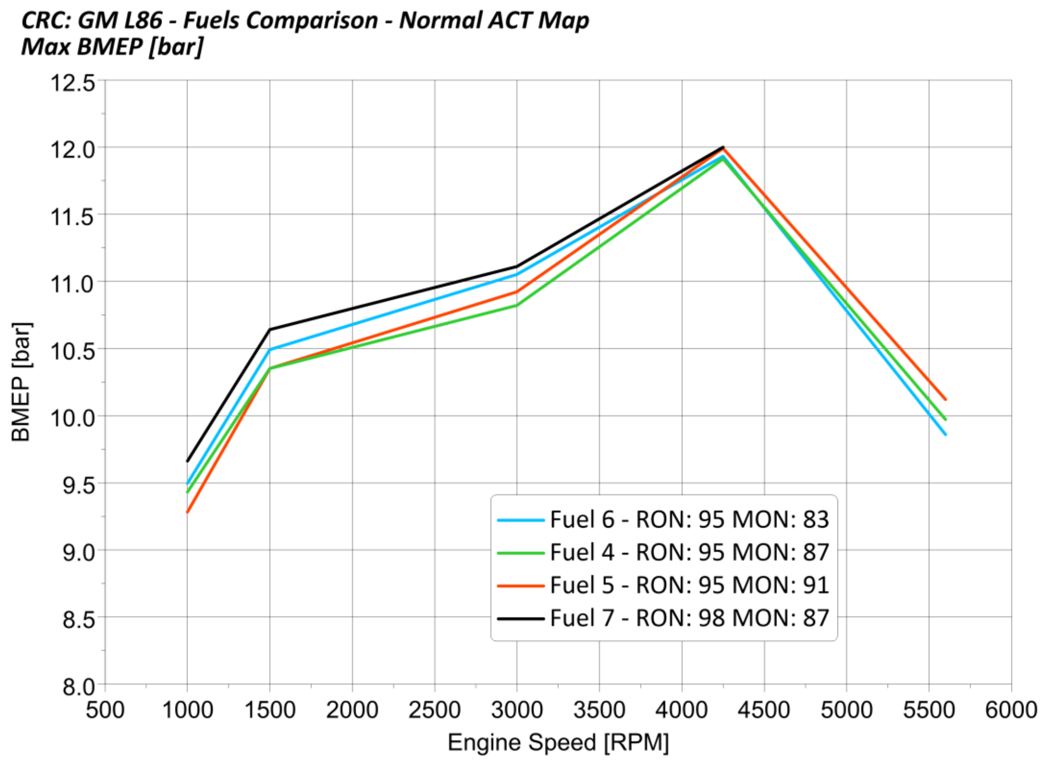

Figure 17: Comparison of the maximum loads achieved at WOT operation, Normal ACT map.

Figure 18 shows the comparison of fuels for the enrichment at WOT operation. All the fuels can run stoichiometric at 1000 and 1500 RPM, as exhaust temperatures are not a limiting factor. At 3000 RPM, for the fuels with the same RON, as the MON increases the enrichment required at 3000 RPM also decreases, fuel 6 being more knock limited needs to enrich to maintain exhaust temperatures. For high-speed operation, the enrichment needed by the fuels increases as the MON of the fuel decreases, as seen with fuel 6 running the highest enrichment of all fuels.

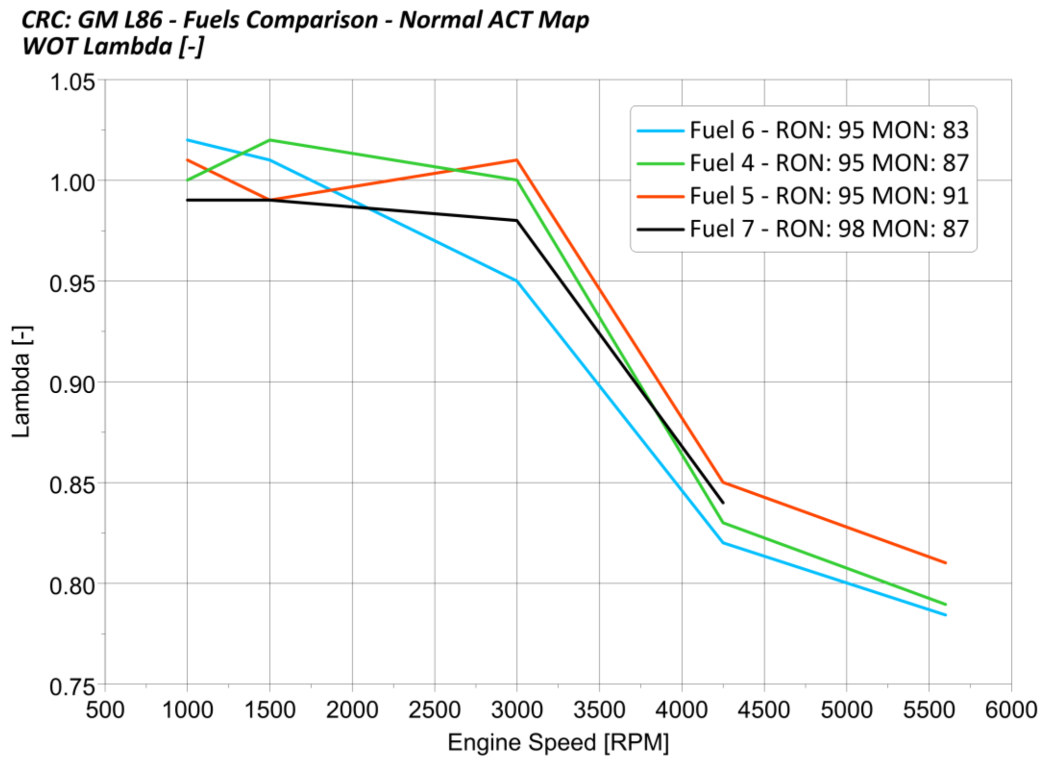

Figure 18: Comparison of the enrichment/lambda at WOT operation, Normal ACT map.

Figure 19 shows the comparison of fuels for the enrichment at WOT operation. None of the fuels are limited by exhaust temperatures at low speeds i.e., 1000-1500 RPM. At 3000 RPM, the lowest MON fuel i.e., fuel 6 was limited by exhaust temperature limits but all other fuels ran stoichiometric. At the high speeds i.e., 4250 and 5600 RPM, all fuels run enrichment to maintain exhaust temperatures within limits. With fuel 6, the engine was unable to maintain exhaust temperatures within limits without running high enrichment.

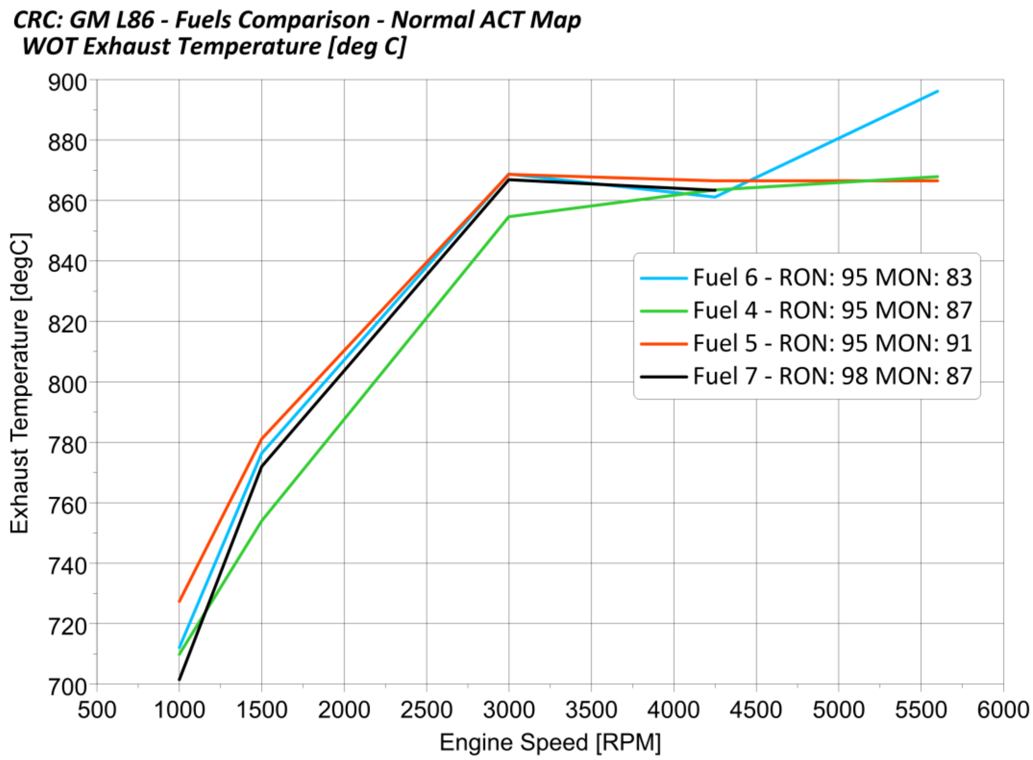

Figure 19: Comparison of exhaust temperatures achieved at WOT operation, Normal ACT map.

Figure 20 shows the comparison of fuels for the engine average CA50 at WOT operation. At 1000 and 1500 RPM, CA50 is more advanced as the fuel MON decreases for a constant RON. At 3000 RPM and above the trend of CA50 reverses and the fuels with the higher MON can run a more advanced CA50. Overall, the data shows that at lower speeds, a lower MON fuel can run more advanced, and at higher speeds a higher MON fuel is able to run more a more advanced spark timing at a fixed RON. Again, a small change in RON affects knock limited CA50 more than a large change in MON.

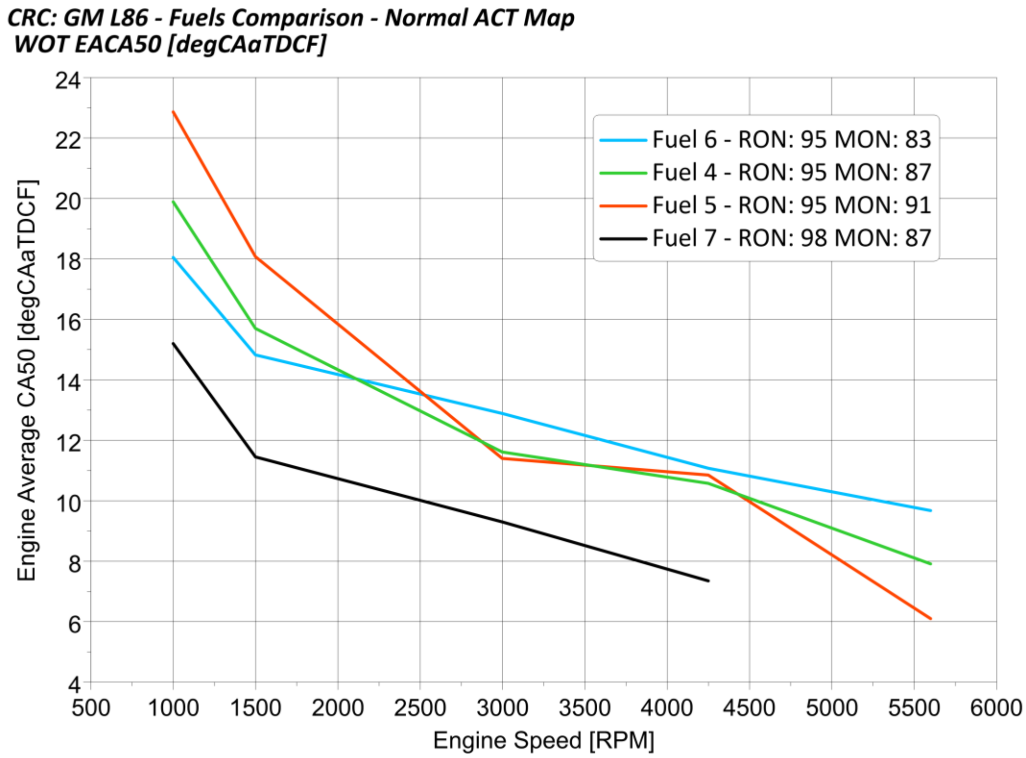

Figure 20: Comparison of engine average CA50 at WOT operation, Normal ACT map.

ii. High ACT Map

This section details the results on fuels 4-6 on the GM L86 engine, for the High ACT map, i.e., engine coolant temperature at 115 °C, engine oil temperature at 115 °C, and manifold air temperature at 45 °C. Additional information regarding the knock mapping thresholds crossed at each operating point are listed in Appendix G.

Figure 21 shows a comparison between the fuels for engine average CA50, for the load sweep at 1500 RPM. It is seen from the data that all fuels are CA50 limited up to a load of 6 bar BMEP, a decrease in 1.75 bar from the low ACT map at the point of knock onset. Above 6 bar BMEP, from the fuels running the same RON, the fuels with the lower MON run a more retarded CA50. This is opposite to what was observed with the low ACT map where fuels with higher S values (lower MON) were less knock limited. At WOT operation, the lower MON fuels run a comparable CA50, while the highest MON fuel runs a more retarded CA50, which more closely matches full load, low ACT mapping data.

Figure 22 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 1500 RPM. It is seen from the data that all the fuels can run stoichiometric for the complete load sweep at 1500 RPM. As all fuels can run stoichiometric, the differences in exhaust temperatures are due to different combustion phasing dependent on the knock limit of the fuels. Following the trends seen with CA50, fuel 6 runs slightly higher temperatures owing to a retarded spark timing between 6-8 bar BMEP, and fuels 4 and 5 run very similar exhaust temperatures.

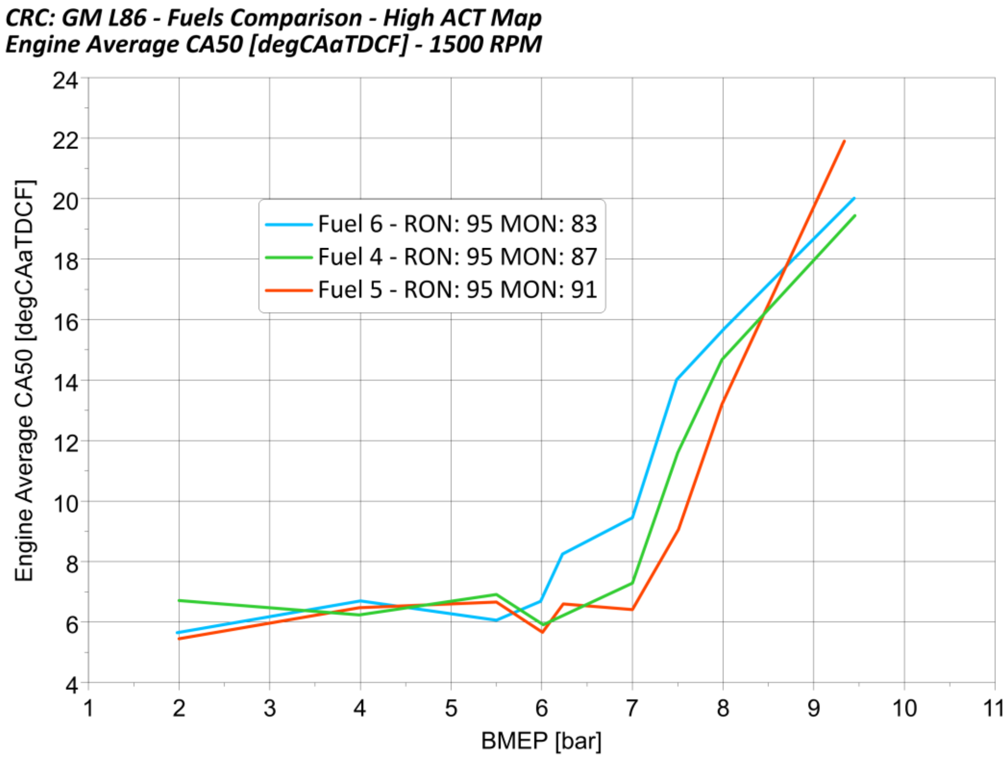

Figure 21: Comparison of Engine Average CA50 at 1500 RPM, High ACT map.

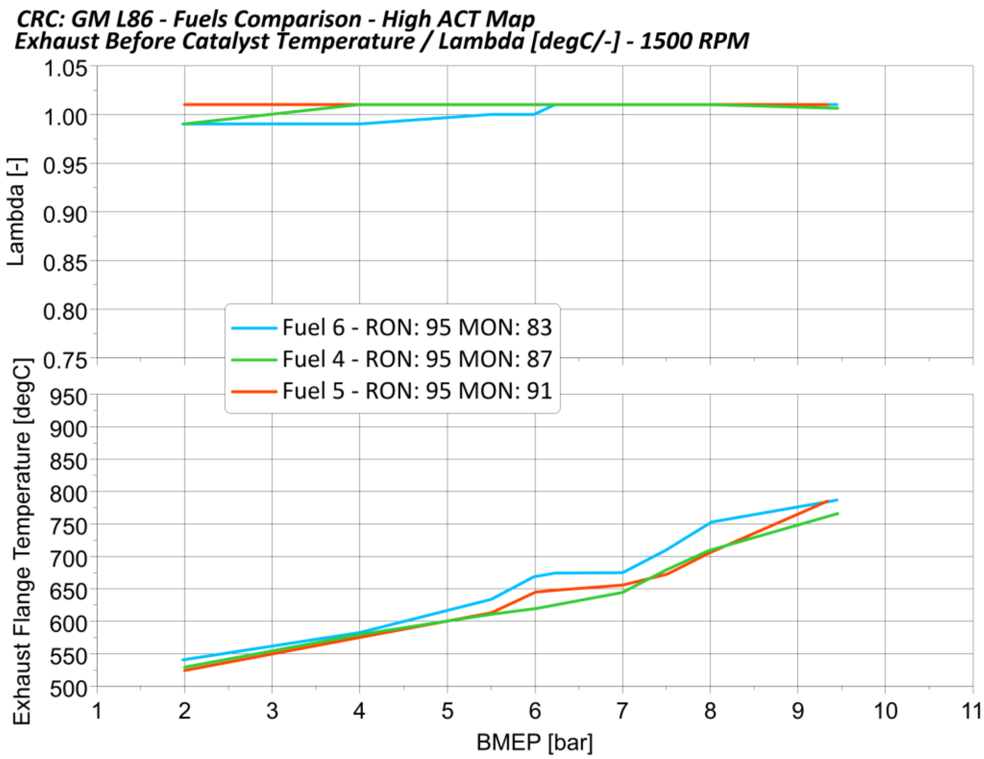

Figure 22: Comparison of enrichment and exhaust temperatures at 1500 RPM, High ACT map.

Figure 23 shows a comparison between fuels for the engine average CA50, for the load sweep at 4250 RPM. It is seen from the data that all the fuels are CA50 limited at 4 bar BMEP and become increasingly knock limited at the higher loads. At the higher loads, it is seen that the lower MON fuels run a more retarded CA50, as seen from fuel 6 which runs the most retarded CA50 of all fuels. This trend matches the results from low ACT mapping where higher AKI fuels with a decreased S value were less knock prone.

Figure 24 shows the comparison between fuels, for the enrichment and exhaust temperatures, for the load sweep at 4250 RPM. All fuels can run stoichiometric at 4 bar BMEP but require enrichment to maintain exhaust temperatures at the higher loads. As the load increases, it is seen that at the same RON, the fuels with the lower MON generally require higher enrichment to maintain exhaust temperatures. The higher MON fuels run a more advanced spark timing and hence need lower enrichment to maintain exhaust temperatures.

