CRC Report No. AVFL-26

FUTURE GASOLINE ENGINE TECHNOLOGIES AND HIGH OCTANE FUELS FOR REDUCING FUEL CONSUMPTION AND GHG EMISSIONS, PARTS A & B

Final Report

August 2020

COORDINATING RESEARCH COUNCIL, INC.
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Foreword

CRC Project No. AVFL-26 was conducted by two contractors, the Oak Ridge National Laboratory in Oak Ridge, TN (Part A), and IAV Automotive Engineering in Northville, MI (Part B). Both Contractor Final Reports are presented here with an overview Executive Summary prepared by the CRC Advanced Vehicle/Fuel/Lubricants Committee. Part A begins immediately following the AVFL Committee's Executive Summary with the text body and appendices spanning pages 1-27. Part B begins immediately following Part A with the report spanning newly numbered pages 1-44. See the respective Part A and Part B Tables of Contents for details on the placement of the information presented in the two reports.

AVFL Committee Executive Summary

This work investigated improving engine efficiency to reduce fuel consumption by 25% with future engine technologies combined with higher octane fuels. A production direct injection turbocharged engine was modified to incorporate an increased compression ratio (CR) from 9.5 to 11.5, a two-stage turbocharger and increased levels of external cooled EGR. The octane of the fuels ranged from 92 RON to 102 RON, the ethanol from 0% to 30%. The final boiling point, (a surrogate for PMI) as an indication of the propensity of the fuel to create additional particulate matter, ranged from 363°F to 438°F. IAV Automotive Engineering was contracted to conduct steady state engine dynamometer testing. Several steady state speed and load test points were run and fuel consumption and emissions were measured and recorded. That data was then used in the Autonomie model for vehicle- level modeling to determine fuel consumption and CO_2 emissions benefits.

To establish a baseline to compare the future engine to, a production direct injection, turbocharged engine was run under several steady state speeds and loads at Oak Ridge National Laboratory (ORNL) and fuel consumption and emissions measurements were made. That data was input into the Autonomie model. Attributes of a typical production mid-size vehicle were used to develop a vehicle for use in the Autonomie model: vehicle mass, transmission gearing, drive ratios, aerodynamics.

The Autonomie modeling resulted in the high-octane 102-RON fuels consistently providing the lowest energy consumption values for the advanced engine on all four test cycles, the UDDS, Highway Fuel Economy Test and the city and highway portions of the US06. A 25% reduction in fuel consumption is projected to be achievable with the advanced engine and fuel L, a 102-RON 30% ethanol fuel, in mixed driving. Although the 30% ethanol fuel produced lowest fuel consumption, the high octane 102 RON 0% ethanol fuels produced lowest volumetric fuel consumption, primarily because of the higher volumetric heating value of gasoline compared to ethanol. For high-octane 102 RON fuels with same ethanol level, higher final boiling point produced lower volumetric fuel consumption for all test cycles.

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Gasoline Engine and Fuels Offering Reduced Fuel Consumption and Emissions: Vehicle Modeling Final Report

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August 2020

OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

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EXECUTIVE SUMMARY

The Gasoline Engine and Fuels Offering Reduced Fuel Consumption and Emissions (GEFORCE) project was proposed in response to the U.S. Department of Energy's Funding Opportunity Announcement 0991 by a team made up of the members of the Coordinating Research Council (CRC) and the research staff at Oak Ridge National Laboratory (ORNL.) The project focused on investigating the potential benefits that might be attained through synergistic use of specific engine technology together with fuels formulated to represent potential directions that high-octane fuels of the future might progress. A stated objective in the DOE FOA was to demonstrate a 25% reduction in petroleum consumption through optimization of the engine technologies together with a suitable fuel.

An advanced engine was constructed and used with a matrix of research fuels to investigate potential avenues for efficiency improvement. The engine incorporated technologies expected to become mainstream for boosted engines in the next 10 to 20 years. These included increased compression ratio, a two-stage turbocharger, and cooled external exhaust gas recirculation (EGR). The fuel matrix was designed to investigate impacts from research octane number (RON), volumetric ethanol content, and the final boiling point of the fuel. The engine calibration was optimized for each fuel individually and data collected to enable vehicle system modelling that projected energy consumption, fuel economy, tailpipe CO_2 emissions, and impact on petroleum consumption for an industry-average mid-size sedan.

The engine calibration and data collection were carried out at IAV in Michigan and is the subject of a separate report. IAV provided the engine data to Oak Ridge National Laboratory to support the vehicle modelling portion of the project.

The vehicle modelling results show the following trends:

- Ethanol content does have a consistently strong influence on the fuel economy results for all cycles and all fuels. Among the fuels of a nominal RON level, increasing ethanol content consistently lowers fuel economy, with the 30% ethanol fuels always providing the lowest fuel economy for a given RON level. However, in some cases the energy consumption improvement allows the 30% ethanol fuels to match the fuel economy of the ethanol-free fuel P. These observations underscore the importance of both engine efficiency and fuel volumetric energy content on vehicle fuel economy.

- There was no consistent trend in the projected energy consumption results for differences in fuel T90 for all fuels and cycles. Fuel economy projections did show a consistent trend, with the higher T90 fuel providing slightly greater fuel economy when compared to the low T90 fuel of the same ethanol content. The observed trends were consistent with differences in the heating value of the fuels.

- The 102-RON fuels provided reduced energy consumption and greater fuel economy for the advanced engine on all drive cycles. The engine compression ratio of 11.5 was higher than would typically be used in a turbocharged engine when 92-RON fuel use is expected. Hence, the engine experiences more efficiency degradation from knock avoidance when using the 92-RON fuels. This degradation causes the fuel economy results for the 92-RON fuels to be lower than those for the 102-RON fuels.

- Fuels E and F (92-RON, 30% ethanol) are projected to achieve 10% or greater reduction in petroleum consumption, with fuels K (102-RON, 30% ethanol) and O (97 RON, 30% ethanol) achieving greater than a 20% reduction. Fuel L (102-RON, 30% ethanol) achieves greater than

25% reduction, meeting the petroleum reduction target of the project. All of the fuels that achieve 10% or greater reduction in petroleum consumption are 30% ethanol blends.

