CRC Report No. 660

FUEL ANTIKNOCK QUALITY – ENGINE RESPONSE TO RON VERSUS MON

SCOPING TESTS

Final Report

May 2011

COORDINATING RESEARCH COUNCIL, INC.
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Fuel Antiknock Quality – Engine Response to RON versus MON - Scoping Tests

(CRC Project No. CM-137-07)

Prepared by the

CRC Octane Group

May 2011

CRC Performance Committee
of the
Coordinating Research Council

ACKNOWLEDGEMENT

The Coordinating Research Council (CRC) would like to acknowledge engine testing by Chrysler Group and General Motors at their own expense, as well as fuel acceptance testing by BP, Chevron, ConocoPhillips and Shell,.

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ABSTRACT

The Coordinating Research Council (CRC) conducted a program to investigate the relative importance of Research octane number (RON) versus Motor octane number (MON) on two late-model US vehicle engines operating in a wide-open throttle (WOT) mode at two different intake air temperatures, "standard" and "high temperature." Engines tested were a Chrysler 5.7-liter HEMI engine and a GM 2.0-liter ECOTEC turbocharged direct-injected engine. Engine tests were performed on controlled-environment brake dynamometers.

The specific objective of the program was to determine the relative knock-limited performance of five, all-hydrocarbon (i.e. containing no oxygenates) test fuels with varying RON, MON, and sensitivity (RON – MON). Sensitivities of the fuels ranged from 2 to 12, and anti-knock indices (AKI = (RON+MON)/2) varied from 86 to 89, nominally.

Results showed that the high-RON, high-sensitivity fuel exhibited the most resistance to knocking in both engines at most of the conditions tested. Performance shifts, as demonstrated by spark loops, are due to fuel knock susceptibility. The low-RON, low-sensitivity fuel showed the least resistance to knocking at most of the conditions as opposed to the other two test fuels which had the same nominal (R+M)/2. For the larger displacement engine, at high intake temperature, and RPM above 4400, the highest MON fuel had the greatest knock resistance. . Based on the results of this study and for the engines and conditions tested, RON has a stronger effect on resistance to knock than MON, except for the large displacement engine at high intake air temperatures and speeds above 4400 RPM. The importance of RON for spark knock avoidance is in agreement with latest octane literature studies cited in this report. The importance of MON for knock avoidance in the large engine at high speeds is also not unexpected based on the studies of the sensitivity of K to engine speed and intake temperature conducted by Mittal&Heywood(4) Future work is recommended.

I. INTRODUCTION

The Coordinating Research Council (CRC) conducted an experimental scoping test program to investigate the relative importance of Research octane number (RON) versus Motor octane number (MON) on two late-model vehicle engines (one port-fuel-injection and one direct injection). Interest in this topic was sparked when researchers at Shell Global Solutions, UK (Dr. G. T. Kalghatgi) presented three SAE technical papers [1, 2, 3] reporting on the octane requirement of modern vehicles, defined as

Octane Requirement (or Octane Index, OI) = (1-K)*RON + K*MON   Eq. 1

where RON = Research octane number,
MON = Motor octane number, and
K = a constant that will vary with different engines, different engine loads, and different conditions (e.g. engine speed, intake air temperature and pressure).

Expressed differently as a function of octane sensitivity:
Octane Requirement (or OI) = RON - K*S   Eq. 2
where S = RON – MON.

Historically, the value of K in this equation has been positive; however, Kalghatgi's and others' research suggest that the value of K has been steadily decreasing for modern engines, such that K is now negative for most engines under most conditions. The implication is that, in Kalghatgi's words, "Thus in most cases, for a given RON, a sensitive fuel (lower MON) will have a higher Octane Index and give higher power and faster acceleration (i.e. greater knock resistance) in these cars equipped with knock sensors."[3] This finding is counter-intuitive for many who have believed that a fuel with a given RON would always perform equal or better with a higher MON. Other studies [4, 6-14] corroborate this concept of a negative K for many engines under most operating conditions. The RON versus MON relationship was also explored at the Massachusetts Institute of Technology (MIT) by Heywood and Mittal.[4] The MIT experiments used a single-cylinder, four-valve, pent-roof research engine. The fuels tested were blends of primary reference fuels (PRF) and toluene, di-isobutylene, and ethanol. The results show that K is negative for the all engine operating conditions tested. Thus from these studies, fuels with greater sensitivities at the same RON gave better anti-knock performance. Other engine variables and their effect on knock influence were investigated, including spark location, compression ratio, air-fuel ratio, engine speed, and intake air temperature and pressure. Results show that K has strong dependence on intake air temperature and pressure, along with engine speed. MIT also used the annual CRC Octane Number Requirement Survey data to demonstrate the trend of lower importance of MON in modern engines. (The reports on the CRC Octane Number Requirement Surveys may be found on the CRC website: crcao.org.)

The CRC Octane Group recognized that the majority of the engines and vehicles tested in the Shell UK intriguing octane work were relatively small displacement; small cylinder bore European engines with manual transmissions. The CRC Octane Group contemplated whether similar conclusions on the benefits of high RON, high sensitivity fuels would prove true for larger vehicles in the U.S. operating with larger cylinder bored engines, at generally lower engine operating speeds and naturally aspirated. The CRC Octane Group thus prepared and revised a proposal to perform scoping work to observe the effects of RON versus MON on a limited set of more typical U.S. commercial engines. Over time, the project became more important as the search for efficient use of gasoline in modern engines has intensified with the demands to use less petroleum-based fuels and the increasing corporate average fuel economy (CAFÉ) requirements. The CRC scoping study engine tests were conducted at Chrysler Powertrain Engineering and General Motors Powertrain Engineering, each using one of their own engines. Members of the Data Analysis Panel are listed in Appendix A.

Kalghatgi's anti-knock index constant (K) is related to the temperature of the unburnt gas of the combustion chamber end gas region as the progressing flame front approaches the cylinder bore wall. Figure 10 of Kalghatgi's paper [(1)] shows the wide-open-throttle (WOT) condition unburnt gas temperatures of the two standard ASTM octane rating engines, RON and MON relative to later model, high efficiency engines. In short, as the efficiency of the engine increases more energy is released as work instead of wasted heat and the unburnt gas temperature decreases relative to that in the ASTM octane MON and RON rating engines with K values equal to 1 and 0, respectively. Kalghatgi concludes that today's high efficiency engines have cooler unburnt gas temperatures than the RON test and therefore the parameter K is negative for modern engines.

By contrast, any engine operating condition and/or duty cycle that increases the unburnt gas temperature however will have a more positive K and therefore require more MON to prevent auto-ignition. This is discussed in Sections 3.2 and 3.3 of Kalghatgi's [(1)] paper as well as in Mittal's SAE Paper [(4)] and shown below in this report in Figures 3 and 4. For example, as engine speed increases and there is less time for cylinder heat transfer between successive combustion events, in-cylinder end gas temperatures increase and MON becomes more necessary to prevent spark knock. Therefore, while higher sensitivity fuels are shown to enable new high efficiency engines to greater thermal efficiency under normal operating conditions, it is likely certain operating conditions will continue to benefit from a higher MON value in controlling auto-ignition. Low-engine-speed, high-load knock conditions benefit from higher RON, while high-engine-speed, high-load knock conditions benefit from higher MON.

II. BACKGROUND

The Coordinating Research Council Octane Group has a long history of performing octane requirement and other octane tests on engines and vehicles. The most recent CRC report is #643 "Critique and Recommendations for the CRC Octane Acceleration Technique."[(5)] The report gives an analysis of a CRC acceleration method for octane requirement rating for vehicles with knock sensors.

Other investigators have been studying the relationship of RON and MON to engine performance for many years. A.G. Bell of Shell in "The Relationship between Octane Quality and Octane Requirement" [6] found that at low engine speeds, engine performance was most responsive to RON. At moderate speeds, RON + MON was found to best describe engine response, while at high speeds, MON seemed to dominate over the octane range for modern gasolines.

W. Leppard of GM described "The Chemical Origin of Fuel Octane Sensitivity."[7] He found that paraffin combustion chemistry was different than olefin or aromatic chemistries. The difference is that paraffins exhibited a *negative* temperature coefficient for auto ignition. That is to say, for paraffins over a certain temperature range, the auto ignition time *increases* with increasing temperature. Olefins and aromatics do not show such behavior.

Millo, et al. reported on the "Effect of Unleaded Gasoline Formulation on Antiknock Performance."[8] Tests were performed on a standard European engine with different fuels over the RON range of 95 to 100. They found that an increase in aromatics content did not show appreciable differences between the expected knock behavior and its standard octane numbers; however, for higher olefin content, the difference between observed engine octane index and standard test octane numbers was substantial. Thus for fuels with the same RON and MON, substantial differences were found with gasolines with different compositions.

The measurement of gasoline properties on vehicle acceleration was described by Y. Sugawara, et al. in "Effects of Gasoline Properties on Acceleration Performance of Commercial Vehicles."[9] This study examined four Japanese vehicles with automatic transmissions and knock sensors using two fuels: one made of primary reference fuels (PRF) and another made from 50 percent PRF and 50 percent commercial gasoline. Octane sensitivities ranged from 2 to 13. Results showed that acceleration performance was strongly tied to octane numbers.

Dr. Gautam T. Kalghatgi of Shell UK has studied and reported on octane effects on vehicles and engines for many years. Research was performed on a single-cylinder test engine using Coherent Antistokes Raman Spectroscopy (CARS) and fuels of mostly binary blends of pure components with RONs from 90 to 111. Kalghatgi and co-workers at Shell Thornton examined the "Fuel Effects on Knock, Heat Release and 'CARS' Temperatures in a Spark-Ignition Engine."[10] They found that heat release rates of aromatic fuels were lower than that of paraffinic fuels. They also noted that the maximum heat release rate is solely associated with engine knock intensity.

Kalghatgi also reported on "Fuel Anti-Knock Quality – Part I. Engine Studies."[1] He defined the Octane Index or Engine Octane Requirement as OI = RON – K*(RON-MON). Tests were conducted with different fuels (binary mixtures of refinery streams or pure components – 85 to 100 RON) in different single-cylinder engines. Kalghatgi concluded that the factor "K" is different for different operating conditions and can even be negative. Thus for a given RON, a fuel of higher sensitivity (i.e. *lower* MON), can have a higher Octane Index, and so have greater knock resistance. His studies continued with "Fuel Anti-Knock Quality - Part II. Vehicle

Studies – How Relevant is Motor Octane Number (MON) in Modern Engines?"[2] In this study, Kalghatgi tested 23 European and Japanese vehicles with knock sensors and both manual and automatic transmissions using acceleration metrics to observe octane effects. RON of the test fuels ranged 86 to 101. Results showed that for most cases, the parameter K was negative, i.e. the influence of greater RON on acceleration was beneficial, while the influence of greater MON was detrimental.

C. Bradley and co-workers at Shell reported on the "Relevance of Research and Motor Octane Numbers to the Prediction of Engine Auto-ignition."[11] They found that through modeling efforts using literature data, knock was correlated with the creation of local "hot" spots in the cylinder.

Kalghatigi examined and reported on the "Antiknock Quality of Practical Fuels and Implications for Fuel Requirements of Future SI and HCCI Engines."[12] In this report, Kalghatgi makes the claim that RON is far more important for engine performance in modern engines than MON, and in fact gasolines with the same (R+M)/2 will perform better (greater antiknock performance) with higher sensitivity (i.e. greater RON – MON). Views on direct injection (DISI) and HCCI fuel requirements are also discussed in this comprehensive paper.

Kalghatgi and coworkers reported on the influence of RON vs. MON for engine performance in direct-injection, spark-ignition engines: "Octane Appetite Studies in Direct Injection Spark Ignition (DISI) Engines."[14] In this work, they tested a wide range of fuels of different RON (86 to 101) and MON (82 to 93) in prototype DISI engines with compression ratios of 11 and 12.5 and different engine speeds up to 6000 rpm. Knock limited spark advance was used to characterize the anti-knock quality of the fuel. RON was found to be dominant for fuel anti-knock quality at all engine speeds. At low to moderate speeds for a given RON, a lower MON resulted in better anti-knock quality.

Professor John B. Heywood and his graduate student Dr. Vikram Mittal reported some fundamental work done on a single cylinder engine with different fuels having varying RON and MON in their paper: "The Relevance of Fuel RON and MON to Knock Onset in Modern Engines."[4] They found from their experiments on a single-cylinder, pent-roof engine that fuels with greater sensitivities (RON-MON, ranging from 0 to 17) with the same RON had better anti-knock performance. Experiments were performed to study the effects on "K" in Octane Index = K*MON + (1-K) * RON. They found that K had strong dependence upon intake air temperature, pressure, and engine speed. Lesser effects were found for spark plug location, compression ratio, and relative air/fuel ratio.

Heywood and Mittal also reported on "The Shift in Relevance of Fuel RON and MON to Knock Onset in Modern SI Engines Over the last 70 Years."[14] This work examined historic octane requirement results from the CRC Annual Octane Surveys run from 1947 to 1996. Their analysis showed a shift in the importance of RON over MON for anti-knock performance for engines from 1950s through 1990s.

The influence of alcohols upon octane has taken on increased importance with recent government requirements to use more renewable fuels. Anderson, et al. from Ford recently published a paper on examining the blending octane of alcohols in gasoline: "Octane Number Effects of Ethanol- and Methanol-Gasoline Blends Estimated from Molar Concentrations."[(15)] They found that by using a molar blending basis, rather than a liquid volume basis, they were able to show more linear octane blending behavior for methanol and ethanol.

III. TEST ENGINES

Chrysler and General Motors provided and tested at their own expense a 5.7-liter V8 HEMI engine and a 2.0-liter I4 ECOTEC engine, respectively. The test engines are described below:

Chrysler 5.7 Liter Spark Ignited HEMI Engine (Port-Fuel-Injected)	
Model Year	2008
Cylinders	8
Valves per Cylinder	2
Valve Assembly Drive	Overhead Valve
Fuel System	Port Fuel Injected
Induction System Pressure	Naturally Aspirated
Octane Requirement	Regular Unleaded
Compression Ratio	9.6 : 1
Horsepower (kW)	345(258) @ 5000 rpm
Torque – ft/lbs (Nm)	375(508) @ 4000 rpm
Bore x Stroke (mm)	99.5 x 90.9

GM 2.0 Liter Spark Ignited ECOTEC Engine (Direct-Injected)	
Model Year	2008
Cylinders	4 - Inline
Valves per Cylinder	4
Valve Assembly Drive	Dual Over Head Cam
Fuel System	Direct-Injected, Side Spray, Homogenous
Induction System	Turbocharged with Charged Air Cooler
Octane Requirement	Premium Unleaded Recommended
Compression Ratio	9.2:1
Horsepower (kW)	260 (194) @ 5300 rpm
Torque – ft/lbs (Nm)	260 (353) @ 2500 – 5250 rpm
Bore x Stroke (mm)	86 x 86

IV. TEST FUELS

The range of fuel octane was designed to measure statistically significant differences in fuel knock resistance as measured by engine performance.

The strategy of the fuel blending was a deliberate attempt at fuel comparisons using constant properties such as (R+M)/2 (Fuels 1, 2, 3); constant RON (Fuels 2 and 4); constant octane sensitivity (Fuels 1, 4, and 5); and constant MON (Fuels 2 and 5). To enable easy comparisons of the results with the octane properties of the fuels, abbreviations were used: the target RON followed by the level of octane sensitivity was the moniker used. For example, Fuel 3 with 88 RON and low sensitivity is abbreviated 88LS, while Fuel 5 with 95 RON and high sensitivity is 95HS. Fuel 1 with 93 RON and high sensitivity is 93HS; likewise Fuel 2 is 92MS, and Fuel 4 is 92HS.

The test fuel matrix consisted of five hydrocarbon-only test fuels with varying sensitivities ranging from 2 to 12. Average dry vapor pressure equivalent (DVPE), distillation temperatures, RON, MON, and other property inspection results as determined by the Fuel Acceptance Panel (Laboratories A, B, C, and D) are shown in Table 1. Individual test results obtained by each inspecting laboratory are shown in Appendix B. The comparison of RON versus MON for the targeted fuels and the octane numbers of the actual fuels are shown in Figure 1 along with the lines showing levels of sensitivities and constant (R+M)/2. The abbreviations of each of the five fuels are shown also.

The octane numbers of the test fuels fall within a relatively close range. A wider spread would be desirable, but an attempt was made to keep the fuels close to what might be found in the marketplace. Fuel 2 is representative of commercially available unleaded regular-grade gasoline. The design of the fuel set intentionally provides specific means for data analysis; the octane numbers of the fuels were not chosen randomly. The fuel set allows for comparison of Fuels 1, 2, and 3 at a constant (R+M)/2; comparison of Fuels 1, 4, and 5 at a constant sensitivity; comparison of Fuels 2 and 4 at a constant RON; and comparison of Fuels 2 and 5 at a constant MON. Fuels were prepared using conventional refinery components found in current retail fuels.

The fuels as a group had very close net heats of combustion, ranging over 18347 to 18973 BTU/Lb. over the five fuels despite the relatively large variation in compositions (e.g. aromatics contents ranged 6 to 35 wt %).

V. TEST CONDITIONS

This test was designed to evaluate the relative importance of RON and MON as it pertains to knock. The knock resistance of the test fuels was determined by observing the change in knock-limited engine performance as measured by changes in spark advance and relative torque. It is understood by engine designers that as improvements are made in the knock resistance in an engine, it enables other hardware and calibration changes which will result in improved engine efficiency (e.g. increased compression ratio); however, quantifying the improvement in efficiency was not part of the scope of this program.

The engines selected reflected the objective to study a large-bore, light-duty vehicle engine typical of the US marketplace, as well as smaller displacement engine, recognizing the direction of the US vehicle population is toward downsized, boosted, direct-injection engines.

Testing was conducted at both standard and high-temperature intake air conditions on engine dynamometers. Measured conditions included inlet air temperature, coolant temperature, inlet pressure, and dew point temperature. Nominal (standard) and high-temperature test conditions are detailed for both the Chrysler and the GM engines in Tables 2 and 3, respectively. Steady-state wide-open-throttle engine tests were performed over the entire speed range of the engines. Knock limited spark advance was determined using similar cylinder pressure measurement-based calibration methods in use at both Chrysler and GM. Production calibration fuel mixture control was used with both engines, rather than lean best torque fuel control. This resulted in constant equivalence ratio at each speed from fuel to fuel. Production boost level was used for the GM engine testing. Chrysler and GM both installed one heat range colder spark plugs than the production-released spark plugs. Spark advance for both Chrysler and GM testing was determined using normal production methods. Triplicate testing for spark sweep was performed at Chrysler, while a single determination was performed at GM.

Use of an engine dynamometer with controlled charge air conditions enabled better accuracy metrics, e.g. engine speed, cylinder-pressure-based knock determination, consistent with production calibration techniques, rather than needing to develop a new test procedure.

Both engines were equipped with knock sensors; however, for engine dynamometer testing, it is standard practice for the knock sensors to be disabled, and this was the condition used for this testing. Knock detection was determined through cylinder pressure analysis at both laboratories.

VI. RESULTS

Results of the engine tests with the five different fuels are shown in Figures 5 through 8. Each figure has two plots: one for the spark advance sweep (degrees before top dead center BTDC) versus engine speed, and a second plot of normalized torque versus engine speed. Torque was normalized to that for engine operation at a given speed on Fuel 2 (92MS). Spark sweeps were done at engine speeds of 1200 to 6000 rpm using standard air intake temperature and heated air; hence, there is a plot for each air temperature. For the Chrysler 5.7-liter Hemi engine, the plots are the arithmetic averages of the triplicate runs. For the GM 2.0-liter Ecotec boosted DI engine, the plots are the single sweep run data.

VII. DISCUSSION OF RESULTS

A. Comparisons of Fuels with Similar Octane Properties

The design of the fuel set and use of large and smaller displacement engines, along with the ambient and heated air conditions, makes several interesting comparisons possible. Table 4 shows these comparisons for several octane metrics: (relatively) constant (R+M)/2, constant sensitivity, constant RON, and constant MON. For each octane metric, the fuels are ranked from most to least in terms of their resistance to knock.

Using the **constant (R+M)/2** metric (as posted for motor gasoline in the US) for Fuels 1, 2, and 3, Fuel 1 (93HS = moderate Research octane, high sensitivity) shows the best resistance to engine knock for the GM Ecotoec under all conditions (i.e. standard and heated intake air, and all engine speeds). Fuel 1 is also most resistant for the Chrysler engine up to about 4400 rpm speed.

At higher speeds in the big bore engine, however, Fuel 3 (88LS) with higher Motor octane is most knock resistant. Fuel 2 (92MS) is the second-most knock resistant fuel for all cases at constant (R+M)/2.

Examination of the ranking of fuels at relatively **constant Sensitivity** (S = RON - MON), compares Fuels 1, 4, and 5. The comparison shows under all conditions and in both engines, Fuel 5 (95HS) is the superior fuel for knock resistance; however, the performance for Fuel 1 (93HS) in the GM and heated-air intake Chrysler engine is similar. Fuel 4 (92HS) is the least knock resistant in all engines and at all conditions tested among the three constant sensitivity fuels.

Comparison of the fuels on a **constant Research octane** basis uses Fuels 2 (92MS) and 4 (92HS). For the GM engine and under all conditions, both fuels seem to offer the same resistance to knock. For the larger bore Chrysler engine, Fuel 2 shows a slight advantage toward knock resistance over Fuel 4. Both fuels are the same when comparing spark advance for resisting knock.

Finally comparison of the fuels at **constant Motor octane**, Fuel 5 (95HS) and Fuel 2 (92MS) shows that Fuel 5 is superior for resistance to knock in both engines and at all but one of the conditions tested. For the big bore Chrysler engine at high speeds, Fuel 2 seems equivalent to Fuel 5 when comparing normalized torque.

Most of these results are in general agreement with the prior studies by other researchers discussed in the BACKGOUND section of this report. Namely, for the smaller bore, direct-injection GM Ecotec engine, fuels with high RON and high sensitivity seem to offer the best knock resistance at a variety of operating conditions (e.g. standard and heated intake air temperatures, low to high engine speeds).

For the larger bore Chrysler engine, the fuels with high RON and high sensitivity seem to offer the best knock resistance at relatively mild operating conditions; although at heated air intake and higher speeds, a fuel with higher MON resists knock the best among the fuels tested. This latter finding has not been presented in the many previous studies cited in the BACKGROUND section of this report.

B. Modeling and Statistical Analysis

Models were constructed to fit the observed spark timing and corrected normalized torque results. These models were then used to extract statistical comparisons of the fuels in both engines at various operating conditions. The models were also used to extract information on the relative influence of RON versus MON in the antiknock Eq.1.

Data for the responses **spark timing** and **corrected normalized torque** from each engine at each temperature were fit to general linear models (GLM) with the general form:

$$\text{Response} = a_0 + P(\text{speed, phi, VE}) + a_1{*}\text{RON}{*}G(\text{speed, phi, VE}) + a_2{*}\text{MON}{*}H(\text{speed, phi, VE}) \qquad \text{Eq. 4}$$

Where: a_i are coefficients;
speed = scaled engine speed (rpm/1000);
phi = equivalence ratio based on H/C composition of fuel and measured fuel/air ratio;
VE = volumetric efficiency;
P(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -2 to 3 and exponents for phi and VE equal to unity;
RON = fuel average measured RON;
MON = fuel average measured MON;
G(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -1 to 3 and exponents for phi and VE equal to unity;
H(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -1 to 3 and exponents for phi and VE equal to unity.

General linear models were developed in an iterative fashion by deleting statistically non-significant higher order terms and occasionally omitting an outlier datum that was inconsistent with replicates or general trends. As anticipated from the general non-linear behavior of the data (see Figures 5a through 8b), non-linear terms were needed to represent the data. The results of this modeling effort were quite representative with goodness-of-fit measured by adjusted R squared values from 82 to 95%. Appendix C contains the details of the modeling procedures and results.

The RON and MON effects can be estimated by collecting the terms and parameters that include these variables. The collected octane coefficient may be a function of engine speed and/or other independent variables. For example, the RON coefficient based on spark timing for the Chrysler engine at standard temperature is:

RON coefficient = b_1 = -0.26274*speed + 1.78682*VE, Eq. 5
where VE = volumetric efficiency,

and the corresponding MON coefficient is:

MON coefficient = b_2 = 1.35779 + 0.26090*speed - 2.5057*VE. Eq. 6

Using the engine speed and corresponding VE, the octane coefficients as a function of engine speed can be calculated. For the several trials and all fuels, VE and phi vary by speed, but at constant speed and temperature the VE and phi are fairly constant (standard deviations are about 1% of the average variable value). Average VE and phi values by speed and temperature were thus employed to calculate the coefficients. Plots were made showing the dependence of RON and MON coefficients b_1 and b_2. Figures 9a through 12b show the trends for these coefficients as a function of engine speed for the two engines and two air temperatures used in this study. Coefficients are shown for both the spark timing effect and the normalized torque effect.

Figures 9a through 10b show the coefficients for the GM engine. For the spark timing effect (Fig. 9a), the coefficient for RON is very constant at +0.6 across the speed range, while the coefficient for MON starts near zero and drops to -0.6 at high speed. The relative error on the coefficients is very low indicated by the small error bar ticks indicating one standard error limits. For the coefficients based on torque (Fig. 9b) the coefficient for RON starts small and increases over the speed range while the coefficient for MON also starts near zero but then become more negative. For the GM engine at high intake air temperature (Fig. 10a), the RON coefficient is very constant at +0.5 while the MON coefficient again starts near zero and becomes more negative. For the coefficients based on torque (Fig. 10b), the RON value is very constant and the MON value starts positive but trends to zero at about 2700 rpm continuing to trend negative.

Figures 11a through 12b show the coefficients for the Chrysler engine. For both the spark timing effect (Figure 11a) and the normalized torque effect (Figure 11b), coefficient for RON is strongly positive but decreasing from 1200 to 6000 rpm to near zero. The MON coefficient is negative for much of the speed range and becomes slightly positive at about 4700+ rpm. For the Chrysler engine at high air temperature (Figures 12a and 12b), the coefficient plots for both spark and torque show that the coefficient for RON drops off at about 2700+ rpm approaching zero at 4700 rpm, while the behavior for the MON coefficient is a very slight increasing trend from about zero to +0.5.

As noted in the BACKGROUND section of this report, various investigators have attempted to characterize fuel impact on engine knock limited spark performance by the equation:

"Octane Index" = RON –K*S

where S = sensitivity = (RON – MON) and K is a constant.

If the RON and MON coefficients are defined as b_1 and b_2, then K is related to the octane coefficients by (for values of $b_1 + b_2$ not equal to zero):

$$K = b_2 / (b_1 + b_2). \qquad \text{Eq. 7}$$

Using the octane coefficients calculated above, values of "K" can be calculated as a function of speed. Figures 13a through 14b show the results of "K" as a function of engine speed for the two engines under various conditions. Each figure contains trends for K for both standard and heated intake air as a function of engine speed.

Figures 13a and 13b show the trends in K for the GM engine for the spark timing effect and the normalized torque effect, respectively. Figure 13a shows that K at standard intake air temperature is slightly negative at low speed and exponentially decreases to lower than -2.5 at 5200 rpm. The value at 6000 rpm was -30 because the value of b1 + b_2 was close to zero and not displayed. For high intake air temperature, the behavior on the plot is again slightly negative at low speed and decreases to near -1.0 at high rpm. Thus based on the spark timing effect, the value of K for the GM engine remains negative over all speeds for both standard and heated intake air. Thus knock resistance is completely dependent upon RON and to a greater or lesser extent, negatively dependent upon MON.