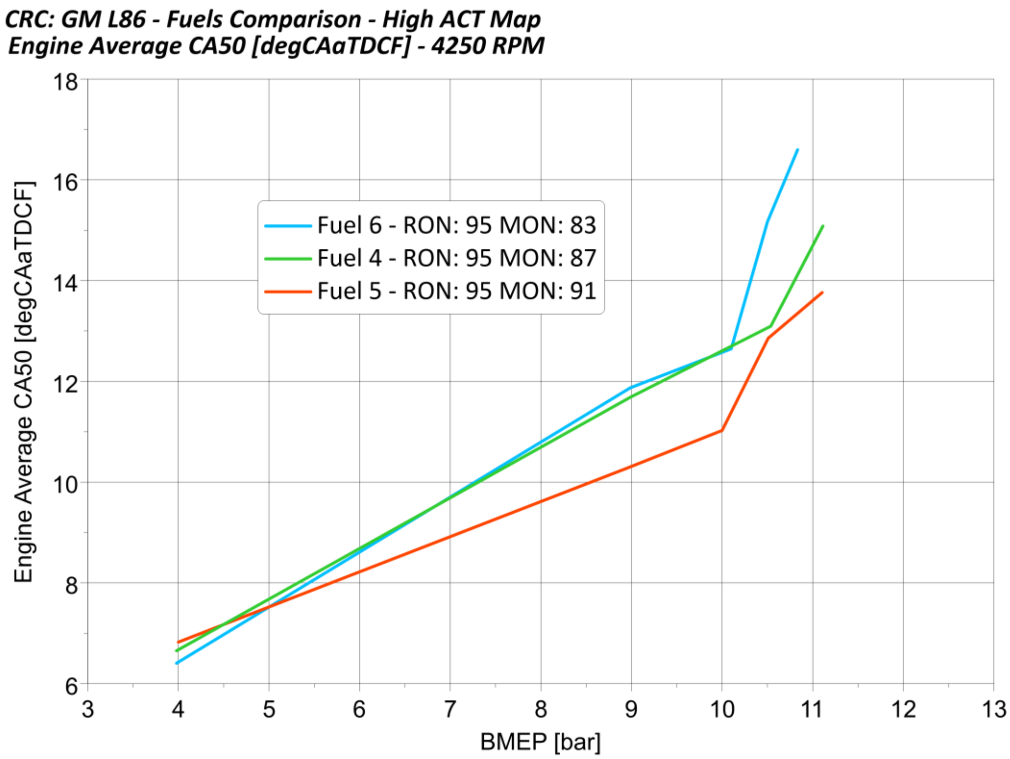

Figure 23: Comparison of Engine Average CA50 at 4250 RPM, High ACT map.

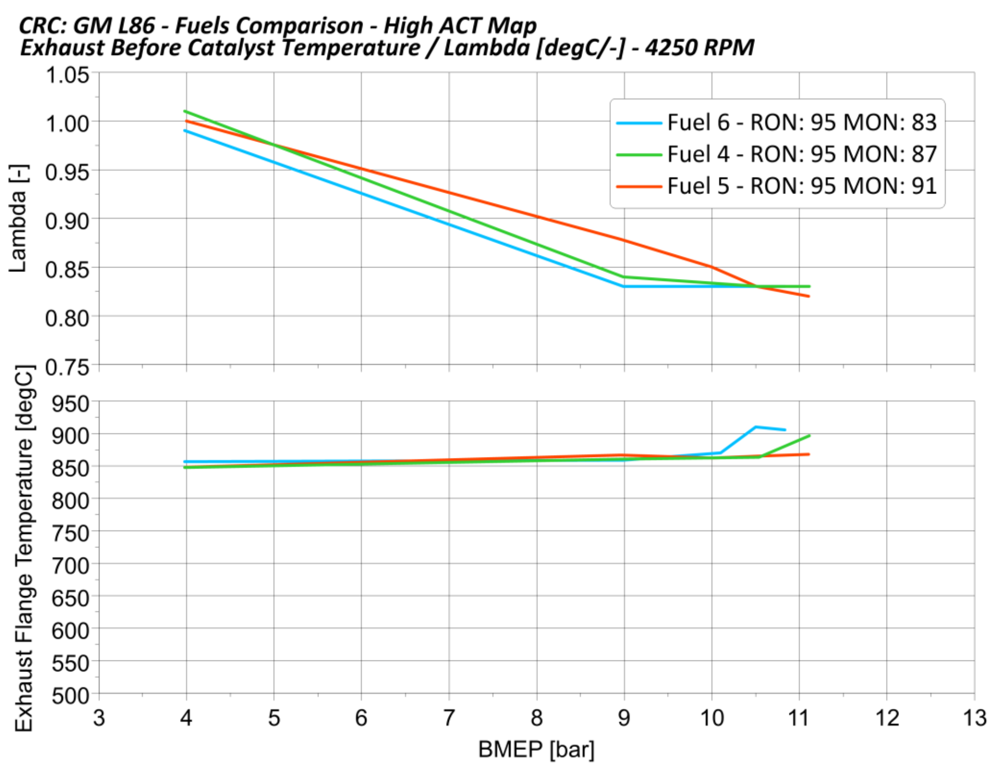

Figure 24: Comparison of enrichment and exhaust temperatures at 4250 RPM, High ACT map.

Figure 25 shows a comparison of the fuels for the engine average CA50, for the load sweep at 5600 RPM. From 8 bar BMEP and above, some differences appear between the fuels, with higher MON fuels being able to run a more advanced spark timing, and hence CA50, as evidenced from the fuel 5 which has the highest MON fuel and runs the most advanced CA50.

Figure 26 shows a comparison of the fuels for the enrichment and exhaust temperatures, for the load sweep at 5600 RPM. All fuels must run enrichment all the load points to maintain the exhaust temperature. In line with the trends seen in the engine average CA50 fuels with the higher MON run a more advanced spark timing and need lower enrichment to maintain exhaust temperatures. Low ACT mapping data also supports fuels with increased AKI and lower S values performing better with respect to knock tolerance.

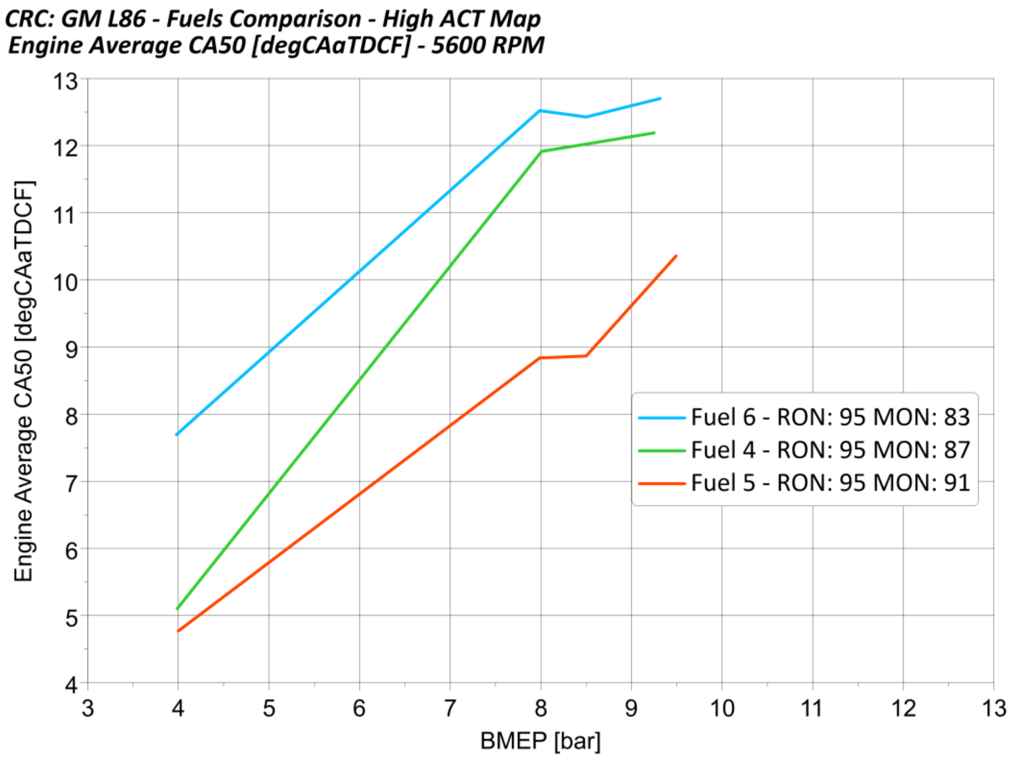

Figure 25: Comparison of the Engine Average CA50 at 5600 RPM, High ACT map.

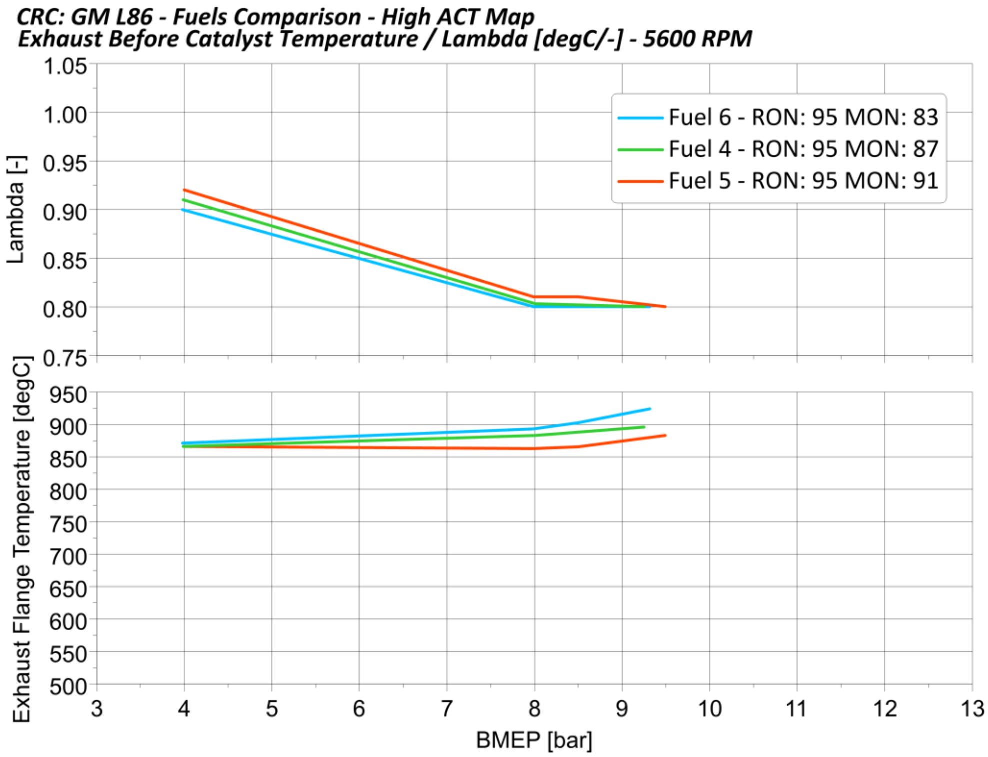

Figure 26: Comparison of enrichment and exhaust temperatures at 5600 RPM, High ACT map.

Figure 27 shows the comparison of fuels for the maximum load achieved at WOT operation. Additional points were run at 1000 RPM and 3000 RPM for the WOT operation. At low to mid speeds i.e., 1000 – 3000 RPM, from the constant RON fuels, the peak load achieved decreases as MON increases. As engine shifts to high-speed operation at 4250 and 5600 RPM, the trend reverses, and the peak load achieved increases with an increasing MON. No 3000 RPM WOT point was run for fuel 4. The trends at full load from high ACT mapping match the trends observed from low ACT mapping.

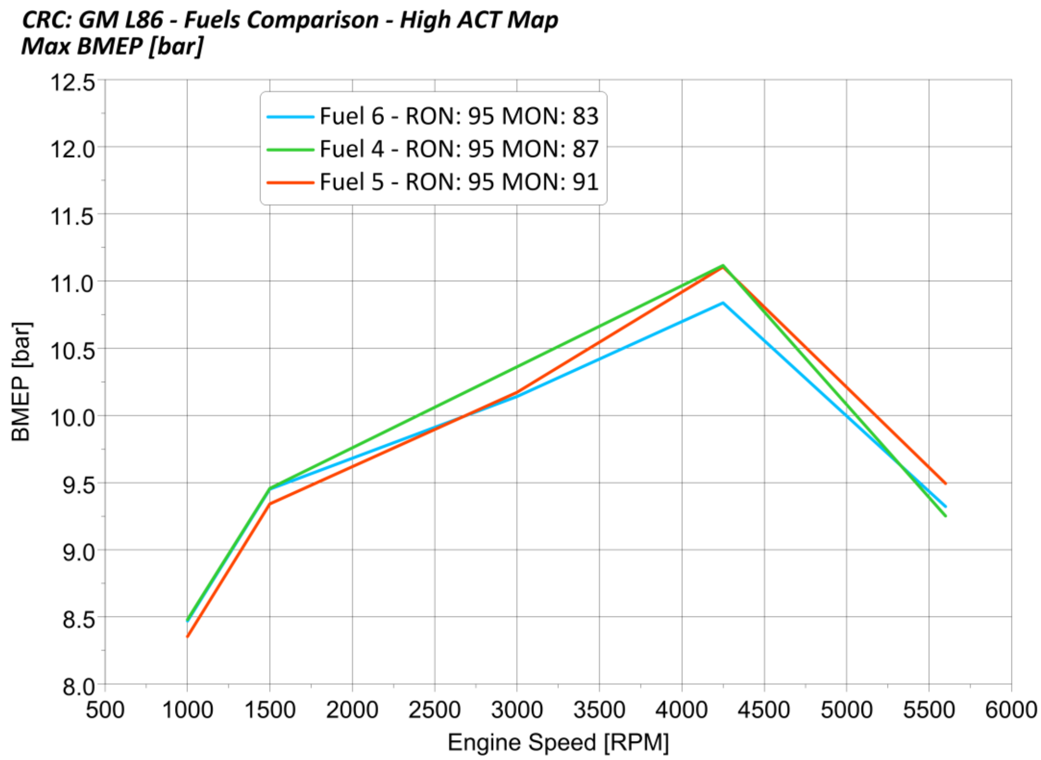

Figure 27: Comparison of the maximum loads achieved at WOT operation, High ACT map.

Figure 28 shows the comparison of fuels for the enrichment at WOT operation. All the fuels can run stoichiometric at 1000 and 1500 RPM, as exhaust temperatures are not a limiting factor. At 3000 RPM, for the fuels with the same RON, as the MON increases the enrichment required at 3000 RPM decreases. For high-speed operation, the enrichment needed by the fuels increases as the MON of the fuel decreases, as seen with fuel 6 running the highest enrichment of all fuels.

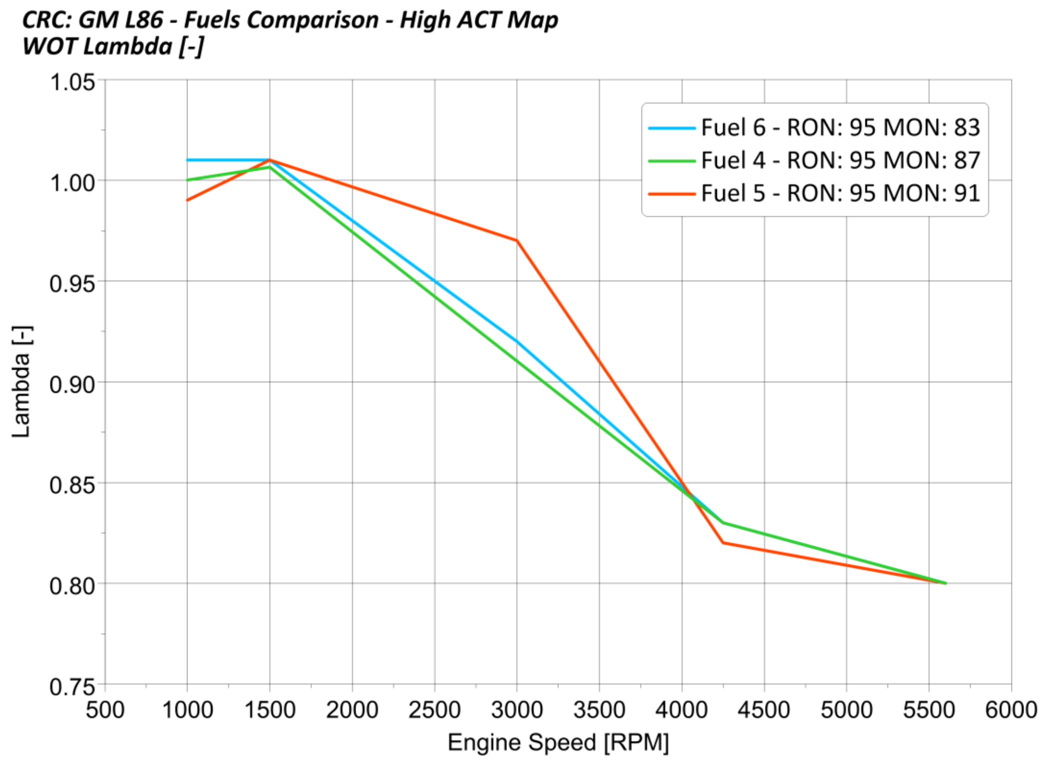

Figure 28: Comparison of the enrichment/lambda at WOT operation, High ACT map.

Figure 29 shows the comparison of fuels for Exhaust Gas Temperature at WOT operation. None of the fuels are limited by exhaust temperatures at low speeds i.e., 1000-1500 RPM. At the high speeds i.e., 4250 and 5600 RPM, all fuels run enrichment to maintain exhaust temperatures within limits, the increase in exhaust gas temperature is due to relative differences in combustion phasing advance or retard.

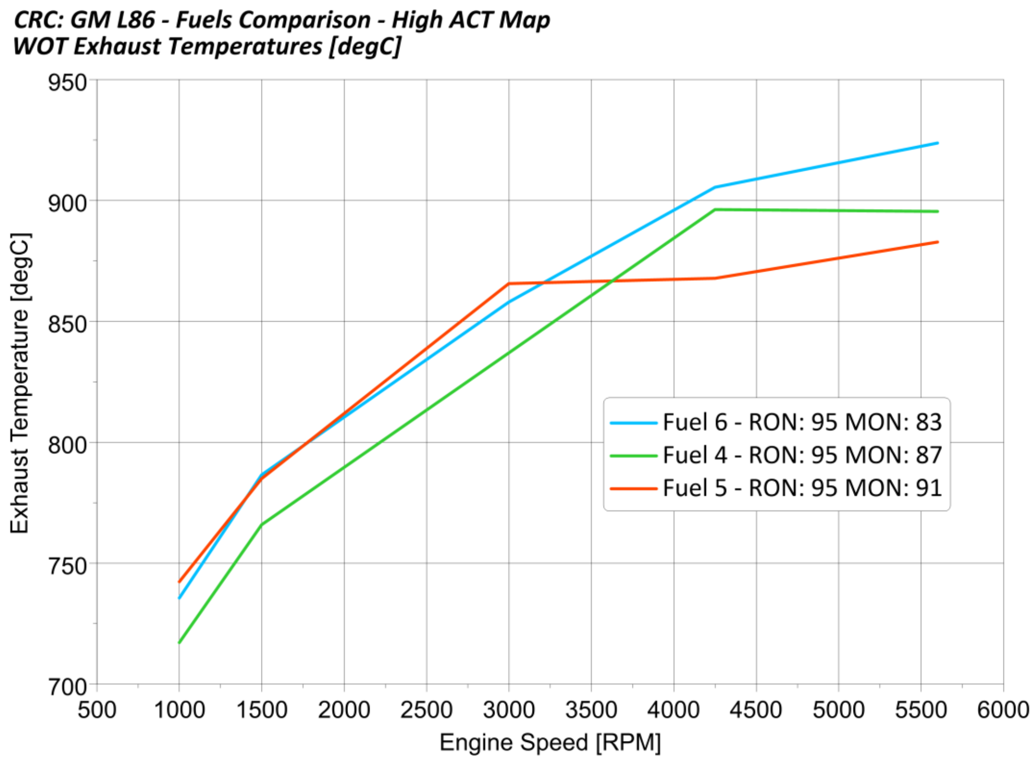

Figure 29: Comparison of exhaust temperatures achieved at WOT operation, High ACT map.