- Increasing final boiling point increased fuel economy at fixed ethanol content when the 102-RON fuels were used. This trend is a result of differences in the volumetric energy content of the fuels and the projected energy consumption values for the fuels. In the case of the 102-RON fuels, increasing final boiling point also resulted in an increase in the energy content of the fuel. There was not a consistent trend between the energy content and final boiling point for the 92-RON fuels at fixed ethanol content.

1. INTRODUCTION

1.1 BACKGROUND

The current state-of-the-art in gasoline engine architecture is the gasoline turbocharged, direct-injection engine. Such engines are presently in production but are prevented from achieving even greater efficiency because of the onset of knock, which can irreversibly damage the engine. Techniques for avoiding knock include delaying the ignition timing relative to the piston position, which reduces peak temperatures and pressures in the cylinder and thus removes the knocking condition. Under some conditions where changing ignition timing is insufficient to remove knock, additional fuel is added to cause the combustion conditions to be fuel-rich, which can further cool the in-cylinder conditions. However, the displacement of ignition timing from the thermodynamic optimum location and the use of fuel-rich combustion both degrade the fuel efficiency of the engine. Historically, the onset of knock is most often associated with very high power driving events that occurred infrequently and did not have a significant impact on fuel efficiency. However, the current trend of reducing engine displacement while improving specific power ratings (downsizing) and reducing the engine speeds experienced during most driving modes (downspeeding) are increasing the importance of knock avoidance during a larger portion of typical driving conditions (both on certification cycles and those typical of consumer use). Thus, knock avoidance is rapidly becoming one of the most important limitations to increasing vehicle fuel efficiency.

Ever-tightening emissions regulations have challenged engine designs for many years, and continue to do so. Recent emissions regulations have continued to apply more pressure to reduce emissions, particularly of non-methane organic gas (NMOG) and nitrogen oxides (NO_X). Particulate matter (PM) emissions have historically not been problematic for gasoline engines; however, tightening regulatory limits require that direct-injection gasoline engines be designed with more attention to their PM emissions than had been the case with previous gasoline engine architectures, perhaps requiring the use of gasoline particulate filters. Fuel formulation could also play a strong role in PM emissions reductions, since in-cylinder charge motion and fuel injection strategies could benefit from consideration for fuel properties such as the distillation curve, fuel chemistry, density, and viscosity in order to minimize NMOG, NO_X, and PM formation during the combustion process. Hence, there is also a strong opportunity to reduce emissions by taking advantage of potential future fuel formulations.

Existing studies have been undertaken to investigate the potential for exhaust gas recirculation (EGR) to aid in both knock avoidance and emissions reduction. Southwest Research Institute's HEDGE consortium, for example, has demonstrated a 10% brake specific fuel consumption benefit at low loads characteristic of certification cycles using many of the future technologies anticipated to be included in this proposed activity[1]. The HEDGE consortium did not make use of advantageous fuel properties, which can afford additional opportunities for performance optimization leading to further reductions in fuel consumptions, and in some cases direct petroleum displacement. Szybist et al. have shown that inclusion of ethanol in fuel can enable

[1] "SwRI's HEDGE Technology for High Efficiency, Low Emissions Gasoline Engines," presented at the 2010 DEER Conference by Terry Alger.

additional benefits beyond chemical octane improvement that provides an opportunity for improved ignition timing during knock-limited combustion that further improves brake engine efficiency[2]. Storey et al. showed that inclusion of ethanol in the fuel could provide a significant reduction in PM emissions, and Aikawa et al. showed that the distillation of the fuel, regardless of ethanol inclusion, also plays a significant role in PM formation [3,4]. Similarly, Jung et al. showed that a GTDI engine modified to achieve higher compression ratio could achieve sufficient efficiency improvement in a near-term engine architecture to balance the lower volumetric heating value caused by inclusion of ethanol in the fuel[5]. None of these studies have brought all of these potential interactions between fuel and engine technology together in one designed experiment to assess the simultaneous ranges of both engine technologies and fuel formulations that provide the most joint benefit.

There are a number of future directions that US gasoline formulations could take in response to regulatory requirements, but none of these directions are definitive, and this situation leads to considerable uncertainty in engine and vehicle development as a result. For example, the biofuel mandates promulgated under the Renewable Fuel Standard could lead to increased ethanol content in fuel, but whether this increased content will result in higher octane ratings that can be used to improve fuel efficiency is unknown. PM emissions regulations under the EPA Tier 3 and California LEV III regulations may result in another round of gasoline reformulation to aid in PM reduction, but again the collateral impact on other emissions and fuel efficiency is not clear. Finally, the status quo of gasoline blended with 10% ethanol to produce an 87- 93 anti-knock index (AKI) fuel may continue as these fuels will continue to be useful for the legacy fleet. Future engines will need to provide higher levels of efficiency simultaneously with lower levels of emissions than have ever been achieved, regardless of the direction fuel formulation may take. As has already been discussed, there are opportunities for co-evolution of engine design with gasoline formulation that can enhance efficiency while simultaneously reducing emissions. Identifying the opportunities in self-reinforcing fuel formulation and engine technology could significantly improve opportunities for the OEMs to balance the expectations of customers, manufacturing costs, and national energy and environmental policy objectives. The energy industry (producers, distributors, and retailers) also stands to benefit from this information, as it will identify key fuel formulation directions that are most promising, allowing the industry to subsequently determine the capital improvements that would be needed for changes to fuel formulation towards the proposed solutions.

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[2] "Advantageous Fuel Properties of Ethanol Beyond Octane Number," presented at the 2014 SAE Government/Industry Meeting by Jim Szybist.

[3] "Exhaust Particle Characterization for Lean and Stoichiometric DI Vehicles Operating on Ethanol-Gasoline Blends," John M.E. Storey et al., SAE Paper 2012-01-0437.

[4] "Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions," Koichiro Aikawa et al., SAE Paper 2010-01-2115.

[5] "Fuel Economy and CO2 Emissions of Ethanol-Gasoline Blends in a Turbocharged DI Engine," Hosuk Jung, et al., SAE Paper 2013-01-1321.