Examining the dependence of K for the GM engine based on torque (Fig. 13b), shows a constant value of about -1 for standard intake air temperature. For heated air K starts slightly positive at low speeds and gradually crosses zero at about 1700 rpm and then continues trending negative to lower than -2 at high speed 6000 rpm. Thus, based on torque, K is negative for all speeds at normal intake air temperature, and therefore dependent upon RON for knock resistance.

Figures 14a and 14b show the trends for K for the Chrysler engine, again for the spark timing effect and normalized torque effect, respectively. Figure 14a for the spark effect with standard air temperature indicates that K is negative -0.4 or greater over the speed range to about 4700 rpm. At greater speeds, K increases steadily to positive 0.7 at 6000 rpm. When the intake air is heated to the Chrysler engine, K is now near zero and slightly positive until about 2700 rpm, when K increases to about +0.7. The error bars (one standard error) on the values of K also show that the uncertainty in K is large and these are general trends, but with high uncertainty. For the value of K for the Chrysler engine based on normalized torque (Figure 14b), the trends are similar to that for the spark effect. At the standard temperature, the torque-based K is highly negative at low speed, and gradually increases to become positive at 4700 rpm, increasing to 0.8 at 6000 rpm. For heated air intake in the Chrysler engine, K starts off as slightly positive and increases at 2700 rpm to unity at high speed, indicating a complete dependence on MON for knock resistance. Again the error bars on the K values derived from torque indicate a high degree of uncertainty in K.

VIII. CONCLUSIONS

The conclusions of the CRC scoping study on engine response to RON versus MON are as follows:

1. Scoping tests were performed with 5 hydrocarbon-only gasolines of varying RON and MON octane levels in two engines. One engine was a 2008 Chrysler 5.7 liter HEMI large bore, and the other was a 2.0 liter direct-injection, turbocharged GM Ecotec engine. Each manufacturer ran their own engine at their test facilities. Measurements were made over a speed ranges 1200 to 6000 rpm with normal and heated air intakes. Both spark advance and normalized torque were the response variables measured in these engine dynamometers tests. Significant differences in ability to resist knock were observed among the five fuels tested.

2. Changes in engine performance measured by spark loops are due to fuel knock resistance. As an example, Fuel 5 with high RON and high Sensitivity (95HS) allows greater spark advance that improves combustion phasing relative to Fuel 2 (92MS) that has a similar MON for both engines at most conditions (but not for the Chrysler engine at high speeds)..

3. Fuel 5 (95HS) showed the most resistance to knocking in both engines at most of the conditions tested.

4. For the larger displacement Chrysler engine, at high intake air temperature, and RPM above 4400, the lowest sensitivity fuel (Fuel 3 – 88LS) with the highest MON had the greatest knock resistance.

5. Fuel 3 (88LS) showed the least resistance to knocking at most of the conditions compared to Fuels 1 (93HS) or 2 (92MS). All three of which had approximately the same (R+M)/2, about 88.

6. For fuels of approximately constant sensitivity (Fuels 1, 4 and 5); Fuels 1 (93HS) and 5 (95HS) provided greater resistance to knock under all conditions in both engines compared to Fuel 4 (92HS).

7. The value of "K" was determined for the Octane Index equation OI = (1-K)*RON + K*MON as a function of speed and engine intake air temperature.

   7.1 For the GM Ecotec engine at most engine speeds and standard and heated air conditions, K is negative over the entire speed range when determined from either the spark advance or the normalized torque results.

7.2 This means that the knock resistance is predominately dependent upon the RON of the fuel and to a greater or lesser extent, negatively dependent upon the MON of the fuel.

7.3 For the GM engine with heated air and speeds below 2700 rpm, K is marginally positive.

7.4 The error bars around K suggest a degree of uncertainty in the value of K.

8. For the value of K from tests done on the Chrysler big-bore engine, variable results are seen.

8.1 Based on spark timing or normalized torque at standard intake air temperature, K is negative -0.4 or greater over the speed range to about 4700 rpm. This indicates a knock resistance dependence upon increased RON and decreased MON.

8.2 At greater speeds, K increases steadily to a positive 0.7-0.8 at 6000 rpm now indicating a knock resistance related to (R+M)/2.

8.3 When the intake air is heated to the Chrysler engine, based on the spark advance, K at low rpm is now near zero and slightly positive until about 2700 rpm, when K increases to about +0.7.

8.4 The error bars (one standard error) on the values of K based on spark also show that the uncertainty in K is large and these are general trends, but with high uncertainty.

8.5 For heated air intake in the Chrysler engine, K starts off as slightly positive and increases at 2700 rpm to unity at high speed, indicating a complete dependence on MON for knock resistance.

8.6 Again the error bars on the K values derived from torque indicate a high degree of uncertainty in K.

9. Based on the results of this study for both engines and most, but not all conditions tested, RON has a stronger effect on resistance to knock than MON. This conclusion is in agreement with the latest octane studies cited in this report. There are some conditions that are an exception to this conclusion: for example the large displacement engine at high intake air temperatures and speeds above 4400 RPM. Thus MON still is an important octane characteristic for certain engines. This finding is not unexpected given the studies of the sensitivity of K to engine speed and intake temperature conducted by Mittal&Heywood[(4)].

IX. RECOMMENDATIONS

Recommendations resulting from this CRC scoping study for future work are as follow:

- Perform a thorough literature search of octane effects on modern engine and vehicle performance. Use engineering analysis to estimate the range of engine and vehicle performance improvements possible with changes in the RON, MON, and octane sensitivity. Specifically, obtain good estimate for the potential increase in compression ratio and thermal efficiency with the increase of one octane. Define any data and technology gaps in the octane area.

- Evaluate octane sensitivity effects under part-throttle conditions, studying combustion efficiency, emissions, and fuel economy, among others.

- Evaluate octane sensitivity effects for US fleet vehicles under varying operating conditions, including knock-limited and non-knock-limited tests, and the influence of intake air temperature on the MON requirement of vehicles using an all-weather chassis dynamometer.

- Evaluate the RON and MON effects of ethanol-blended fuels including efficiency improvements from high sensitivity ethanol fuel blends.

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TABLES

AND

FIGURES

Table 1

CRC RON vs MON Program Average Blend Inspections

Fuel Description			**#1 93HS**	**#2 92MS**	**#3 88LS**	**#4 92HS**	**#5 95HS**
Property	**Method**	**Units**	**Average**	**Average**	**Average**	**Average**	**Average**
Gravity	ASTM D4052	°API	56.5	58.9	69.6	56.8	56.6
Relative Density		g/gal	0.7526	0.7433	0.7036		0.7524
DVPE	ASTM D5191	psi	8.4	7.9	7.8	7.7	7.9
Distillation	ASTM D86						
Initial Boiling Point		°F	94.7	95.0	93.8	95.3	94.3
5% Evaporated		°F	120.9	122.2	120.2	123.2	121.4
10% Evaporated		°F	130.9	134.8	132.0	135.0	132.5
20% Evaporated		°F	146.6	156.2	153.3	154.9	149.8
30% Evaporated		°F	163.5	178.3	177.6	174.3	168.8
40% Evaporated		°F	183.9	201.9	205.3	195.5	190.5
50% Evaporated		°F	208.4	222.3	219.2	220.9	214.3
60% Evaporated		°F	234.7	241.1	230.4	251.3	238.4
70% Evaporated		°F	259.6	261.4	239.7	281.6	264.0
80% Evaporated		°F	283.7	295.0	254.7	311.4	294.2
90% Evaporated		°F	319.7	326.5	296.8	325.4	323.2
95% Evaporated		°F	332.3	337.0	333.4	332.0	331.7
End Point		°F	356.7	368.6	371.4	351.5	353.1
Recovery		vol %	98.3	97.9	97.3	97.8	97.3
Residue		vol %	1.1	1.0	1.5	1.1	0.9
Loss		vol %	0.6	1.1	1.2	1.1	0.7
Research ON			93.8	92.4	89.1	91.7	94.3
Research ON			93.9	92.5	89.2	91.7	94.3
Research ON Average			93.8	92.4	89.1	91.6	94.3
Motor ON			82.3	83.4	86.6	80.9	83.4
Motor ON			82.2	83.5	86.5	81.0	83.7
Motor ON Average			82.3	83.4	86.6	80.9	83.5
(R+M)/2			88.0	87.9	87.8	86.3	88.9
Sensitivity			11.5	9.0	2.5	10.7	10.8
Sulfur			45.0	29.5	5.5	32.0	41.5
Benzene	DHA	vol %	0.6	0.4	0.2	0.6	0.7
Hydrocarbon**							
Aromatics	DHA	vol %	35.2	28.4	6.4	32.6	34.5
Olefins	DHA	vol %	20.0	12.0	0.5	26.0	15.4
Saturates	DHA	vol %	44.8	59.6	93.2	41.3	50.2
Net Heat of Combustion							
Measured	D4809	BTU/LB					
Calculated	DHA	BTU/LB					
Calculated	D3338	BTU/LB	18347	18492	18973	18411	18368

RON Target			93.4	91.9	88.4	91.9	94.9
MON Target			81.4	82.9	86.4	79.9	82.9
(R+M)/2 Range			86.9-87.9	86.9-87.9	86.9-87.9	85.4-86.4	88.4-89.4
Sensitivity Target			12.0	9.0	2.0	12.0	12.0

Table 2

Test Conditions Used for the Chrysler 5.7-Liter HEMI Engine

Standard Conditions	**Minimum**	**Maximum**
Inlet Air Temperature (°C)	22	28
Coolant Temperature (°C)	97	103
Pcorr F (kPa)	96	100
Vapor Pressure (kPa)	0.8	1.2

High-Temperature Conditions	**Minimum**	**Maximum**
Inlet Air Temperature (°C)	55	65
Coolant Temperature (°C)	117	123
Pcorr F (kPa)	96	100
Vapor Pressure (kPa)	0.8	1.2

Table 3

Test Conditions Used for the GM 2.0-Liter Ecotec Engine

Standard Conditions	**Minimum**	**Maximum**
Charge Air Cooler Outlet Temperature (°C)	29	35
Coolant Temperature (°C)	88	93
Pcorr F (kPa)	99	101
Dew Point Temperature (°C)	6.3	6.8

High-Temperature Conditions	**Minimum**	**Maximum**
Charge Air Cooler Outlet Temperature (°C)	58	64
Coolant Temperature (°C)	88	93
Pcorr F (kPa)	98.2	100.3
Vapor Pressure (kPa)	5.6	6.4

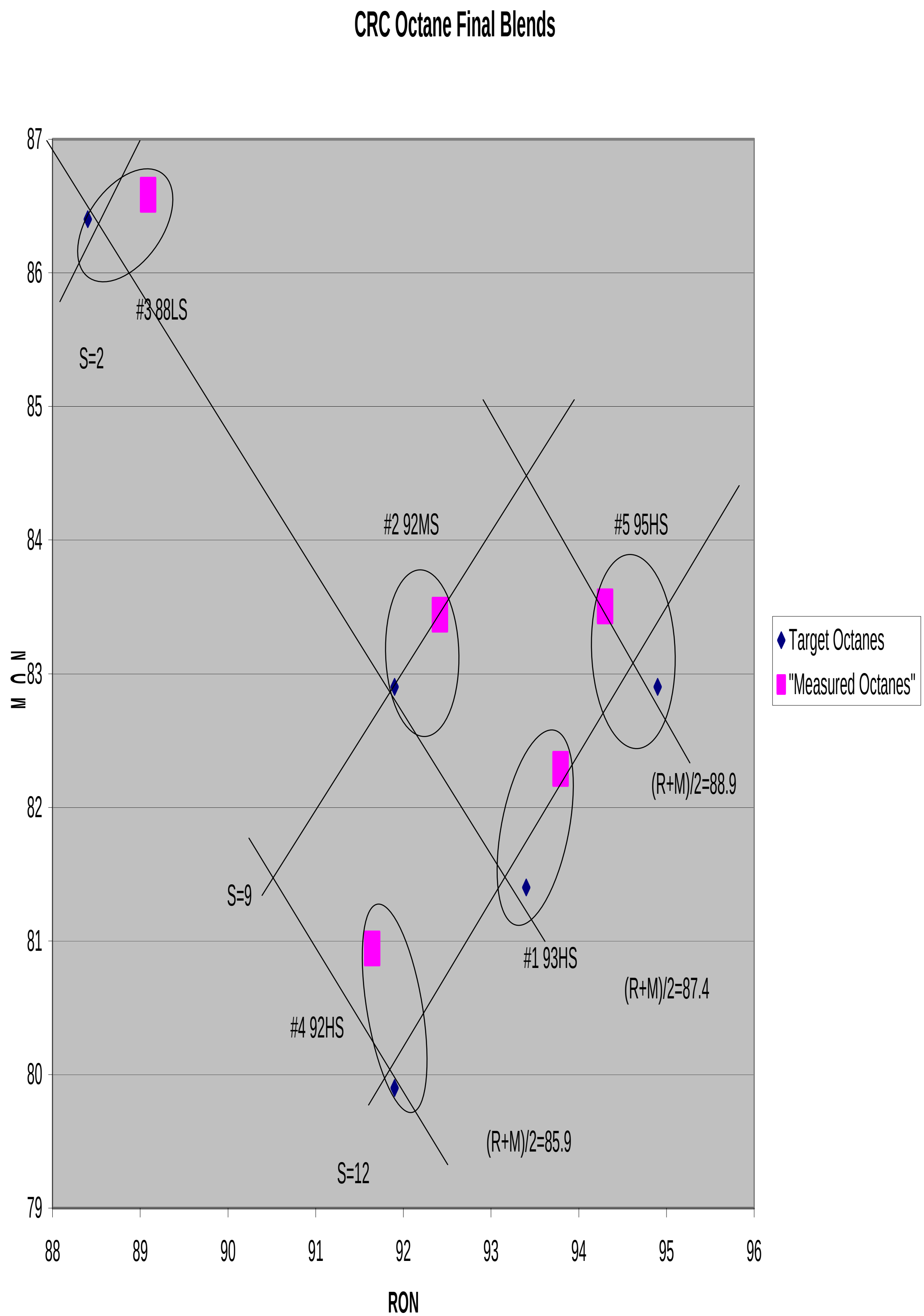
Table 4

CRC RON vs MON Scoping Tests Results Trends Analysis

Engine	Speed range	Air Temp.	Constant	Fuels	Knock Resistance Most	Next	Least	Notes
GM 2.0l	1200-6000	Std.+ Htd.	(R+M)/2	1,2,3	**1**	**2**	**3**	For heated air, similar spark adv. for fuels 1+2 at 5000+ rpm.
Chry. 5.7l	1200-5200	Std.	(R+M)/2	1,2,3	**1**	**2**	**3**	
Chry. 5.7l	1200-4400	Htd.	(R+M)/2	1,2,3	**1**	**2**	**3**	
Chry. 5.7l	4400+	Htd.	(R+M)/2	1,2,3	**3**	**2=1**	**1=2**	
GM 2.0l	1200-6000	Std.+ Htd.	S=RON-MON	1,4,5	**5=1**	**1=5**	**4**	
Chry. 5.7l	1200-5200	Std.	S=RON-MON	1,4,5	**5**	**1**	**4**	
Chry. 5.7l	1200-6000	Htd.	S=RON-MON	1,4,5	**5=1**	**1=5**	**4**	
GM 2.0l	1200-6000	Std.+Htd.	RON	2,4	**2=4**		**4=2**	Similar knock resistance using Torque.
Chry.5.7l	1200-5200	Std.+Htd.	RON	2,4	**2**		**4**	Slight differences seen using torque, no difference using spark adv.
GM 2.0l	1200-6000	Std.+Htd.	MON	2,5	**5**		**2**	
Chry. 5.7l	1200-5200	Std..	MON	2,5	**5**		**2**	Similar torque for all fuels at 5200+ rpm
Chry. 5.7l	1200-4000	Htd.	MON	2,5	**5**		**2**	Similar torque for all fuels at 4000+ rpm

Fuels	**Name**	**RON**	**MON**	**(R+M)/2**	**S=RON-MON**
1	93HS	93.8	82.3	88	11.5
2	92MS	92.4	83.4	87.9	9
3	88LS	89.1	86.6	87.8	2.5
4	92HS	91.6	80.9	86.3	10.7
5	95HS	94.3	83.5	88.9	10.8

Figure 1



CRC Octane Final Blends
87
86
85
84
83
82
81
80
79
88
89
90
91
92
93
94
95
96
RON
M O N
#3 88LS
S=2
#2 92MS
#5 95HS
(R+M)/2=88.9
S=9
#1 93HS
(R+M)/2=87.4
#4 92HS
(R+M)/2=85.9
S=12
Target Octanes
"Measured Octanes"

Figure 2

Targets for Fuel Blends

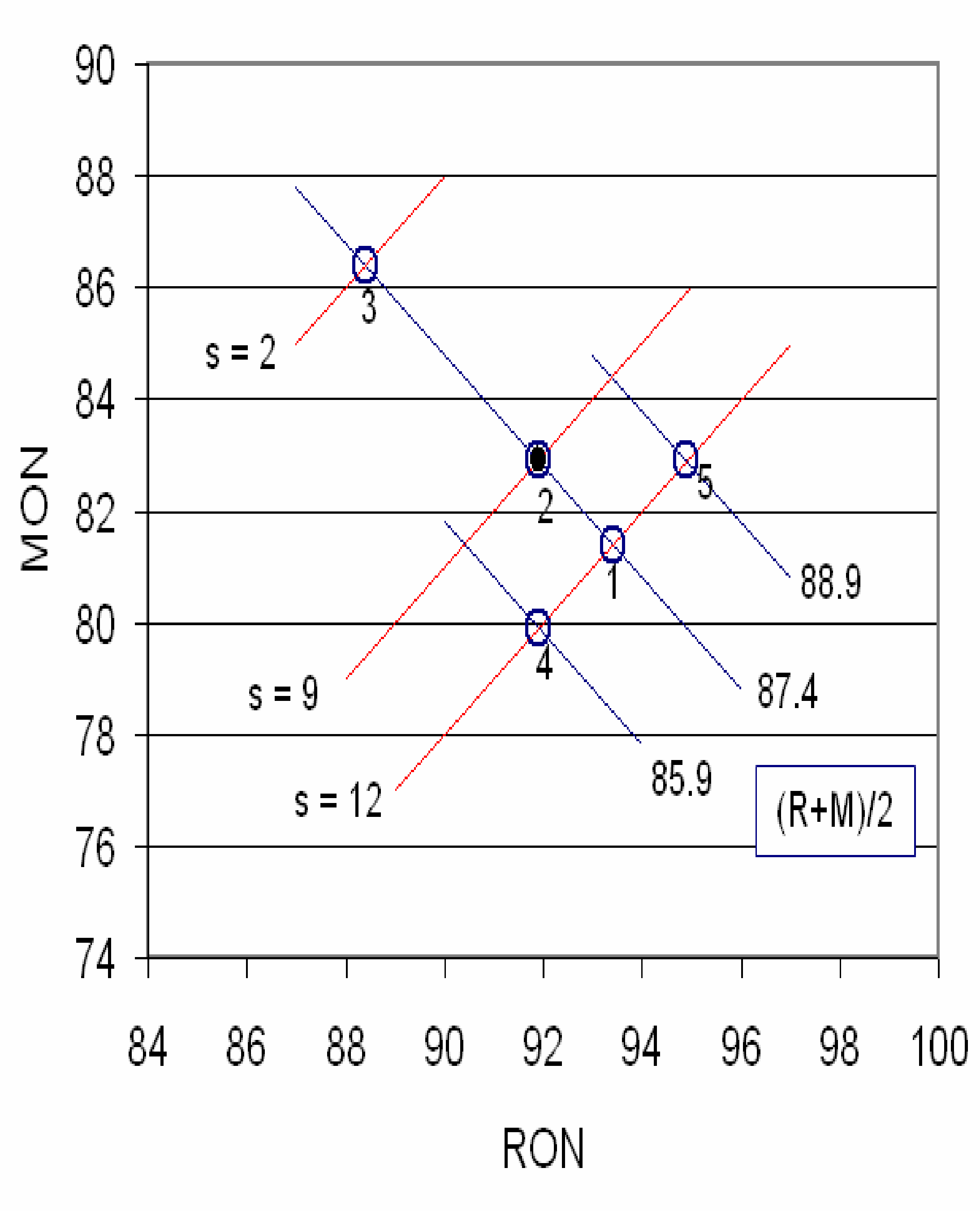


Figure 3

Note: Figure 3 References Mittal SAE Paper 2008-01-2414[(4)]

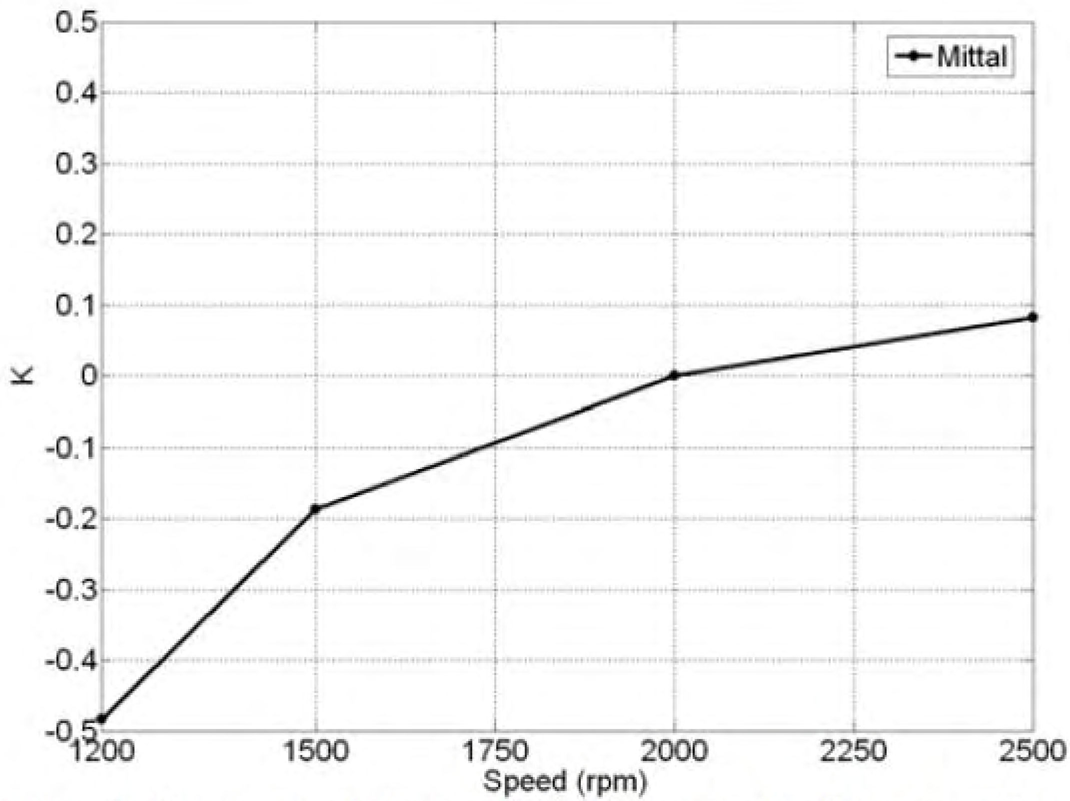


Figure 9: K as a function of engine speed. The results show a strong dependence K and engine speed.

Figure 4

NOTE: Figure 4 References Mittal SAE Paper 2008-01-2414[4]

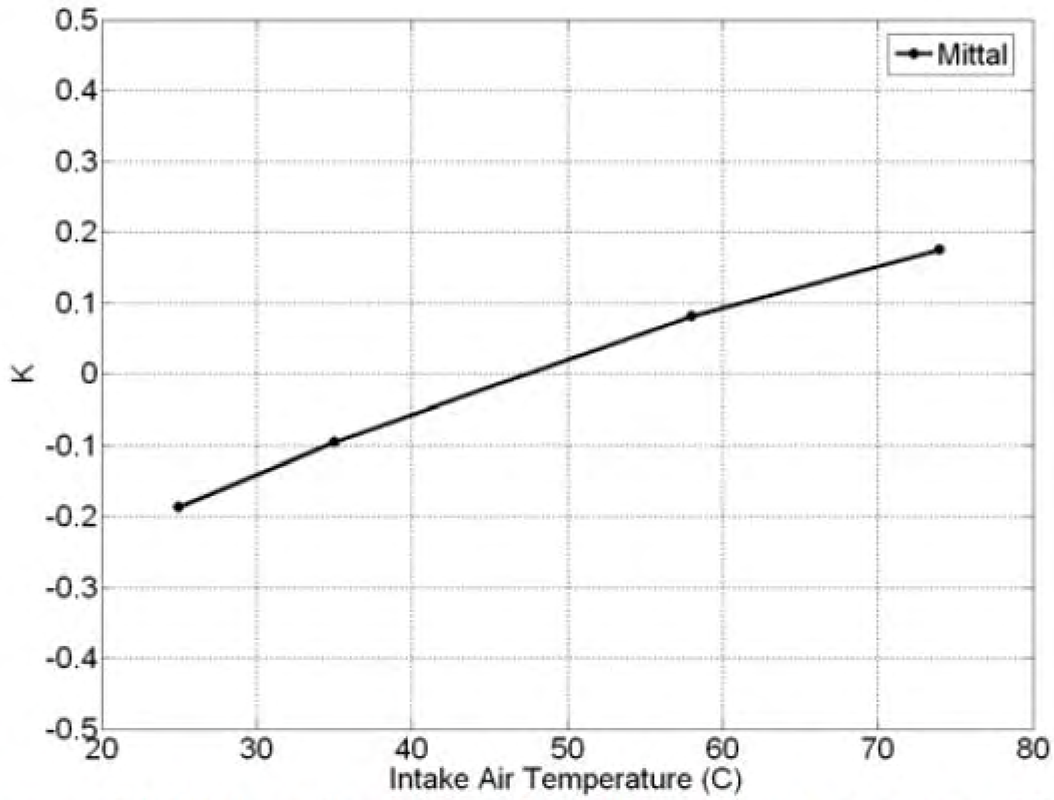


Figure 11: K as a function of intake air temperature. The results show a very linear relationship between K and intake air temperature

Figure 5a

Test Results from GM 2.0-Liter Ecotec Engine on Standard Intake Air – Spark Advance

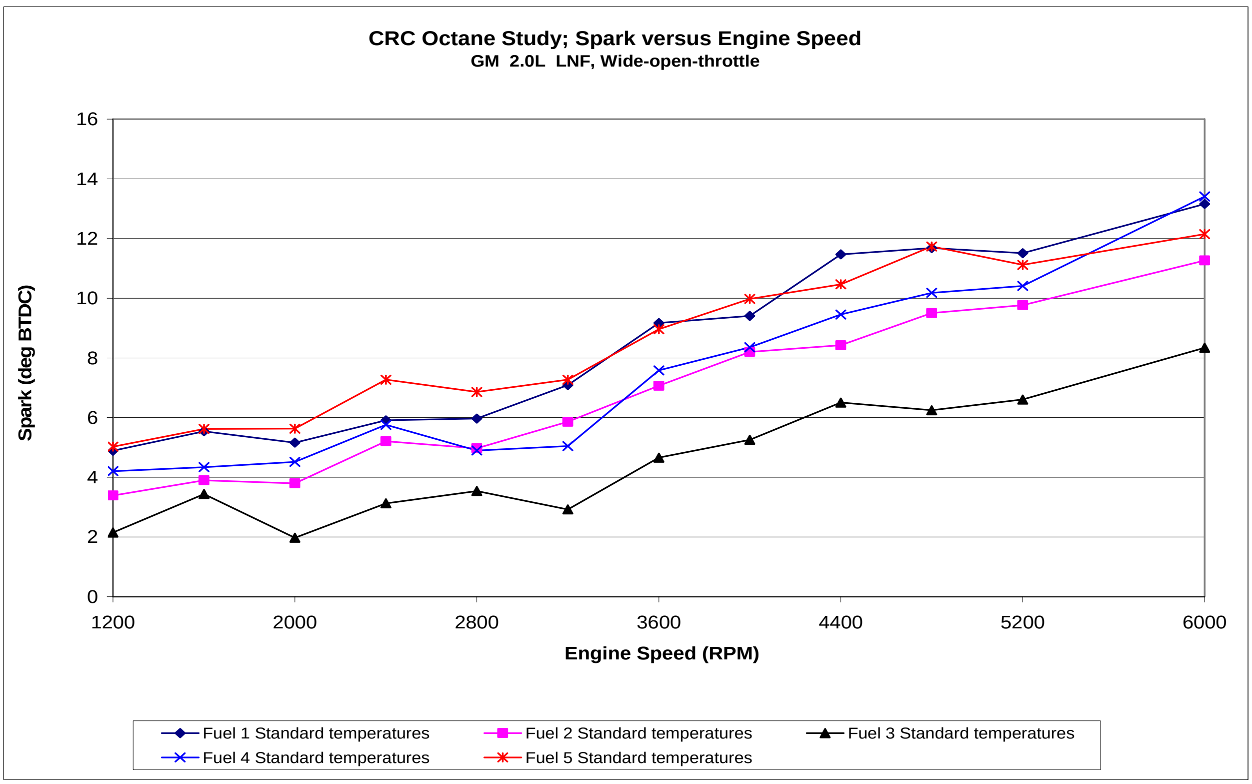


Figure 5b

Test Results from GM 2.0-Liter Ecotec Engine on Standard Intake Air – Normalized Torque