Figure 30 shows the comparison of fuels for the engine average CA50 at WOT operation. At 1000 and 1500 RPM, CA50 is more advanced as the fuel MON decreases, for a constant RON. At 3000 RPM and above the trend of CA50 reverses and the fuels with the higher MON can run a more advanced CA50. Overall, the data shows that at lower speeds, a lower MON fuel can run more advanced, and at higher speeds a higher MON fuel is able to run more advanced.

Overall, it is seen that at High ACT operation, at the lower speeds the lower MON fuels can run a more advanced spark timing, and at the higher speeds the trend reverses and the higher MON fuels are able to run a more advanced spark timing.

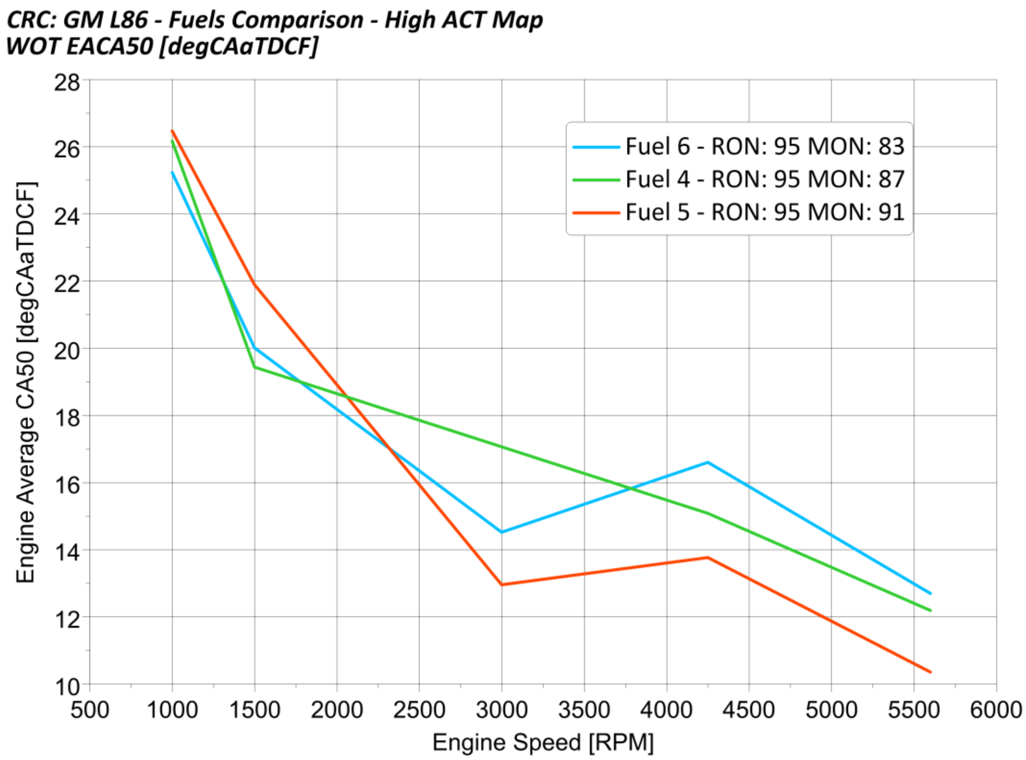

Figure 30: Comparison of engine average CA50 achieved at WOT operation, High ACT map.

b. Ford 7.3L Engine

This section discusses the results of the fuel comparison for the Ford 7.3L engine, performed on fuels 1-4. The Ford 7.3L engine is a Regular Unleaded Gasoline (87 AKI) rated engine and fuels 1-4 reflect this. The fuels have been compared based on spark advance, fuel enrichment and the CA50 for each fuel.

iii. Normal ACT Map

This section analyzes the results of fuels 1-4, on the Ford 7.3L engine, for the Normal ACT map, i.e., engine coolant temperature at 90 °C, engine oil temperature at 90 °C, and manifold air temperature at 25 °C. All the legends in the plots are arranged in increasing order of MON, with the final fuel being the fuel with higher RON. Additional information regarding the knock mapping thresholds crossed at each operating point are listed in Appendix H.

Figure 31: Engine Average CA50 comparison at 1500 RPM, Normal ACT map. shows the comparison between fuels for the engine average CA50, for the load sweep at 1500 RPM. It is seen from the data that all the fuels are CA50 limited until a load of 7 bar, and then show different KLSA limits depending on the fuel. Fuel 4 being a higher RON fuel, as expected performs better the rest of the lower RON fuels. The engine is significantly more sensitive to RON values compared to MON, even more so than the GM L86 engine. As spark advance becomes knock limited both the MON 80 and 83 fuel retard combustion phasing more significantly. However, as

the load reaches closer to WOT operation, all the similar RON fuels seem to converge to a similar operating CA50.

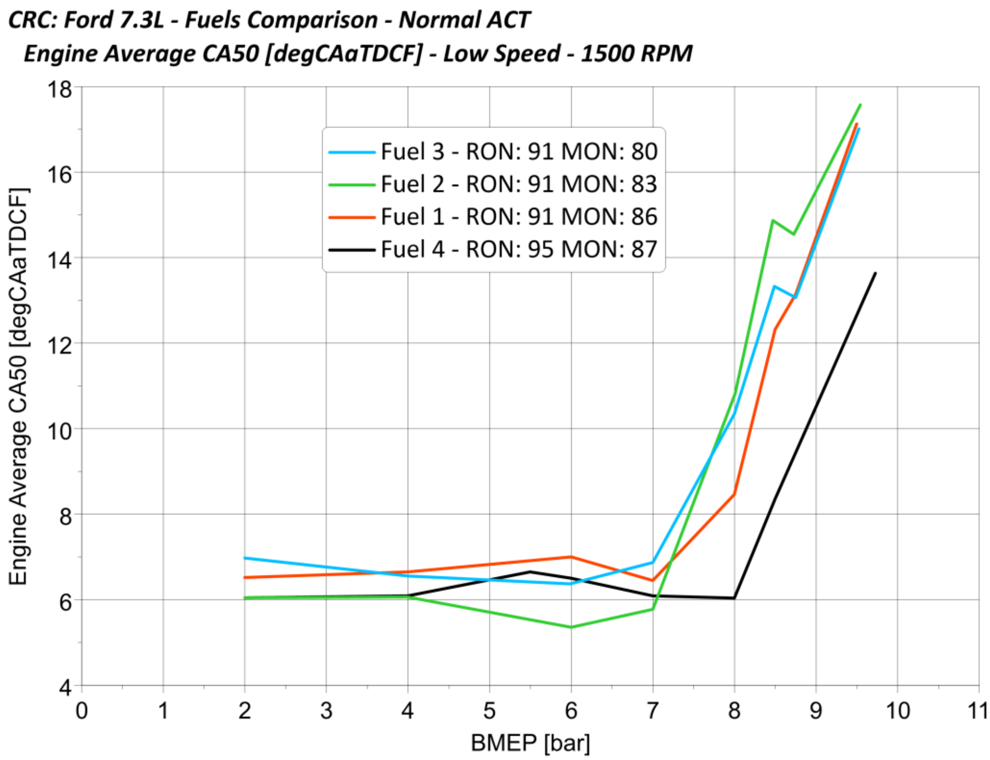

Figure 31: Engine Average CA50 comparison at 1500 RPM, Normal ACT map.

Figure 32 shows the comparison between fuels for the final engine average CA50, for the load sweep at 2250 RPM. It is seen from the data that all the fuels are CA50 limited until a load of 8 bar, and then show different KLSA limits depending on the fuel. Fuel 4 being a higher RON fuel, as expected performs better the rest of the lower RON fuels. The equal RON fuels display similar knock tolerance, as observed at 1500 rpm the engine is more sensitive to RON and changes in MON does not result in significant combustion phasing differences.

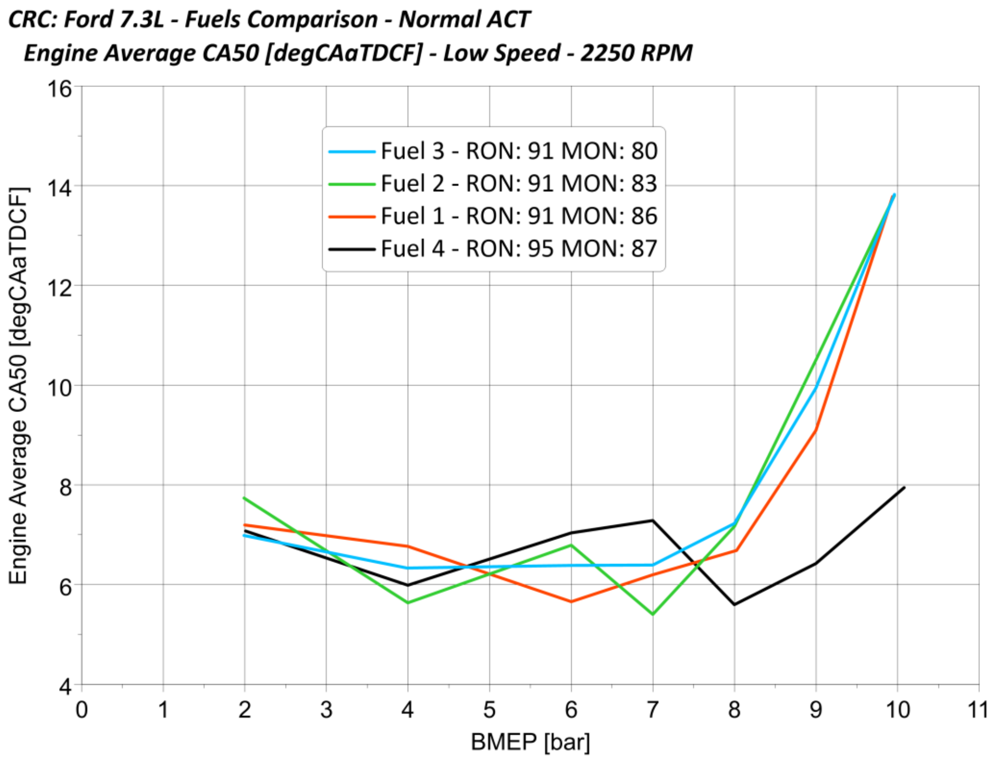

Figure 32: Engine average CA50 comparison at 2250 RPM, Normal ACT map.

Figure 33 and Figure 34 show the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 1500 RPM and 2250 RPM, respectively. It is seen from the data that the exhaust temperatures are not a limiting factor for enrichment for any of the fuels, and all fuels are able to run stoichiometric at all load points. As all fuels run stoichiometric, the minor differences in exhaust temperatures are due to differences in combustion phasing, as different fuels hit knock limits earlier or later, and these trends follow what was seen in the CA50 trends.

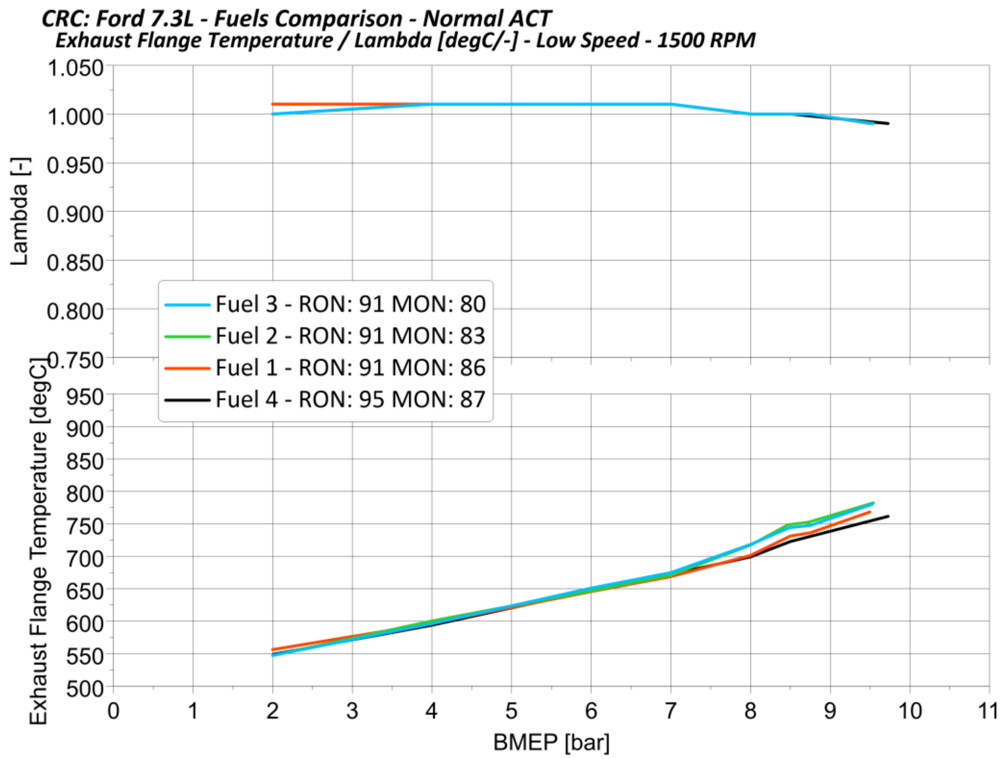

Figure 33: Enrichment and exhaust temperature comparison at 1500 RPM, Normal ACT map.

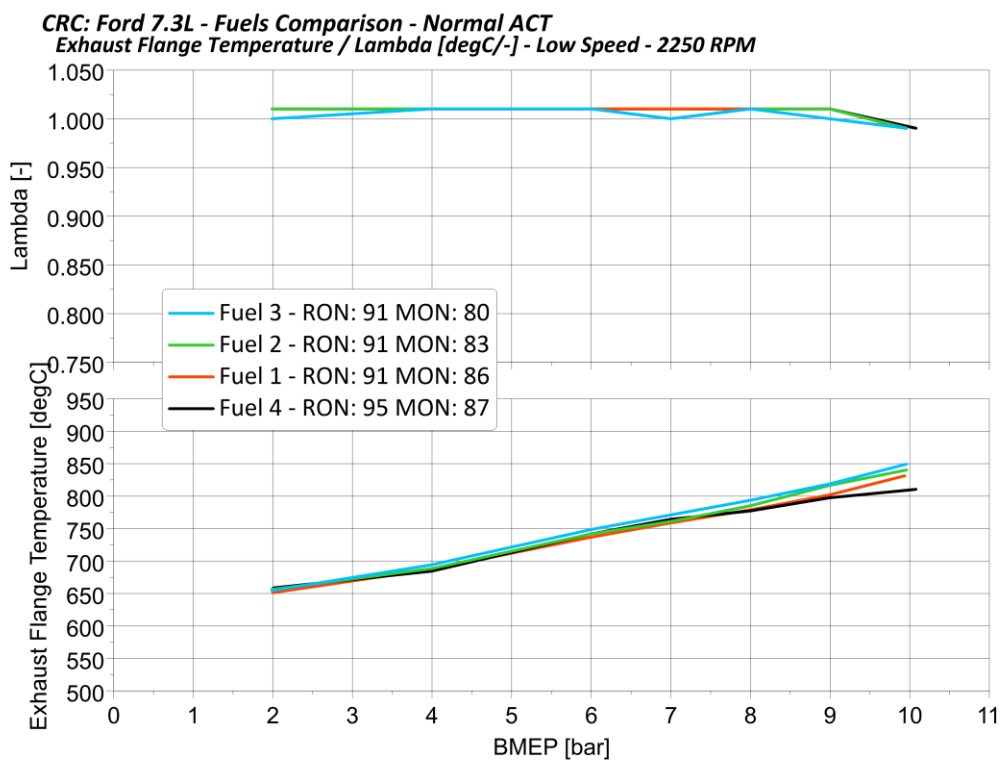

Figure 34: Enrichment and exhaust temperature comparison at 2250 RPM, Normal ACT map.

Figure 35 shows the comparison between fuels for the engine average CA50, for the load sweep at 3900 RPM. It is seen from the data that the CA50 is more advanced with an increasing MON, and fuel 4 being the higher RON fuel runs more advanced than all the other fuels. Fuels with increased AKI values and lower S values have better knock tolerance and improved combustion phasing at these operating points. All the higher load points at 3900 RPM ran enriched to maintain the exhaust temperatures within the limits, and hence the CA50 is affected by both spark timing and enrichment at those loads.

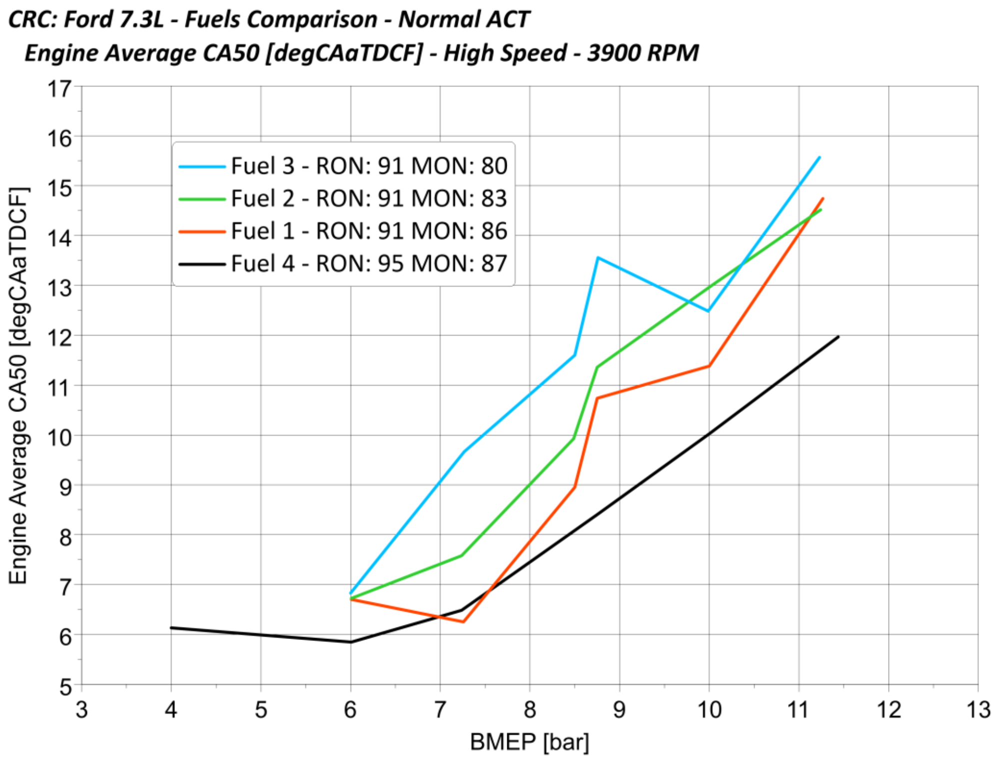

Figure 35: Engine average CA50 comparison at 3900 RPM, Normal ACT map.