The Gasoline Engine and Fuels Offering Reduced Fuel Consumption and Emissions (GEFORCE) project was proposed in response to the U.S. Department of Energy's Funding Opportunity Announcement 0991 by a team made up of the members of the Coordinating Research Council (CRC) and the research staff at Oak Ridge National Laboratory (ORNL.) The project focused on investigating the potential benefits that might be attained through synergistic use of specific engine technology together with fuels formulated to represent potential directions that high-octane fuels of the future might progress. A stated objective in the DOE FOA was to demonstrate a 25% reduction in petroleum consumption through optimization of the engine technologies together with a suitable fuel. This objective was carried into the project, with a vehicle modeling exercise focused on examining the vehicle fuel economy metric based on data generated using an experimental engine and a matrix of potential future fuel formulations.

1.2 ENGINE EXPERIMENTAL STUDY

The largest effort in the GEFORCE project was the assembly and calibration of an engine to include technologies expected to become mainstream in the next 10-20 years using fuels formulated to explore potential fuel formulation pathways that may emerge during a similar timeframe. This work was carried out at GM and at IAV in Michigan and is documented in a companion report.[6] Some information is repeated here for the convenience of the reader.

The experimental engine was developed with component parts from a GM 2.0-liter LTG and other engines as well as purpose-built components. The swept volume of the engine was increased by replacing the crankshaft with a production model to achieve increased stroke while retaining the bore size and pistons from the original LTG engine. Increasing swept volume in this manner increases compression ratio which in turn is needed to take advantage of fuels with improved anti-knock performance. The swept volume increased from 2.0 to 2.35 liters; the compression ratio increased from 9.5 to 11.5. Additionally, a high-volume exhaust gas recirculation (EGR) system was added and a two-stage turbocharger system fitted to the engine. These technologies were anticipated to provide flexibility in the engine system to explore potential fuel-related optimization strategies. A production LTG engine was used to provide baseline data against which the performance of the advanced engine could be compared. The baseline data were collected using a premium-grade, ethanol-free certification gasoline (Haltermann Tier 2 EEE) at ORNL.

Staff at IAV performed calibration optimization on the advanced engine using a matrix of fuels formulated to support this project. The fuel matrix was designed to explore the impacts of research octane number (RON), ethanol content (volume %), and the fuel distillation final boiling point. The fuel matrix is shown in Figure 1. The experimental work at IAV developed fuel consumption and emissions data for the engine for each fuel. These data were developed by operating the engine at a series of speeds from 1,000 RPM to 5,000 RPM and at a range of output up to maximum output torque at each speed.

[6] Chi Binh La, Shane Macfarlane, Kevin Sittner, "AVFL-26 Calibration Study on Modified GM LTG Engine Using a Matrix of 15 Fuels," available from the CRC website, www.crcao.org.

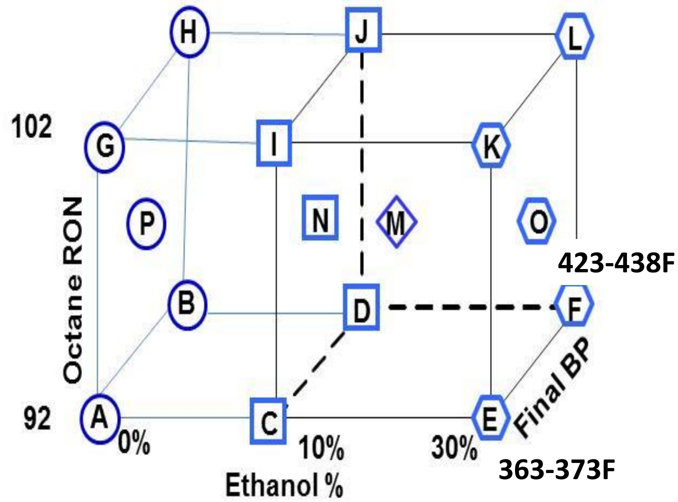

Figure 1. The GEFORCE matrix of fuels was formulated to explore impacts of RON, ethanol content, and final boiliing point on the fuel economy and emissions of the experimental engine.

2. VEHICLE MODELING STUDY

A vehicle modeling study was used to evaluate the engine data developed at IAV to estimate potential impacts on vehicle fuel economy, energy consumption, and tailpipe CO_2 emissions. A related study was previously carried out to evaluate these impacts for a near-term gasoline, turbocharged, direct-injection (GTDI) engine using near-term technology in the AVFL-20 project.[7] The Autonomie simulation package was used to support vehicle modeling in the AVFL-20 project and is also used in the current investigation.

Vehicle modeling investigations were carried out by using an industry-average mid-size sedan as the target vehicle for both the baseline engine and the advanced engine. A detailed description of the development of parameters to describe this vehicle in the Autonomie environment is contained in the AVFL-20 report. The vehicle parameters used in AVFL-20 were carried forward for the current study, with the exception that transmission and final drive ratios were taken from a production vehicle that is equipped with the baseline LTG engine to better match the engine and transmission for the mid-size sedan application. The vehicle model parameters are shown in Table 1.

Table 1. Parameters used in Autonomie to describe the industry-average mid-size sedan.

Parameter	Value
Target Coefficient A (lbf)	34.0501
Target Coefficient B (lbs / MPH)	0.2061
Target Coefficient C (lbs / MPH^2)	0.0178
Equivalent Test Weight (lbs)	4000
1st Gear Ratio	4.69
2nd Gear Ratio	3.31
3rd Gear Ratio	3.01
4th Gear Ratio	2.44
5th Gear Ratio	1.92
6th Gear Ratio	1.44
7th Gear Ratio	1.00
8th Gear Ratio	0.75
9th Gear Ratio	0.62
Final Drive Ratio	2.89
Tire Rolling Radius (m)	0.32775

As in the AVFL-20 study, the urban dynamometer driving schedule (UDDS), the highway fuel economy test (HWFET), and both the city and highway portions of the US06 driving schedule (US06_city and US06_hwy) were used to investigate vehicle fuel economy, energy consumption, and tailpipe CO_2 emissions. The UDDS is the driving schedule used in the U.S. Federal Test Procedure (FTP). The FTP together with the HWFET are used in fuel economy certification calculations in the U.S. The two portions of the more aggressive US06 driving schedule are additionally used in calculation of the 5-cycle fuel economy value that is posted on the window sticker of new vehicles offered for sale.