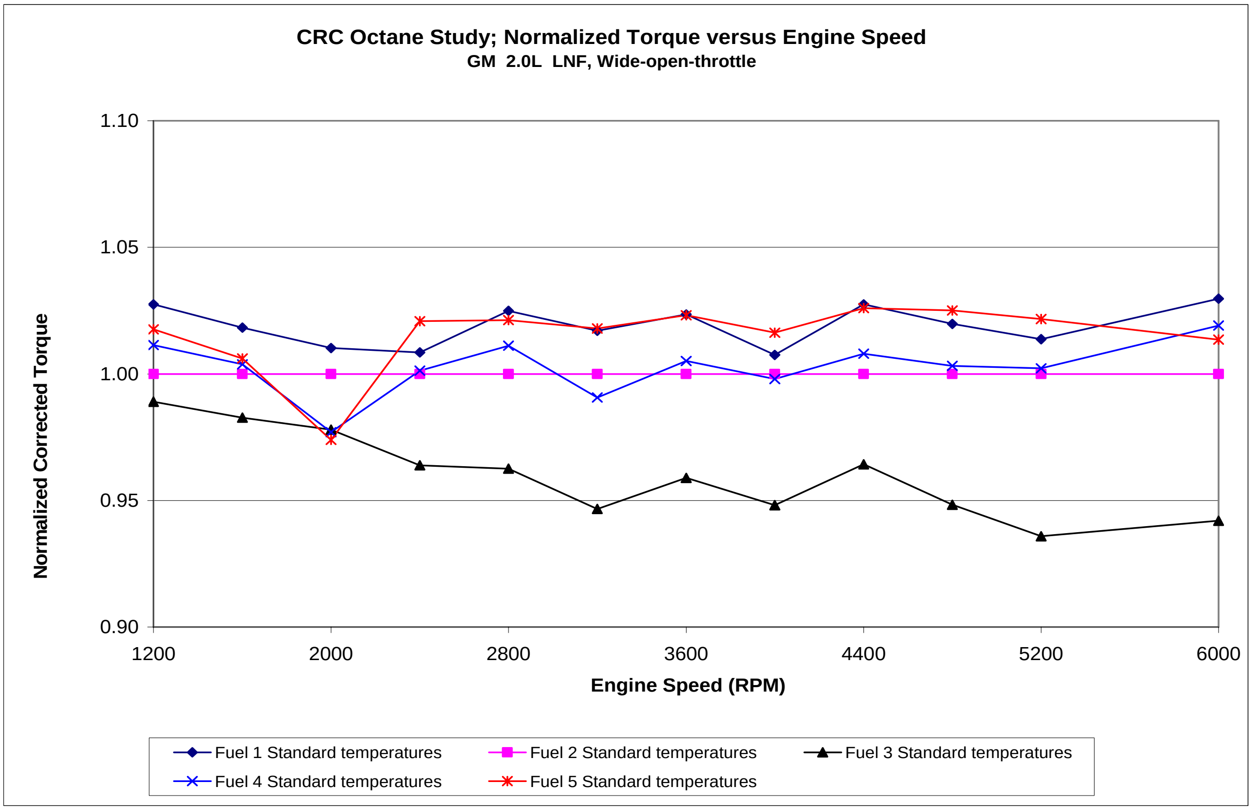


Figure 6a

Test Results from GM 2.0-Liter Ecotec Engine on Heated Intake Air – Spark Advance

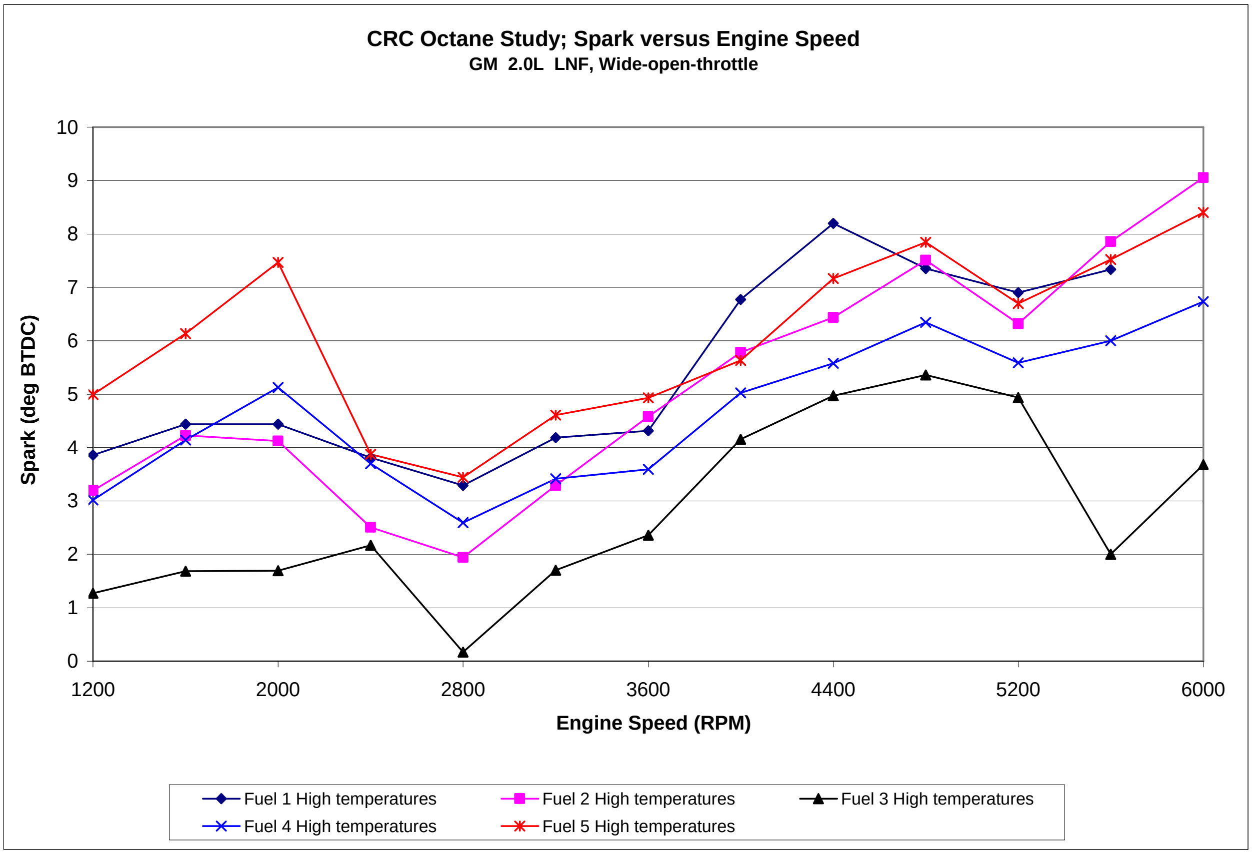


Figure 6b

Test Results from GM 2.0-Liter Ecotec Engine on Heated Intake Air – Normalized Torque

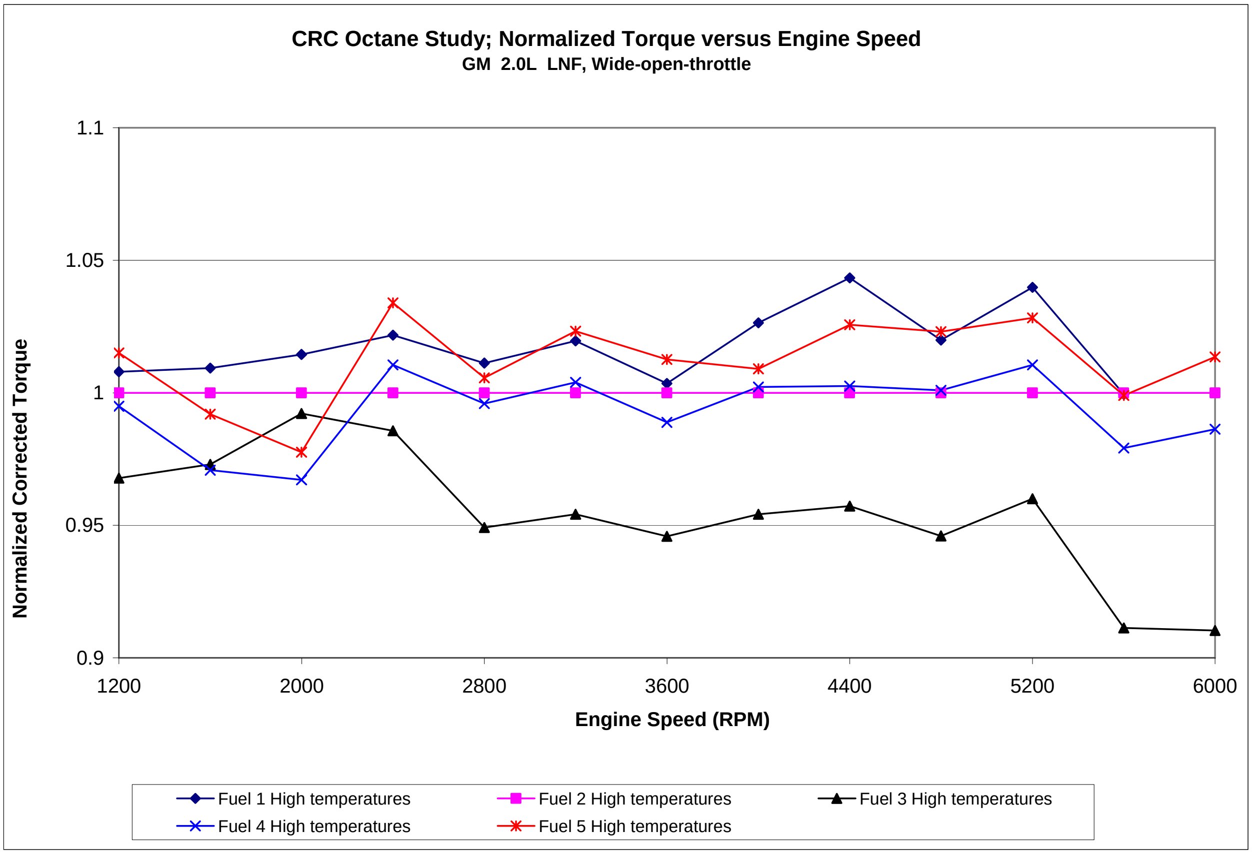


Figure 7a

Test Results from Chrysler 5.7-Liter Hemi Engine on Standard Intake Air – Spark Advance

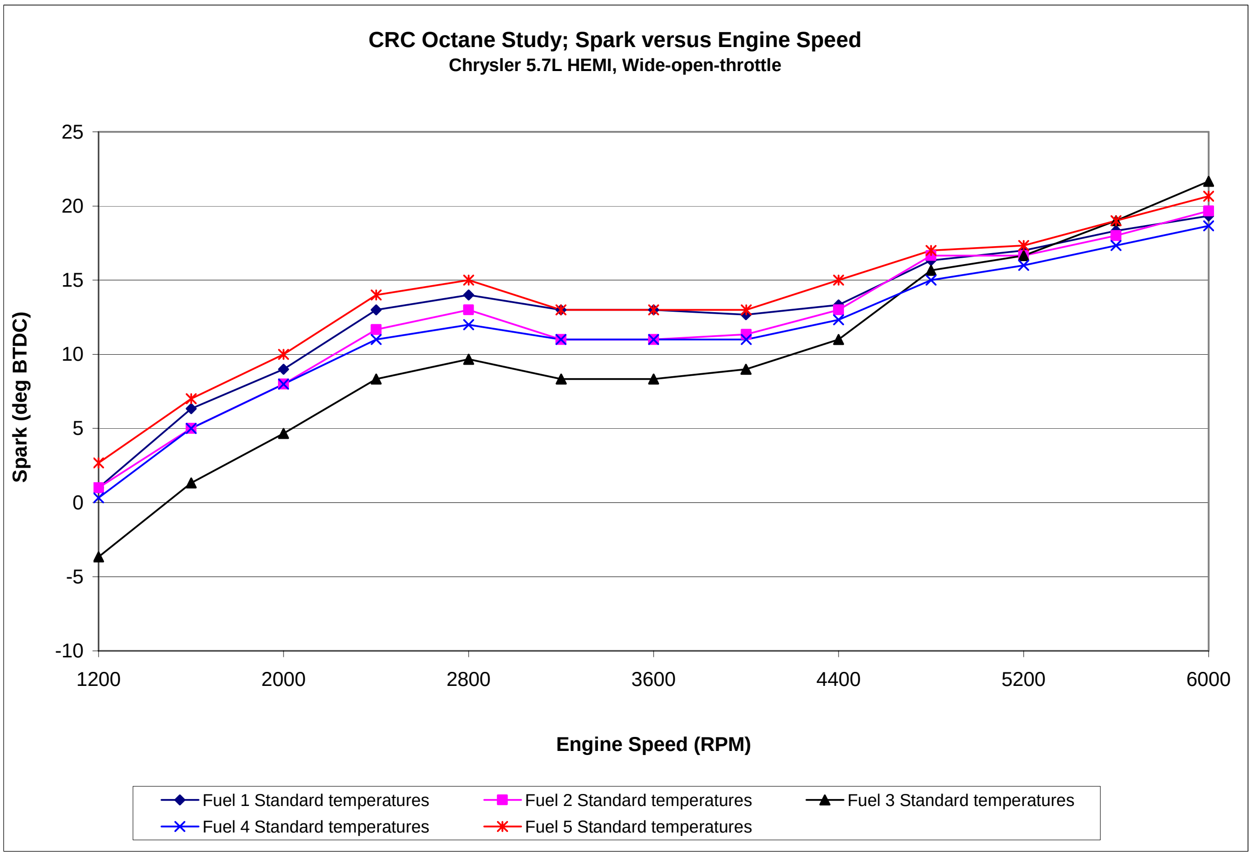


Figure 7b

Test Results from Chrysler 5.7-Liter Hemi Engine on Standard Intake Air – Normalized Torque

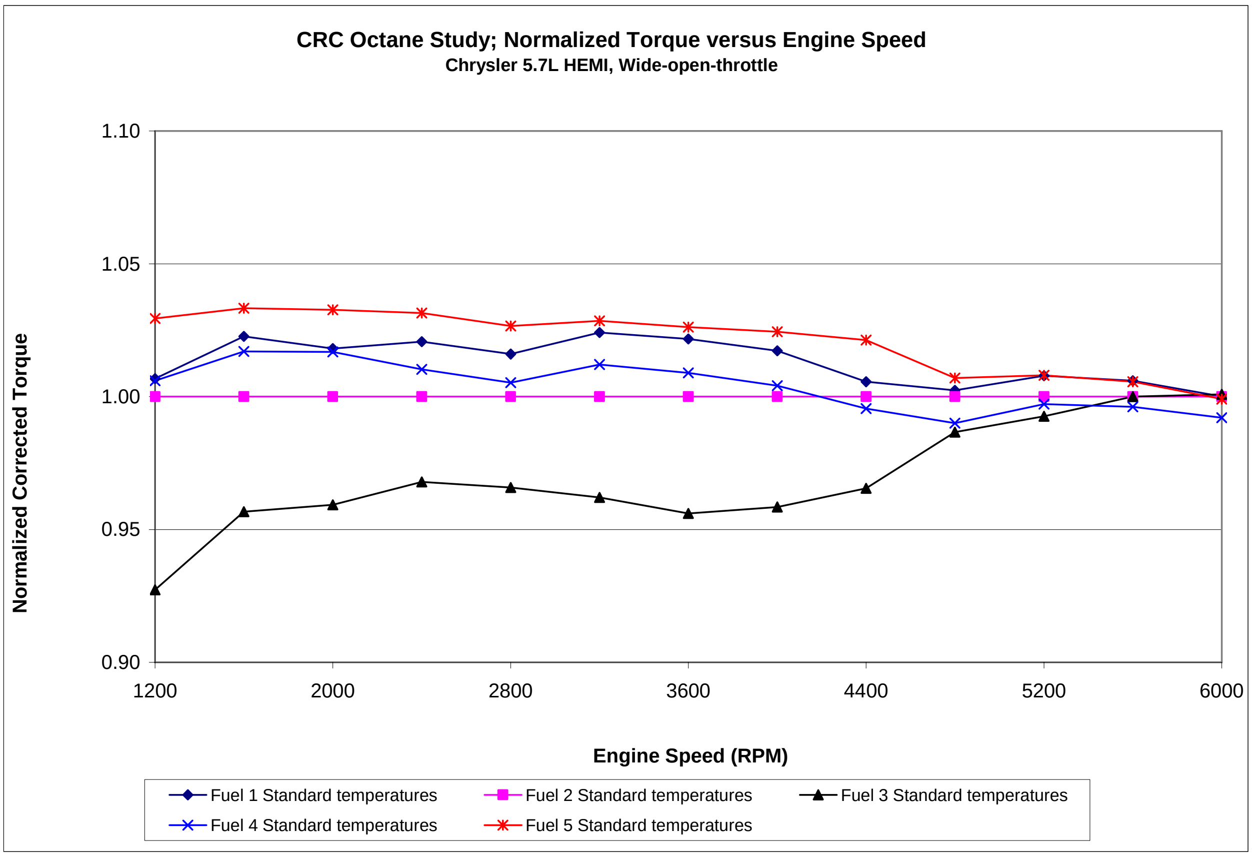


Figure 8a

Test Results from Chrysler 5.7-Liter Hemi Engine on Heated Intake Air – Spark Advance

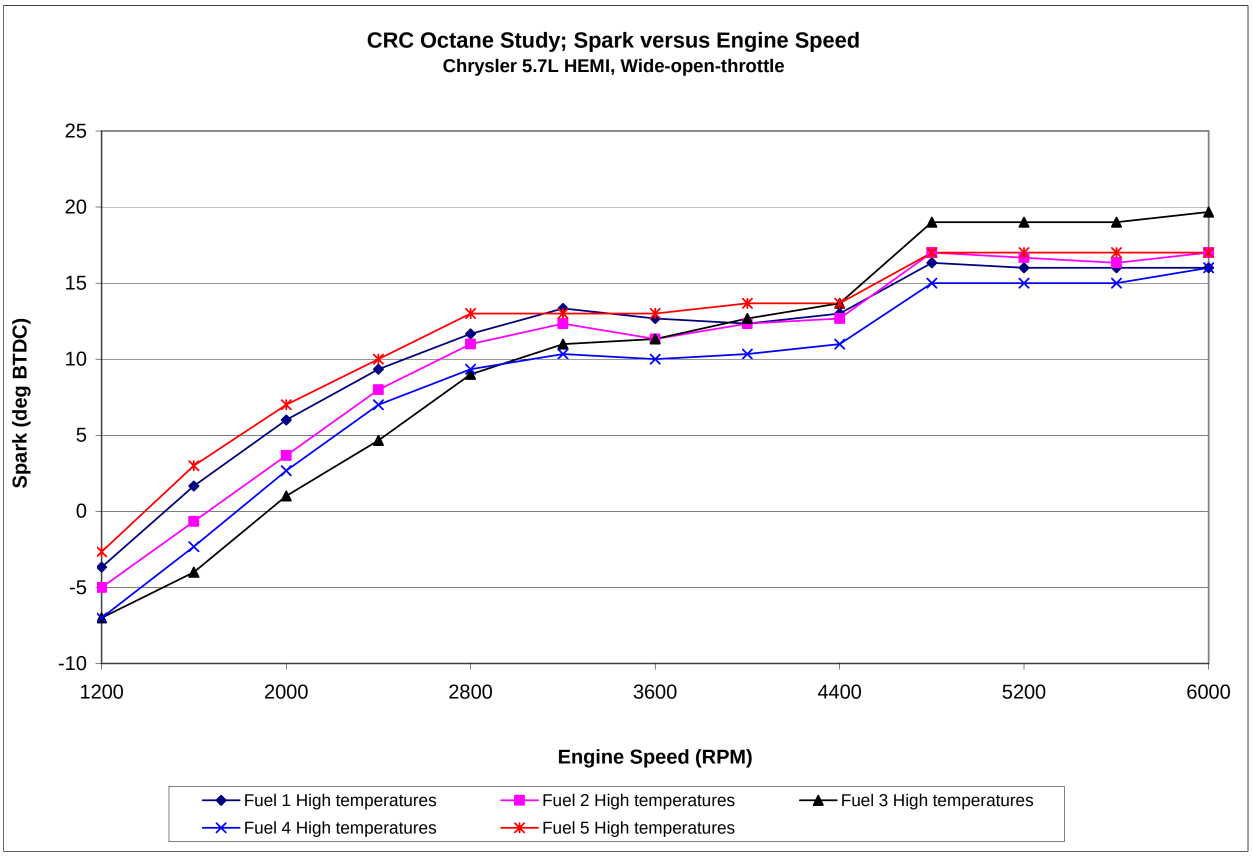


Figure 8b

Test Results from Chrysler 5.7-Liter Hemi Engine on Heated Intake Air – Normalized Torque

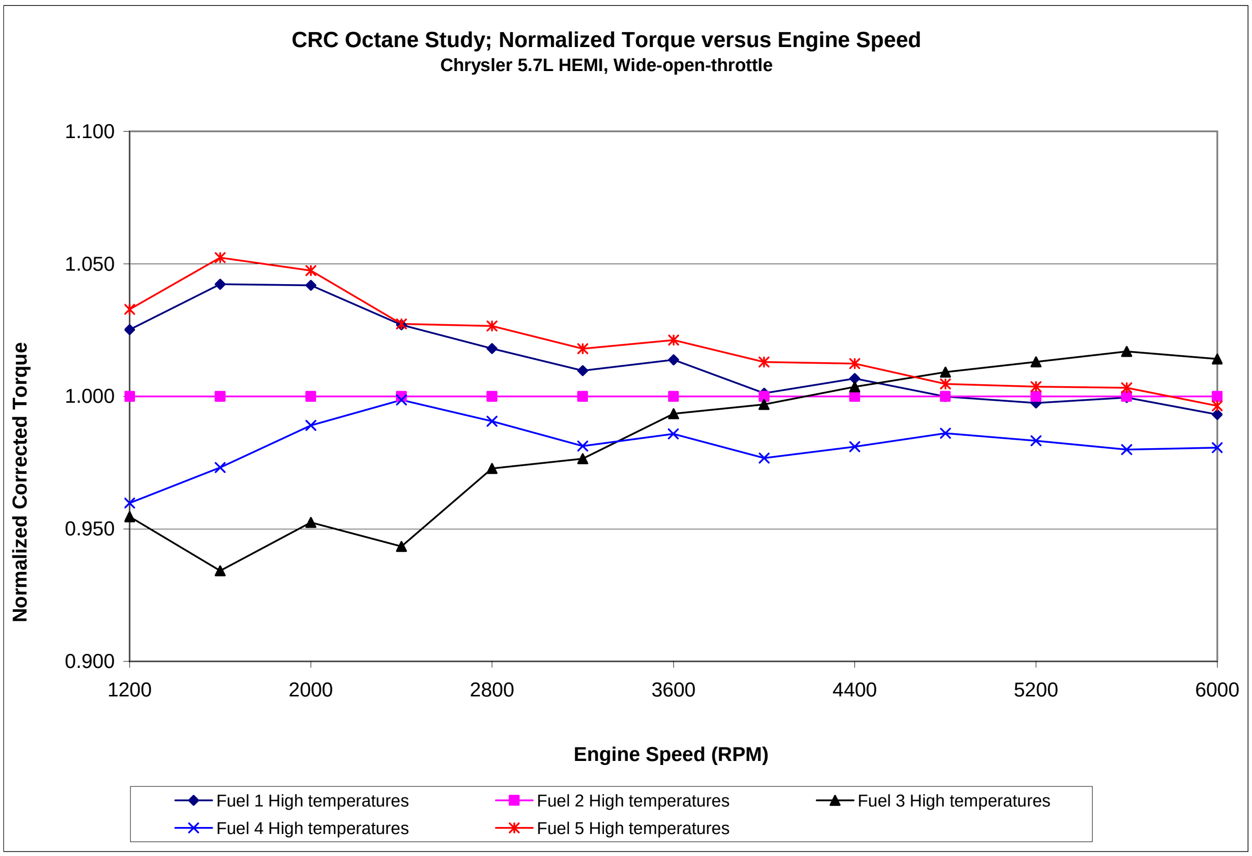


Figure 9a

Octane Coefficients for GM Engine,
Spark Timing Effect – Standard Air Temperature