Figure 36 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 3900 RPM. It is seen from the data that for fuels 4 and 1, little to no enrichment is required up to a load of 7.5 bar BMEP, and as the load increases more enrichment is required to maintain exhaust temperature limits. For fuels 3 and 2, little to no enrichment is required at 6 bar BMEP, but as the load increases above that more enrichment is required to maintain exhaust temperatures. Fuels 1 and 4 tend to run similar enrichment at the different load points, with fuels 2 and 3 requiring increasing amounts of enrichment. Based on the data a trend of increasing enrichment with decreasing MON is seen, which follows the trends seen in the CA50 data.

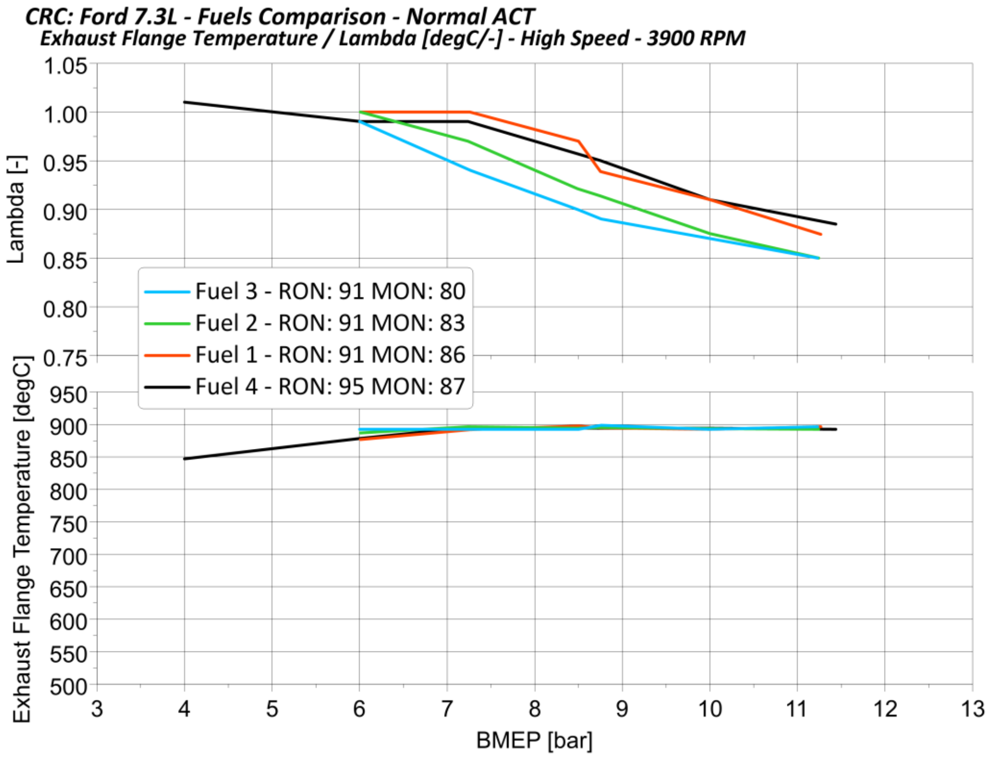

Figure 36: Enrichment and exhaust temperature comparison at 3900 RPM, Normal ACT map.

Figure 37 shows the comparison between fuels for the final engine average CA50, for the load sweep at 4500 RPM. It is seen from the data that the CA50 is more advanced with an increasing MON, and fuel 4 being the higher RON fuel runs more advanced than all the other fuels, at the WOT operating points all the lower RON fuels almost converge to a similar operating condition. At 4500 RPM, all the fuels run enriched at 6 bar BMEP and above to maintain the exhaust temperatures within limits, and hence the CA50 is affected by a combination of spark timing and enrichment.

Figure 38 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 4500 RPM. It is seen from the data that fuels 1 and 4 run similar amounts of enrichment up to 9 bar, with fuel 1 running slightly higher enrichment at high loads, where it starts deviating from fuel 4 in knock limits, needing a more retarded spark timing. Fuels 2 and 3 run higher enrichment than fuels 1 and 4, with fuel 3 requiring slightly higher enrichment than fuel 2, and this also evidenced in the slightly retarded CA50 of fuel 3 compared to fuel 2. Overall, it is seen that the enrichment requirement increases with a decreasing MON due to more retarded ignition timing.

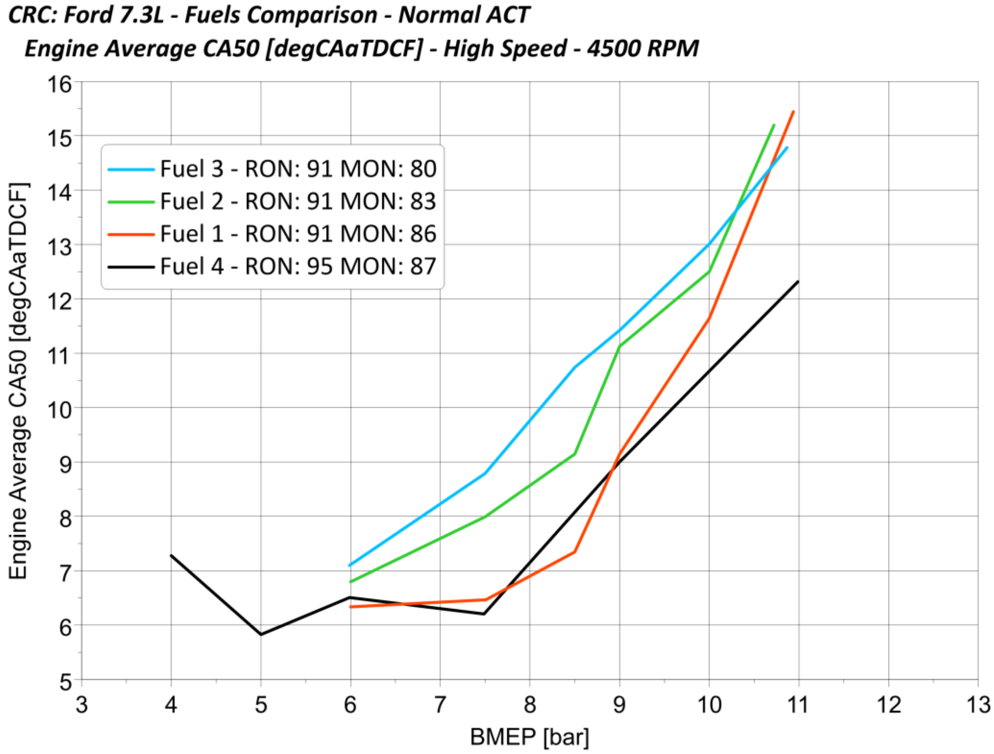

Figure 37: Engine average CA50 comparison at 4500 RPM, Normal ACT map.

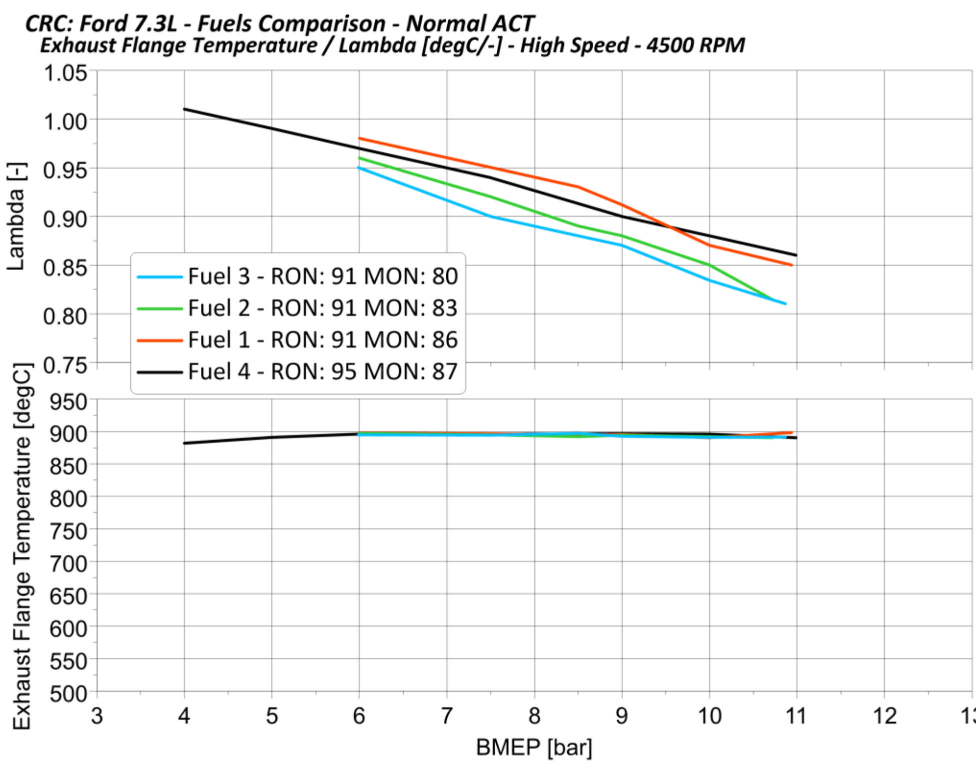

Figure 38: Enrichment and exhaust temperature comparison at 4500 RPM, Normal ACT map.

Figure 39 shows the comparison of fuels for the maximum load achieved at WOT operation. Added points were run at 1000 RPM and 3000 RPM for the WOT operation. At all speeds, the higher RON fuel i.e., fuel 4 can achieve a higher load, owing to its higher knock resistance. Also, a small change in RON (95 vs. 91 RON) has a larger effect on WOT load than a large change in MON (86 vs. 80 MON). For fuels to 1-3, fuel 1 achieves a lower peak load at 1000 RPM, but the differences at other speeds are minor. At 3000 RPM, fuel 3 achieves a lower load compared to the other fuels, but the peak loads then converge at 3900 RPM for fuels 1-3. The peak loads have a bigger separation at 4500 RPM, where fuel 1 achieves a higher load compared to fuel 3, with fuel 2 achieving the lowest peak load.

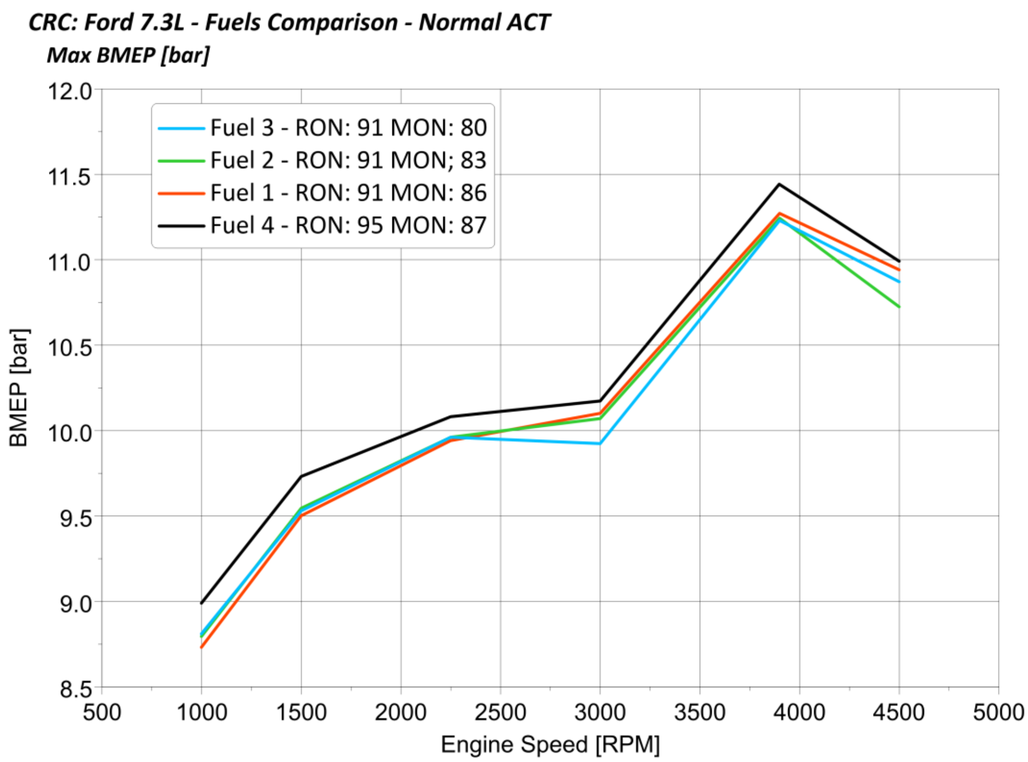

Figure 39: Comparison of max loads achieved at WOT operation, Normal ACT map.

Figure 40 and Figure 41 show the comparison of fuels for the maximum exhaust temperatures and enrichment seen at WOT operation, respectively. Up to 2250 RPM, all fuels can run stoichiometric without exceeding exhaust temperature limits. At 3900 and 4500 RPM, all fuels run enriched with the engine operating at the exhaust temperature limit. Up to 3000 RPM, fuel 4 owing to a higher RON and better knock resistance runs lower exhaust temperatures due to a more advanced spark timing. Up to 3000 RPM, fuel 3 runs slightly hotter than the other fuels, and this is especially apparent at 3000 RPM, where the differences between the fuels are more pronounced, the data suggests that a higher MON fuel results in comparatively advanced combustion phasing and therefore decreased need for enrichment.

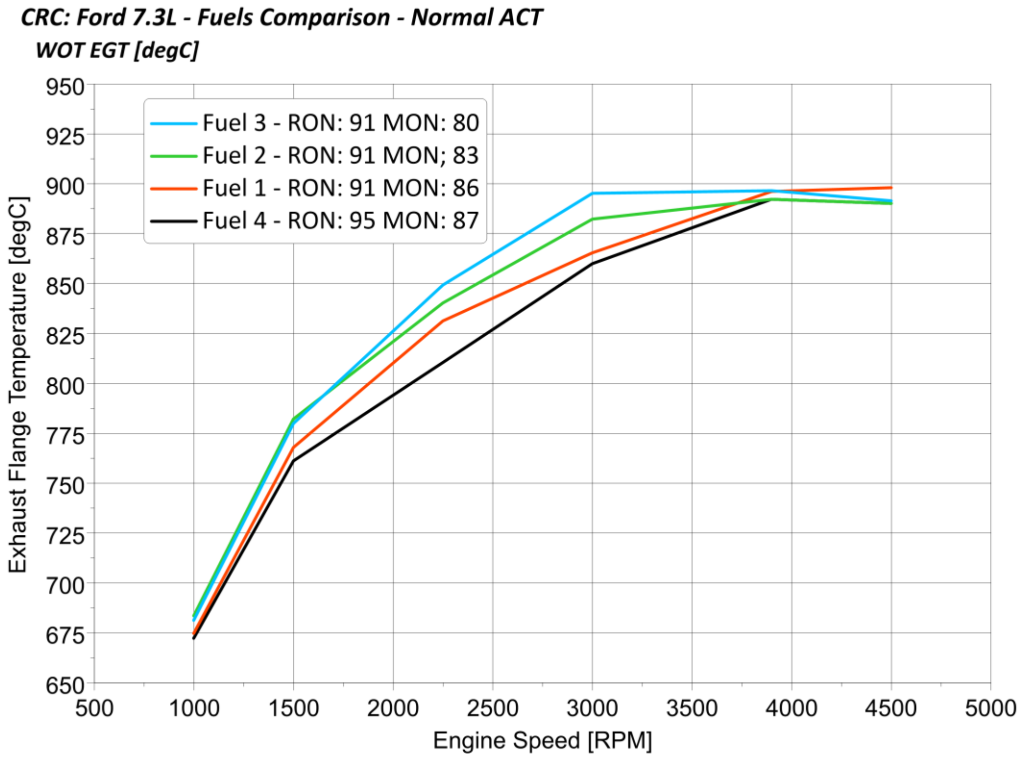

Figure 40: Comparison of maximum exhaust temperatures achieved at WOT operation, Normal ACT map.

Figure 41 shows the comparison of fuels for enrichment at WOT operation. All fuels can run stoichiometric up to 2250 RPM while maintaining exhaust temperatures. Above 2250 RPM, fuel 3 runs slightly higher enrichment owing to a more retarded spark timing, where fuels 1, 2 and 4 can run stoichiometric up to 3000 RPM. At 3900 and 4500 RPM all fuels run some enrichment, with fuel 4 running the least enrichment owing to higher RON and knock resistance. Fuels 2 and 3, converge and run similar enrichment at 3900 and 4500 RPM. Fuel 1 runs slightly higher enrichment than fuel 4, owing to a comparable knock resistance to fuel 4.

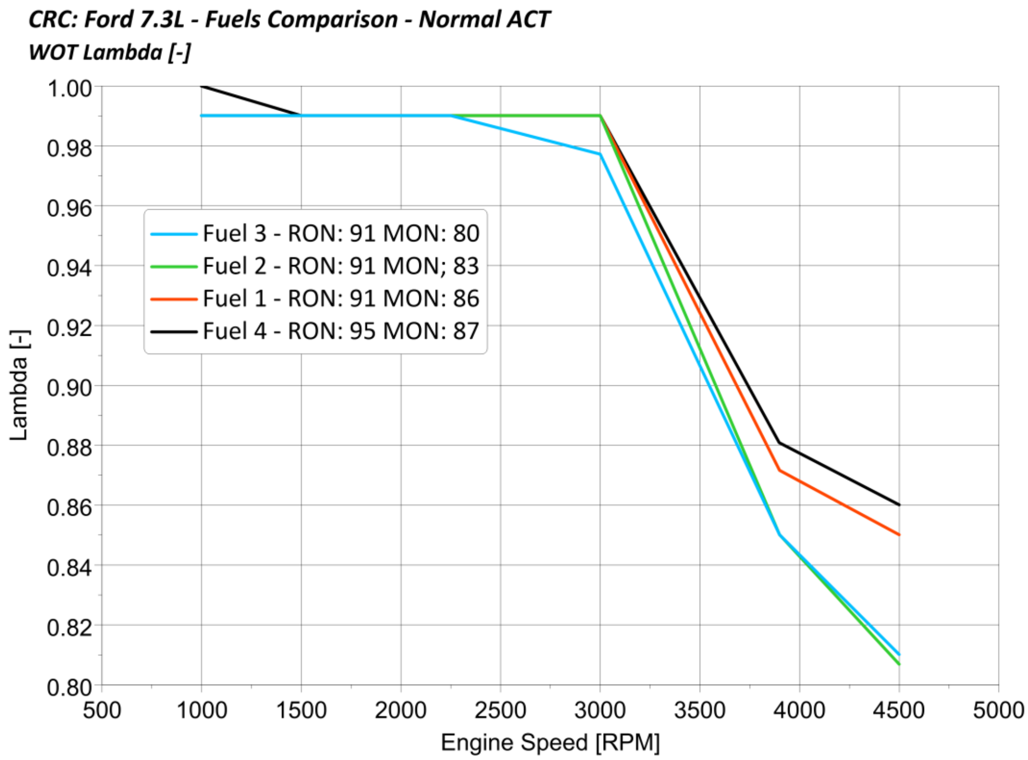

Figure 41: Comparison of enrichment/lambda at WOT operation, Normal ACT map.

Figure 42 shows the engine average CA50 achieved at WOT operation. Fuel 4 owing to higher RON and better knock performance, can run a more advanced CA50, by up to 6 degrees, compared to the lower RON fuels. For the lower RON fuels, Fuel 1 runs a slightly retarded CA50 at 100 RPM, but fuels 1-3 run similar CA50s at 1500 and 2250 RPM. The biggest difference in CA50s is seen at 3000 RPM, where a lower MON equates to a more retarded CA50. The differences in CA50 are less pronounced at 3900 and 4500 RPM, with the lower RON fuels running similar CA50s. Again, a small change in RON affects CA50 more than a large change in MON.