[7] C. Scott Sluder, David E. Smith, Martin Wissink, James E. Anderson, Thomas G. Leone, and Michael H Shelby, "Effects of Octane Number, Sensitivity, Ethanol Content, and Engine Compression Ratio on GTDI Engine Efficiency, Fuel Economy, and CO2 Emissions," AVFL-20 Project Final Report, available from the CRC website, www.crcao.org.

2.1 BASELINE VEHICLE MODEL RESULTS

Projected energy consumption results for the baseline engine and vehicle using the Haltermann EEE 97 RON gasoline are shown in Figure 2. Lowest energy consumption occurs for the HWFET cycle; highest energy consumption occurs on the city portion of the US06 cycle. This trend in energy consumption is typical of light-duty vehicles and was also observed in modeling results from the AVFL-20 project. Projected fuel economy values depend on the energy consumption for a given cycle combined with the volumetric energy content for the fuel being used. The projected fuel economy values are shown in Figure 3.

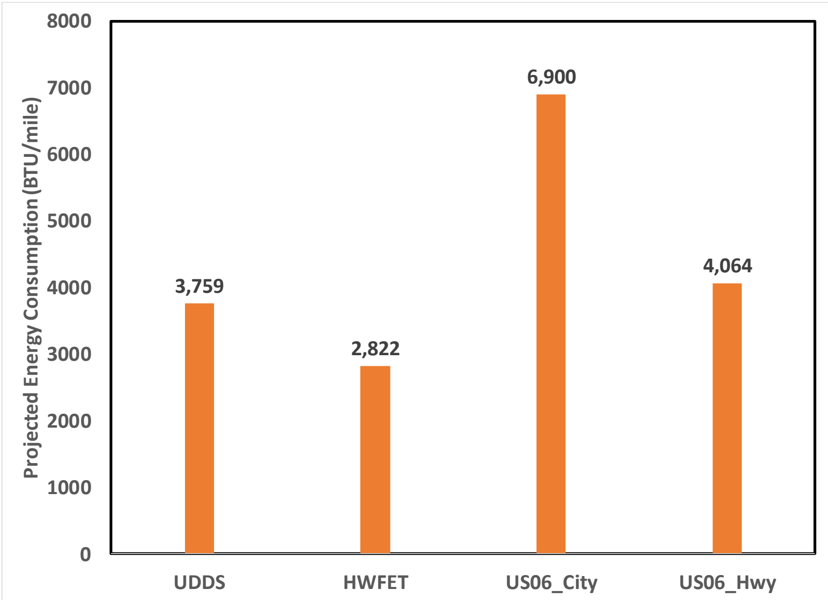

Figure 2. Projected energy consumption for the baseline engine and vehicle using Haltermann EEE 97 RON gasoline.

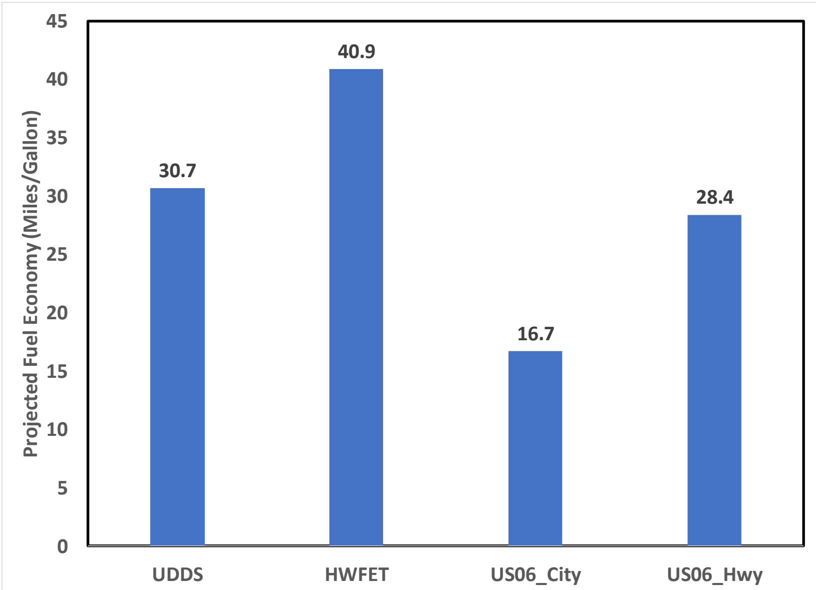

Figure 3. Projected fuel economy results for the baseline engine and vehicle using Haltermann EEE 97 RON gasoline.

2.2 FUEL ECONOMY RESULTS FOR THE ADVANCED ENGINE AND VEHICLE

The advanced engine has a 17.5% larger displacement than the baseline engine. Comparing this engine using a fuel similar to the fuel used in the baseline engine is a useful comparison to assess differences in energy consumption and fuel economy that may result from the difference in engine displacement. Fuel P is a 97 RON, ethanol-free fuel used in the advanced engine and is therefore similar to the EEE gasoline used in the baseline engine. Comparison of the energy consumption and fuel economy results are shown in Figures 4 and 5.

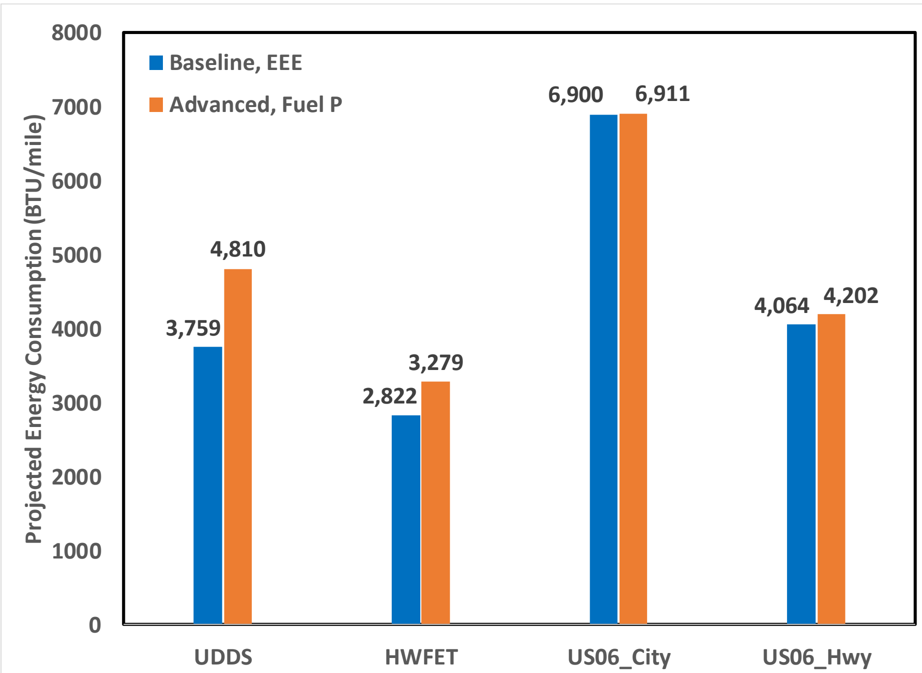

Figure 4. Comparison of projected energy consumption values for the baseline engine using EEE gasoline and the advanced engine using fuel P.