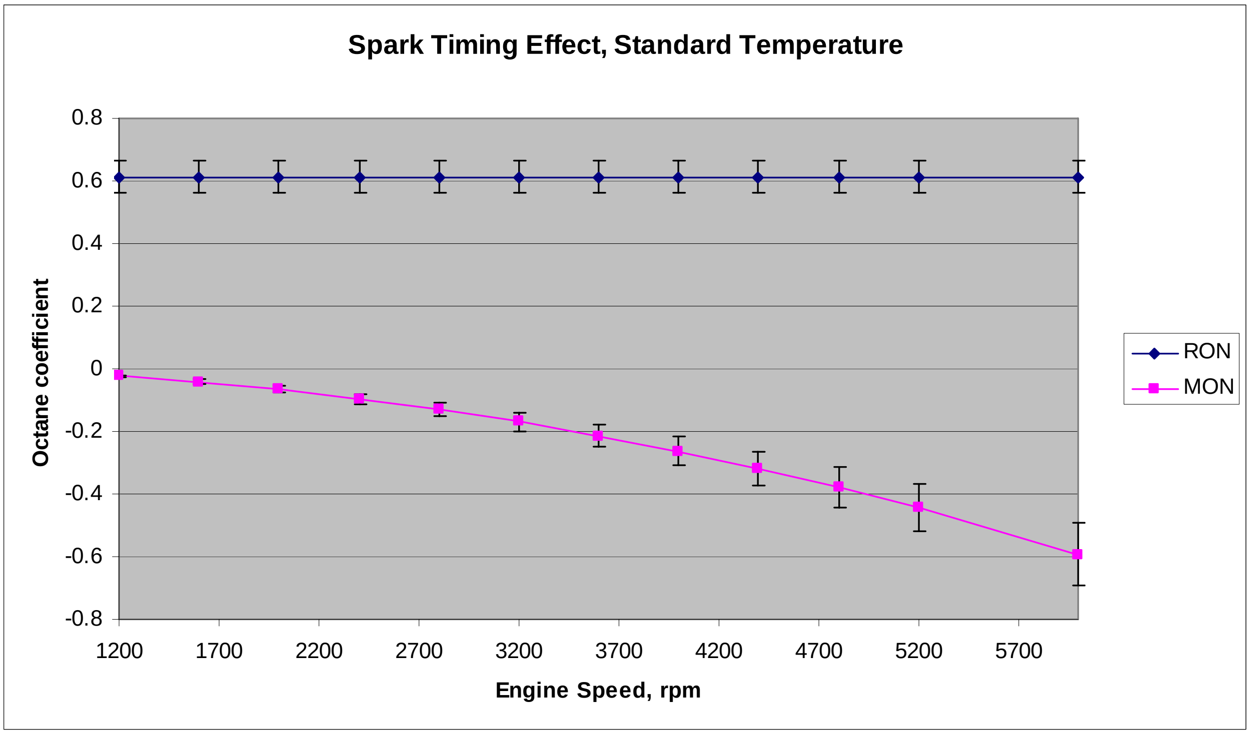


Figure 9b

Octane Coefficients for GM Engine
Torque Effect – Standard Air Temperature

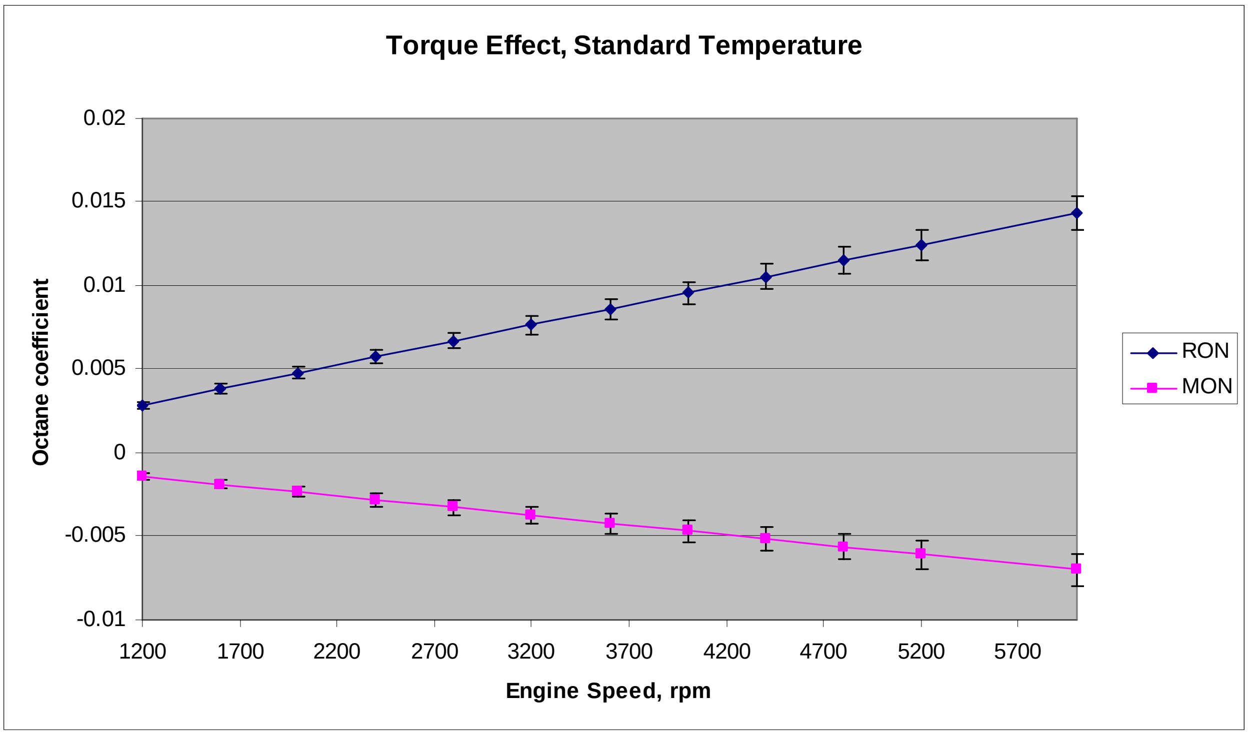


Figure 10a

Octane Coefficients for GM Engine
Spark Timing Effect – Heated Air Temperature

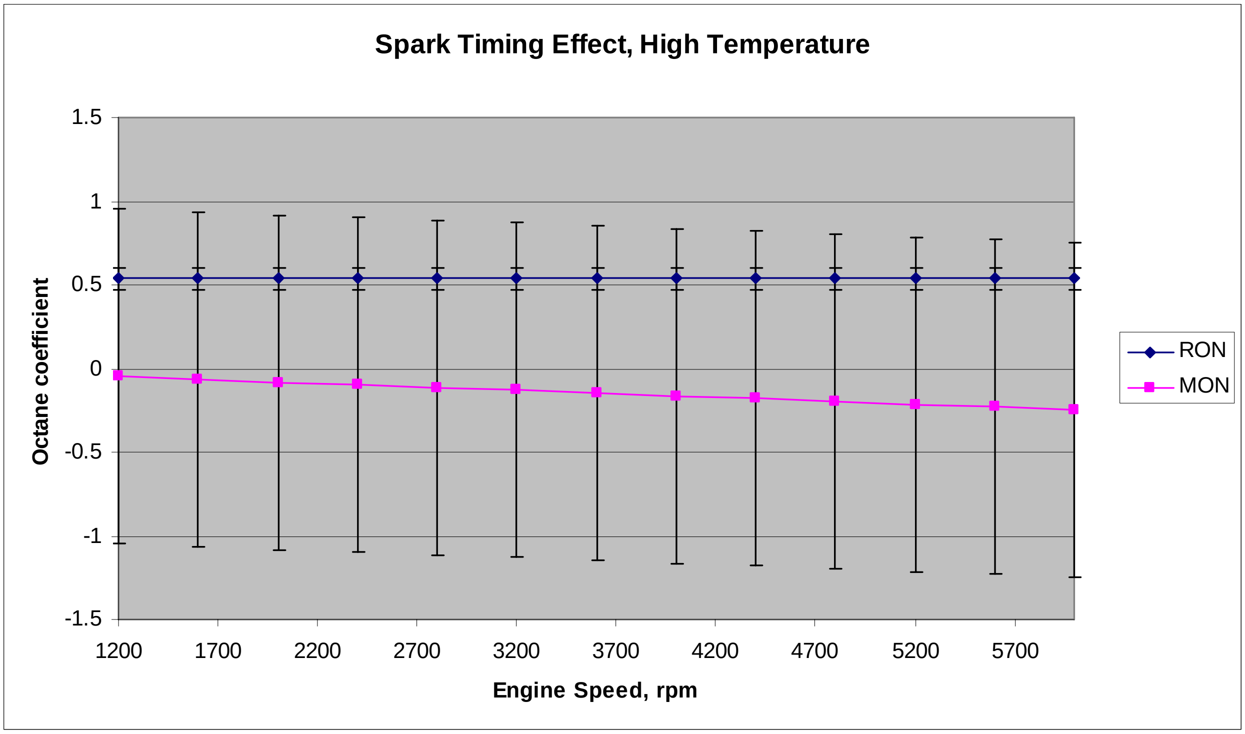


Figure 10b

Octane Coefficients for GM Engine
Torque Effect – Heated Air Temperature

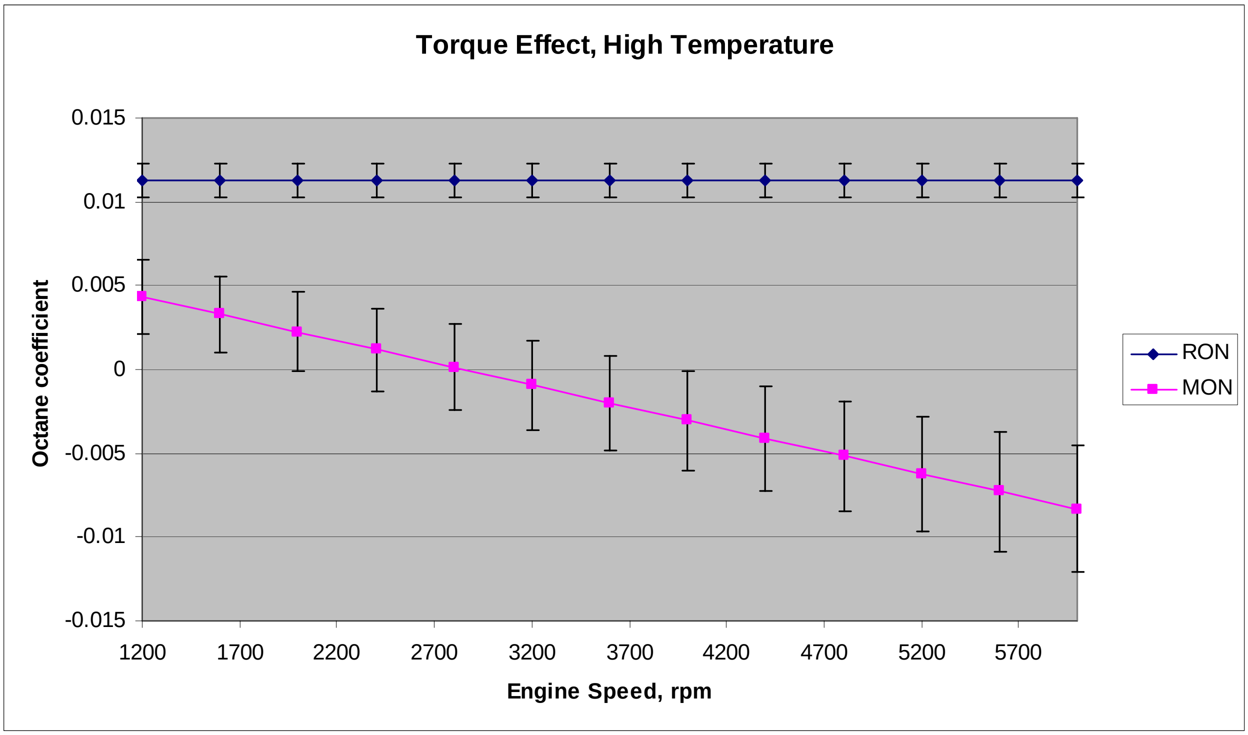


Figure 11a

Octane Coefficients for Chrysler Engine
Spark Timing Effect – Standard Air Temperature

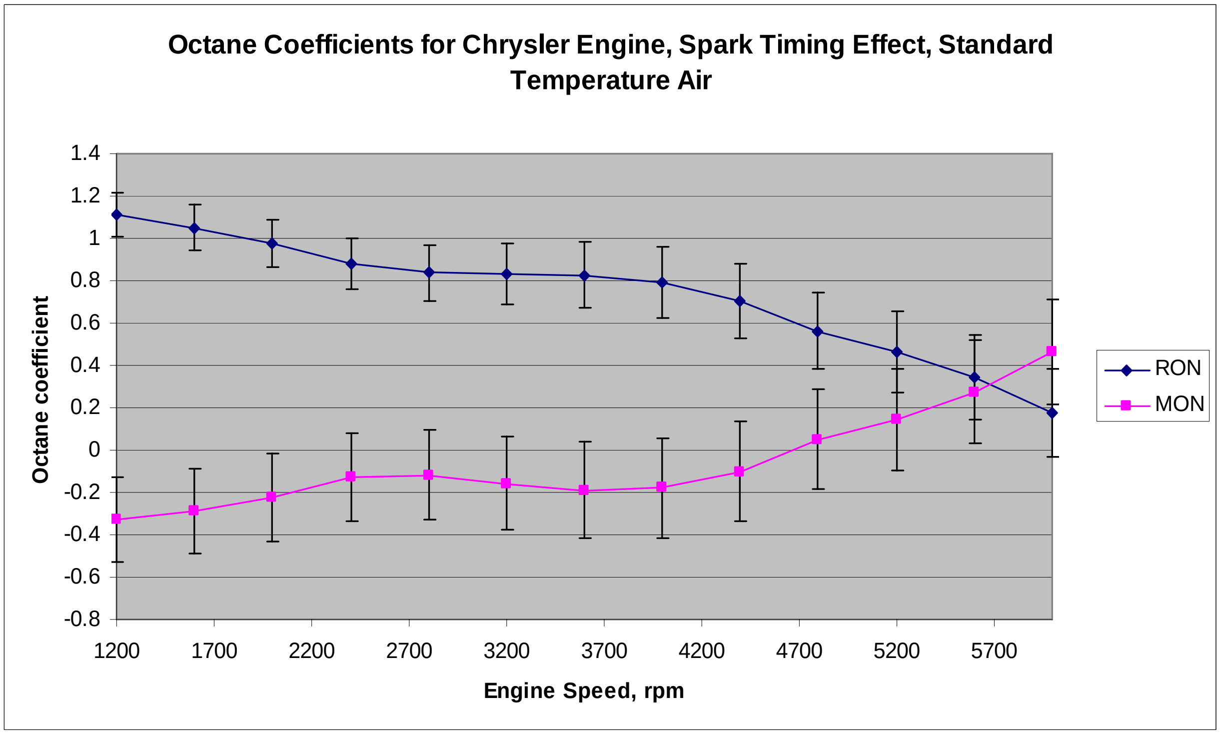


Figure 11b

Octane Coefficients for Chrysler Engine
Torque Effect – Standard Air Temperature

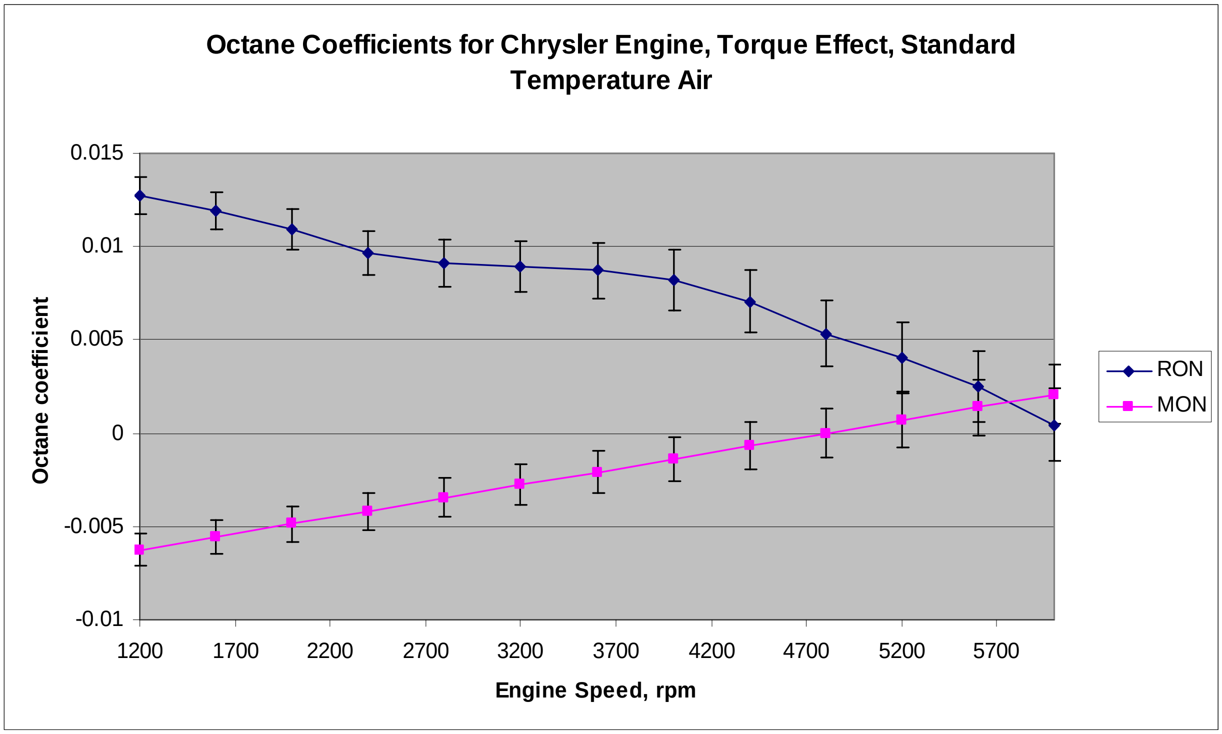


Figure 12a

Octane Coefficients for Chrysler Engine
Spark Timing Effect – Heated Air Temperature