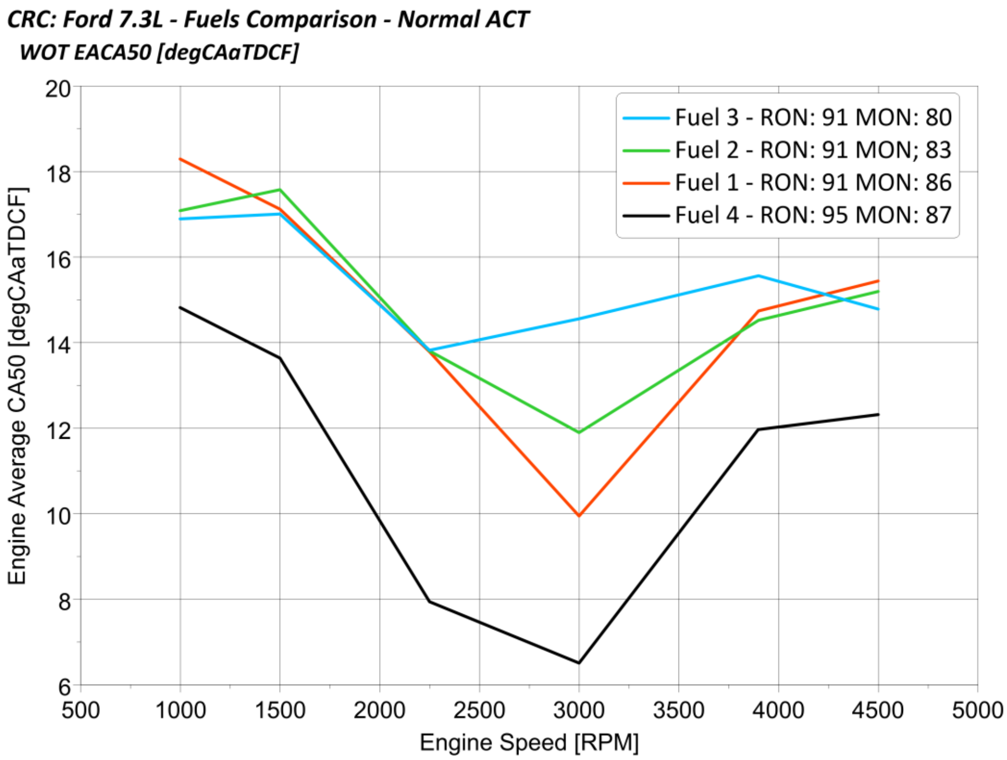

Figure 42: Comparison of engine average CA50 achieved at WOT operation, Normal ACT map.

iv. High ACT Map

This section details the results on fuels 1-4 on the Ford 7.3L engine, for the High ACT map, i.e., engine coolant temperature at 115 °C, engine oil temperature at 115 °C, and manifold air temperature at 45 °C. Additional information regarding the knock mapping thresholds crossed at each operating point are listed in Appendix I.

Figure 43 shows the comparison between fuels for the final engine average CA50, for the load sweep at 1500 RPM. Fuel 4 being a higher RON fuel, as expected performs better than the rest of the lower RON fuels. It is seen from the data fuel 1 is CA50 limited up to a load of 6 bar BMEP, and then becomes increasingly knock limited at higher loads, as evidenced by the retarded CA50. Fuels 2 and 3 are knock limited beginning at 6 bar BMEP and are increasingly knock limited at higher loads. It is seen that at mid loads, a decreasing MON leads to a more retarded CA50, but as the load increases the fuels converge, and then near WOT operation a lower MON leads to a more advanced CA50. At high ACT and 1500 RPM, a small change in RON affects CA50 dramatically more than a large change in MON.

Figure 44 shows the comparison between fuels for the final engine average CA50, for the load sweep at 2250 RPM. It is seen from the data that fuel 4 being a higher RON, performs better than the rest of the fuels. Fuel 1, with the highest MON of the similar RON fuels can run a more advanced CA50 compared to the rest of the fuels at all operating points. Fuels 2 and 3 run similar

CA50s at the different load points, with fuel 3 running slightly retarded compared to 2, and as the load moves closer to WOT operation, both fuels converge towards similar operation.

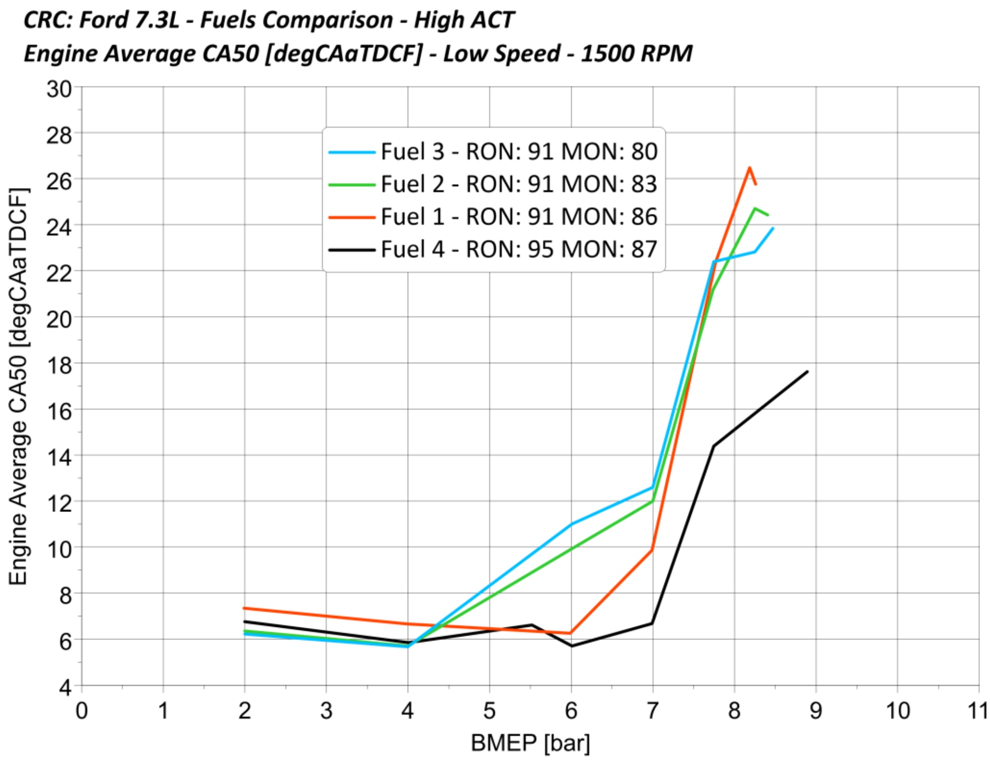

Figure 43: Engine Average CA50 comparison at 1500 RPM, High ACT map.

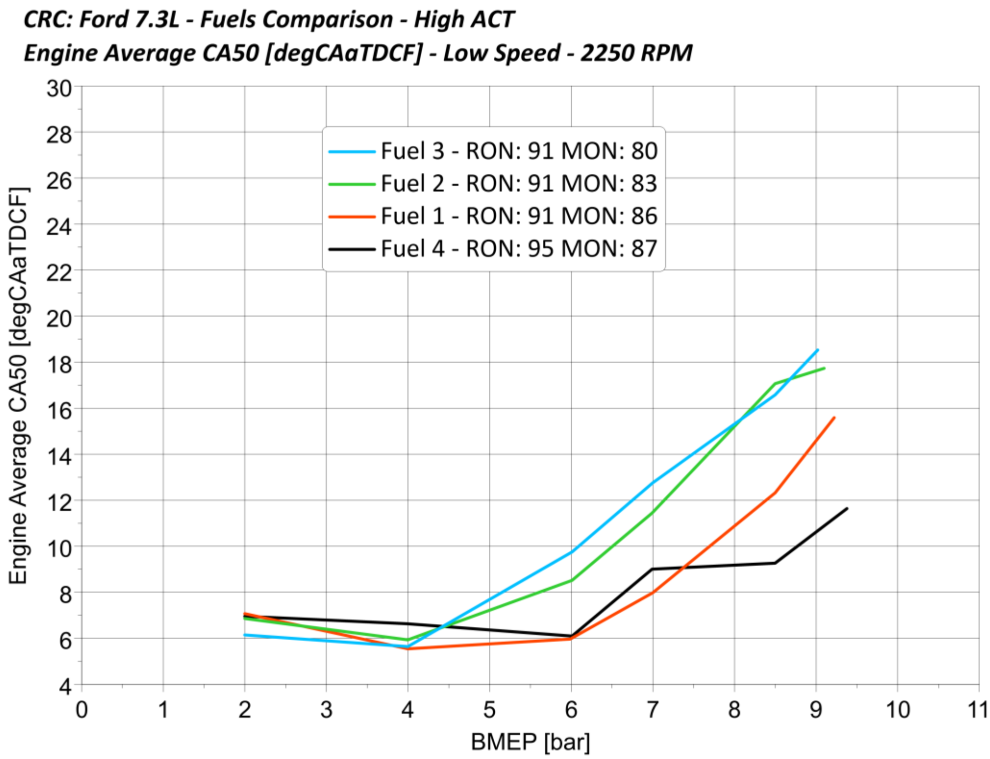

Figure 44: Engine average CA50 comparison at 2250 RPM, High ACT map.

Figure 45 and Figure 46 show the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 1500 RPM and 2250 RPM, respectively. It is seen from the data that the exhaust temperatures are not a limiting factor for enrichment, for any of the fuels, and all fuels are able to run stoichiometric at load points. As all fuels run stoichiometric, the minor differences in exhaust temperatures are due to differences in combustion phasing, as different fuels hit knock limits earlier or later, and these trends follow what was seen in the CA50 trends.

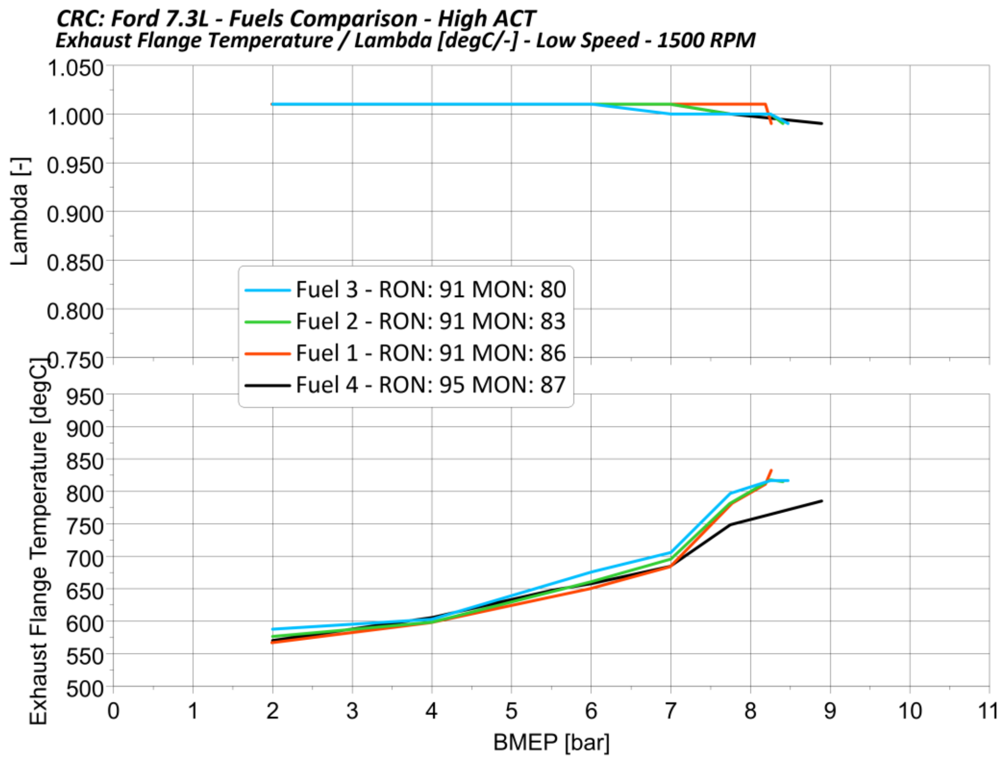

Figure 45: Enrichment and exhaust temperature comparison at 1500 RPM, High ACT map.

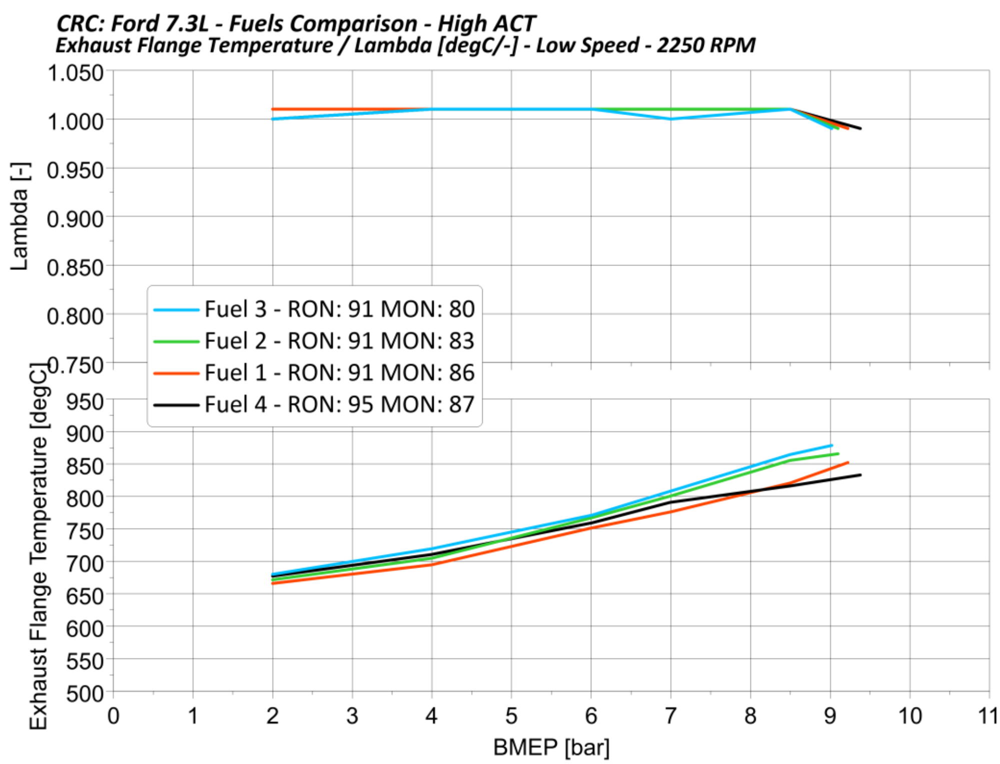

Figure 46: Enrichment and exhaust temperature comparison at 2250 RPM, High ACT map.

Figure 47 shows the comparison between fuels for the final engine average CA50, for the load sweep at 3900 RPM. The legend in the figure is arranged in increasing order of MON, with the final fuel being the higher RON fuel. It is seen from the data that the higher RON fuel i.e., fuel 4, runs the most advanced CA50 compared to the other lower RON fuels. For the fuels with a similar RON, fuel 3 seems to lie between fuel 2 and fuel 1, with fuel 2 running the most retarded CA50 out of all the fuels. At higher loads, fuel 2 and 3 converge to a similar operating CA50. All the high load points at 3900 RPM require enrichment to maintain exhaust temperatures within limits, so the CA50 is affected both by enrichment and spark timing. Again, a small change in RON generally has larger effects on CA50 than a large change in MON.

Figure 48 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 3900 RPM. It is seen from the data that for fuels 4 and 1, little to no enrichment is needed up to a load of 6 bar BMEP, and as the load increases more enrichment is required to maintain exhaust temperature limits. For fuels 3 and 2, all the operating loads require enrichment to maintain exhaust temperatures. Fuels 1 and 4 tend to run similar enrichment to each other, with increasing enrichment required at higher loads. Fuels 2 and 3 run similar enrichment to each other, and run higher enrichment compared to fuels 1 and 4. The trend in enrichment requirement follows the trend seen with CA50 for the different fuels. In general, the higher MON fuel can run lower enrichment at the same operating load.

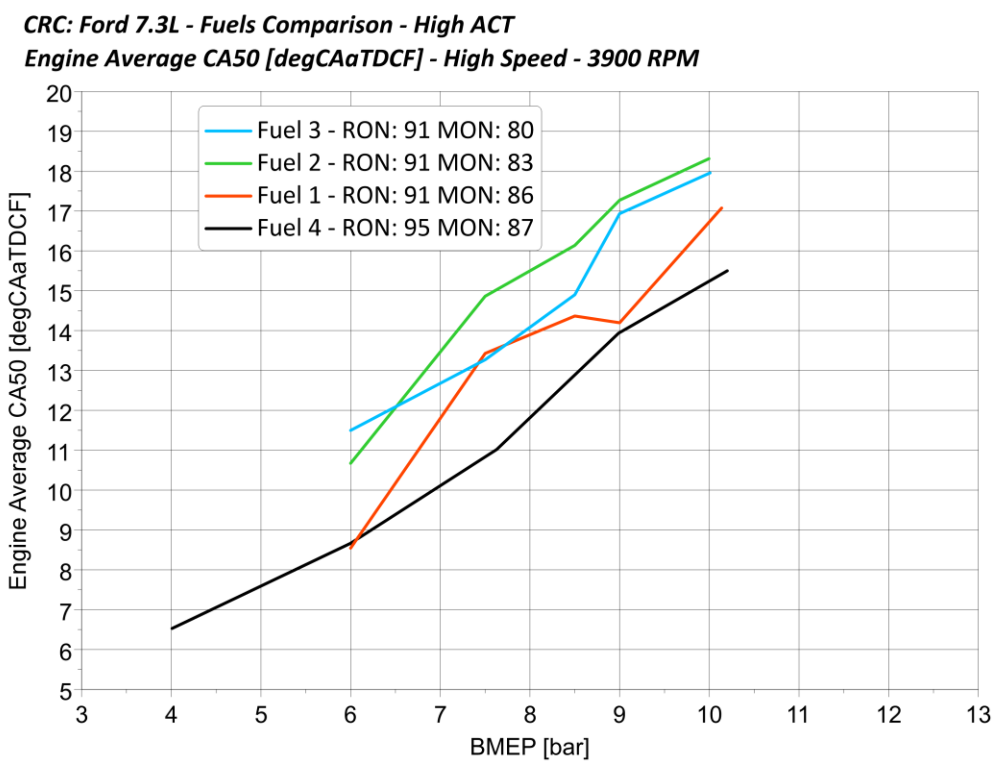

Figure 47: Engine average CA50 comparison at 3900 RPM, High ACT map.