The projected energy consumption on a per-mile basis is higher for the advanced engine using fuel P than for the baseline engine using the EEE fuel on all cycles. This outcome is consistent with a greater degree of throttling loss when the larger displacement engine is used in the same vehicle as the smaller baseline engine. The difference between the two engines is much smaller for the city portion of the US06 cycle, indicating that the advanced engine may be more efficient than the baseline engine at high-load conditions that are more prevalent on this portion of the US06 cycle.

Fuel P has a volumetric energy density of 123,615 BTU/gallon compared with 115,421 for EEE. This difference reduces the mpact of the energy consumption differences noted previously on fuel economy. Nevertheless, for UDDS and HWFET cycles the fuel economy values for the advanced engine are lower than the baseline because of the difference in engine displacement.

Figure 6 shows the projected energy consumption for the UDDS for all the study fuels used in the advanced engine. A broken green line indicates the result achieved with fuel P for comparison. The 92 and 97 RON fuels (except for fuel O) provide similar energy consumption results. The 102 RON fuels all provide lower (better) energy consumption results.

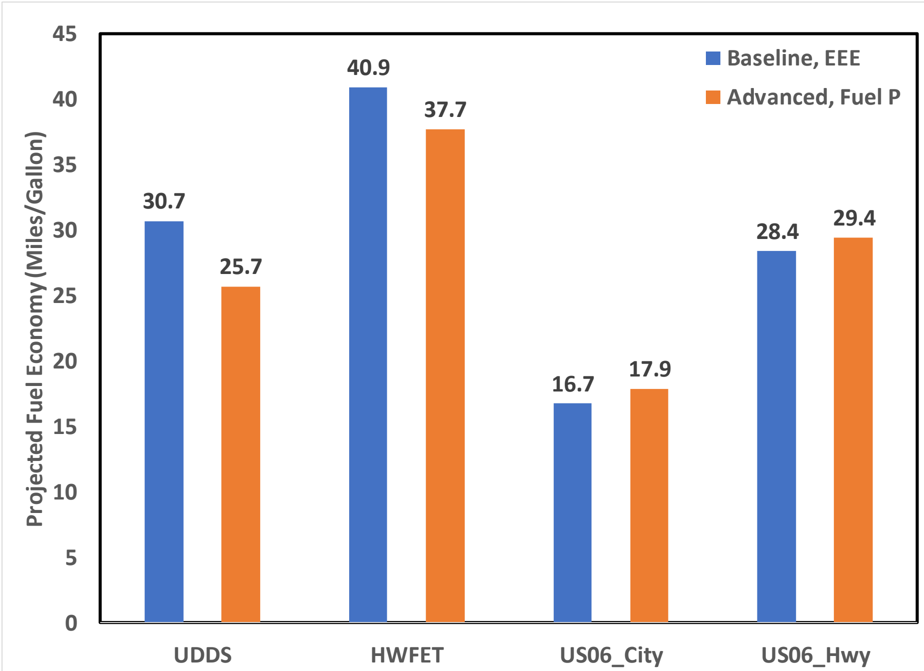

Figure 5. Comparison of projected fuel economy values for the baseline engine using EEE gasoline and the advanced engine using fuel P.

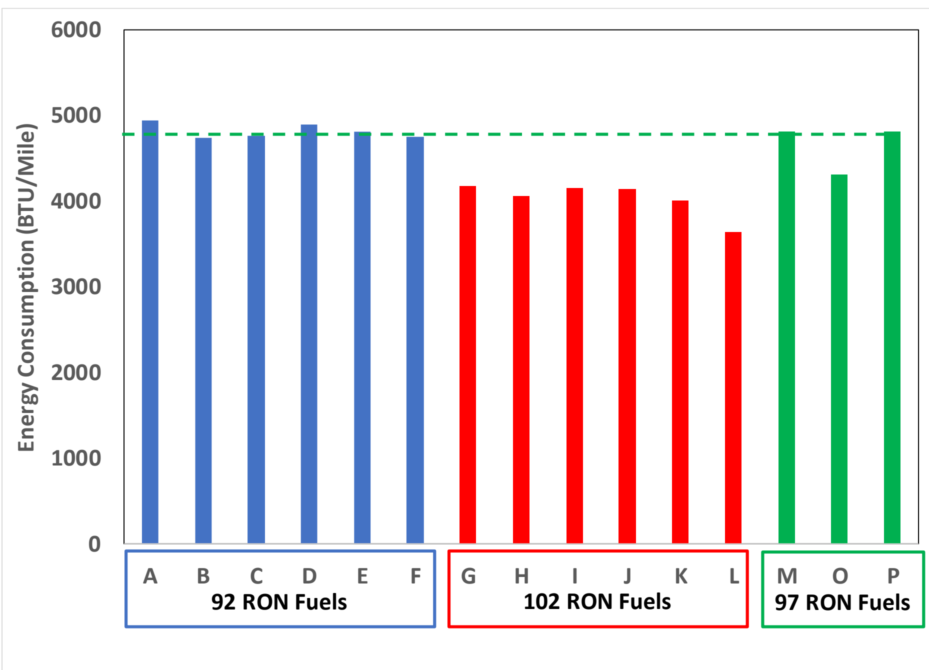

Figure 6. Projected energy consumption for the advanced engine on the UDDS cycle using the study fuels.