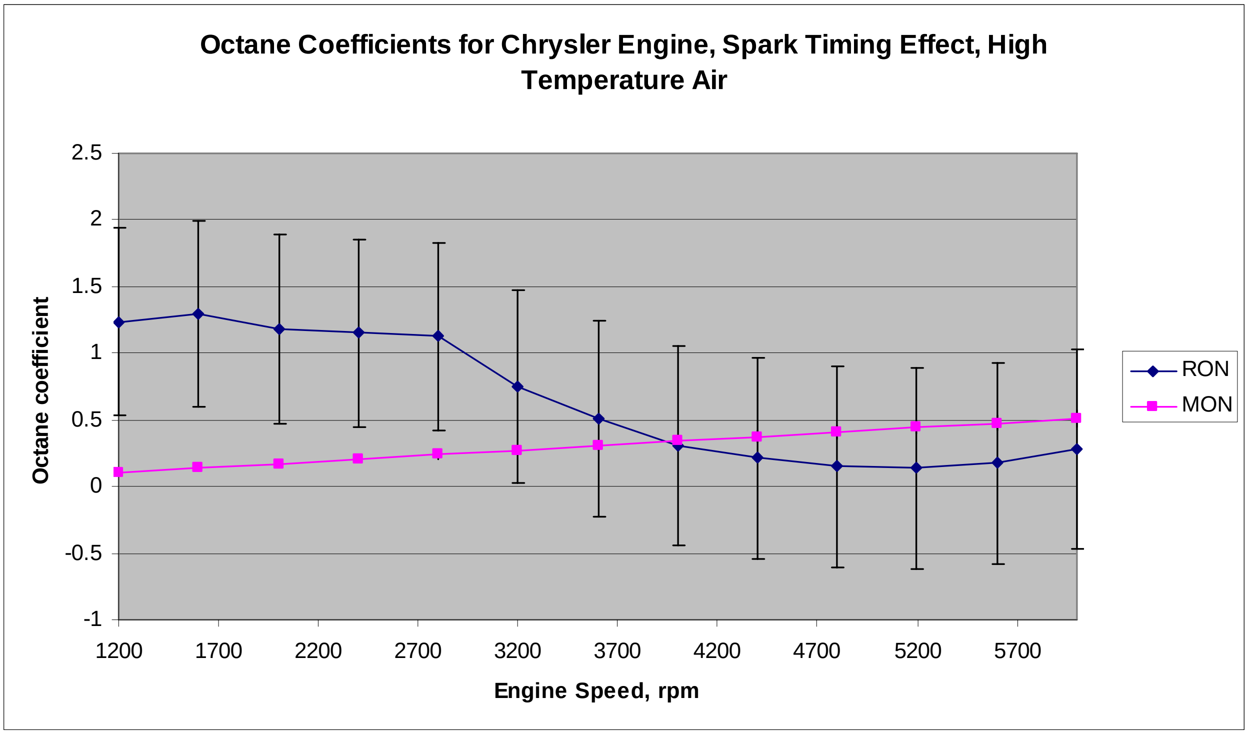


Figure 12b

Octane Coefficients for Chrysler Engine – Torque Effect

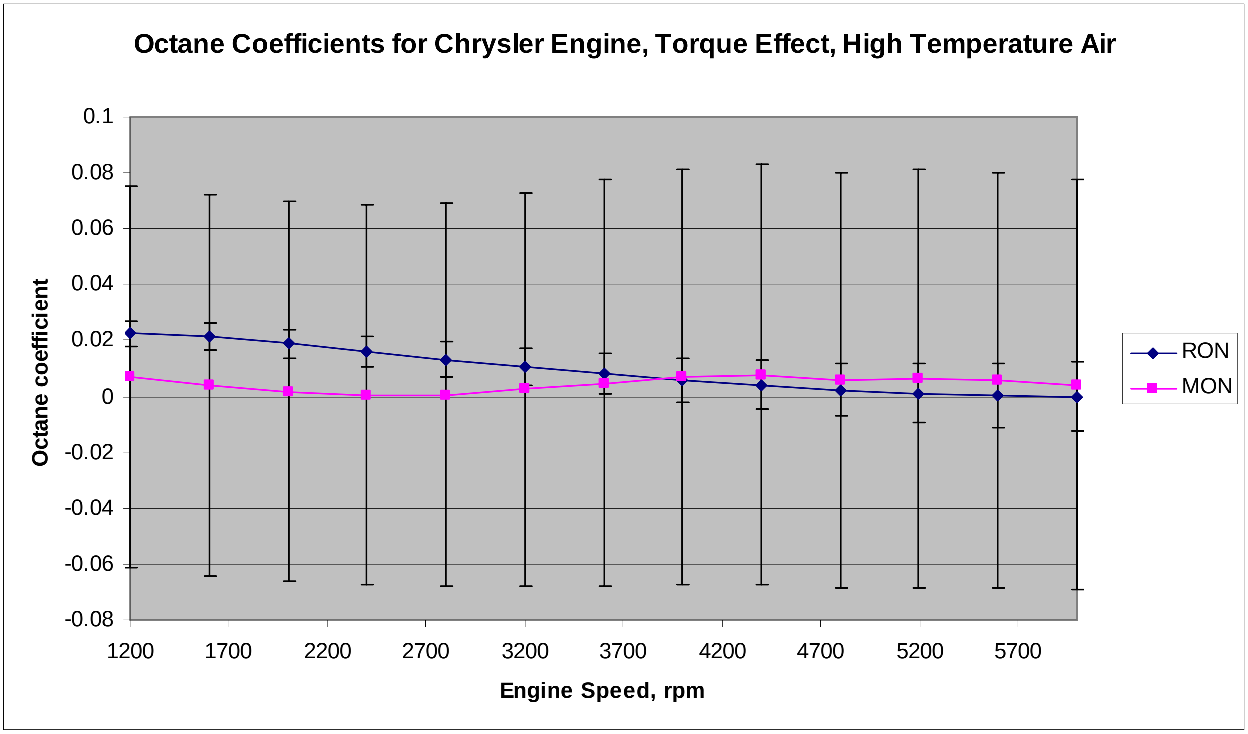


Figure 13a

Octane K Coefficient for GM Engine – Spark Timing Effect

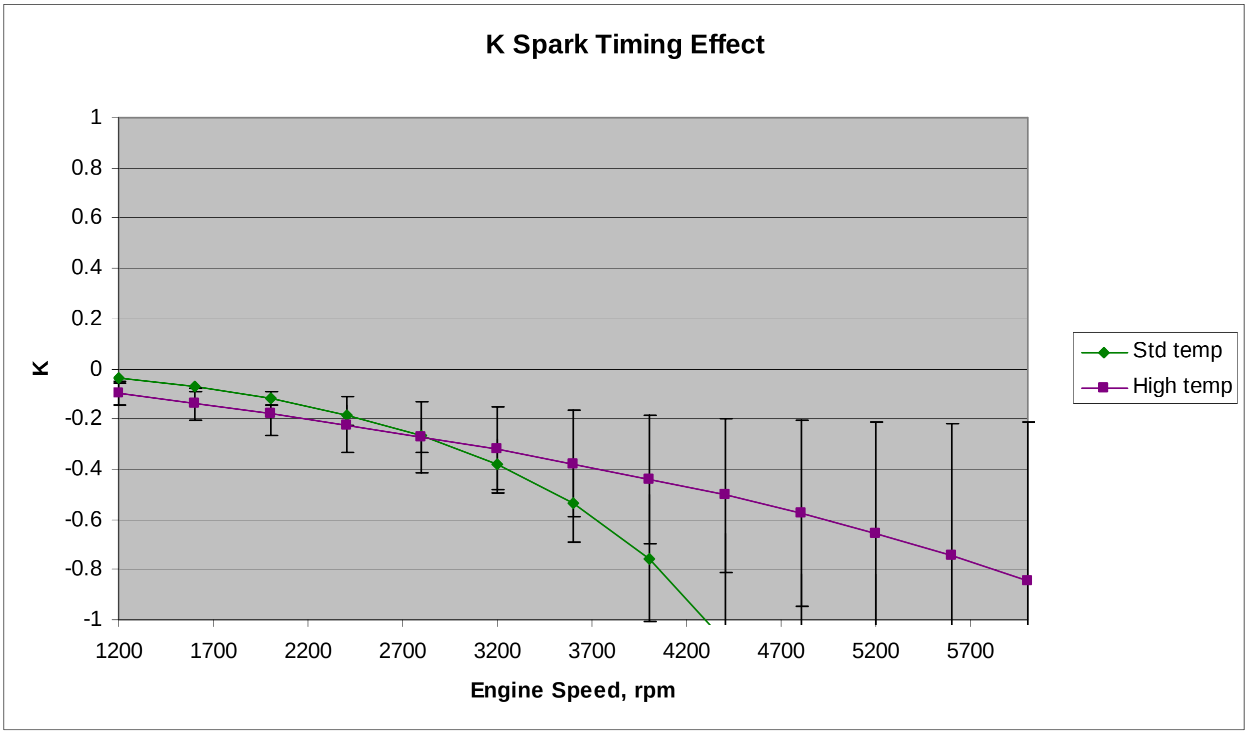


Figure 13b

Octane K Coefficient for GM Engine – Torque Effect

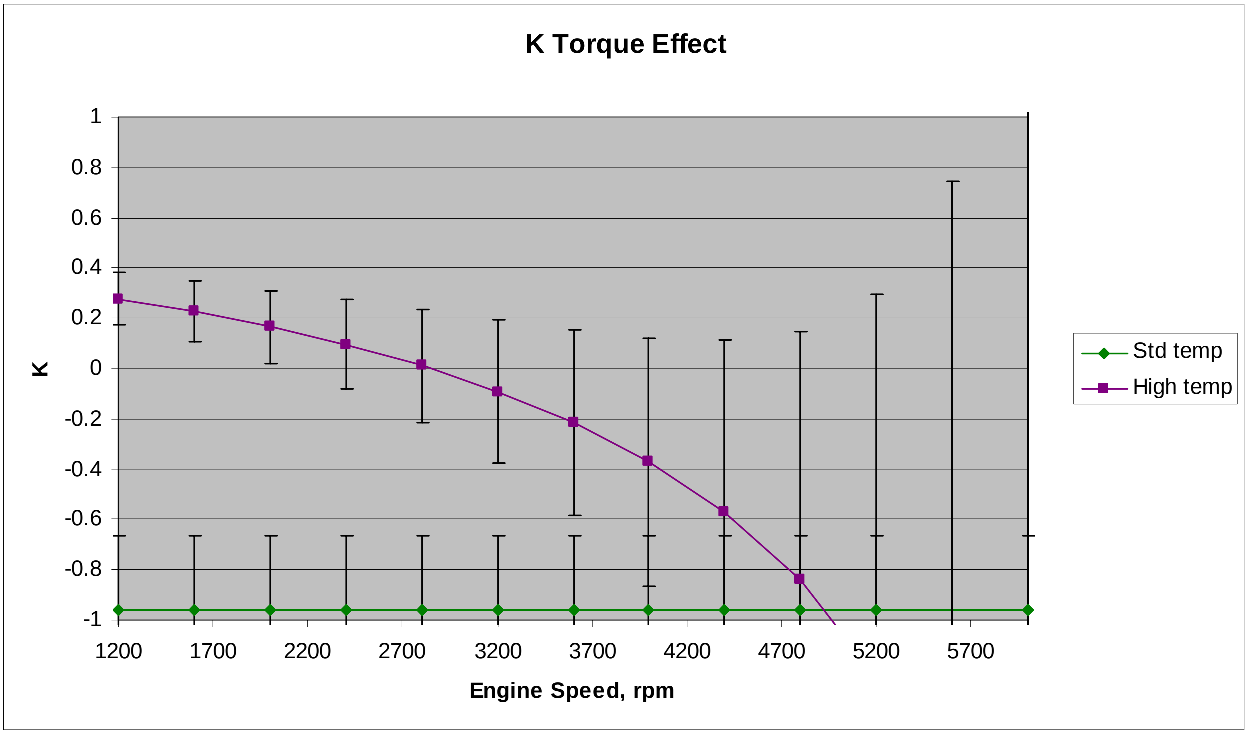


Figure 14a

Octane K Coefficient for Chrysler Engine – Spark Timing Effect

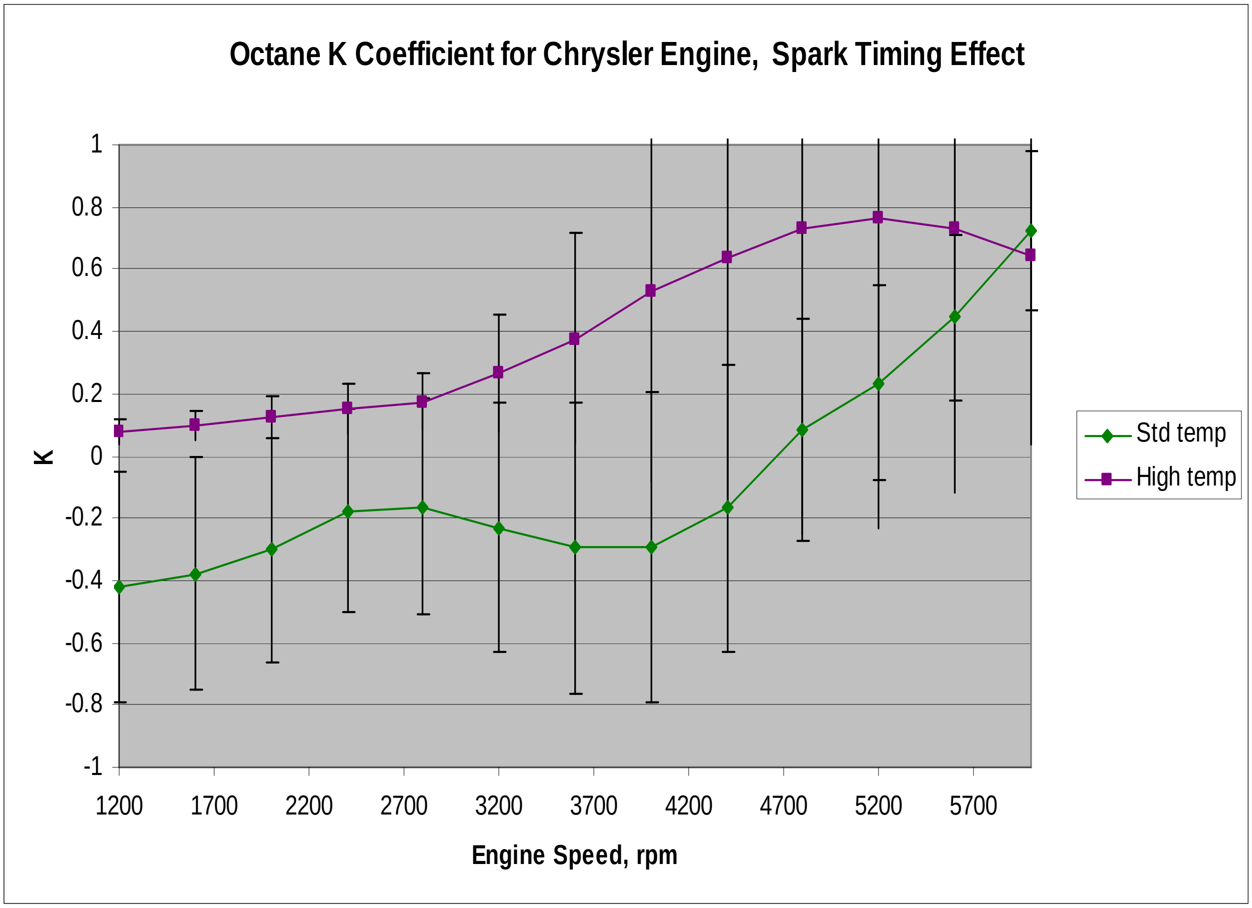
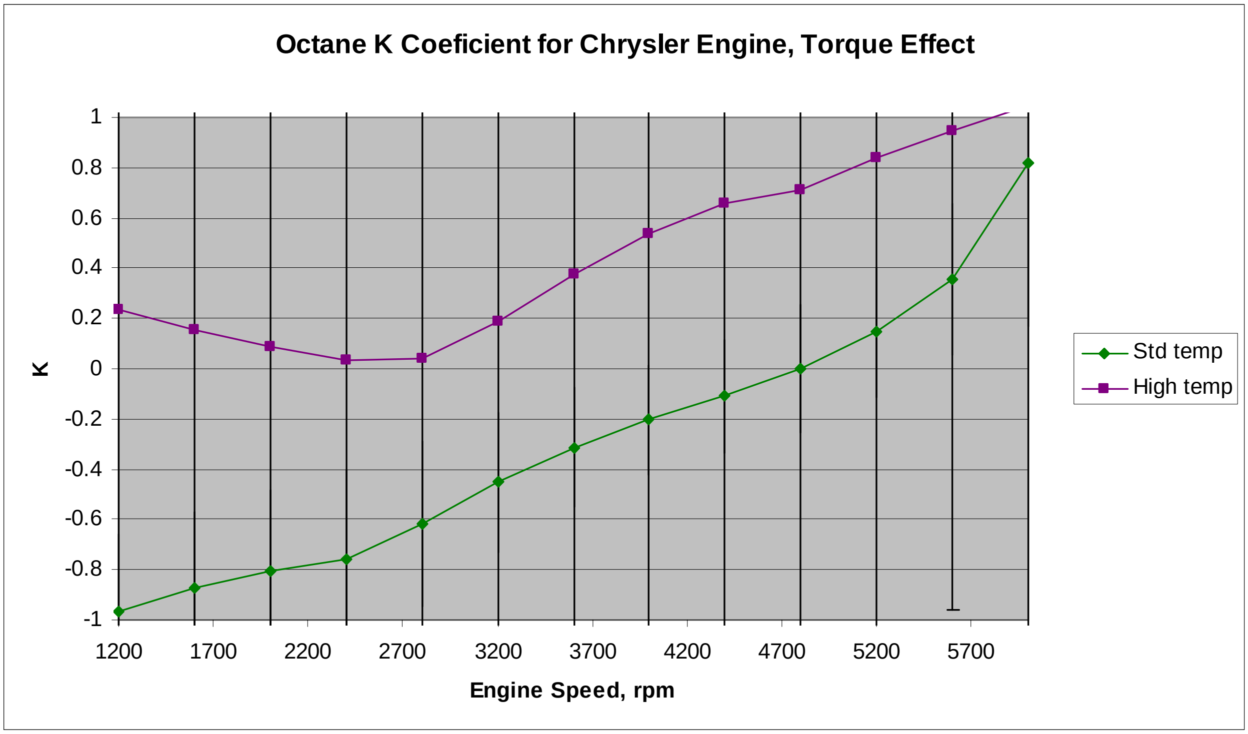


Figure 14b

Octane K Coefficient for Chrysler Engine – Torque Effect



APPENDIX A

MEMBERS OF THE

CRC RON VS MON ENGINE RESPONSE

DATA ANALYSIS PANEL

Appendix A

Members of the
CRC RON vs MON Engine Response
Data Analysis Panel

Name	Affiliation
Jim Simnick	BP America
King Eng	Shell Global Solutions (US)
Beth Evans	Evans Research Consultants
Harold (Arch) Archibald	Consultant
Jeff Farenback-Brateman	ExxonMobil Research & Engineering
Jerry Horn	Chevron Products Company
Paul Nahra	General Motors Powertrain
Ron Reese	Chrysler Group LLC
Bill Studzinski	General Motors Powertrain
Saad Umer	Chrysler Group LLC
Roger Vick	Chrysler Group LLC
Les Wolf	BP

APPENDIX B

INDIVIDUAL LABORATORY FUEL INSPECTIONS

CRC Octane Program Final Blend Inspection
Fuel 1

Fuel Description			**1**					
Property	**Method**	**Units**	**A**	**B**	**C**	**D**	**E**	**Average**
Gravity	ASTM D4052	°API	56.6		56.4	56.63	56.4	56.5
Relative Density		g/gal	0.7523		0.7531	0.7521	0.7531	0.7526
DVPE	ASTM D5191	psi	7.99	8.11	7.48	10.7	7.7	8.4
Distillation	ASTM D86							
Initial Boiling Point		°F	90.7	91.4	96.9	95.5	99.0	94.7
5% Evaporated		°F	118.9	120.0	122.0	122.4	121.0	120.9
10% Evaporated		°F	129.2	129.9	132.0	131.5	132.0	130.9
20% Evaporated		°F	145.1	145.8	147.7	146.5	148.0	146.6
30% Evaporated		°F	162.2	163.1	165.3	163.0	164.0	163.5
40% Evaporated		°F	182.5	183.3	186.4	183.2	184.0	183.9
50% Evaporated		°F	206.7	207.9	211.2	208.2	208.0	208.4
60% Evaporated		°F	234.1	234.3	236.8	234.3	234.0	234.7
70% Evaporated		°F	258.1	259.8	261.3	258.8	260.0	259.6
80% Evaporated		°F	286.2	267.1	290.8	287.6	287.0	283.7
90% Evaporated		°F	322.1	319.9	323.6	321.1	312.0	319.7
95% Evaporated		°F	332.1	332.4	333.5	331.5	332.0	332.3
End Point		°F	355.7	361.2	352.9	355.8	358.0	356.7
Recovery		vol %	98.3	98.4	97.2	98.9	98.5	98.3
Residue		vol %	0.9	0.9	1.8	0.8	1.0	1.1
Loss		vol %	0.7	0.7	1.0	0.3	0.5	0.6
Research ON			93.4	94.8	94.0	93.50	93.3	93.8
Research ON			93.3	94.9	94.0	93.43		93.9
Research ON Average			93.4	94.9	94.0	93.5	93.3	93.8
Motor ON			82.2	81.6	82.5	82.51	82.6	82.3
Motor ON			82.3	81.5	82.5	82.56		82.2
Motor ON Average			82.3	81.6	82.5	82.5	82.6	82.3
(R+M)/2			87.8	88.2	88.3	88.0	88.0	88.0
Sensitivity			11.1	13.3	11.5	10.9	10.7	11.5
Sulfur			42.0				48.0	45.0
Benzene	DHA	vol %	0.61		0.6		0.56	0.6
Hydrocarbon**								
Aromatics	DHA	vol %	35.3		37.14		33.20	35.2
Olefins	DHA	vol %	21.8		19.47		18.60	20.0
Saturates	DHA	vol %	42.9		43.39		48.20	44.8
Net Heat of Combustion								
Measured	D4809	BTU/LB					18502	
Calculated	DHA	BTU/LB			18517			
Calculated	D3338	BTU/LB						18347
RON Target								93.4
MON Target								81.4
(R+M)/2 Range								86.9-87.9
Sensitivity Target								12.0

CRC Octane Program Final Blend Inspection
Fuel 2

Fuel Description			2					
Property	**Method**	**Units**	**A**	**B**	**C**	**D**	**E**	**Average**
Gravity	ASTM D4052	°API	58.8		58.6	58.92	59.1	58.9
Relative Density		g/gal	0.7435		0.7443	0.7431	0.7424	0.7433
DVPE	ASTM D5191	psi	8.1	8.03	7.73	7.83	8.0	7.9
Distillation	ASTM D86							
Initial Boiling Point		°F	87.0	95.2	99.8	95.0	98.0	95.0
5% Evaporated		°F	119.4	124.4	120.3	123.1	124.0	122.2
10% Evaporated		°F	132.3	136.6	134.0	135.1	136.0	134.8
20% Evaporated		°F	154.9	157.6	156.0	156.6	156.0	156.2
30% Evaporated		°F	176.9	179.2	178.8	178.7	178.0	178.3
40% Evaporated		°F	199.9	201.5	202.4	204.6	201.0	201.9
50% Evaporated		°F	220.4	221.9	224.0	223.2	222.0	222.3
60% Evaporated		°F	239.7	240.9	242.0	241.7	241.0	241.1
70% Evaporated		°F	260.1	261.9	262.4	261.7	261.0	261.4
80% Evaporated		°F	293.6	294.2	297.3	295.7	294.0	295.0
90% Evaporated		°F	325.3	326.6	327.5	326.3	327.0	326.5
95% Evaporated		°F	336.7	336.7	338.5	336.0	337.0	337.0
End Point		°F	367.7	374.3	368.2	367.9	365.0	368.6
Recovery		vol %	98.3	98.4	95.9	98.5	98.3	97.9
Residue		vol %	0.8	0.9	1.5	0.9	1.0	1.0
Loss		vol %	0.8	0.7	2.6	0.6	0.7	1.1
Research ON			91.9	94.0	92.2	91.87	92.2	92.4
Research ON			91.7	94.0	92.3	91.82		92.5
Research ON Average			91.8	94.0	92.3	91.8	92.2	92.4
Motor ON			83.3	83.5	83.7	83.37	83.3	83.4
Motor ON			83.2	83.5	83.7	83.54		83.5
Motor ON Average			83.3	83.5	83.7	83.5	83.3	83.4
(R+M)/2			87.5	88.8	88.0	87.7	87.8	87.9
Sensitivity			8.6	10.5	8.6	8.4	8.9	9.0
Sulfur			28.0				31.0	29.5
Benzene	DHA	vol %	0.46		0.46		0.40	0.4
Hydrocarbon**								
Aromatics	DHA	vol %	28.60		30.17		26.4	28.4
Olefins	DHA	vol %	13.70		12.52		9.80	12.0
Saturates	DHA	vol %	57.70		57.31		63.80	59.6
Net Heat of Combustion								
Measured	D4809	BTU/LB					18731	
Calculated	DHA	BTU/LB			18637			
Calculated	D3338	BTU/LB						18492
RON Target								91.9
MON Target								82.9
(R+M)/2 Range								86.9-87.9
Sensitivity Target								9.0

CRC Octane Program Final Blend Inspection
Fuel 3

Fuel Description			3					
Property	**Method**	**Units**	**A**	**B**	**C**	**D**	**E**	**Average**
Gravity	ASTM D4052	°API	69.6		69.5	69.69	69.6	69.6
Relative Density		g/gal	0.7035		0.7040	0.7033	0.7036	0.7036
DVPE	ASTM D5191	psi	7.99	7.96	7.73	7.82	7.5	7.8
Distillation	ASTM D86							
Initial Boiling Point		°F	84.7	93.3	98.7	93.4	99.0	93.8
5% Evaporated		°F	116.4	118.8	116.9	123.8	125.0	120.2
10% Evaporated		°F	129.7	131.9	131.5	135.0	132.0	132.0
20% Evaporated		°F	150.3	152.4	151.8	154.8	157.0	153.3
30% Evaporated		°F	174.7	176.3	177.8	178.3	181.0	177.6
40% Evaporated		°F	204.3	203.6	204.9	204.8	209.0	205.3
50% Evaporated		°F	220.6	220.3	221.7	220.6	213.0	219.2
60% Evaporated		°F	229.4	229.8	230.5	229.5	233.0	230.4
70% Evaporated		°F	238.9	239.9	239.9	239.0	241.0	239.7
80% Evaporated		°F	253.9	254.7	253.5	254.2	257.0	254.7
90% Evaporated		°F	296.9	294.4	298.9	296.8	297.0	296.8
95% Evaporated		°F	333.3	331.2	333.8	332.8	336.0	333.4
End Point		°F	369.7	375.9	357.4	380.1	374.0	371.4
Recovery		vol %	97.2	97.0	95.0	98.3	99.0	97.3
Residue		vol %	1.4	1.0	3.0	1	0.9	1.5
Loss		vol %	1.2	2.0	2.0	0.7	0.1	1.2
Research ON			88.6	90.9	89.0	88.55	88.5	89.1
Research ON			88.6	90.8	89.0	88.45		89.2
Research ON Average			88.6	90.9	89.0	88.5	88.5	89.1
Motor ON			86.7	86.4	86.8	86.55	86.7	86.6
Motor ON			86.7	86.2	86.6	86.47		86.5
Motor ON Average			86.7	86.3	86.7	86.5	86.7	86.6
(R+M)/2			87.65	88.58	87.85	87.51	87.60	87.8
Sensitivity			1.9	4.5	2.3	2.0	1.8	2.5
Sulfur			5.0				6.0	5.5
Benzene	DHA	vol %	0.26		0.25		0.2	0.2
Hydrocarbon**								
Aromatics	DHA	vol %	6.5		7.46		5.1	6.4
Olefins	DHA	vol %	0.10		0.25		1.0	0.5
Saturates	DHA	vol %	93.30		92.29		93.9	93.2
Net Heat of Combustion								
Measured	D4809	BTU/LB					19154	
Calculated	DHA	BTU/LB			19003			
Calculated	D3338	BTU/LB						18973
RON Target								88.4
MON Target								86.4
(R+M)/2 Range								86.9-87.9
Sensitivity Target								2.0

CRC Octane Program Final Blend Inspection
Fuel 4

Fuel Description			4					
Property	**Method**	**Units**	**A**	**B**	**C**	**D**	**E**	**Average**
Gravity	ASTM D4052	°API	56.7		56.5	56.81	57.2	56.8
Relative Density		g/gal	0.7519		0.7527	0.7514	0.7499	
DVPE	ASTM D5191	psi	7.82	7.72	7.54	7.67	7.6	7.7
Distillation	ASTM D86							
Initial Boiling Point		°F	86.4	92.9	98.6	98.8	100.0	95.3
5% Evaporated		°F	121.3	123.6	124.5	123.4	123.0	123.2
10% Evaporated		°F	134.1	135.2	136.4	135.3	134.0	135.0
20% Evaporated		°F	153.9	155.2	157.1	155.3	153.0	154.9
30% Evaporated		°F	173.1	174.9	176.7	174.7	172.0	174.3
40% Evaporated		°F	194.4	196.1	197.6	196.2	193.0	195.5
50% Evaporated		°F	218.9	221.5	223.8	222.3	218.0	220.9
60% Evaporated		°F	250.4	251.1	253.5	252.7	249.0	251.3
70% Evaporated		°F	280.8	282.0	283.4	282.6	279.0	281.6
80% Evaporated		°F	312.7	312.7	312.2	311.4	308.0	311.4
90% Evaporated		°F	326.0	325.2	325.9	325.0	325.0	325.4
95% Evaporated		°F	332.2	332.5	332.4	331.9	331.0	332.0
End Point		°F	351.0	357.7	350.4	349.2	349.0	351.5
Recovery		vol %	98.4	97.8	97.2	98.3	97.5	97.8
Residue		vol %	0.9	1.1	1.5	0.8	1.1	1.1
Loss		vol %	0.7	1.1	1.3	0.9	1.4	1.1
Research ON			91.6	91.6	92.0	91.58	91.5	91.7
Research ON			91.4	91.7	92.0	91.57		91.7
Research ON Average			91.5	91.7	92.0	91.6	91.5	91.6
Motor ON			80.8	81.1	81.0	80.97	80.7	80.9
Motor ON			80.8	81.3	81.0	81.05		81.0
Motor ON Average			80.8	81.2	81.0	81.0	80.7	80.9
(R+M)/2			86.15	86.43	86.50	86.29	86.10	86.3
Sensitivity			10.7	10.5	11.0	10.6	10.8	10.7
Sulfur			31.0				33.0	32.0
Benzene	DHA	vol %	0.6	0.6	0.6		0.60	0.6
Hydrocarbon**								
Aromatics	DHA	vol %	31.80	34.80	34.00		29.9	32.6
Olefins	DHA	vol %	28.60	21.70	25.95		27.80	26.0
Saturates	DHA	vol %	39.50	43.50	40.05		42.30	41.3
Net Heat of Combustion								
Measured	D4809	BTU/LB					18677	
Calculated	DHA	BTU/LB			18569			
Calculated	D3338	BTU/LB						18411
RON Target								91.9
MON Target								79.9
(R+M)/2 Range								85.4-86.4
Sensitivity Target								12.0

CRC Octane Program Final Blend Inspection
Fuel 5

Fuel Description			5					
Property	**Method**	**Units**	**A**	**B**	**C**	**D**	**E**	**Average**
Gravity	ASTM D4052	°API	56.6		56.3	56.58	56.9	56.6
Relative Density		g/gal	0.7526		0.7535	0.7523	0.7511	0.7524
DVPE	ASTM D5191	psi	8.06	7.93	7.75	7.88	7.7	7.9
Distillation	ASTM D86							
Initial Boiling Point		°F	86.9	91.5	94.8	99.3	99.0	94.3
5% Evaporated		°F	119.3	122.2	122.0	124.3	119.0	121.4
10% Evaporated		°F	130.7	132.6	132.9	134.1	132.0	132.5
20% Evaporated		°F	148.5	150.4	150.8	150.4	149.0	149.8
30% Evaporated		°F	167.6	169.2	170.2	169.0	168.0	168.8
40% Evaporated		°F	189.9	190.7	192.5	190.6	189.0	190.5
50% Evaporated		°F	212.5	213.8	217.2	213.8	214.0	214.3
60% Evaporated		°F	237.5	237.7	240.4	237.2	239.0	238.4
70% Evaporated		°F	261.7	261.8	264.2	267.5	265.0	264.0
80% Evaporated		°F	292.8	292.9	296.0	293.5	296.0	294.2
90% Evaporated		°F	323.6	323.3	324.1	322.0	323.0	323.2
95% Evaporated		°F	331.5	331.1	332.4	330.3	333.0	331.7
End Point		°F	352.7	354.3	353.4	349.3	356.0	353.1
Recovery		vol %	98.5	98.7	97.1	98.8	98.5	98.3
Residue		vol %	0.8	0.6	1.6	0.7	1.0	0.9
Loss		vol %	0.7	0.7	1.3	0.5	0.5	0.7
Research ON			94.1	94.2	94.5	94.28	94.4	94.3
Research ON			94.1	94.2	94.6	94.23		94.3
Research ON Average			94.1	94.2	94.6	94.3	94.4	94.3
Motor ON			83.3	84.0	83.7	83.06	83.1	83.4
Motor ON			83.2	84.1	83.7	83.76		83.7
Motor ON Average			83.3	84.1	83.7	83.4	83.1	83.5
(R+M)/2			88.68	89.13	89.13	88.83	88.75	88.9
Sensitivity			10.9	10.2	10.9	10.8	11.3	10.8
Sulfur			41.0				42.0	41.5
Benzene	DHA	vol %	0.71		0.70		0.66	0.7
Hydrocarbon**								
Aromatics	DHA	vol %	34.6		35.75		33.0	34.5
Olefins	DHA	vol %	16.70		15.42		14.0	15.4
Saturates	DHA	vol %	48.80		48.83		53.0	50.2
Net Heat of Combustion								
Measured	D4809	BTU/LB					18594	
Calculated	DHA	BTU/LB			18546			
Calculated	D3338	BTU/LB						18368
RON Target								94.9
MON Target								82.9
(R+M)/2 Range								88.4-89.4
Sensitivity Target								12.0

Summary data

Fuel #	RON Target	MON Target	(R+M)/2 Target	Sens Target	RON	MON	(R+M)/2	Sens
1	93.4	81.4	86.9-87.9	12.0	93.8	82.3	88.0	11.5
2	91.9	82.9	86.9-87.9	9.0	92.4	83.4	87.9	9.0
3	88.4	86.4	86.9-87.9	2.0	89.1	86.6	87.8	2.5
4	91.9	79.9	85.4-86.4	12.0	91.6	80.9	86.3	10.7
5	94.9	82.9	88.4-89.4	12.0	94.3	83.5	88.9	10.8

APPENDIX C

STATISTICAL ANALYSIS

STATISTICAL ANALYSIS

Data for the responses: **spark timing** and **corrected normalized torque** from each engine at each temperature were fit to general linear models (GLM) with the general form:

Response = a_0 + P(speed, phi, VE) + a_1*RON*G(speed, phi, VE) + a2*MON*H(speed, phi, VE)

Where: a_i are parameters;
speed = scaled engine speed (rpm/1000);
phi = equivalence ratio based on H/C composition of fuel and measured fuel/air ratio;
VE = volumetric efficiency;
P(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -2 to 3 and exponents for phi and VE equal to unity;
RON = fuel average measured RON;
MON = fuel average measured MON;
G(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -1 to 3 and exponents for phi and VE equal to unity;
H(speed, phi, VE) is a polynomial in the variables speed, phi and VE with exponents for speed ranging from -1 to 3 and exponents for phi and VE equal to unity.

General linear models were developed in an iterative fashion by deleting statistically non-significant higher order terms and occasionally omitting a datum that was inconsistent with replicates or general trends. As anticipated from the general forms of the data, (see Figures 5a to 8b) non-linear terms were needed to represent the data.

Chrysler Engine

A summary of the GLM fits are given in Table C-1 for the Chrysler engine data. Root mean square errors (RMSE) for spark timing were less than one degree and RMSE for torque were less that 0.01 (i.e. < 1% relative to Fuel 2). Figures below suggest satisfactory model fit.

Table C-1
Chrysler Engine General Linear Models Summary of Fits

	Spark Timing, Standard Temperature	Spark Timing, High Temperature	Corrected Normalized Torque, Standard Temperature	Corrected Normalized Torque, High Temperature
RSquare	0.981546	0.988688	0.897769	0.909078
RSquare Adjusted	0.980753	0.988265	0.893942	0.904137
Root Mean Square Error	0.754396	0.748206	0.007019	0.0072
Mean of Response	11.9641	10.25128	1.001436	0.999732
Observations	195	195	195	195

Table C-2 shows the parameter estimates and their standard errors for the spark timing response models. Quadratic or cubic terms for speed and interactions with octanes were needed to describe the data as anticipated from Figures 7a and 8a presented earlier in the report under the “Tables and Figures” heading. Figures C-15 and C-16 show the fits of the models to the spark timing data for standard and high temperature, respectively. Error bars in these figures are one standard error of the predicted model value. There were slight differences in phi or VE for the three replicates sets of data, the prediction for the third run is shown for each fuel and differs negligibly from the predictions for the other two runs.