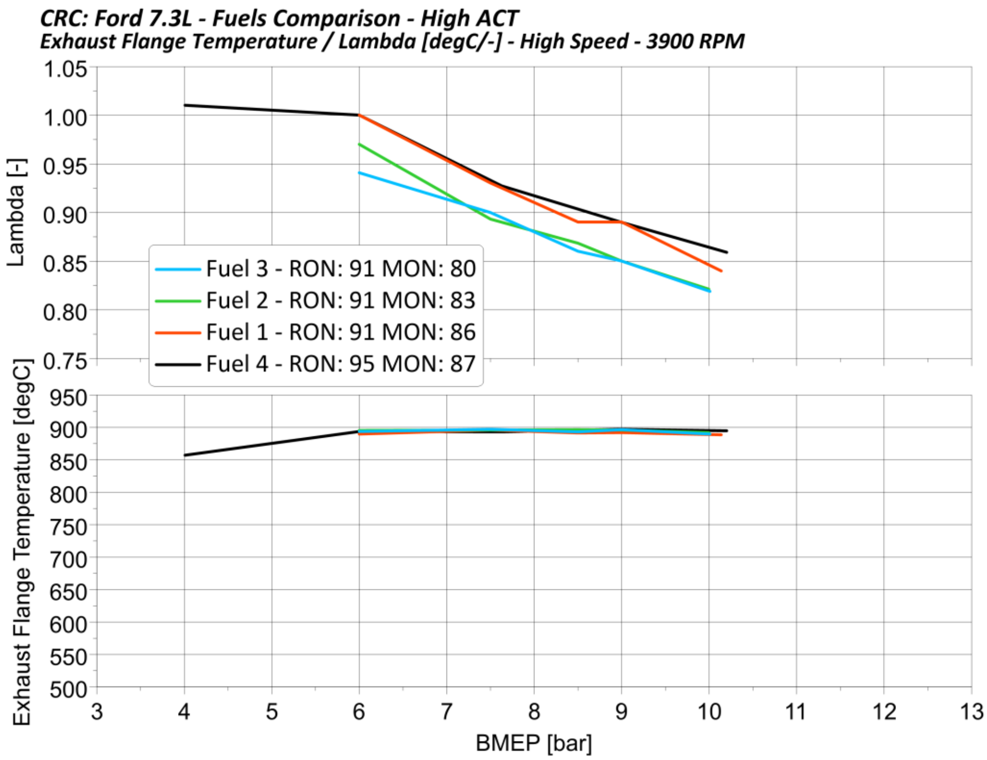

Figure 48: Enrichment and exhaust temperature comparison at 3900 RPM, High ACT map.

Figure 49 shows the comparison between fuels for the final engine average CA50, for the load sweep at 4500 RPM. The legend in the figure is arranged in increasing order of MON, with the final fuel being the higher RON fuel. It is seen from the data that the CA50 is more advanced with an increasing MON, and fuel 4 being the higher RON fuel runs more advanced than all the other fuels, at the WOT operating points fuels 2 and 3 converge to a similar operating CA50. At 4500 RPM, all the fuels run enriched at 5 bar BMEP and above to maintain the exhaust temperatures within limits, and hence the CA50 is affected by a combination of spark timing and enrichment. At this condition, a small change in RON has similar effects to a large change in MON.

Figure 50 shows the comparison between fuels for the enrichment and exhaust temperatures, for the load sweep at 4500 RPM. It is seen from the data that fuels 1 and 4 run similar amounts of enrichment throughout the load sweep, which follows the trends seen for CA50 between these fuels. Fuel 3 runs the highest enrichment of all the fuels, with fuel 2 running the next highest enrichment. Overall, at 4500 RPM the higher MON fuels can run lower enrichment at the same operating load.

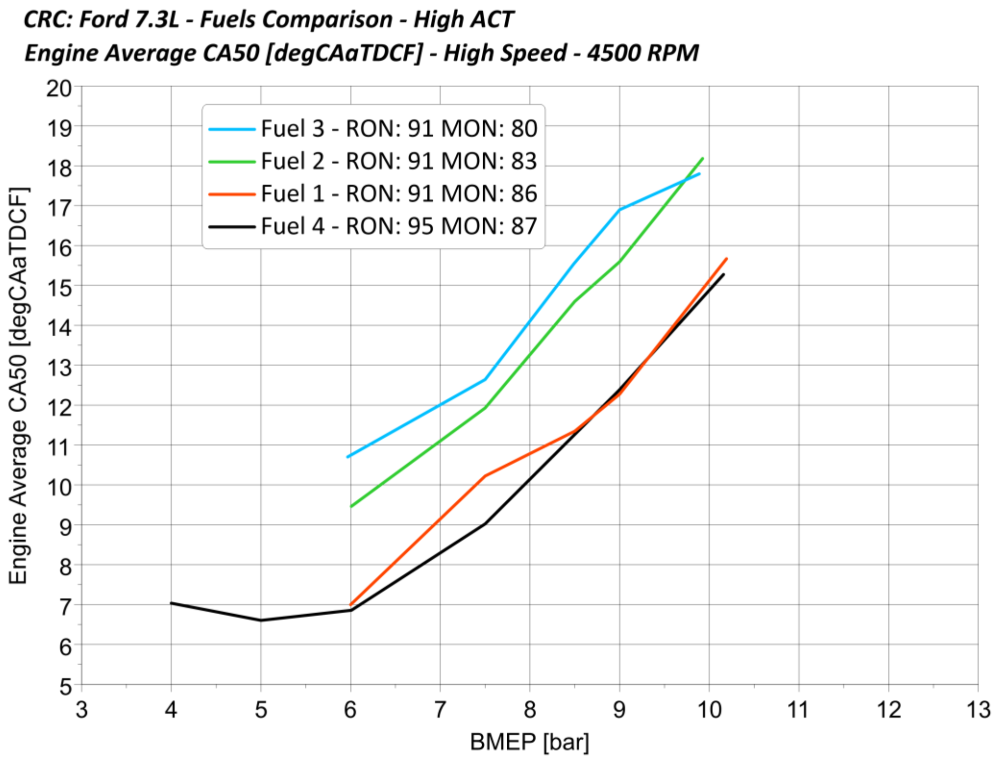

Figure 49: Engine average CA50 comparison at 4500 RPM, High ACT map.

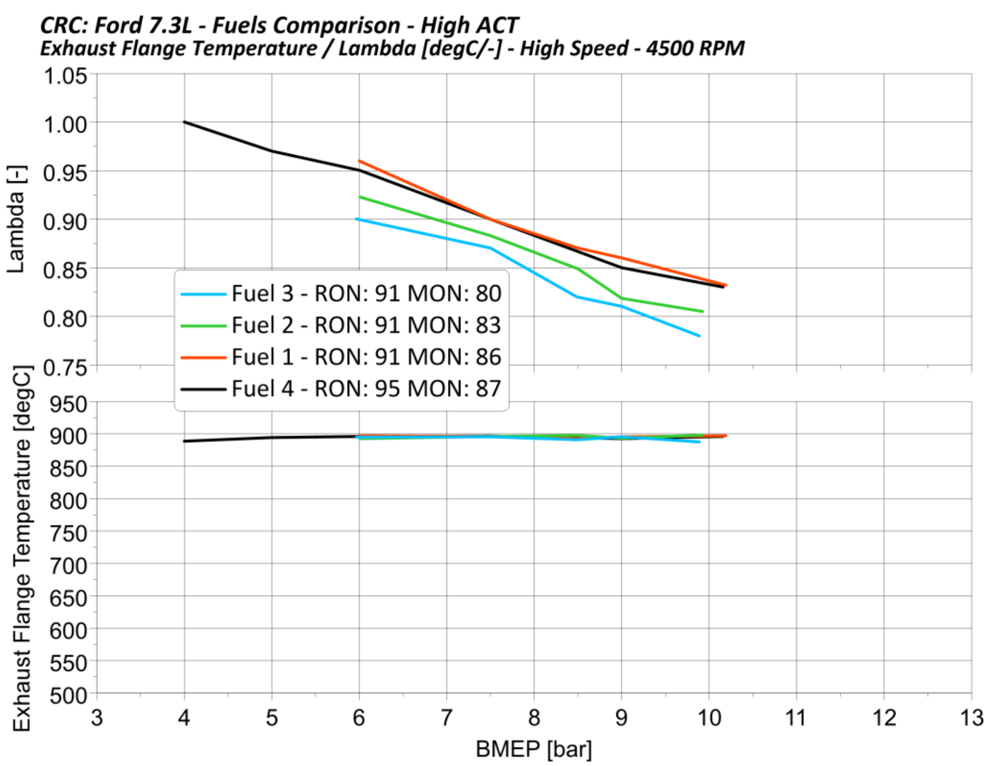

Figure 50: Enrichment and exhaust temperature comparison at 4500 RPM, High ACT map.

Figure 51 shows the comparison of fuels for the maximum load achieved at WOT operation. Added points were run at 1000 RPM and 3000 RPM for the WOT operation. At lower speeds fuel 4 owing to a higher RON and better knock resistance can run higher loads at WOT operation. At 1000 and 1500 RPM, it is seen that fuels with lower MON can run higher peak loads, but this trend reverses at 2000 RPM, where a lower MON equates to a lower peak load. All fuels run similar loads at 3000 RPM, at 3900 and 4500 RPM, fuel 4 and fuel 1 run very similar peak loads, while fuels 2 and 3 run very similar peak loads. A small change in RON (91 vs. 95 RON) has equal or larger effects on WOT load as a large change in MON (80 vs. 86 MON).

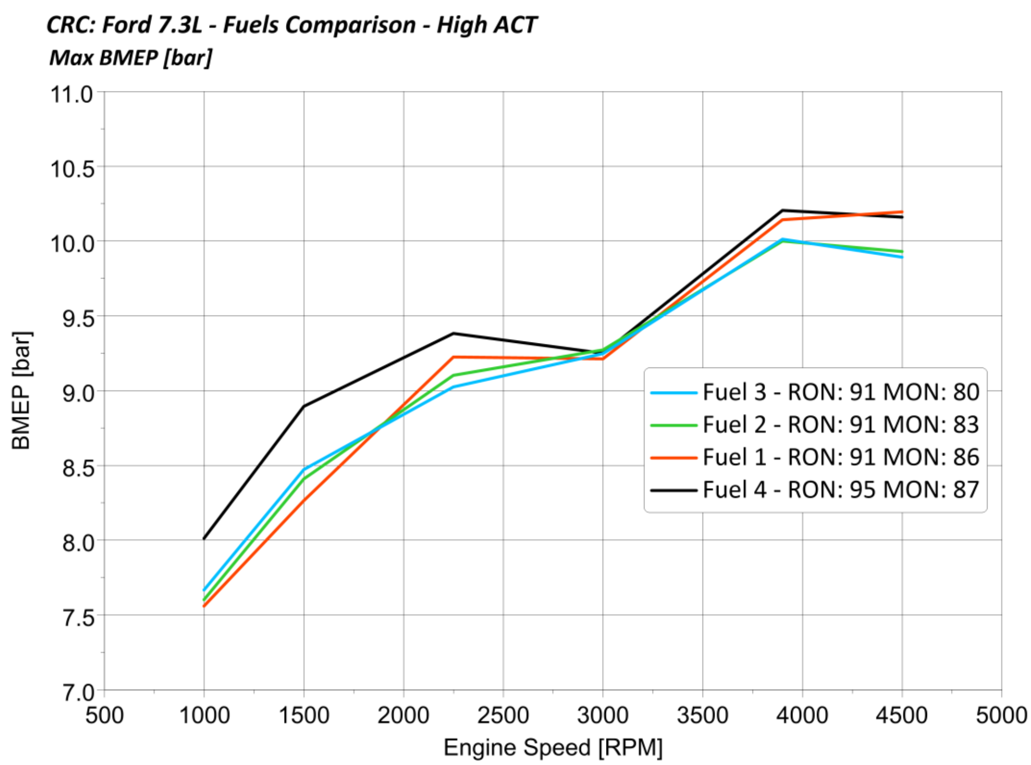

Figure 51: Comparison of max loads achieved at WOT operation, High ACT map.

Figure 52 shows the comparison of fuels for the maximum exhaust temperatures seen at WOT operation. Up to 2250 RPM, all fuels can run stoichiometric without exceeding exhaust temperature limits. All fuels run enriched from 3000 RPM and above to maintain exhaust temperatures within limits, hence the exhaust temperatures are similar for all fuels. From 1000 to 2250 RPM, fuel 4 owing to higher RON and better knock resistance can run a more advanced timing, and hence runs lower exhaust temperatures compared to other fuels. For the lower MON fuels, at 1000 and 1500 RPM fuel 1 runs slightly higher exhaust temperatures and then switches to lower exhaust temperatures at 2250 RPM, this trend follows what was seen with the CA50 data.

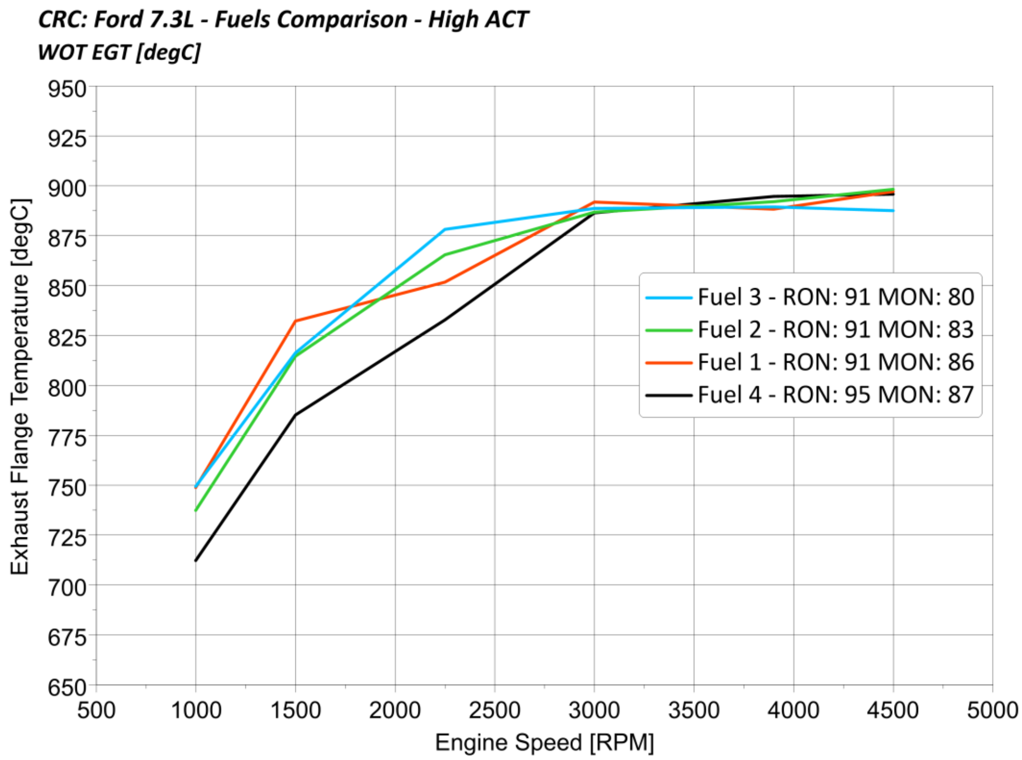

Figure 52: Comparison of maximum exhaust temperatures achieved at WOT operation, High ACT map.

Figure 53 shows the comparison of fuels for the enrichment at WOT operation. All fuels can run stoichiometric up to 2250 RPM while maintaining exhaust temperatures. Above 2250 RPM all fuels run some amount of enrichment to maintain exhaust temperatures within limits. At higher speeds, fuel 4 owing to higher RON and better knock resistance can run an advanced spark timing, and hence a reduced enrichment compared to other fuels. Fuel 1 runs slightly higher enrichment compared to fuel 4, but runs lower enrichment compared to fuels 2 and 3. Fuels 2 and 3 run nearly identical enrichment at 3000 and 3900 RPM, and at 4500 RPM fuel 3 runs with slightly higher enrichment.

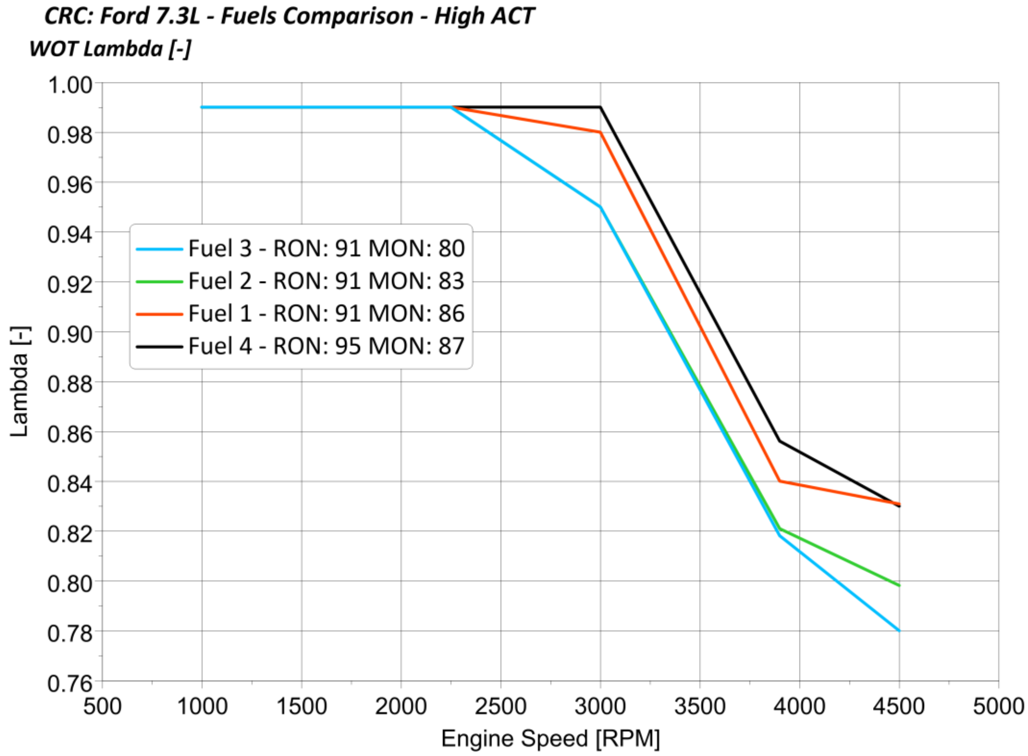

Figure 53: Comparison of enrichment/lambda at WOT operation, High ACT map.

Figure 54 shows the engine average CA50 achieved at WOT operation. Fuel 4 owing to higher RON and better knock performance, can run a much more advanced CA50 compared to the lower RON fuels. For the lower RON fuels, Fuel 1 runs a slightly retarded CA50 at 1000 and 1500 RPM but runs a more advanced CA50 from 2250 to 4500 RPM. Fuels 2 and 3 generally run very similar CA50s compared to each other at all the speeds for WOT operation.

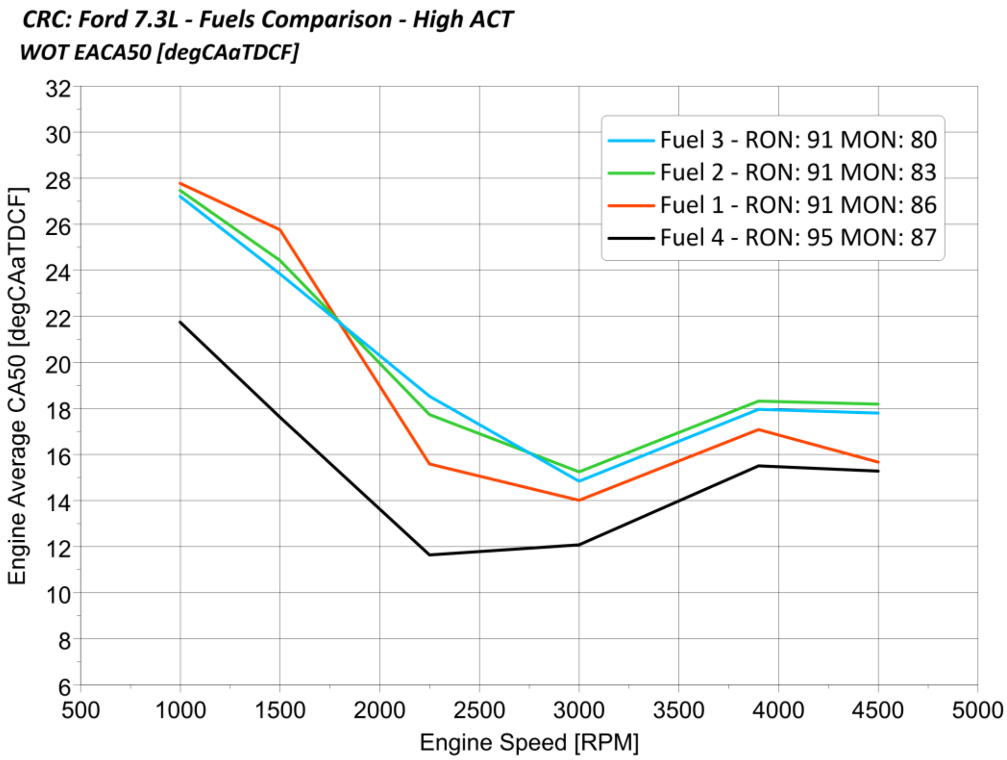

Figure 54: Comparison of engine average CA50 achieved at WOT operation, High ACT map.