Figure 7 shows the fraction of time spent at each engine operating condition on the UDDS for fuels L and P. The highest concentration of points occurs in very similar locations for the two fuels, but the calibration of the engine for fuel L causes the efficiency contours to move relative to fuel P. These differences at low output torque values are not likely a result of differing fuel anti-knock properties at low load conditions but are instead more likely an outcome of the overall calibration strategy enabled by the 102-RON fuels. Since the 102-RON fuels span a range of ethanol content, this difference is also not likely a result that is strongly tied to the ethanol content of the fuel

Fuel economy projections for the advanced engine on the UDDS cycle are shown in Figure 8. The lower energy consumption noted for the 102-RON fuels enables them to achieve greater fuel economy than other fuels when evaluated at fixed ethanol content. In fact, Fuel L (a 30% ethanol fuel) is projected to achieve the same fuel economy as fuel P (an ethanol-free fuel). This occurrence is noteworthy since ethanol blending reduces fuel volumetric energy content and frequently reduces fuel economy. The remainder of the 97- and 92-RON fuels were projected to provide lower fuel economy than fuel P on the UDDS.

Figure 9 shows the energy consumption for the advanced engine and study fuels for the HWFET cycle. Figure 10 shows a comparison between the fraction of time spent at each operating condition for the HWFET cycle for fuels L and P. Figure 11 shows the projected fuel economy for the study fuels for the HWFET cycle. Fuels M and P exhibit nearly identical energy consumption, with the remainder of the fuels providing lower energy consumption on the HWFET. Comparing the time spent at each condition for fuels L and P shows that for these two fuels, the difference in energy consumption is primarily driven by the difference in size and shape of the 35% efficiency contour of the engine map. The fuel economy results for many fuels still fall below that of fuel P. Four of the six 102-RON fuels (with ethanol content less than 30%) do provide an improvement in fuel economy relative to fuel P. Fuel L, a 30% ethanol fuel, provides parity with fuel P in terms of fuel economy and the lowest energy consumption of any of the fuels on the HWFET cycle.

Figure 12 shows the energy consumption and fuel economy results for the city portion of the US06 cycle. Although the energy consumption levels are higher for the city portion of the US06 than for the UDDS, the trend among the fuels is similar. The 92-RON fuels provide energy consumption results that are comparable to fuel P, with four fuels providing improved energy consumption. All of the 102-RON fuels provide improvements in energy consumption, with fuel L providing the lowest energy consumption. Comparison of the fraction of time spent at each condition for fuels L and P on this cycle (Figure 13) shows that the primary driver of improved cycle-average energy efficiency for fuel L is the size and shape of the 35% efficiency contour. Figure 14 shows the projected fuel economy for the study fuels for the city portion of the US06 cycle. Two of the 102-RON fuels (G and H, both ethanol-free fuels) provide higher fuel economy than fuel P.

Figure 15 shows the energy consumption and fuel economy projections for the highway portion of the US06 cycle. Figure 16 show the comparison of fraction of time spent at each point for fuels L and P for the highway portion of the US06 cycle. As noted previously, the size and shape of the 35% efficiency contour is the prevailing difference between the two engine calibrations.

Figure 17 show the projected fuel economy for the study fuels on the highway portion of the US06 cycle. All fuels except fuel M offer reduced energy consumption compared to fuel P on this cycle, with four fuels (G, H,I , and J) simultaneously offering equal or higher fuel economy. Among the 92-RON fuels there does not seem to be a strong overall trend linking ethanol content to energy consumption for all the drive cycles examined. In some cases the 30% ethanol fuels (E and F) provide the lowest energy consumption of the 92-RON fuels, but in other cases the greatest benefit is provided by fuel A, a 10% ethanol fuel. Fuel O consistently provided the lowest energy consumption of the 97-RON fuels, but the results from fuels M and P don't provide as much consistency. This trend suggests that ethanol content may be a contributor, but is not the only factor in the consistently low energy consumption of fuel O. Fuel L has the lowest energy consumption, K is the second lowest, and G, H, I, and J are higher. Although fuel L consistently provided the lowest energy consumption of the 102-RON fuels the results for all the 102-RON fuels do not present a consistent trend with respect to ethanol content. Thus, while ethanol content is perhaps a contributing factor in the energy consumption results of the study fuels, it is not the only fuel formulation characteristic that determines energy consumption for all the cycles.

Ethanol content does have a consistently strong influence on the fuel economy results for all cycles and all fuels. Among the fuels of a nominal RON level, increasing ethanol content consistently lowers fuel economy, with the 30% ethanol fuels always providing the lowest fuel economy for a given RON level. However, in some cases the energy consumption improvement allows the 30% ethanol fuels to match the fuel economy of the ethanol-free fuel P. These observations underscore the importance of both engine efficiency and fuel volumetric energy content on vehicle fuel economy.

Similarly, there was no consistent trend in the projected energy consumption results for differences in fuel T90 for all fuels and cycles. Fuel economy projections did show a consistent trend, with the higher T90 fuel providing slightly greater fuel economy when compared to the low T90 fuel of the same ethanol content. The observed trends were consistent with differences in the heating value of the fuels.

The 102-RON fuels provided reduced energy consumption and greater fuel economy for the advanced engine on all drive cycles. The engine compression ratio of 11.5 was higher than would typically be used in a turbocharged engine when 92-RON fuel use is expected. Hence, the engine experiences more efficiency degradation from knock avoidance when using the 92-RON fuels. This degradation causes the fuel economy results for the 92-RON fuels to be lower than those for the 102-RON fuels.

Increasing final boiling point increased fuel economy at fixed ethanol content when the 102-RON fuels were used. This trend is a result of differences in the volumetric energy content of the fuels and the projected energy consumption values for the fuels. In the case of the 102-RON fuels, increasing final boiling point also resulted in an increase in the energy content of the fuel. There was not a consistent trend between the energy content and final boiling point for the 92-RON fuels at fixed ethanol content.