Table C-2
Chrysler Engine Spark-Timing Models Parameter Estimates

Spark - Timing	Standard Temperature		High Temperature	
Parameter	Estimate	Standard error	Estimate	Standard error
Intercept	-69.8071	14.16014	-761.812	46.91553
Speed	8.306565	3.783619	6.872342	0.916532
Speed^2	-0.32341	0.139831		
Speed^3			-0.15707	0.003528
1/speed	-17.269	2.585868		
Phi			573.998	37.38511
VE			-47.8153	3.606842
RON			8.493937	0.51273
RON*speed	-0.26274	0.028465		
RON*phi			-6.24302	0.413013
RON*VE	1.786815	0.118123		
MON	1.357786	0.167529		
MON*speed	0.260899	0.02058	0.084965	0.010107
MON*phi				
MON*VE	-2.50572	0.134852		

Table C-3 shows the parameter estimates and their standard errors for the corrected normalized torque response models. A quadratic term at high temperature for speed and interactions with octanes was needed to describe the data as anticipated from Figures 7a and 8b presented earlier in the report. Figures C-17 and C-18 show the fits of the models to the corrected normalized torque data. Error bars in these figures are one standard error of the predicted model value. There were slight differences in phi or VE for the three replicates sets of data, the prediction for the third run is shown for each fuel and differs negligibly from the predictions for the other two runs

Table C-3
Chrysler Engine Corrected Normalized Torque Model Parameter Estimates

Torque	Standard Temperature		High Temperature	
Parameter	Estimate	Standard error	Estimate	Standard error
Intercept	1.891927	0.078134	0.107091	0.391738
Speed	0.170726	0.038669	1.506587	0.14719
Speed^2			-0.11544	0.01725
Speed^3				
1/speed				
Phi	-0.17613	0.031549		
VE	-1.94374	0.104814	-3.98797	0.42939
RON			0.056863	0.003723
RON*speed	-0.00336	0.000274	-0.01663	0.001599
RON*1/speed			-0.01963	0.002418
RON*phi				
RON*VE	0.021005	0.00113		
MON	-0.00834	0.000844	-0.05164	0.005979
MON*speed	0.001738	0.000218		
MON*1/speed			0.020946	0.00266
MON*phi				
MON*VE			0.048269	0.00516

Figure C-15
Chrysler Spark-Timing Model, Standard Temperature

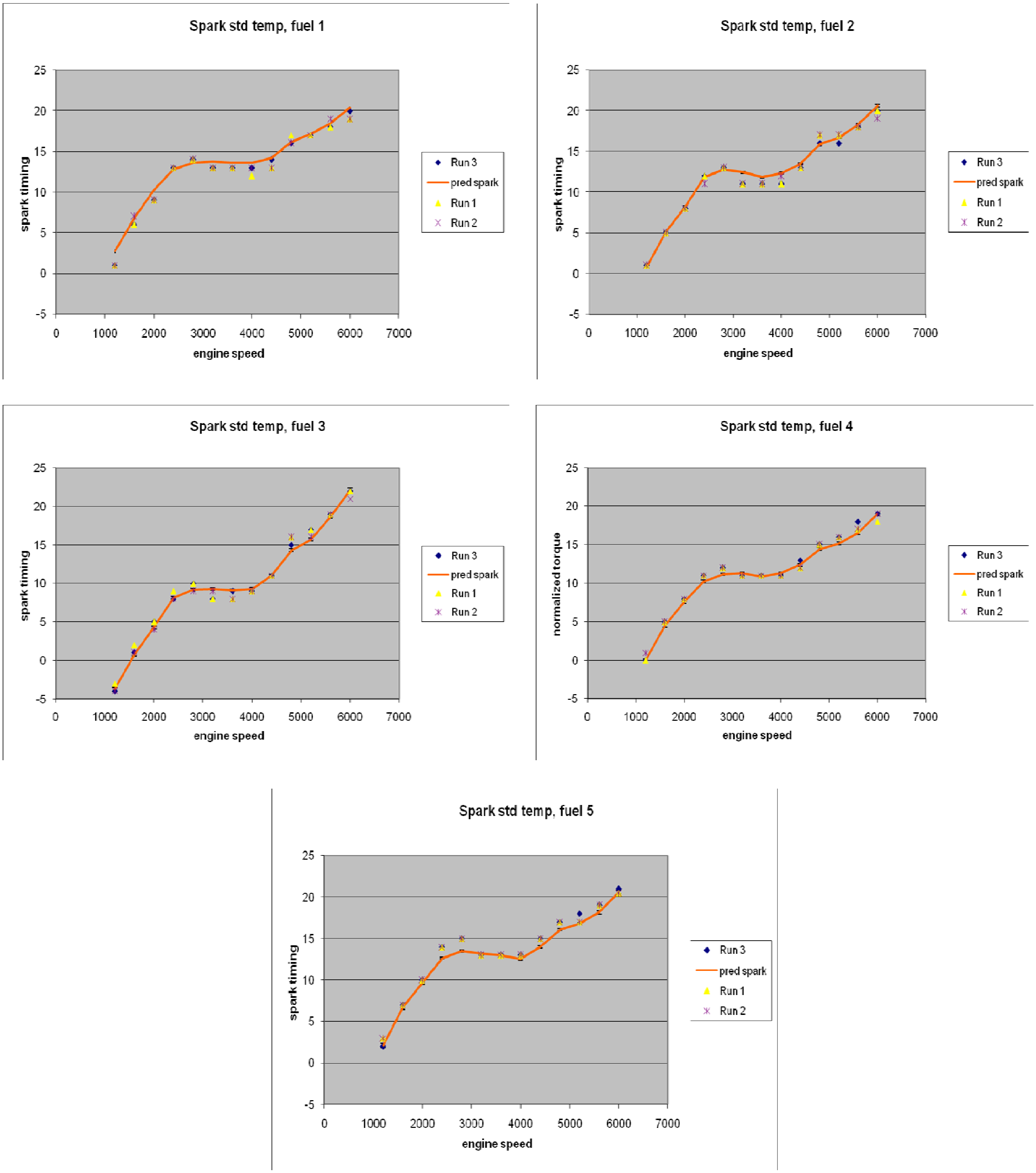
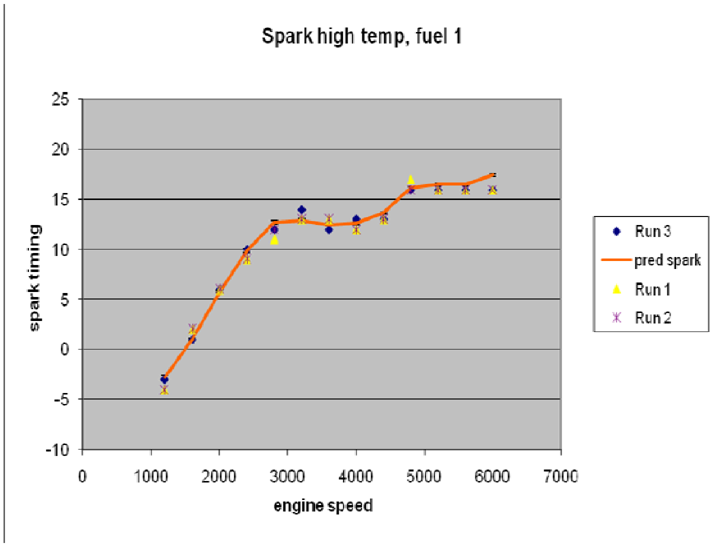
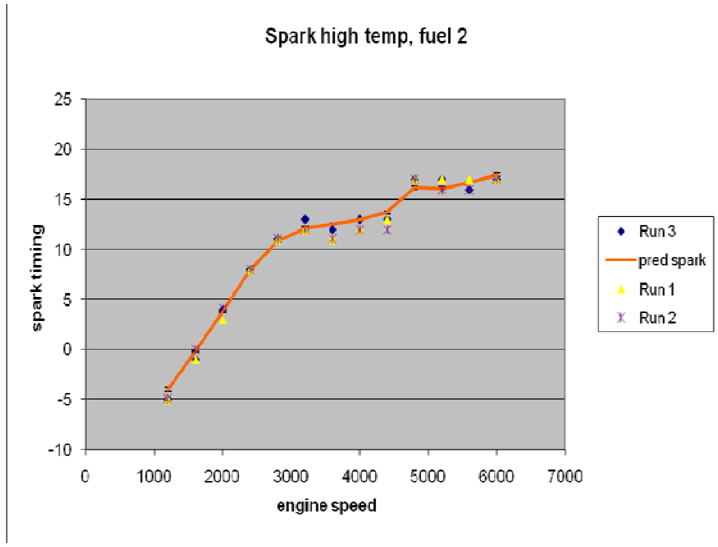
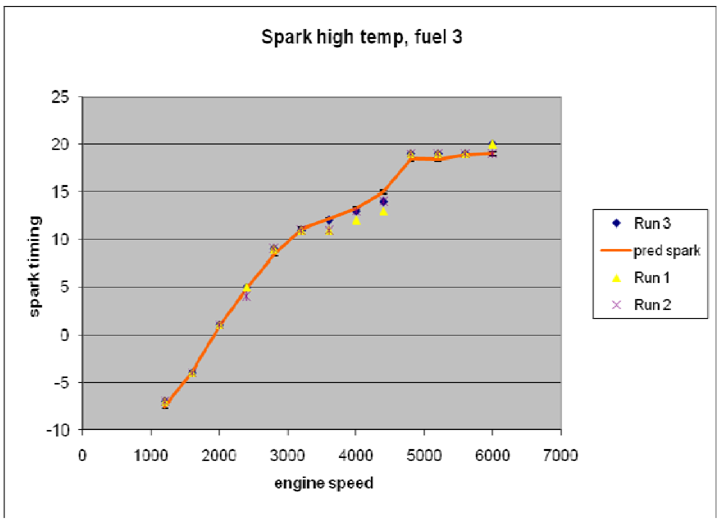
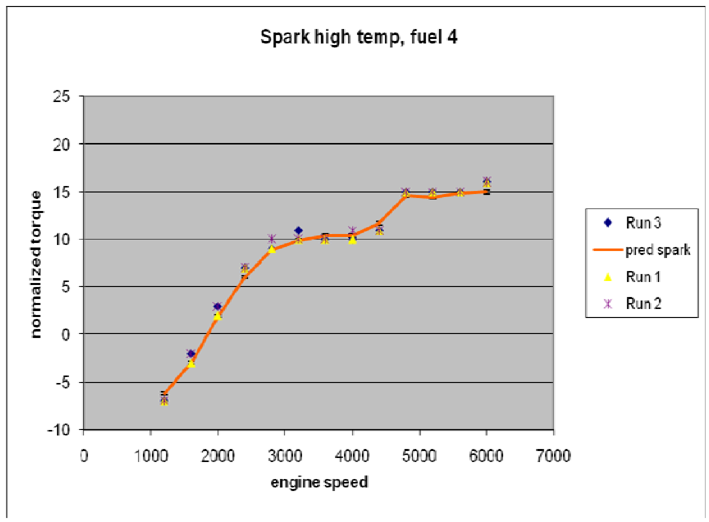


Figure C-16
Chrysler Spark-Timing Model, High Temperature









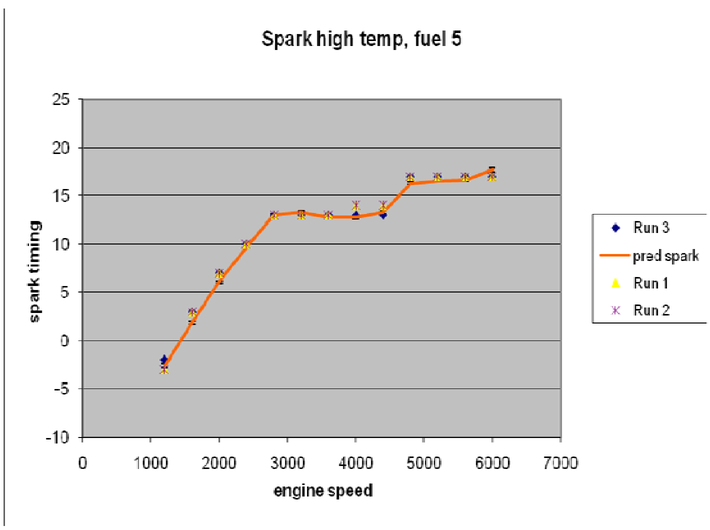


Figure C-17
Chrysler Corrected Normalized Torque Model, Standard Temperature

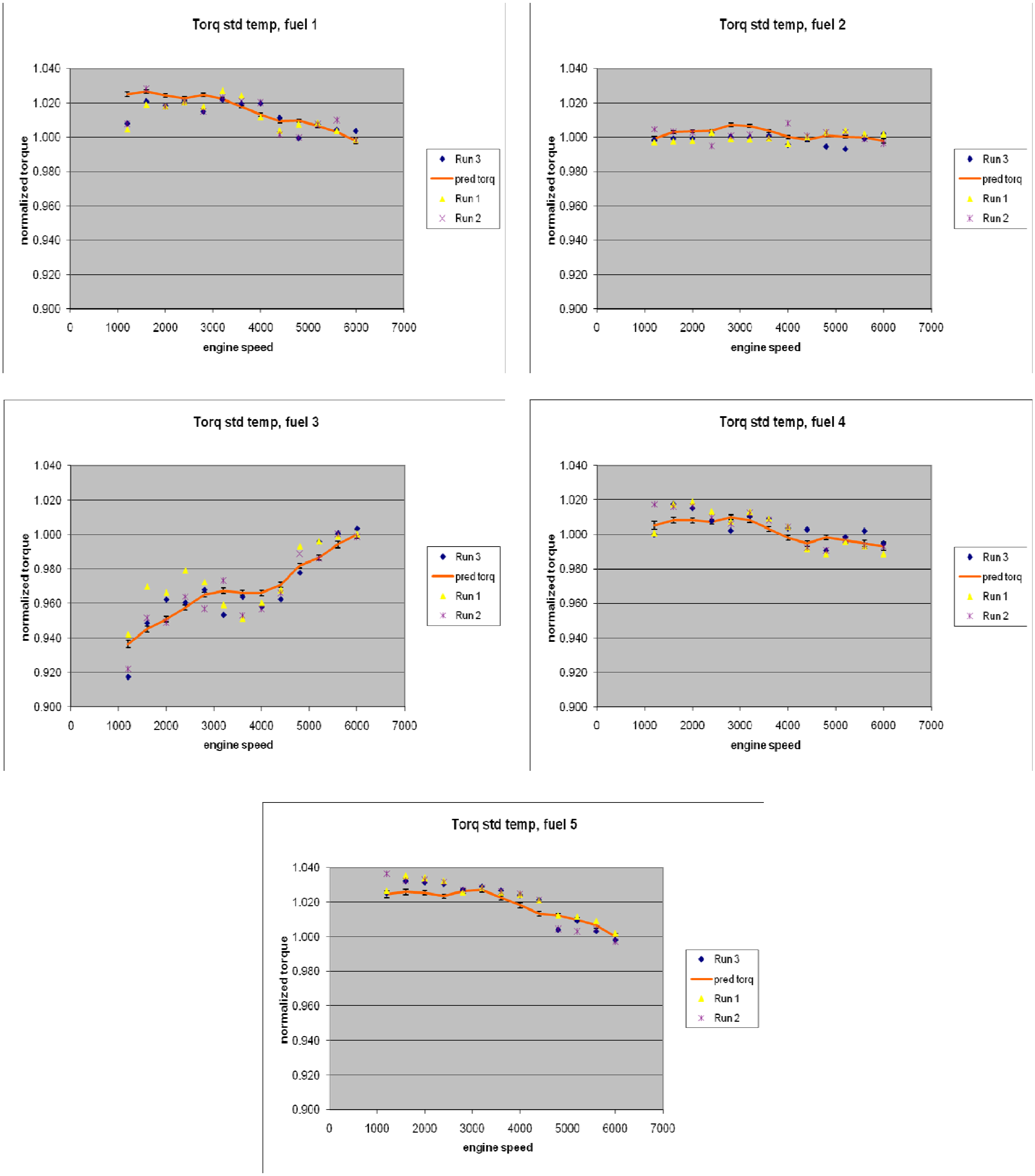
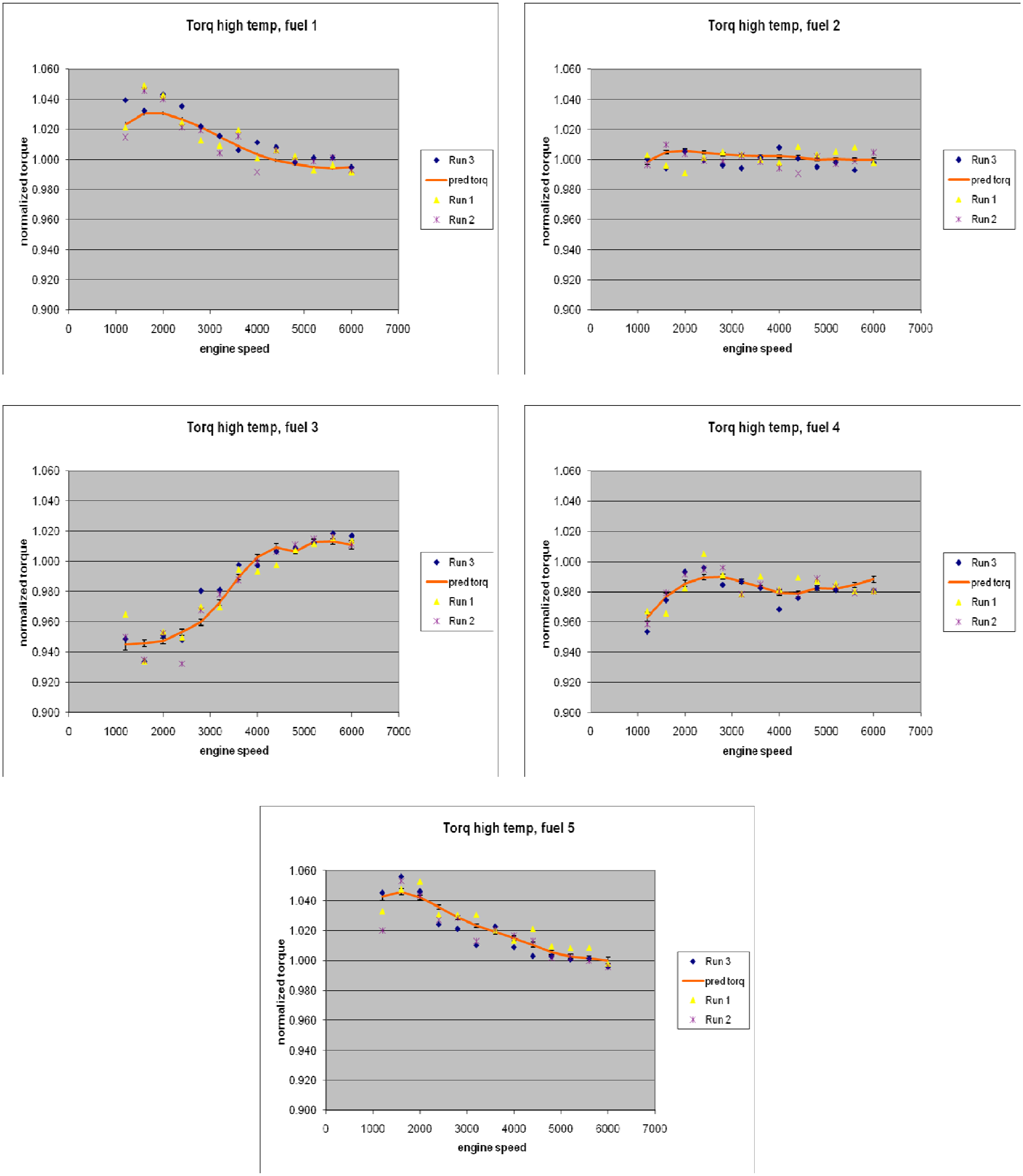


Figure C-18
Chrysler Corrected Normalized Torque Model, High Temperature



GM Engine

A summary of the GLM fits are given in Table C-4 for the GM engine data. VE data were not available for the GM engine. So this variable was not included in the model development. Root mean square errors (RMSE) for spark timing were less than one degree and RMSE for torque were about 0.01 (i.e. ~1% relative to Fuel 2). For spark timing, the datum at 2000 rpm, high temperature Fuel 5 was not used. This same datum and the datum at 1600 rpm, high temperature Fuel 5 were neglected for the high temperature torque model fit. For normalized torque at standard temperature, the two neglected data were 2000 rpm Fuel 4 and 2000 rpm Fuel 5. It is not known if the neglected data are special operating situations or simply ordinary data variation. Examination of Figures 5a, 5b, 6a, and 6b presented earlier in the report suggest that the neglected data do not follow the same trends as the other fuels.

Table C-4
GM Engine General Linear Models Summary of Fits

	Spark Timing, Standard Temperature	Spark Timing, High Temperature	Corrected Normalized Torque, Standard Temperature	Corrected Normalized Torque, High Temperature
RSquare	0.958613	0.868913	0.911849	0.832364
RSquare Adjusted	0.954781	0.852229	0.906951	0.817397
Root Mean Square Error	0.628682	0.770573	0.007271	0.011741
Mean of Response	7.122135	4.761409	1.000205	0.995598
Observations	60	63	58	62
Deleted observations	0	1	2	2

Table C-5 shows the parameter estimates and their standard errors for the spark timing response models for the GM engine. Quadratic and cubic terms for speed and interactions with octanes were needed to describe the data as anticipated from Figures 5a and 6a presented earlier in the report. Figures C-19 and C-20 show the fits of the models to the spark timing data. Error bars in these figures are one standard error of the predicted model value.

Table C-5
GM Engine Spark-Timing Models Parameter Estimates

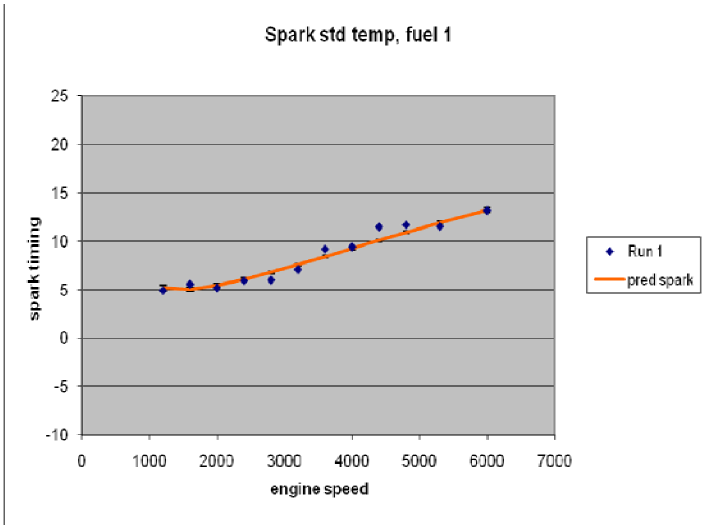
Spark – Timing	Standard Temperature		High Temperature	
Parameter	Estimate	Standard error	Estimate	Standard error
Intercept	-61.7114	5.353622	5.254458	12.90256
Speed	3.436666	0.950137	-29.7887	6.363836
Speed^2	1.238573	0.253706	6.772777	1.320908
Speed^3			-0.46148	0.098679
1/speed	6.508456	2.328871	-37.5659	7.702309
Phi			10.73572	2.235192
RON	0.612818	0.049646	0.53705	0.062306
RON*speed			-0.04095	0.015925
RON*phi				
MON				
MON*speed			-0.04095	0.015925
MON*speed^2	-0.01648	0.002813		
MON*phi				

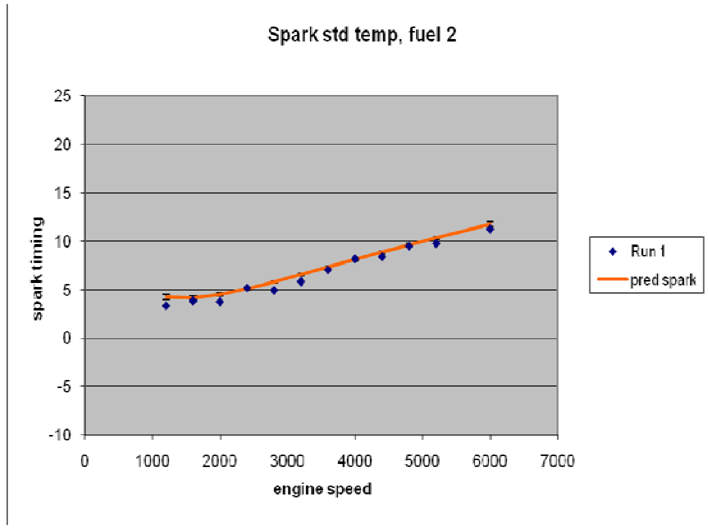
Table C-6 shows the parameter estimates and their standard errors for the corrected normalized torque response models. A quadratic term at high temperature for speed and interactions with octanes were needed to describe the data as anticipated from Figures 5b and 6b presented earlier in the report. Figures C-21 and C-22 show the fits of the models to the corrected normalized torque data. Error bars in these figures are one standard error of the predicted model value.

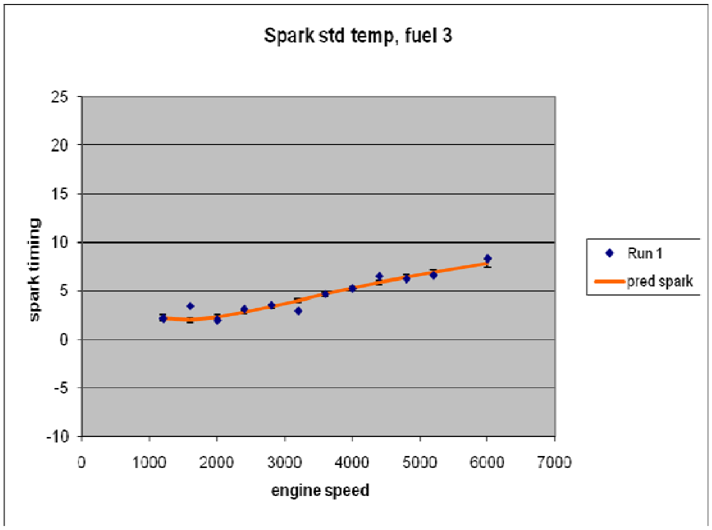
Table C-6
GM Engine Corrected Normalized Torque Model Parameter Estimates

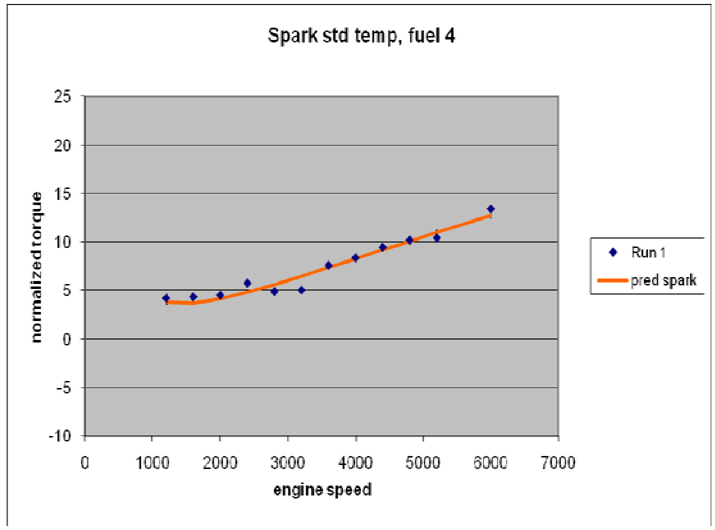
Torque	Standard Temperature		High Temperature	
Parameter	Estimate	Standard error	Estimate	Standard error
Intercept	1.00495	0.002502	-0.6857	0.220193
Speed	-0.124469	0.02613	0.231032	0.04363
Speed^2			-0.00174	0.000759
Speed^3				
1/speed				
Phi				
RON			0.011314	0.001005
RON*speed	0.002393	0.000169		
RON*1/speed				
RON*phi				
MON			0.007524	0.002109
MON*speed	-0.00117	0.000165	-0.002645	0.000521
MON*1/speed				
MON*phi				