Conclusions

Testing was performed on the GM L86 and the Ford 7.3L engines. The GM L86 engine operates with premium fuel and is a naturally aspirated 6.2L V8 engine. The Ford 7.3L operates with regular fuel and is a naturally aspirated 7.3L V8 engine. Further specifications for the engines are provided in Table 1. The GM L86 engine was tested at operating points listed in Table 4 and Table 5, and the Ford 7.3L engine was tested at the operating points listed in Table 6 and Table 7. Engine average CA50 via spark timing, enrichment and exhaust temperatures were used as the main variables to compare the knock resistance of the fuels under each operating conditions.

- For both the GM L86 and Ford 7.3L engine, a higher RON fuel always exhibits superior knock tolerance and engine performance, relative to the lower RON fuels. The knock resistance improvement gained from a smaller spread in RON (GM L86: 95 to 98; Ford 7.3L: 91 to 95) is more pronounced than the gain with an increase in MON (GM L86: 83 to 91; Ford 7.3L: 80 to 86).
- Irrespective of engine, for a fixed RON, at mid-high engine speeds higher MON values led to improved knock resistance and engine performance for both Normal and High Air Charge Temperature (ACT). Operation at low engine speeds was more sensitive to the impact of MON with the GM engine, favoring decreased MON. The Ford engine showed little effect of MON in terms of knock tolerance and engine performance. These trends at low engine speed applied to both Normal and High ACT.
- For all the fuels and knock limited operating conditions, as expected increased Air Charge Temperature (ACT) had a significant impact on knock resistance. For example, at 1500 rpm on the GM engine, knock limited spark advance lowers the peak BMEP from approximately 7.75 bar to 7 bar due to the increase in ACT and engine operating temperatures. At 1500 rpm with the Ford engine, the knock limited spark advance lowered the peak BMEP from 7 bar to 6 bar BMEP with increased ACT.
- Notably at 1500 rpm, the GM engine had improved knock tolerance with fuels that had decreased MON values (higher S value). As engine speed increased to over 3000 RPM, an inflection point occurred and fuels with increased MON values were more resistant to knock. These trends apply to both Normal and High ACT.
- The Ford engine which runs on regular grade fuel was not significantly sensitive to MON at low engine speed. This is different from the GM engine which was tested with premium grade fuel. As engine speed increased for both GM and Ford engines at Normal and High ACT, a general trend emerged where knock resistance improved as MON increased.
- For the GM L86 engine, at Normal ACT and High ACT operating conditions, a higher MON fuel improved knock resistance at higher speed operation i.e., 3000 RPM and above.
- For the Ford 7.3L engine, at Normal ACT operating conditions, a higher MON fuel improved knock resistance at higher speed operation i.e., 3000 RPM and above.
- For the Ford 7.3L engine, at High ACT operating conditions, a higher MON fuel improved knock resistance at higher speed operation i.e., 2250 RPM and above.

- For both engines at high speeds and same RON, a higher MON shows better knock resistance, this follows two recent studies conducted on turbocharged engines, Gopujkar (2020) and Zhou (2020), which show a positive correlation of knock resistance to MON at high speed and load operation.

The effects on knock resistance of increasing MON while keeping RON the same is summarized in Table 10, below. In the table, the ↑ symbol indicates improved knock resistance, ↓ indicates worse knock resistance, and ~ indicates no change in knock resistance.

Table 10: Summary of Effects on Knock Resistance of Increasing MON at Constant RON

Engine	Air Charge Temperature (ACT)	Engine Speed (RPM)	Effect on Knock Resistance
GM L86	Normal & High	1000 & 1500	↓
GM L86	Normal & High	3000, 4250 & 5600	↑
Ford 7.3L	Normal & High	1000 & 1500	~
Ford 7.3L	Normal	2250	~
Ford 7.3L	High	2250	↑
Ford 7.3L	Normal & High	3000, 3900 & 4500	↑

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Appendix

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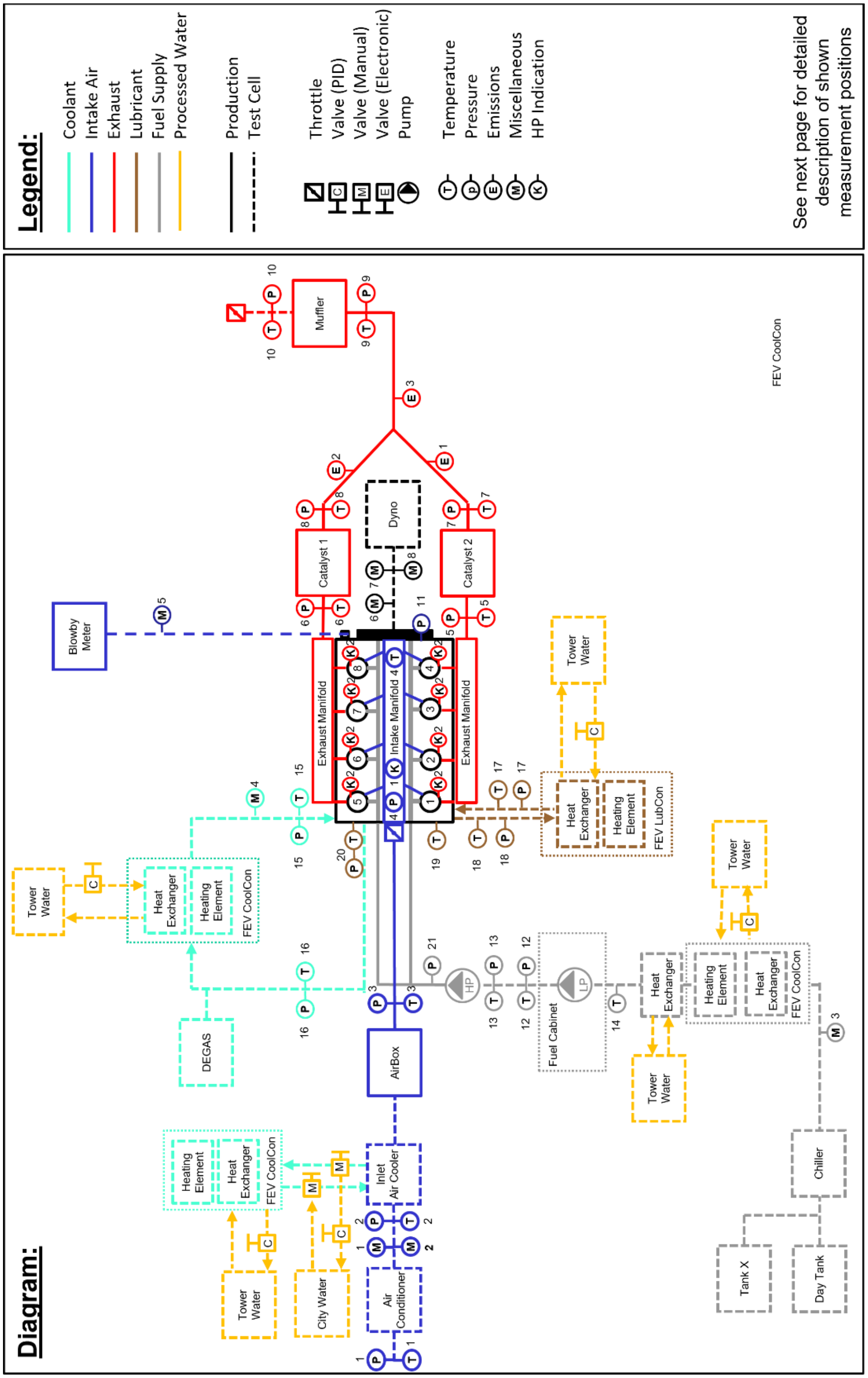
Appendix A. GM L86 Test Cell Layout

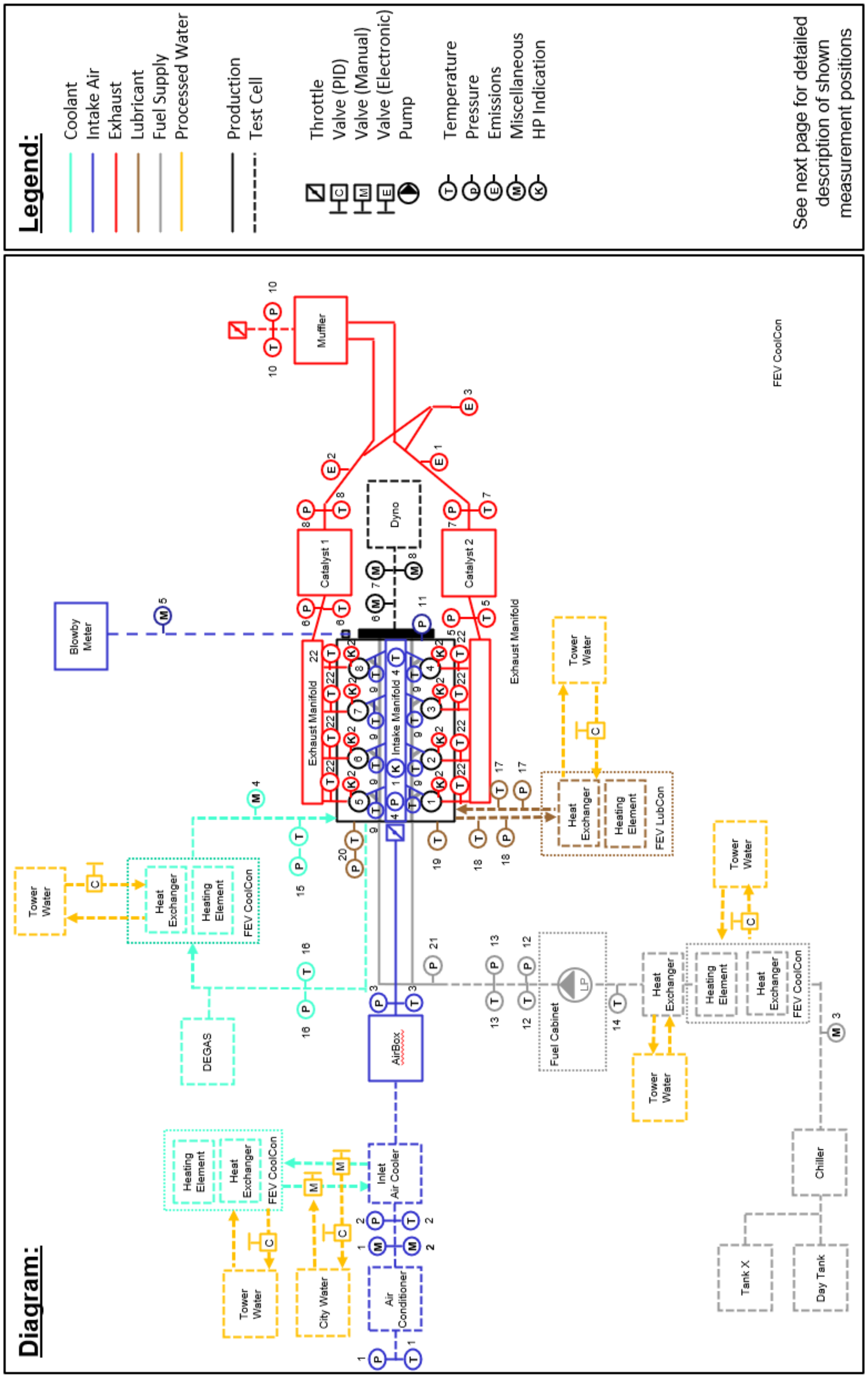


Appendix B. GM L86 Measurements

Static Temperature and Pressure Measurements			
1	Ambient	T	P
2	Before Airbox	T	P
3	Intake Manifold	T	P
4	Before Throttle	T	P
5	Intake Manifold	T	P
6	Exhaust Before Catalyst Bank 1	T	P
7	Exhaust Before Catalyst Bank 2	T	P
8	Exhaust After Manifold Bank 1	T	P
9	Exhaust After Manifold Bank 2	T	P
10	Exhaust Before Muffler	T	P
11	Exhaust After Muffler	-	P
12	Crankcase	T	P
13	Fuel Outlet (Outlet Cabinet)	T	P
14	Fuel Cabinet In	T	-
15	Coolant Inlet	T	P
16	Coolant Out	T	P
17	Lubecon Outlet	T	P
18	Lubecon Inlet	T	P
19	Oil Pan	T	-
20	Oil Gallery	T	P
21	Fuel Rail Pressure	-	P

Emissions and Miscellaneous Measurements		
E1	Lambda Meter Bank 1	Lambda
E2	Lambda Meter Bank 2	Lambda
M1	Air Flow Meter	Flow Rate
M2	Humidity Sensor	Absolute Humidity
M3	Fuel Flow Meter	Flow Rate, Density
M4	Coolant Flow Meter	Flow Rate
M5	Blowby Meter	Flow Rate
M6	Torque Meter	Engine Torque
M7	Engine Speed	Engine Speed
M8	Dyno Speed	Dyno Speed
Dynamic Pressure Measurements		
K1	Intake Runner Pegging Transducer	
K2	In-Cylinder Pressure 1-8	

Appendix C. Ford 7.3L Test Cell Layout



Appendix D. Ford 7.3L Measurements

Static Temperature and Pressure Measurements				**Static Temperature and Pressure Measurements**		
1	Ambient	T	P	23	After Exhaust Manifold Bank 1	T
2	Before Airbox	T	P	24	After Exhaust Manifold Bank 2	T
3	Intake Manifold	T	P			
4	Before Throttle	T	P			
5	Exhaust Before Catalyst Bank 1	T	P	**Emissions and Miscellaneous Measurements**		
6	Exhaust Before Catalyst Bank 2	T	P	E1	Lambda Meter Bank 1	Lambda
7	Exhaust After Catalyst Bank 1	T	P	E2	Lambda Meter Bank 2	Lambda
8	Exhaust After Catalyst Bank 2	T	P			
9	Intake Runner 1-8	T		M1	Air Flow Meter	Flow Rate
10	Exhaust After Muffler	T	P	M2	Humidity Sensor	Absolute Humidity
11	Crankcase	-	P	M3	Fuel Flow Meter	Flow Rate, Density
12	Fuel Out (Outlet Cabinet)	T	P	M4	Coolant Flow Meter	Flow Rate
13	Fuel Inlet (HP Pump In)	T	P	M5	Blowby Meter	Flow Rate
14	Fuel Cabinet In	T	-	M6	Torque Meter	Engine Torque
15	Coolant In	T	P	M7	Engine Speed	Engine Speed
16	Coolant Out	T	P	M8	Dyno Speed	Dyno Speed
17	Lubecon In	T	P			
18	Lubecon Out	T	P	**Dynamic Pressure Measurements**		
19	Oil Pan	T	-	K1	Intake Runner Pegging Transducer	
20	Oil Gallery	T	P	K2	In-Cylinder Pressure 1-8	
21	Fuel Rail Pressure	-	P			
22	Exhaust Runner 1-8	T	-			

Appendix E. Test Boundary Conditions

	Oil Flushing	**Reference Points**	**Knock Mapping Normal ACT**	**Knock Mapping High ACT**
Coolant-Out Temp [°C]	90	90	90 ± 3	115 ± 3
Oil Gallery Temp [°C]	90	90	90 ± 3	115 ± 3
Intake Manifold Temp [°C]	25	25	25 ± 2	45 ± 2
Airbox Inlet Pressure [barA]	1	1	1 ± 0.005	1 ± 0.005
Absolute Humidity [grains/lb]	50	50	50 ± 10	50 ± 10
Exhaust Backpressure [barA]	1	1	1 ± 0.005	1 ± 0.005
Engine Speed [rpm]	3000	2000	-	-
BMEP [bar]	5	2, 5	-	-

Appendix F. Engine 1 – GM L86 – Normal ACT Map

Point#	Speed (RPM)	BMEP (bar)	Fuel 4	Fuel 5	Fuel 6	Fuel 7
1	1000	WOT	KR>20	KR>20	KR>20	KR>20
2	1500	2	CA50	CA50	CA50	CA50
3	1500	4	CA50	CA50	CA50	CA50
4	1500	5.5	CA50	CA50	5% Cycles KR>5	CA50
5	1500	6	CA50	CA50	CA50	CA50
6	1500	7	CA50	CA50	CA50	CA50
7	1500	7.75	CA50	CA50	5% Cycles KR>5	CA50
8	1500	8.5	CA50	5% Cycles KR>5	5% Cycles KR>5	5% Cycles KR>5
9	1500	9.25	KR>15	KR>20	5% Cycles KR>5	5% Cycles KR>5
10	1500	9.5	KR>15	5% Cycles KR>5	5% Cycles KR>5	5% Cycles KR>5
11	1500	WOT	5% Cycles KR>5	5% Cycles KR>5	5% Cycles KR>5	5% Cycles KR>5
12	3000	WOT	KR>15	KR>15	KR>15	KR>20
13	4250	4	CA50	CA50	CA50	NOT RUN
14	4250	9	KR>20	CA50	KR>20	CA50
15	4250	10	KR>20	KR>15	KR>15	CA50
16	4250	11	KR>15	KR>20	KR>20	KR>20
17	4250	WOT	KR>15	KR>15	KR>15	KR>20
18	5600	4	CA50	CA50	CA50	NOT RUN
19	5600	8	CA50	CA50	CA50	CA50
20	5600	9.5	CA50	CA50	KR>20	NOT RUN
21	5600	WOT	KR>20	KR>15	KR>15	NOT RUN

Appendix G. Engine 1 – GM L86 – High ACT Map

Point#	Speed (RPM)	BMEP (bar)	Fuel 4	Fuel 5	Fuel 6	Fuel 7
1	1000	2	CA50	NOT RUN	NOT RUN	NOT RUN
2	1000	4	CA50			
3	1000	5.5	CA50			
4	1000	7	5% Cycles KR>5			
5	1000	WOT	5% Cycles KR>5	KR>20	KR>20	
6	1500	2	CA50	CA50	CA50	
7	1500	4	CA50	CA50	CA50	
8	1500	5.5	CA50	CA50	CA50	
9	1500	6	CA50	CA50	5% Cycles KR>5	
10	1500	6.25	NOT RUN	CA50	KR>20	
11	1500	7	5% Cycles KR>5	CA50	5% Cycles KR>5	
12	1500	7.5	5% Cycles KR>5	5% Cycles KR>5	KR>15	