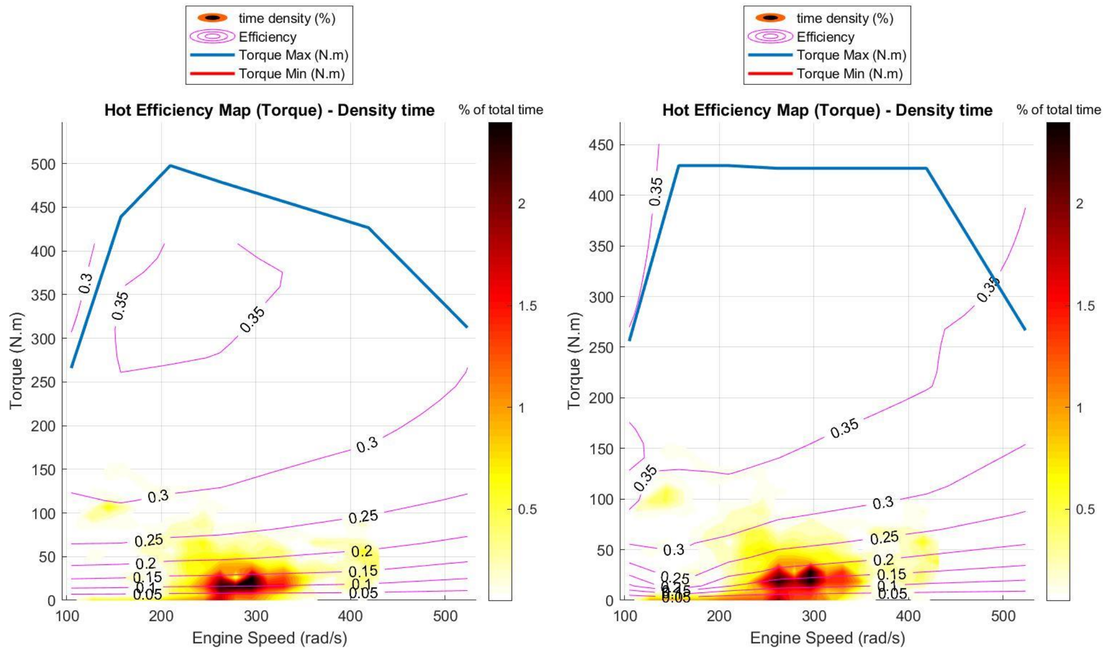

Figure 7. Fraction of time spent at each engine condition for the advanced engine using fuel P (left) and fuel L (right) on the UDDS cycle.

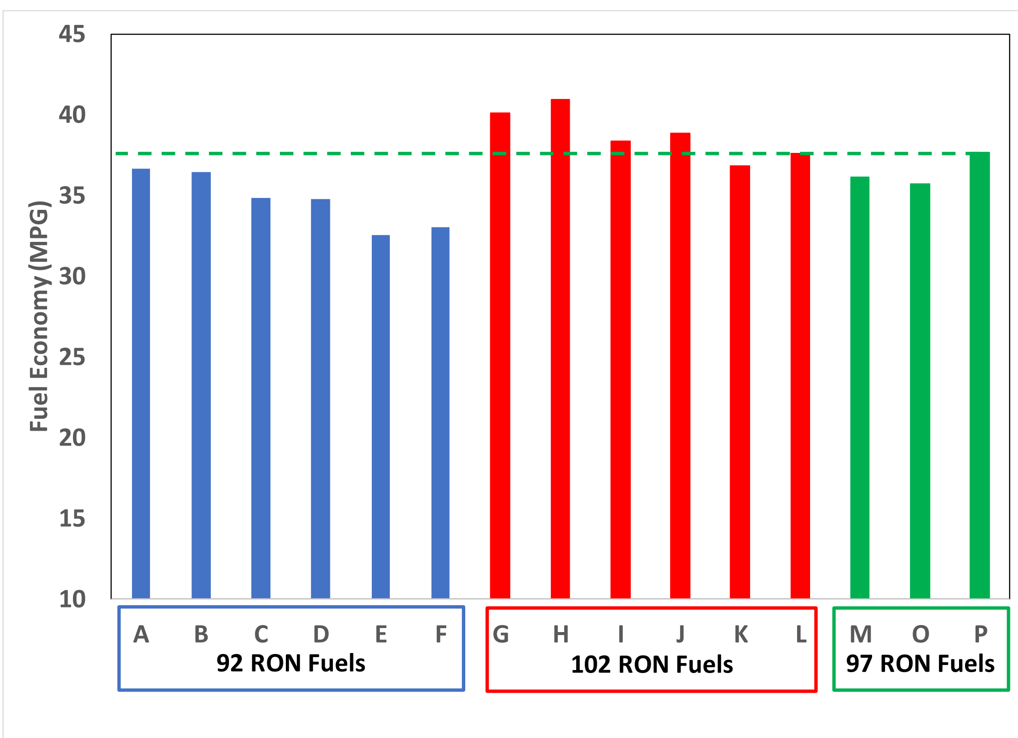

Figure 8. Projected fuel economy on the UDDS drive cycle for the advanced engine using the study fuels.