Figure C-19
GM Spark-Timing Model, Standard Temperature









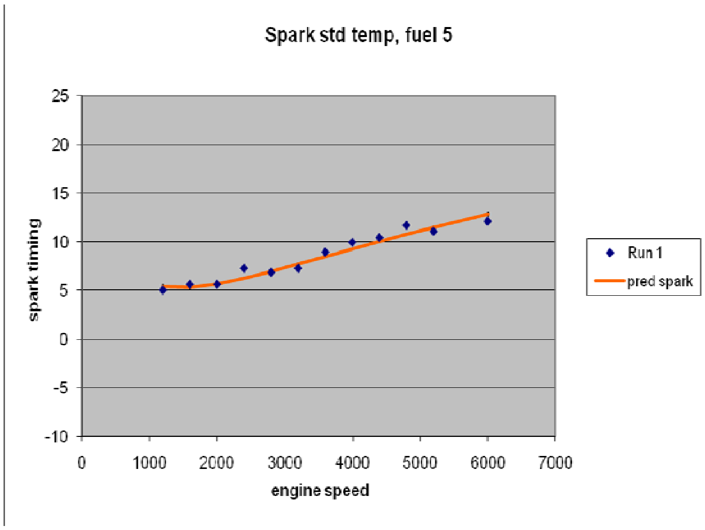


Figure C-20
GM Spark-Timing Model, High Temperature

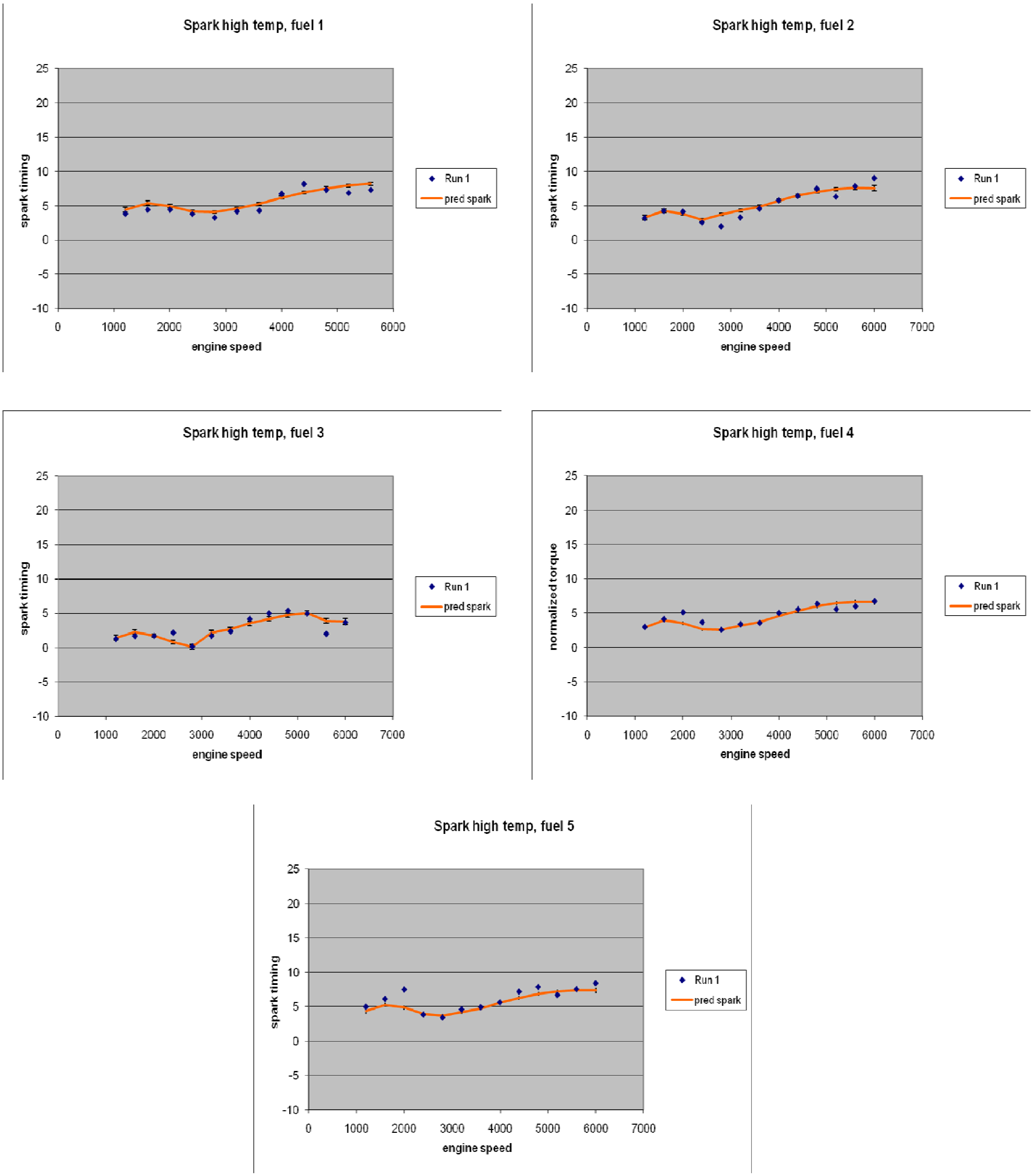
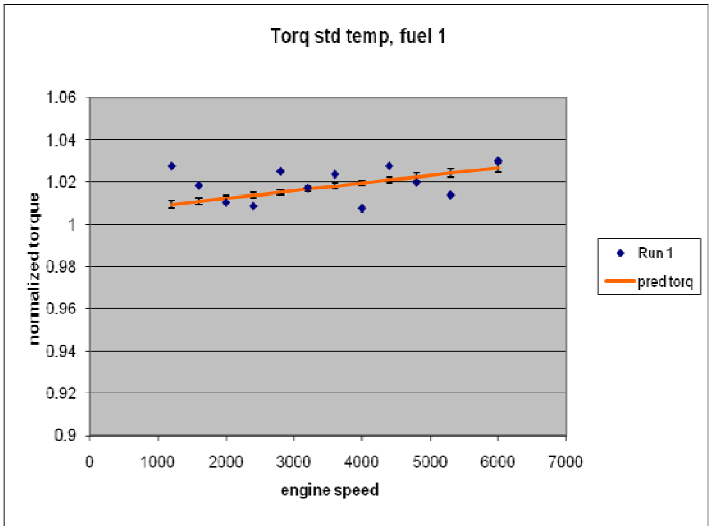
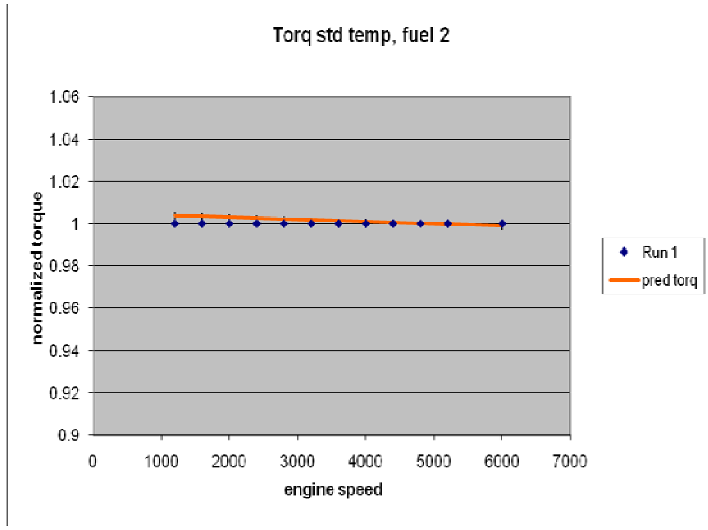
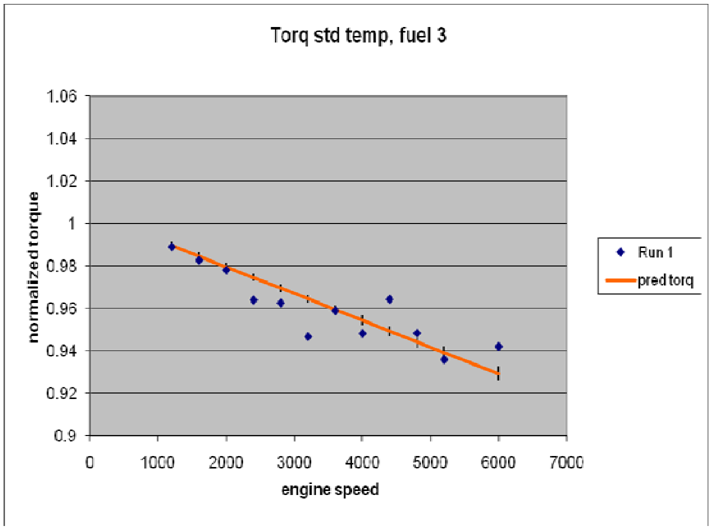
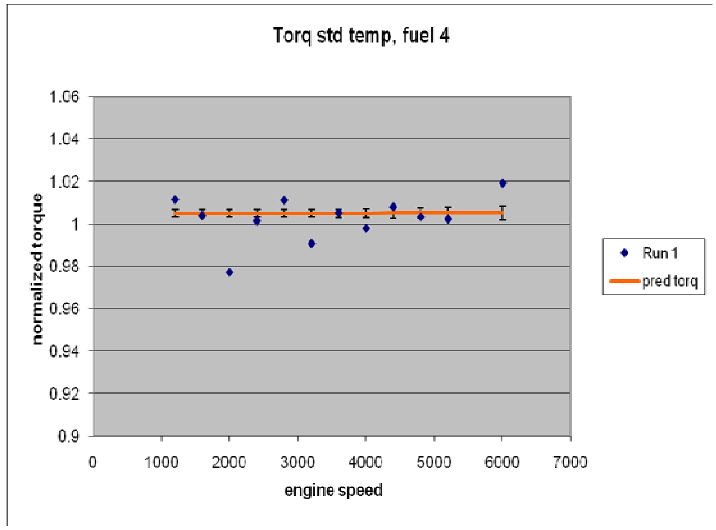


Figure C-21
GM Corrected Normalized Torque Model, Standard Temperature









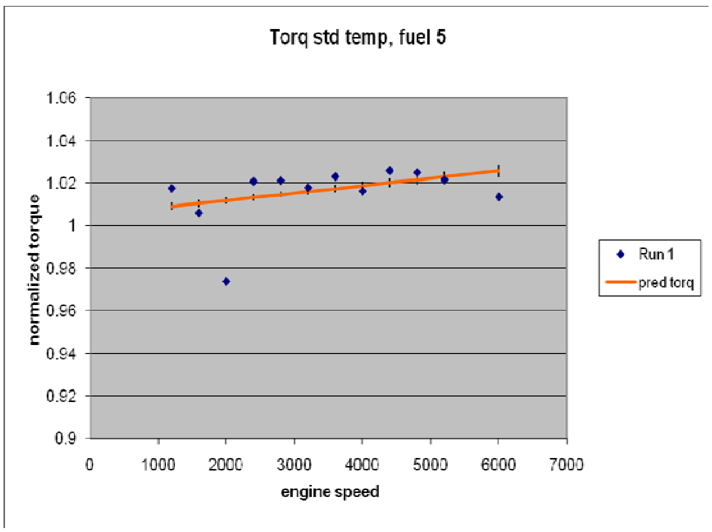
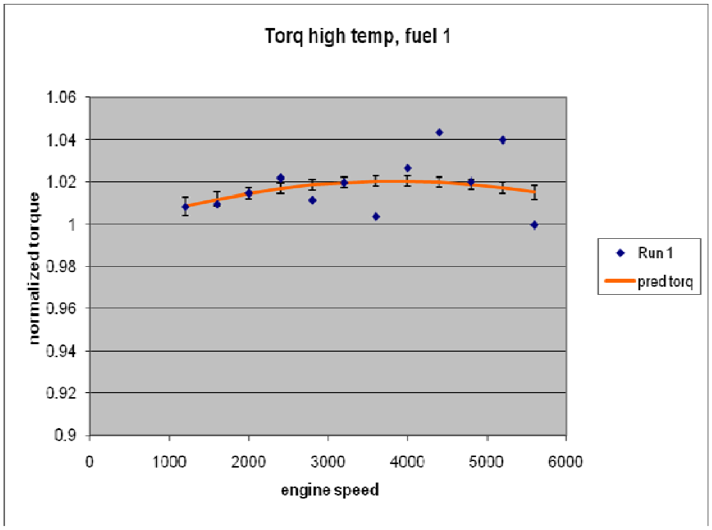
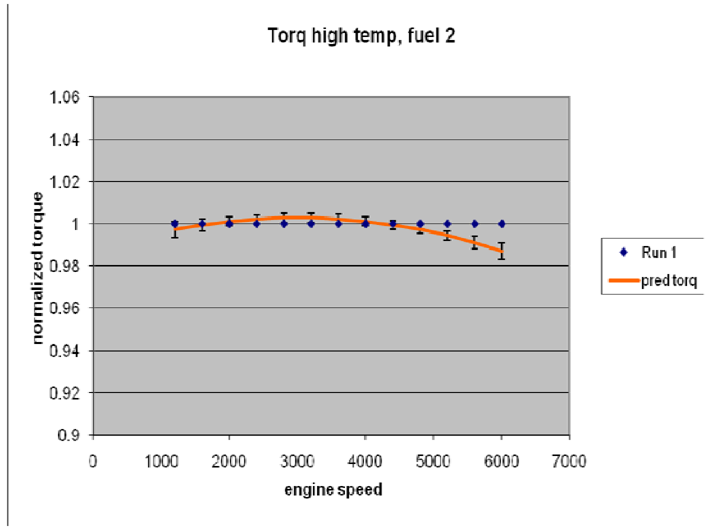
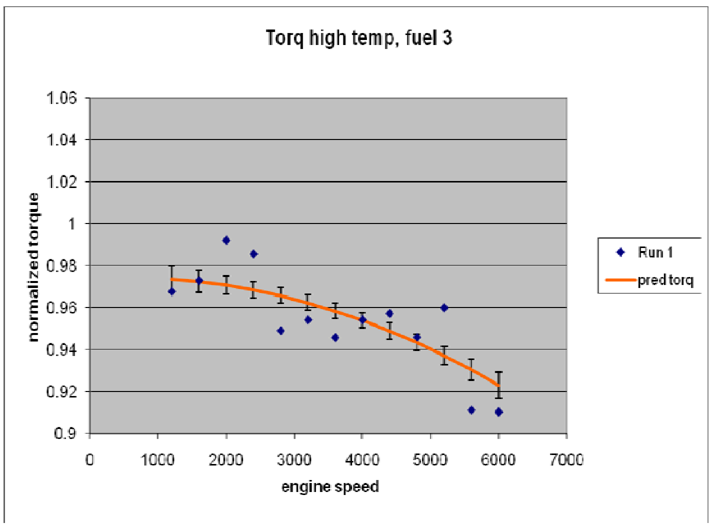
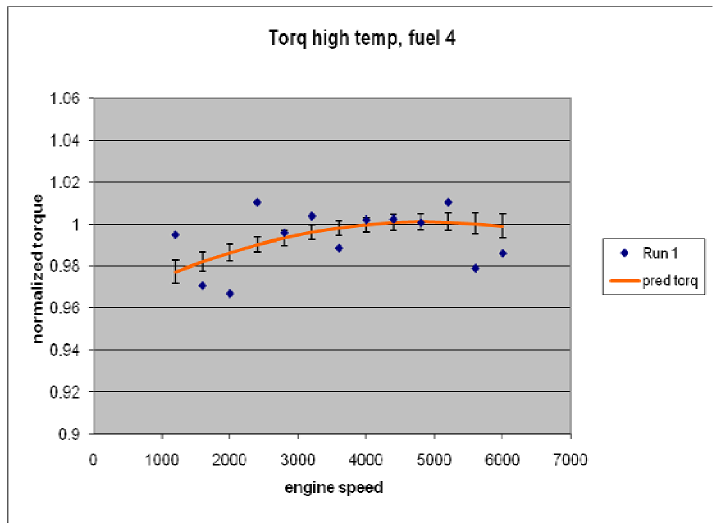


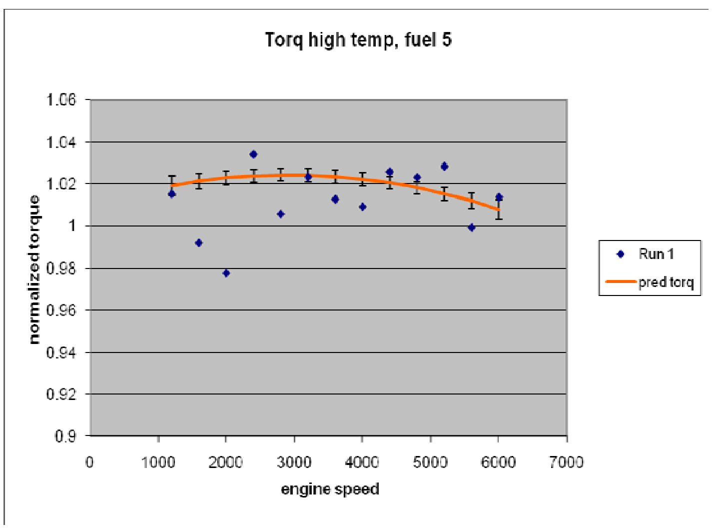
Figure C-22
GM Corrected Normalized Torque Model, High Temperature











RON and MON Effects and Estimated Values of "K"

The RON and MON effects can be estimated by collecting the terms and parameters that include these variables. The collected octane coefficient may be a function of engine speed and/or other independent variables. For example the RON coefficient based on spark timing for the Chrysler engine at standard temperature is:

RON coefficient = -0.26274*speed + 1.78682*VE.
And the corresponding MON coefficient is:

MON coefficient = 1.35779 + 0.26090*speed - 2.5057*VE.

Using the engine speed and corresponding VE the octane coefficients as a function of engine speed can be calculated. For the several trials and all fuels, VE and phi vary by speed, but at constant speed and temperature the VE and phi were fairly constant (standard deviations were about 1% of the average variable value). So, average VE and phi values by speed and temperature were employed to calculate the coefficients. Plots of the octane coefficients are given in Figures 9a through 12b presented earlier in the report. Error bars in these plots are the accumulated standard errors of the coefficients.

As noted in the BACKGROUND section of this report, various investigators have attempted to characterize fuel impact on engine knock limited spark performance by the equation:

"Octane Index" = RON –K*S

where S = sensitivity = RON - MON and K is a constant. If the RON and MON coefficients are b_1 and b_2, then:

$K = b_2 / (b_1 + b_2)$ for $b_1 + b_2$ not equal to zero.

Using the octane coefficients calculated above, values of "K" can be calculated as a function of speed. Figures 13a through 14b shown earlier in the report shows the results.

Relative Fuel Effects

While the above analyses give a description of engine performance in terms of RON and MON of the fuels, one may be interested in comparing relative performance of the five fuels themselves. To do this, the models were used to calculate the effect of each fuel as a function of speed. The relative effect was obtained by subtracting the average effect of all the fuels at each speed. In doing this, the general trend of the engine operation is not included. This information is essentially contained in Figures 5a through 8b shown earlier in the report, but is more easily visualized without the general engine effects. Figures C-23 through C-30 display these results.

Figure C-23
Chrysler Engine Relative Fuel Effects on Spark Timing at Standard Temperature

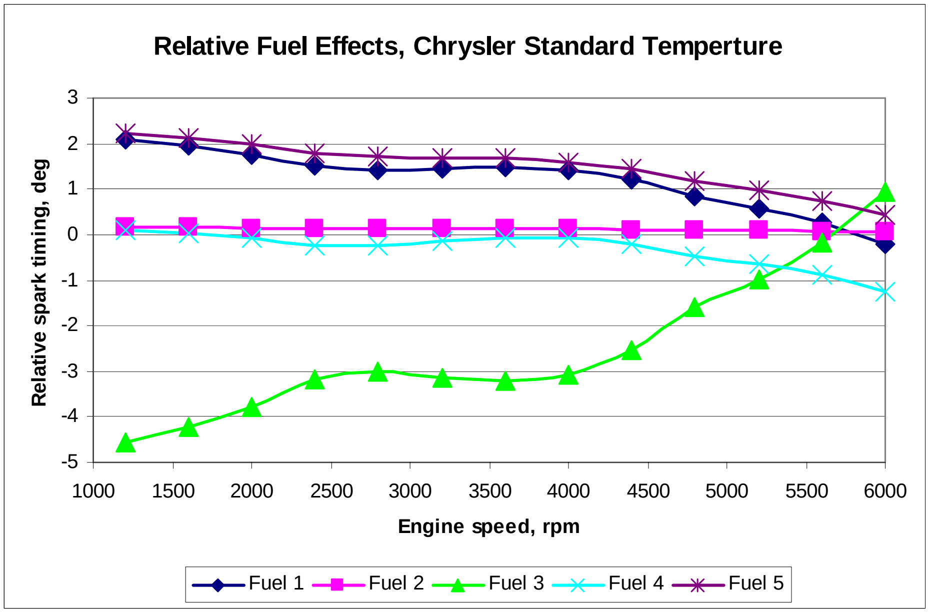


Figure C-24
Chrysler Engine Relative Fuel Effects on Spark Timing at High Temperature

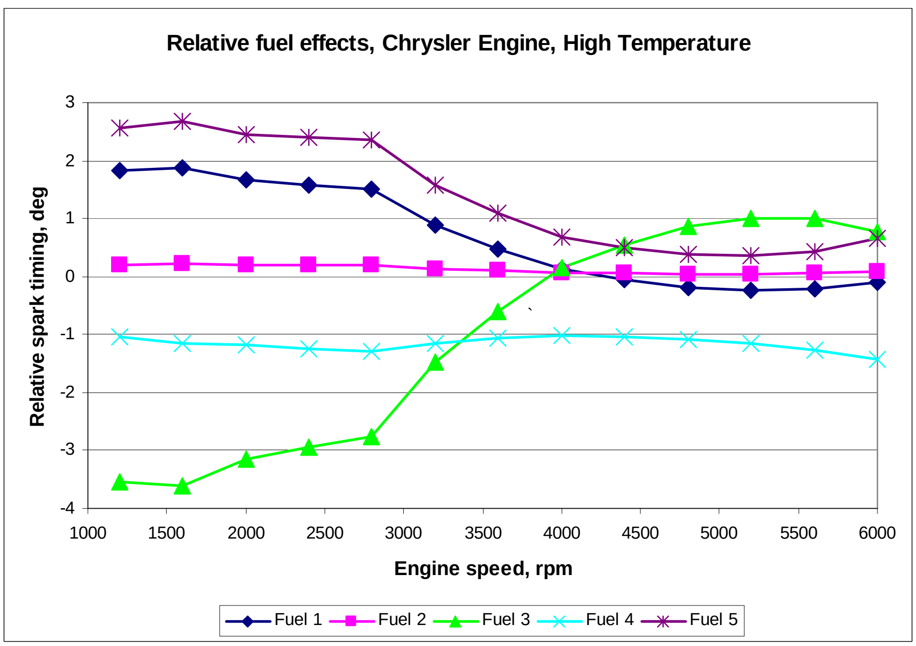


Figure C-25
Chrysler Engine Relative Fuel Effects on Normalized Torque at Standard Temperature

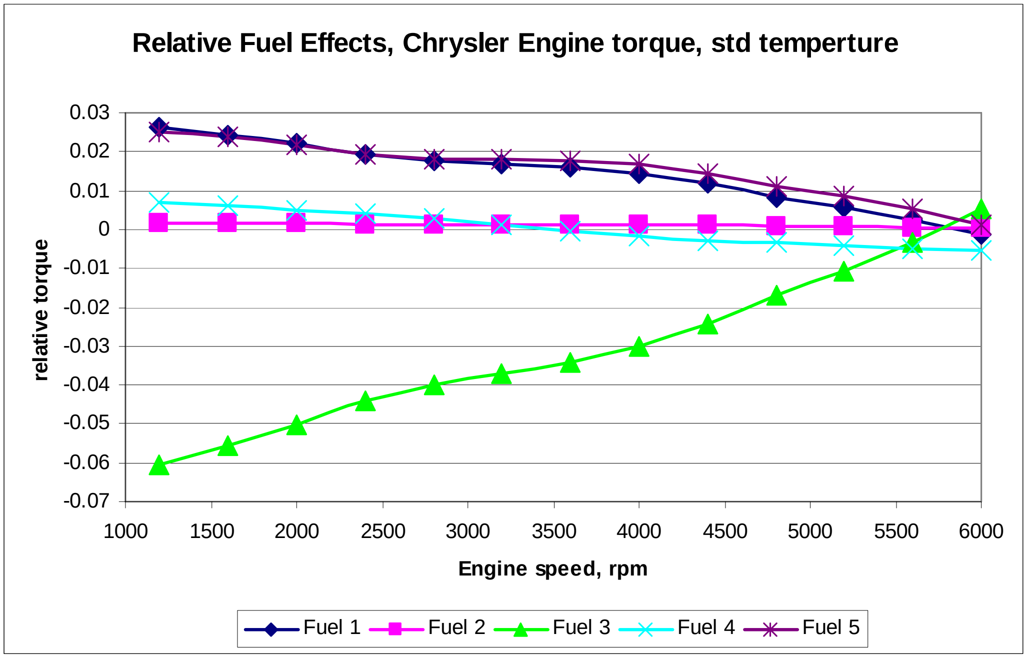


Figure C-26
Chrysler Engine Relative Fuel Effects on Normalized Torque at High Temperature

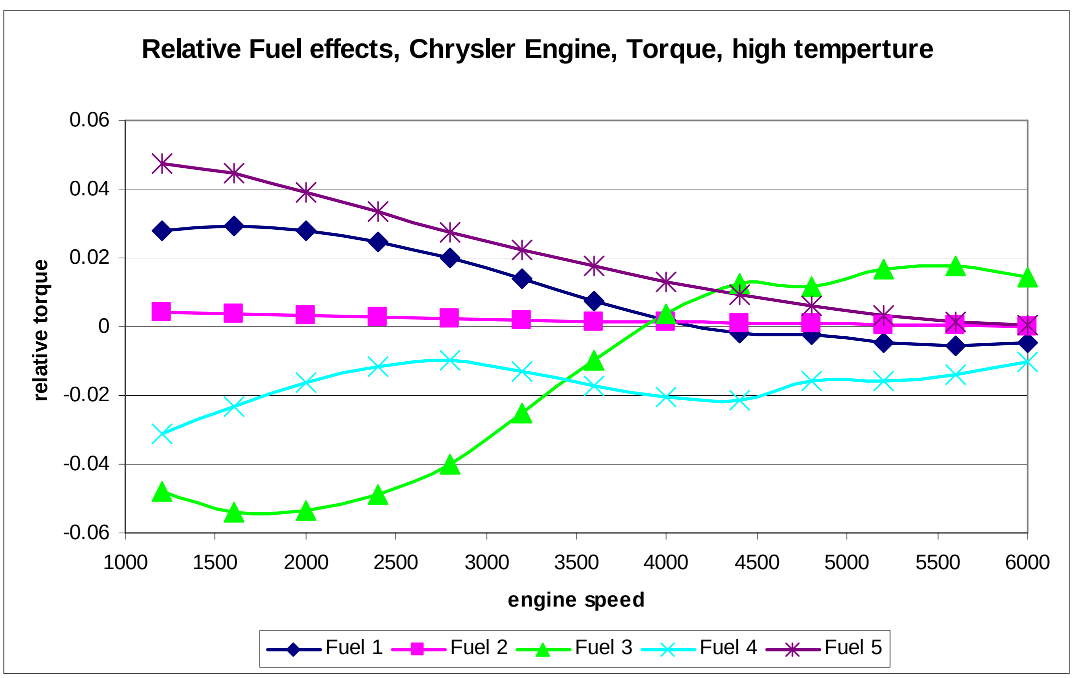


Figure C-27
GM Engine Relative Fuel Effects on Spark Timing at Standard Temperature