13	1500	8	5% Cycles KR>5	5% Cycles KR>5	KR>20	
14	1500	WOT	KR>20	5% Cycles KR>5	KR>20	
15	2250	2	CA50			
16	2250	4	CA50			
17	2250	6	CA50			
18	2250	7	CA50			
19	2250	7.75	CA50	NOT RUN	NOT RUN	
20	2250	8.5	KR>20			
21	2250	9	KR>20			
22	2250	WOT	5% Cycles KR>5			
23	3000	WOT	NOT RUN	KR>15	KR>15	
24	3500	6	CA50			
25	3500	7.75	KR>15			
26	3500	8.5	KR>15	NOT RUN	NOT RUN	
27	3500	9	KR>15			
28	3500	WOT	KR>20			
29	4250	4	CA50	CA50	CA50	
30	4250	9	KR>20	KR>20	KR>15	
31	4250	10	NOT RUN	KR>15	KR>20	
32	4250	10.5	KR>20	KR>15	KR>20	
33	4250	WOT	KR>20	KR>20	KR>20	
34	5000	9	KR>20			
35	5000	10	KR>20	NOT RUN	NOT RUN	
36	5000	WOT	KR>20			
37	5600	4	CA50	CA50	KR>20	
38	5600	8	KR>20	KR>20	KR>15	
39	5600	8.5	NOT RUN	KR>20	KR>15	
40	5600	WOT	KR>15	KR>20	KR>20	

Appendix H. Engine 2 – Ford 7.3L – Normal ACT Map

Point#	Speed (RPM)	BMEP (bar)	Fuel 4	Fuel 1	Fuel 2	Fuel 3
1	1000	WOT	KR>20	KR>20	KR>20	5% Cycles KR>5
2	1500	2	CA50	CA50	CA50	CA50
3	1500	4	CA50	CA50	CA50	CA50
4	1500	5.5	CA50	NOT RUN	NOT RUN	NOT RUN
5	1500	6	CA50	CA50	CA50	CA50
6	1500	7	CA50	CA50	CA50	CA50
7	1500	8	CA50	5% Cycles KR>5	KR>15	5% Cycles KR>5
8	1500	8.25	NOT RUN	5% Cycles KR>5	KR>15	5% Cycles KR>5
9	1500	8.5	KR>15	5% Cycles KR>5	KR>15	5% Cycles KR>5

10	1500	WOT	KR>15	5% Cycles KR>5	KR>20	KR>20
11	2250	2	CA50	CA50	CA50	CA50
12	2250	4	CA50	CA50	CA50	CA50
13	2250	6	CA50	CA50	CA50	CA50
14	2250	7	CA50	CA50	CA50	CA50
15	2250	8	CA50	CA50	KR>15	CA50
16	2250	9	KR>20	KR>15	KR>15	KR>20
17	2250	WOT	KR>15	KR>15	KR>15	KR>15
18	3000	WOT	KR>20	KR>15	KR>15	KR>20
19	3900	4	CA50	NOT RUN	NOT RUN	NOT RUN
20	3900	6	CA50	CA50	CA50	KR>15
21	3900	7.25	CA50	CA50	KR>15	KR>15
22	3900	8.5	NOT RUN	KR>20	KR>20	KR>20
23	3900	8.75	KR>15	KR>20	KR>20	KR>15
24	3900	10	KR>20	KR>15	KR>20	KR>15
25	3900	WOT	KR>20	KR>20	KR>20	KR>15
26	4500	4	CA50	NOT RUN	NOT RUN	NOT RUN
27	4500	5	CA50	NOT RUN	NOT RUN	NOT RUN
28	4500	6	CA50	CA50	CA50	KR>15
29	4500	7.5	CA50	KR>15	KR>15	KR>20
30	4500	8.5	NOT RUN	KR>15	KR>15	KR>15
31	4500	9	KR>15	KR>20	KR>15	KR>15
32	4500	10	KR>15	KR>15	KR>15	KR>20
33	4500	WOT	KR>15	KR>20	KR>20	KR>15

Appendix I. Engine 2 – Ford 7.3L – High ACT Map

Point#	Speed (RPM)	BMEP (bar)	Fuel 4	Fuel 1	Fuel 2	Fuel 3
1	1000	WOT	KR>15	KR>15	5% Cycles KR>5	KR>20
2	1500	2	CA50	CA50	CA50	CA50
3	1500	4	CA50	CA50	CA50	CA50
4	1500	5.5	CA50	NOT RUN	NOT RUN	NOT RUN
5	1500	6	CA50	KR>15	KR>15	KR>15
6	1500	7	CA50	KR>15	5% Cycles KR>5	KR>15
7	1500	7.75	KR>15	KR>15	5% Cycles KR>5	KR>20
8	1500	8.25	NOT RUN	KR>15	5% Cycles KR>5	KR>20
9	1500	WOT	KR>20	KR>20	5% Cycles KR>5	KR>15
10	2250	2	CA50	CA50	CA50	CA50
11	2250	4	CA50	CA50	CA50	CA50
12	2250	6	CA50	CA50	KR>15	KR>15
13	2250	7	KR>15	KR>15	KR>15	KR>15
14	2250	8.75	KR>15	KR>20	KR>15	KR>15

15	2250	WOT	KR>15	KR>20	KR>15	KR>20
16	3000	WOT	KR>15	KR>15	KR>15	KR>20
17	3900	4	CA50	NOT RUN	NOT RUN	NOT RUN
18	3900	6	KR>15	KR>15	KR>15	KR>20
19	3900	7.5	KR>20	KR>15	KR>20	KR>15
20	3900	8.5	NOT RUN	KR>15	KR>20	KR>15
21	3900	9	KR>20	KR>15	KR>15	KR>15
22	3900	WOT	KR>20	KR>15	KR>20	KR>20
23	4500	4	CA50	NOT RUN	NOT RUN	NOT RUN
24	4500	5	CA50	NOT RUN	NOT RUN	NOT RUN
25	4500	6	CA50	CA50	KR>20	KR>20
26	4500	7.5	KR>20	KR>15	KR>20	KR>15
27	4500	8.5	NOT RUN	KR>20	KR>20	KR>15
28	4500	9	KR>20	KR>20	KR>20	KR>15
29	4500	WOT	KR>15	KR>20	KR>20	KR>15

Appendix J. Lab 1 Fuel Properties Analysis

Property	Test Method	UOM	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7
Research Octane Number	ASTM D2699	RON	91.4	91.2	91.4	95.6	95.4	95.4	98.4
Motor Octane Number	ASTMD2700	MON	86.3	83.3	81.1	87	90.7	88.1	87.7
Octane Rating	-	(R+M)/2	88.9	87.3	86.3	91.3	93.1	91.8	93.1
Octane Sensitivity	-	R-M	5.1	7.9	10.3	8.6	4.7	7.3	10.7
Aromatic Content	ASTM D6730mod	Vol%							
Olefin Content	ASTM D6730mod	Vol%							
Saturate Content	ASTM D6730mod	Vol%							
Ethanol Content	ASTM D4815	Vol%							
Specific Gravity @ 60.0 °F	ASTM D4052								
Density @ 15.56 °C	ASTM D4052	g/cc	0.7236	0.74696	0.75759	0.74402	0.70239	0.75615	0.75909
Sulfur Content	ASTM D5453	ppm							
RVP @100 °F	ASTM D5191	psi	10.13	10.63	10.31	10.1	9.93	9.68	10.41
Distillation, IBP	ASTM D86	Deg F	89.2	87.7	81	92.2	92.7	92.3	85.7
Distillation, 5%	ASTM D86	Deg F	111.4	108	110.4	113.2	119.9	115.3	108.9
Distillation, 10%	ASTM D86	Deg F	122.5	118.2	122.3	123.9	130.7	127.2	120.6
Distillation, 20%	ASTM D86	Deg F	137.3	133.4	136.1	139.3	144.6	142.5	137.3
Distillation, 30%	ASTM D86	Deg F	148.3	147.1	146.2	151.7	153.3	152.1	151.3
Distillation, 40%	ASTM D86	Deg F	157	157.6	155.8	163	164	159.5	161.4
Distillation, 50%	ASTM D86	Deg F	205.1	220.9	223.3	224.2	213	221.4	234.2
Distillation, 60%	ASTM D86	Deg F	227.4	255	268.1	240.9	222.1	260.4	262.2
Distillation, 70%	ASTM D86	Deg F	241.7	273.7	284.6	255	227.1	296.3	284.7
Distillation, 80%	ASTM D86	Deg F	263.6	293.9	299.6	274.9	240.2	322.3	311.5
Distillation, 90%	ASTM D86	Deg F	309.4	321.9	323.3	312.3	271.5	353	333.9
Distillation, 95%	ASTM D86	Deg F	339.7	346.7	350.2	341.9	324.6	370.1	347.8

Distillation, Dry Point	ASTM D86	Deg F	368.6	374.2	374.8	374.8	381	390.4	372.8
Recovery	ASTM D86	Vol%	97	97.4	97.2	97.8	97.8	97.5	97.2
Residue	ASTM D86	Vol%	0.8	0.8	0.9	0.7	0.7	1	1.1
Loss	ASTM D86	Vol%	2.2	1.8	1.9	1.5	1.5	1.5	1.7
Drivability Index	ASTM D4814 (Deg F)	Drive Index							
Carbon Content	ASTM D5291	Wt%							
Hydrogen Content	ASTM D5291	Wt%							
Oxygen Content	-	Wt%							
C/H Ratio	-	mole/mole							
H/C Ratio	-	mole/mole							
O/C Ratio	-	mole/mole							
Net Heat of Combustion	ASTM D240mod	MJ/kg							

Appendix K. Lab 2 Fuel Property Analysis

Property	Test Method	UOM	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7
Research Octane Number	ASTM D2699	RON	91.2	90.9	91.1	95.2	95	95	98
Motor Octane Number	ASTMD2700	MON	86.3	83.1	81.3	86.7	90.6	83.4	86.9
Octane Rating	-	(R+M)/2	88.8	87	86.2	90.95	92.8	89.2	92.45
Octane Sensitivity	-	R-M	4.9	7.8	9.8	8.5	4.4	11.6	11.1
Aromatic Content	ASTM D6730mod	Vol%							
Olefin Content	ASTM D6730mod	Vol%							
Saturate Content	ASTM D6730mod	Vol%							
Ethanol Content	ASTM D4815	Vol%							
Specific Gravity @ 60.0 °F	ASTM D4052								
Density @ 15.56 °C	ASTM D4052	g/cc	0.7235	0.7472	0.7572				
Sulfur Content	ASTM D5453	ppm	1	1.8		2	2.7	1.9	2.3
RVP @100 °F	ASTM D5191	psi	10.07	10.62	10.26	10.15	9.8	9.7	10.28
Distillation, IBP	ASTM D86	Deg F	90.3	84.2	90.7	94.8	93.7	94.6	90.9
Distillation, 5%	ASTM D86	Deg F							
Distillation, 10%	ASTM D86	Deg F	127.9	124.2	127.6	124	132.1	127.6	121.6
Distillation, 20%	ASTM D86	Deg F	141.3	137	139.3	139.6	145.8	142.7	138.7
Distillation, 30%	ASTM D86	Deg F	151.3	150.6	148.5	152.2	154	153.1	152.4
Distillation, 40%	ASTM D86	Deg F	160.3	160.2	159.8	164.3	164.1	165.7	161.4
Distillation, 50%	ASTM D86	Deg F	213.6	233.1	237.7	225.1	213.3	224.6	234.5
Distillation, 60%	ASTM D86	Deg F	230.7	259.9	272.1	243.3	221.2	261.9	263.5
Distillation, 70%	ASTM D86	Deg F	241	277.3	286.3	256.5	230.9	297	286.5
Distillation, 80%	ASTM D86	Deg F	267.4	296.8	301.5	276.4	241.5	325.6	313.7
Distillation, 90%	ASTM D86	Deg F	314.4	324.3	327.4	313.2	274.3	354	334.8
Distillation, 95%	ASTM D86	Deg F	341.8	349.3	350.4	340.3	328.1	372.6	348.4
Distillation, Dry Point	ASTM D86	Deg F	368.6	377.4	376.2	375.8	387.1	390.4	376.9

Recovery	ASTM D86	Vol%	98.7	98.8	98.7	96	96.7	96.1	95.8
Residue	ASTM D86	Vol%	1.1	1.1	0.9	1	1.1	1	1
Loss	ASTM D86	Vol%	0.2	0.1	0.4	2.5	1.9	2.4	2.5
Drivability Index	ASTM D4814 (Deg F)	Drive Index	1147	1210		1174	1112	1219	1221
Carbon Content	ASTM D5291	Wt%							
Hydrogen Content	ASTM D5291	Wt%							
Oxygen Content	-	Wt%							
C/H Ratio	-	mole/mole							
H/C Ratio	-	mole/mole							
O/C Ratio	-	mole/mole							
Net Heat of Combustion	ASTM D240mod	MJ/kg							

Appendix L. Lab 3 Fuel Property Analysis

Property	Test Method	UOM	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7
Research Octane Number	ASTM D2699	RON				94.7	95	94.9	98.3
Motor Octane Number	ASTMD2700	MON				87.1	90.8	83.1	87.2
Octane Rating	-	(R+M)/2				90.8	92.9	89	92.8
Octane Sensitivity	-	R-M				7.6	4.2	11.8	11.1
Aromatic Content	ASTM D6730mod	Vol%							
Olefin Content	ASTM D6730mod	Vol%							
Saturate Content	ASTM D6730mod	Vol%							
Ethanol Content	ASTM D4815	Vol%							
Specific Gravity @ 60.0 °F	ASTM D4052					0.744	0.703	0.757	0.76
Density @ 15.56 °C	ASTM D4052	g/cc							
Sulfur Content	ASTM D5453	ppm							
RVP @100 °F	ASTM D5191	psi				10.12	9.67	9.49	10.17
Distillation, IBP	ASTM D86	Deg F				86	92.2	92.4	85.4
Distillation, 5%	ASTM D86	Deg F				115	121.7	119.7	113.2
Distillation, 10%	ASTM D86	Deg F				125	131.2	130.1	123.3
Distillation, 20%	ASTM D86	Deg F				139.9	145.2	144.3	139.5
Distillation, 30%	ASTM D86	Deg F				152	153.6	152.9	152.6
Distillation, 40%	ASTM D86	Deg F				164.4	167.4	167.4	163.5
Distillation, 50%	ASTM D86	Deg F				225.4	213.5	225.2	236.8
Distillation, 60%	ASTM D86	Deg F				242.3	221.6	261.8	263.6
Distillation, 70%	ASTM D86	Deg F				255.5	229.1	297.9	285.3
Distillation, 80%	ASTM D86	Deg F				275.4	241.5	325.8	311.6
Distillation, 90%	ASTM D86	Deg F				313.3	274.4	353	333.7
Distillation, 95%	ASTM D86	Deg F				343.9	326.9	373.7	347.9
Distillation, Dry Point	ASTM D86	Deg F				373.2	380	406	373.4
Recovery	ASTM D86	Vol%							

Residue	ASTM D86	Vol%							
Loss	ASTM D86	Vol%							
Drivability Index	ASTM D4814 (Deg F)	Drive Index							
Carbon Content	ASTM D5291	Wt%							
Hydrogen Content	ASTM D5291	Wt%							
Oxygen Content	-	Wt%							
C/H Ratio	-	mole/mole							
H/C Ratio	-	mole/mole							
O/C Ratio	-	mole/mole							
Net Heat of Combustion	ASTM D240mod	MJ/kg							

Appendix M. Average Fuel Properties

Property	Test Method	UOM	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7
Research Octane Number	ASTM D2699	RON	91.4	91.1	91.233	95.15	95.075	94.9	98.25
Motor Octane Number	ASTMD2700	MON	86.3	83.2	80.933	86.9	90.725	83.2	87.175
Octane Rating	-	(R+M)/2	88.9	87.2	86.1	91.0125	92.9	89.1	92.7375
Octane Sensitivity	-	R-M	5.1	7.9	10.3	8.3	4.4	11.8	11.1
Aromatic Content	ASTM D6730mod	Vol%	14.5	27.9	30.2	26.8	1.7	31.6	37.0
Olefin Content	ASTM D6730mod	Vol%	0.6	5.4	20.9	0.7	2.4	30.2	6.9
Saturate Content	ASTM D6730mod	Vol%	74.9	56.6	39.0	62.6	85.8	28.0	46.1
Ethanol Content	ASTM D4815	Vol%	10.0	10.1	9.9	9.9	10.1	10.2	10.0
Specific Gravity @ 60.0 °F	ASTM D4052		0.7	0.7	0.8	0.7	0.7	0.8	0.8
Density @ 15.56 °C	ASTM D4052	g/cc	0.7	0.7	0.8	0.7	0.7	0.8	0.8
Sulfur Content	ASTM D5453	ppm	0.5	0.9	0.0	1.0	1.4	1.0	1.2
RVP @100 °F	ASTM D5191	psi	10.1	10.6	10.3	10.1	9.9	9.7	10.3
Distillation, IBP	ASTM D86	Deg F	90.1	85.2	87.0	90.2	93.4	93.9	87.7
Distillation, 5%	ASTM D86	Deg F	113.8	109.1	112.7	114.0	121.0	117.6	111.6
Distillation, 10%	ASTM D86	Deg F	125.2	120.7	124.9	124.1	131.1	128.3	122.0
Distillation, 20%	ASTM D86	Deg F	138.9	134.9	137.4	139.3	144.7	143.1	138.4
Distillation, 30%	ASTM D86	Deg F	149.5	148.3	147.1	151.7	153.2	152.6	151.8
Distillation, 40%	ASTM D86	Deg F	158.2	158.5	156.9	163.0	165.0	162.9	162.4
Distillation, 50%	ASTM D86	Deg F	208.1	225.1	228.4	224.4	212.8	223.1	235.0
Distillation, 60%	ASTM D86	Deg F	228.2	256.6	269.8	241.9	221.5	260.8	262.8
Distillation, 70%	ASTM D86	Deg F	241.4	274.9	285.0	255.4	229.1	296.7	285.3
Distillation, 80%	ASTM D86	Deg F	264.6	294.9	300.4	275.4	240.9	324.4	311.5
Distillation, 90%	ASTM D86	Deg F	311.9	317.6	325.5	313.0	272.9	353.4	334.0
Distillation, 95%	ASTM D86	Deg F	340.6	339.6	350.2	342.6	326.2	372.3	348.0
Distillation, Dry Point	ASTM D86	Deg F	368.0	375.3	374.9	374.3	382.4	393.9	374.2
Recovery	ASTM D86	Vol%	97.7	97.9	97.9	97.2	97.3	97.1	96.9
Residue	ASTM D86	Vol%	1.0	1.0	0.9	0.9	0.9	1.0	1.0

Loss	ASTM D86	Vol%	1.3	1.1	1.2	1.7	1.7	1.7	1.9
Drivability Index	ASTM D4814 (Deg F)	Drive Index	1144.0	1200.5	1209.0	1182.5	1118.5	1202.5	1232.5
Carbon Content	ASTM D5291	Wt%	81.8	82.9	83.4	82.8	80.5	83.4	83.5
Hydrogen Content	ASTM D5291	Wt%	14.4	13.4	13.0	13.6	15.6	12.9	12.8
Oxygen Content	-	Wt%	3.8	3.7	3.6	3.7	3.9	3.7	3.6
C/H Ratio	-	mole/mole	5.7	6.2	6.4	6.1	5.2	6.5	6.5
H/C Ratio	-	mole/mole	2.1	1.9	1.9	2.0	2.3	1.8	1.8
O/C Ratio	-	mole/mole	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Heat of Combustion	ASTM D240mod	MJ/kg	42.1	41.6	41.57	41.6	42.7	41.4	41.2

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