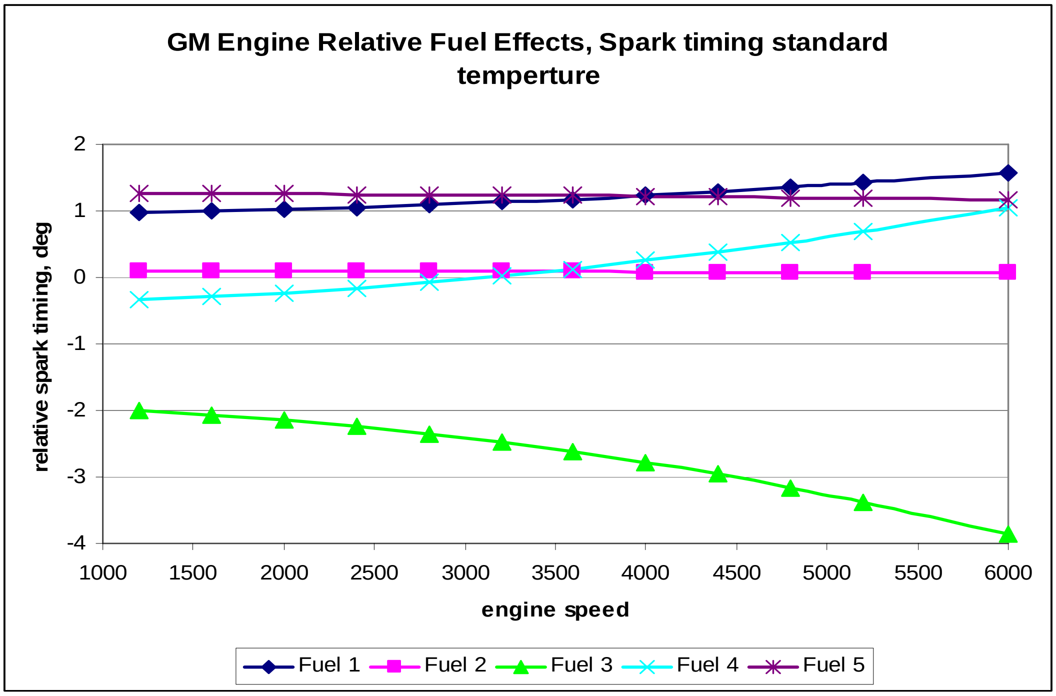


Figure C-28
GM Engine Relative Fuel Effects on Spark Timing at High Temperature

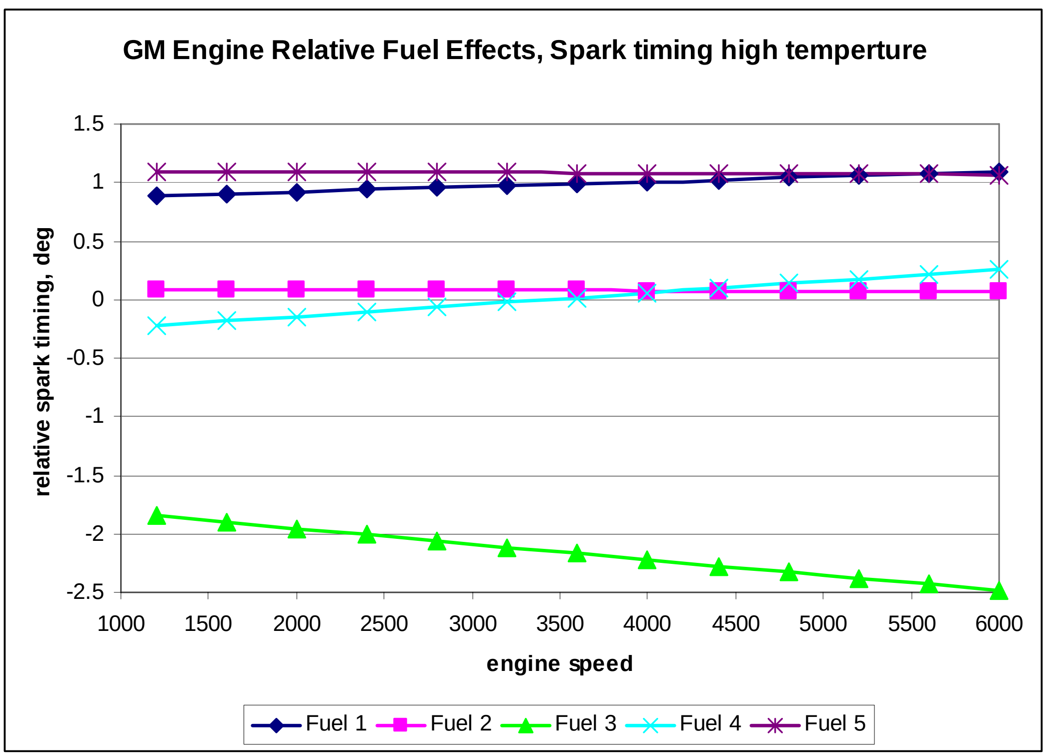


Figure C-29
GM Engine Relative Fuel Effects on Normalized Torque at Standard Temperature

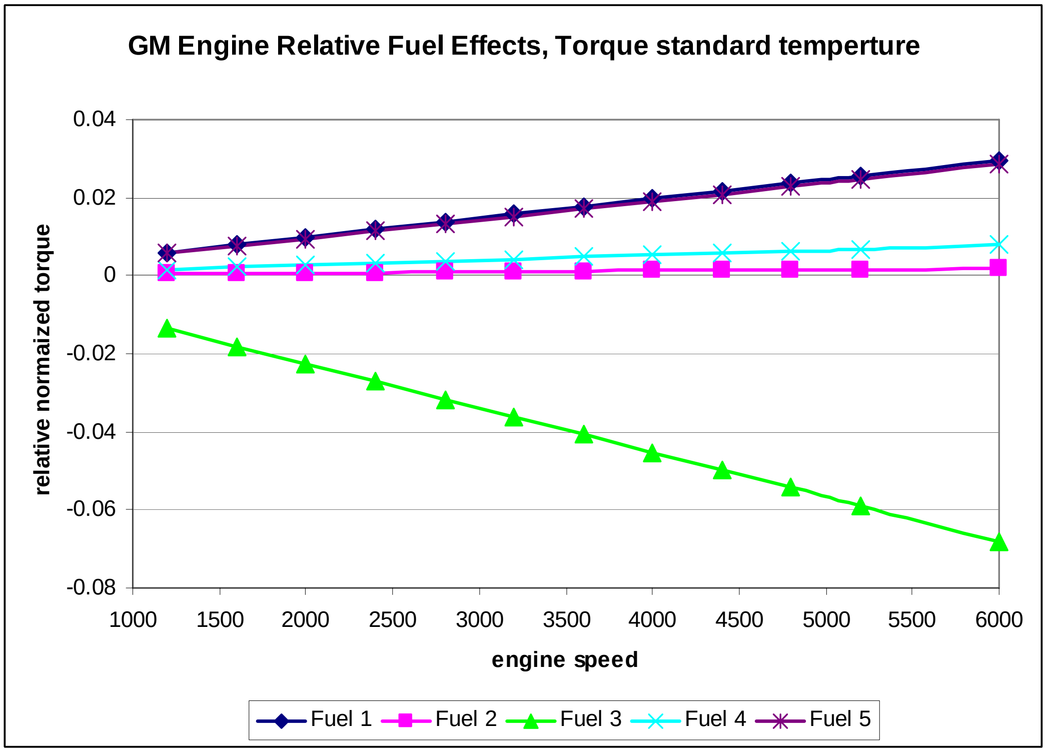
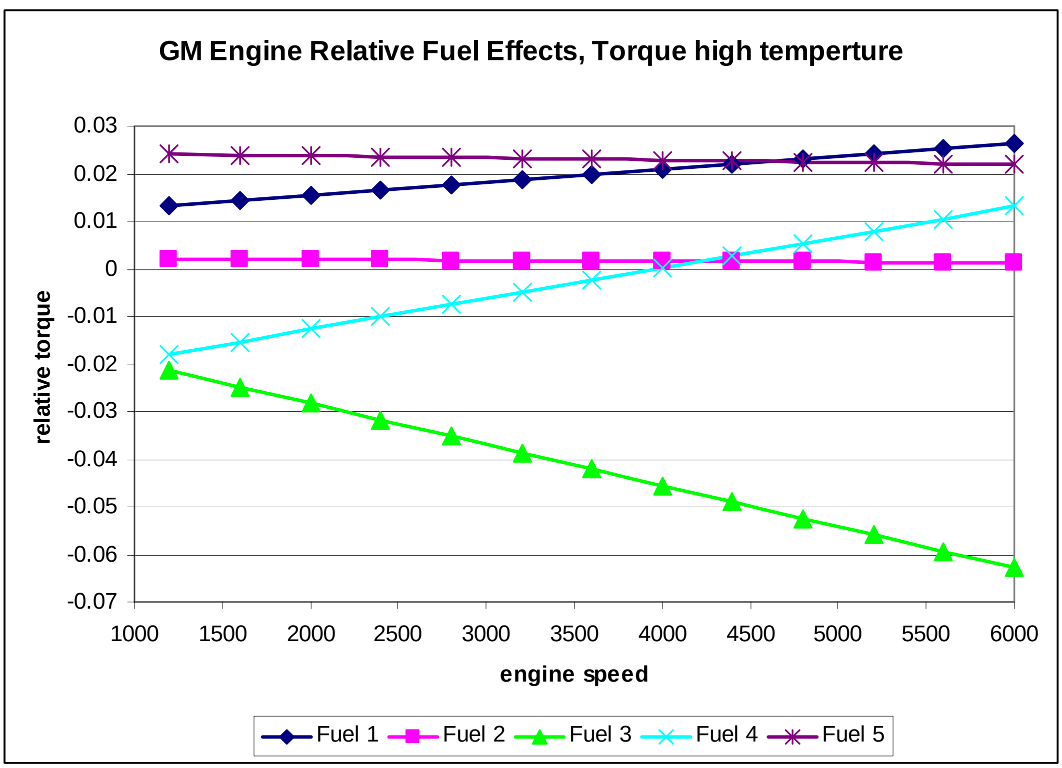


Figure C-30
GM Engine Relative Fuel Effects on Normalized Torque at High Temperature



Regression Data for Testing with Chrysler 5.7-Liter HEMI Engine (Standard Temperature)

speed	spd scale	avg VE	avg Phi	std temp spk RON	std temp spk MON	std temp spk K	SE spk RON	SE spk MON	SE spk K	k+se	k-se
1200	1.2	0.798667	1.138715	1.11178	-0.33037	-0.42278	0.100334	0.200688	0.369419	-0.05336	-0.7922
1600	1.6	0.823333	1.129146	1.050759	-0.28782	-0.37724	0.10739	0.20366	0.371457	-0.00579	-0.7487
2000	2	0.84	1.136174	0.975442	-0.22522	-0.3002	0.114395	0.206377	0.360586	0.060384	-0.66079
2400	2.4	0.844	1.146244	0.877493	-0.13088	-0.1753	0.120857	0.208469	0.329393	0.154091	-0.50469
2800	2.8	0.880667	1.135222	0.837913	-0.1184	-0.16455	0.13105	0.213285	0.346506	0.181952	-0.51106
3200	3.2	0.937333	1.148715	0.83407	-0.15603	-0.23012	0.143374	0.219955	0.402005	0.171885	-0.63212
3600	3.6	0.992	1.180509	0.826653	-0.18865	-0.29569	0.155665	0.226827	0.466266	0.170578	-0.76195
4000	4	1.03	1.211843	0.789455	-0.17951	-0.2943	0.166634	0.232669	0.500225	0.205925	-0.79453
4400	4.4	1.04	1.234852	0.702227	-0.10021	-0.16645	0.175437	0.236505	0.460801	0.294353	-0.62725
4800	4.7999	1.021333	1.230938	0.563803	0.050901	0.082806	0.18227	0.238313	0.356431	0.439237	-0.27362
5200	5.1999	1.026	1.247462	0.467045	0.143567	0.23512	0.191302	0.2422	0.312205	0.547325	-0.07708
5600	5.5999	1.015333	1.261881	0.342889	0.274654	0.444753	0.199482	0.245142	0.2631	0.707853	0.181653
6000	5.9999	0.981333	1.285611	0.177041	0.464208	0.723912	0.20641	0.246628	0.256072	0.979984	0.46784
					average	-0.07231		se average	0.104171	0.03186	-0.17648

std T spark

Parameter Estimates

Term	Estimate	Std Error
Intercept	-69.8071	14.16014
spd scale	8.306565	3.783619
spd scl2	-0.32341	0.139831
recip spd	-17.269	2.585868
MON	1.357786	0.167529
spd scale*MON	0.260899	0.02058
MON*VE	-2.50572	0.134852
spd scale*RON	-0.26274	0.028465
RON*VE	1.786815	0.118123

Regression Data for Testing with Chrysler 5.7-Liter HEMI Engine (Standard Temperature)

speed	spd scale	avg VE	avg Phi	std temp torque RON	torque MON	torque K	SE torque RON	SE torque MON	SE torque K	k+se	k-se
1200	1.2	0.79867	1.138715	0.012744	-0.00626	-0.96418	0.000961	0.000884	0.303206	-0.66098	-1.26739
1600	1.6	0.82333	1.129146	0.011918	-0.00556	-0.87467	0.001028	0.000913	0.304214	-0.57046	-1.17889
2000	2	0.84	1.136174	0.010924	-0.00487	-0.80307	0.001096	0.00095	0.317866	-0.48521	-1.12094
2400	2.4	0.844	1.146244	0.009664	-0.00417	-0.75912	0.001158	0.000993	0.355995	-0.40312	-1.11511
2800	2.8	0.88067	1.135222	0.00909	-0.00348	-0.61892	0.001257	0.001042	0.33072	-0.2882	-0.94964
3200	3.2	0.93733	1.148715	0.008936	-0.00278	-0.45158	0.001375	0.001095	0.277185	-0.17439	-0.72876
3600	3.6	0.992	1.180509	0.008741	-0.00208	-0.31326	0.001493	0.001152	0.238016	-0.07524	-0.55127
4000	4	1.03	1.211843	0.008195	-0.00139	-0.20423	0.001599	0.001214	0.220052	0.015818	-0.42429
4400	4.4	1.04	1.234852	0.007061	-0.00069	-0.10912	0.001684	0.001278	0.22446	0.115338	-0.33358
4800	4.7999	1.02133	1.230938	0.005325	2.66E-07	5E-05	0.00175	0.001344	0.252431	0.252481	-0.25238
5200	5.1999	1.026	1.247462	0.004079	0.000695	0.145648	0.001837	0.001413	0.259028	0.404676	-0.11338
5600	5.5999	1.01533	1.261881	0.002511	0.001391	0.356402	0.001916	0.001484	0.300947	0.657349	0.055454
6000	5.9999	0.98133	1.285611	0.000453	0.002086	0.821606	0.001983	0.001557	0.651078	1.472684	0.170527
					average	-0.29034		se average	0.090991	-0.19935	-0.38133

std T torque

Parameter Estimates

Term	Estimate	Std Error
Intercept	1.891927	0.078134
spd scale	0.170726	0.038669
phi	-0.17613	0.031549
VE	-1.94374	0.104814
MON	-0.00834	0.000844
spd scale*MON	0.001738	0.000218
spd scale*RON	-0.00336	0.000274
VE*RON	0.021005	0.00113

Regression Data for Testing with Chrysler 5.7-Liter HEMI Engine (High Temperature)

high T

speed	spd scale	avg VE	avg Phi	high temp spk RON	high temp spk MON	high temp spk K	SE spk RON	SE spk MON	SE spk K	SE k+se	SE k-se
1200	1.2	0.85	1.162928	1.233755	0.101958	0.076332	0.702556	0.012128	0.041016	0.117348	0.035317
1600	1.6	0.879333	1.153299	1.293869	0.135944	0.095078	0.699843	0.016171	0.04765	0.142728	0.047429
2000	2	0.888667	1.171375	1.181021	0.16993	0.125786	0.704945	0.020214	0.066928	0.192713	0.058858
2400	2.4	0.9	1.176063	1.151755	0.203916	0.150417	0.706275	0.024257	0.079825	0.230242	0.070592
2800	2.8	0.926	1.180296	1.125327	0.237903	0.174514	0.707479	0.0283	0.092175	0.266689	0.082339
3200	3.2	0.985333	1.240529	0.749289	0.271889	0.26625	0.724844	0.032342	0.190411	0.456661	0.075839
3600	3.6	1.049333	1.279032	0.508915	0.305875	0.375403	0.736171	0.036385	0.340325	0.715729	0.035078
4000	4	1.103333	1.311416	0.306742	0.339861	0.52561	0.745826	0.040428	0.606992	1.132601	-0.08138
4400	4.4	1.129333	1.32666	0.211575	0.373847	0.638594	0.750411	0.044471	0.819028	1.457621	-0.18043
4800	4.7999	1.100667	1.336469	0.150333	0.407824	0.730663	0.753374	0.048513	0.986492	1.717155	-0.25583
5200	5.1999	1.116	1.338771	0.135962	0.441811	0.764679	0.754071	0.052555	0.998238	1.762917	-0.23356
5600	5.5999	1.11	1.332708	0.173814	0.475797	0.732433	0.752237	0.056598	0.848464	1.580898	-0.11603
6000	5.9999	1.084667	1.315077	0.283885	0.509783	0.642312	0.746925	0.060641	0.605101	1.247414	0.037211
					average	0.407544		se average	0.158959	0.566503	0.248585

high T
Parameter Estimates

Term	Estimate	Std Error
Intercept	-761.812	46.91553
spd scale	6.872342	0.916532
phi	573.998	37.38511
VE	-47.8153	3.606842
RON	8.493937	0.51273
phi*RON	-6.24302	0.413013
spd scale*spd scl2	-0.15707	0.003528
spd scale*MON	0.084965	0.010107

Regression Data for Testing with Chrysler 5.7-Liter HEMI Engine (High Temperature)

high T speed	spd scale	avg VE	avg Phi	high T torque RON	torque MON	torque K	SE torque RON	SE torque MON	SE torque K	k+se	k-se
				0.022391	0.006847	0.23418	0.004656	0.068222	1.787279	2.021459	-1.5531
1200	1.2	0.85	1.162928	0.021262	0.003899	0.154972	0.004787	0.068111	2.287667	2.442638	-2.1327
1600	1.6	0.87933	1.153299	0.018905	0.001732	0.083909	0.00511	0.067941	3.016001	3.099909	-2.93209
2000	2	0.88867	1.171375	0.016139	0.000533	0.031981	0.005546	0.068041	3.950541	3.982522	-3.91856
2400	2.4	0.9	1.176063	0.013315	0.000541	0.039077	0.006066	0.068703	4.764603	4.80368	-4.72553
2800	2.8	0.926	1.180296	0.010606	0.00247	0.188911	0.006654	0.070506	4.37427	4.563182	-4.18536
3200	3.2	0.98533	1.240529	0.008112	0.004832	0.373313	0.007302	0.072564	3.51945	3.892763	-3.14614
3600	3.6	1.04933	1.279032	0.00589	0.006857	0.537927	0.008005	0.074364	2.716739	3.254666	-2.17881
4000	4	1.10333	1.311416	0.003978	0.007636	0.6575	0.008762	0.075236	2.27359	2.93109	-1.61609
4400	4.4	1.12933	1.32666	0.0024	0.005856	0.709294	0.00957	0.074215	2.739666	3.44896	-2.03037
4800	4.7999	1.10067	1.336469	0.001173	0.00626	0.84216	0.01043	0.074728	1.978411	2.820571	-1.13625
5200	5.1999	1.116	1.338771	0.00031	0.005683	0.948212	0.011341	0.074504	1.906324	2.854536	-0.95811
5600	5.5999	1.11	1.332708	-0.00018	0.004211	1.044605	0.012304	0.073618	3.291053	4.335658	-2.24645
6000	5.9999	1.08467	1.315077		average	0.449695		se average	0.862732	1.312428	-0.41304

high T

Parameter Estimates

Term	Estimate	Std Error
Intercept	0.107091	0.391738
spd scale	1.506587	0.14719
spd scl2	-0.11544	0.01725
VE	-3.98797	0.42939
RON	0.056863	0.003723
MON	-0.05164	0.005979
spd scale*RON	-0.01663	0.001599
spd scl2*RON	0.001277	0.000187
VE*MON	0.048269	0.00516
RON*recip spd	-0.01963	0.002418
MON*recip spd	0.020946	0.00266

Regression Data for Testing with GM 2.0-Liter Ecotec Engine (Standard Temperature)

speed	spd scale	avg VE	avg Phi	std temp spk RON	std temp spk MON	std temp spk K	SE spk RON	SE spk MON	SE spk K	k+se	k-se
1200	1.2			0.612818	-0.02373	-0.04027	0.049646	0.004051	0.007918	-0.03236	-0.04819
1600	1.6			0.612818	-0.04218	-0.07391	0.049646	0.007201	0.015001	-0.05891	-0.08892
2000	2			0.612818	-0.0659	-0.1205	0.049646	0.011252	0.025516	-0.09499	-0.14602
2400	2.4			0.612818	-0.0949	-0.18324	0.049646	0.016203	0.040973	-0.14226	-0.22421
2800	2.8			0.612818	-0.12917	-0.26708	0.049646	0.022054	0.063952	-0.20313	-0.33103
3200	3.2			0.612818	-0.16871	-0.3799	0.049646	0.028805	0.099067	-0.28083	-0.47897
3600	3.6			0.612818	-0.21353	-0.53477	0.049646	0.036456	0.155105	-0.37967	-0.68988
4000	4			0.612818	-0.26362	-0.75491	0.049646	0.045008	0.250359	-0.50455	-1.00527
4400	4.4			0.612818	-0.31898	-1.08553	0.049646	0.05446	0.427831	-0.6577	-1.51336
4800	4.8			0.612818	-0.37961	-1.62774	0.049646	0.064812	0.808317	-0.81943	-2.43606
5200	5.2			0.612818	-0.44551	-2.66284	0.049646	0.076064	1.843218	-0.81963	-4.50606
6000	6			0.612818	-0.59314	-30.1367	0.049646	0.101268	177.3297	147.193	-207.466

OUTLIER

Note: The "K Spark Timing Effect" chart only includes Rows 4 thru 14

spark std temp

Parameter Estimates

Term	Estimate	Std Error
Intercept	-61.7114	5.353622
spd scale	3.43667	0.950137
spd scl2	1.23857	0.253706
recip spd	6.50846	2.328871
RON	0.61282	0.049646
spd scl2*MON	-0.01648	0.002813

Regression Data for Testing with GM 2.0-Liter Ecotec Engine (Standard Temperature)

speed	spd scale			std temp			SE	SE	SE		
		avg	avg	torque	torque	torque	torque	torque	torque		
		VE	Phi	RON	MON	K	RON	MON	K	k+se	k-se
1200	1.2			0.002871	-0.0014	-0.95682	0.000203	0.000198	0.295309	-0.66151	-1.25213
1600	1.6			0.003828	-0.00187	-0.95682	0.00027	0.000264	0.295309	-0.66151	-1.25213
2000	2			0.004786	-0.00234	-0.95682	0.000338	0.00033	0.295309	-0.66151	-1.25213
2400	2.4			0.005743	-0.00281	-0.95682	0.000406	0.000396	0.295309	-0.66151	-1.25213
2800	2.8			0.0067	-0.00328	-0.95682	0.000473	0.000462	0.295309	-0.66151	-1.25213
3200	3.2			0.007657	-0.00374	-0.95682	0.000541	0.000528	0.295309	-0.66151	-1.25213
3600	3.6			0.008614	-0.00421	-0.95682	0.000608	0.000594	0.295309	-0.66151	-1.25213
4000	4			0.009571	-0.00468	-0.95682	0.000676	0.00066	0.295309	-0.66151	-1.25213
4400	4.4			0.010528	-0.00515	-0.95682	0.000744	0.000726	0.295309	-0.66151	-1.25213
4800	4.8			0.011485	-0.00562	-0.95682	0.000811	0.000792	0.295309	-0.66151	-1.25213
5200	5.2			0.012443	-0.00608	-0.95682	0.000879	0.000858	0.295309	-0.66151	-1.25213
6000	6			0.014357	-0.00702	-0.95682	0.001014	0.00099	0.295309	-0.66151	-1.25213

std T torque

Parameter Estimates

Term	Estimate	Std Error
Intercept	1.00495	0.002502
spd scale	-0.12447	0.02613
spd scale*MON	-0.00117	0.000165
spd scale*RON	0.002393	0.000169

Regression Data for Testing with GM 2.0-Liter Ecotec Engine (High Temperature)

high T

speed	spd scale			high temp	high temp	high temp	SE	SE	SE	SE	SE
		avg	avg	spk	spk	spk	spk	spk	spk		
		VE	Phi	RON	MON	K	RON	MON	K	k+se	k-se
1200	1.2			0.53705	-0.04914	-0.10073	0.062306	0.01911	0.044991	-0.05574	-0.14572
1600	1.6			0.53705	-0.06553	-0.13897	0.062306	0.02548	0.064228	-0.07474	-0.2032
2000	2			0.53705	-0.08191	-0.17996	0.062306	0.03185	0.086168	-0.09379	-0.26613
2400	2.4			0.53705	-0.09829	-0.22402	0.062306	0.03822	0.111267	-0.11275	-0.33528
2800	2.8			0.53705	-0.11467	-0.27149	0.062306	0.04459	0.140077	-0.13141	-0.41157
3200	3.2			0.53705	-0.13105	-0.32279	0.062306	0.05096	0.173267	-0.14953	-0.49606
3600	3.6			0.53705	-0.14743	-0.37841	0.062306	0.05733	0.211661	-0.16675	-0.59007
4000	4			0.53705	-0.16382	-0.43891	0.062306	0.0637	0.256277	-0.18263	-0.69519
4400	4.4			0.53705	-0.1802	-0.50496	0.062306	0.07007	0.308381	-0.19658	-0.81335
4800	4.8			0.53705	-0.19658	-0.57738	0.062306	0.07644	0.369567	-0.20781	-0.94694
5200	5.2			0.53705	-0.21296	-0.65711	0.062306	0.08281	0.441862	-0.21524	-1.09897
5600	5.6			0.53705	-0.22934	-0.74533	0.062306	0.08918	0.527866	-0.21746	-1.27319
6000	6			0.53705	-0.24572	-0.84347	0.062306	0.09555	0.630965	-0.2125	-1.47443

spark, high T w/o #114

Parameter Estimates

Term	Estimate	Std Error
Intercept	5.25446	12.90256
spd scale	-29.7887	6.363836
spd scl2	6.77278	1.320908
recip spd	-37.5659	7.702309
spd scale*spd scl2	-0.46148	0.098679
Phi	10.7357	2.235192
RON	0.53705	0.062306
spd scale*MON	-0.04095	0.015925

Regression Data for Testing with GM 2.0-Liter Ecotec Engine (High Temperature)

high T							SE	SE	SE		
speed	spd scale			torque	torque	torque	torque	torque	torque		
		avg	avg	RON	MON	K	RON	MON	K	k+se	k-se
		VE	Phi	0.011314	0.00435	0.277689	0.001005	0.0022	0.102989	0.380678	0.174701
1200	1.2			0.011314	0.003292	0.225368	0.001005	0.002268	0.121268	0.346636	0.1041
1600	1.6			0.011314	0.002234	0.164874	0.001005	0.002352	0.145521	0.310395	0.019354
2000	2			0.011314	0.001176	0.094132	0.001005	0.002452	0.177986	0.272118	-0.08385
2400	2.4			0.011314	0.000118	0.010296	0.001005	0.002564	0.222009	0.232305	-0.21171
2800	2.8			0.011314	-0.00094	-0.09064	0.001005	0.002688	0.282775	0.192134	-0.37342
3200	3.2			0.011314	-0.002	-0.2145	0.001005	0.002822	0.368676	0.154172	-0.58318
3600	3.6			0.011314	-0.00306	-0.37011	0.001005	0.002965	0.493987	0.12388	-0.86409
4000	4			0.011314	-0.00411	-0.57144	0.001005	0.003115	0.684529	0.113091	-1.25597
4400	4.4			0.011314	-0.00517	-0.84213	0.001005	0.003271	0.990809	0.148675	-1.83294
4800	4.8			0.011314	-0.00623	-1.2255	0.001005	0.003433	1.522346	0.29685	-2.74784
5200	5.2			0.011314	-0.00729	-1.81035	0.001005	0.0036	2.553383	0.74303	-4.36374
5600	5.6			0.011314	-0.00835	-2.81219	0.001005	0.003771	4.936357	2.124167	-7.74855
6000	6										

torque high T, w/o #113, #114 (w/o sprk timing)

Parameter Estimates

Term	Estimate	Std Error
Intercept	-0.6857	0.220193
spd scale	0.231032	0.04363
spd scl2	-0.00174	0.000759
RON	0.011314	0.001005
MON	0.007524	0.002109
Spark timing		
spd scale*MON	-0.00265	0.000521