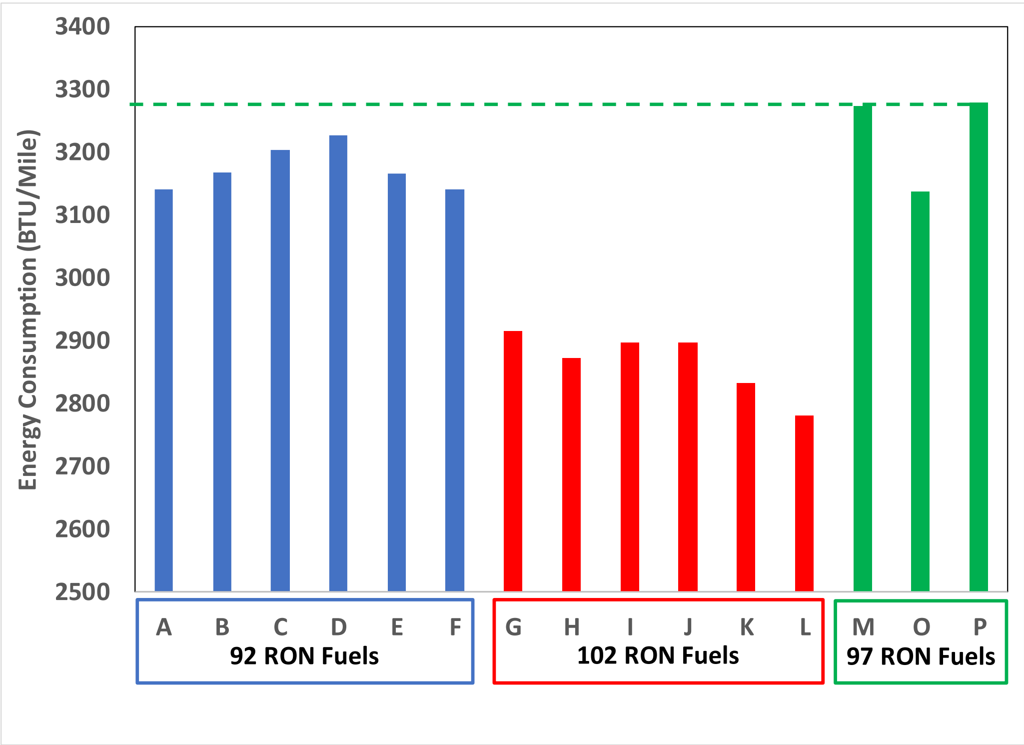

Figure 9. Projected energy consumption for the advanced engine using study fuels on the HWFET cycle.

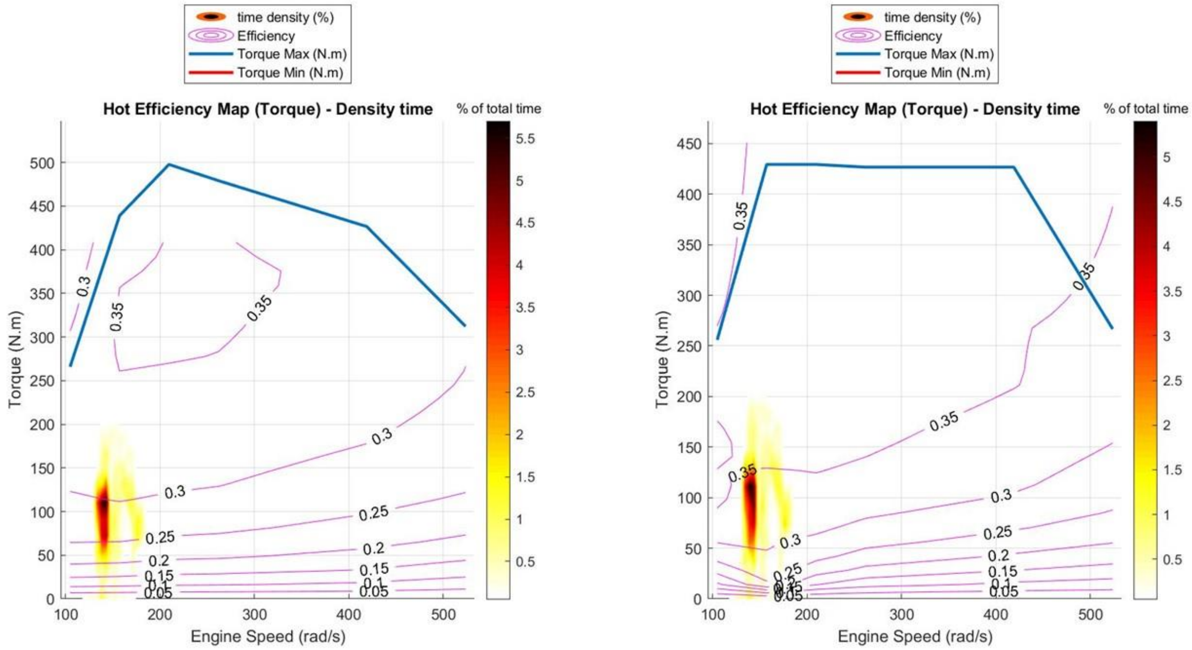

Figure 10. Fraction of time spent at each operating condition for the HWFET cycle for fuel P (left) and fuel L (right).

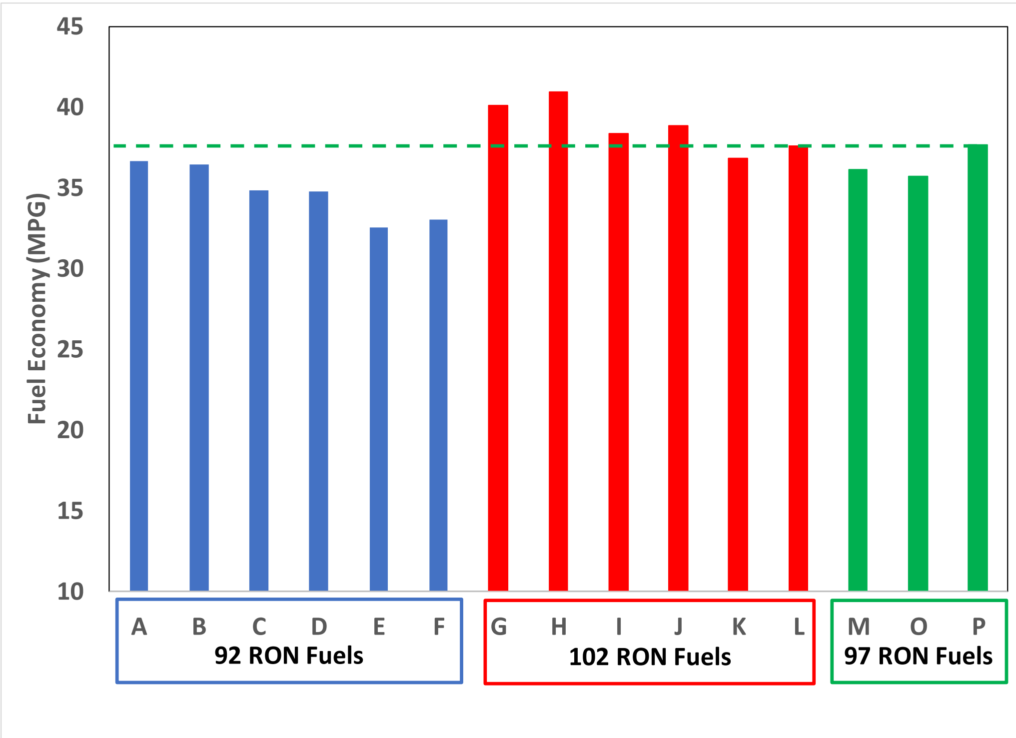

Figure 11. Projected fuel economy results for the advanced engine using study fuels on the HWFET cycle.

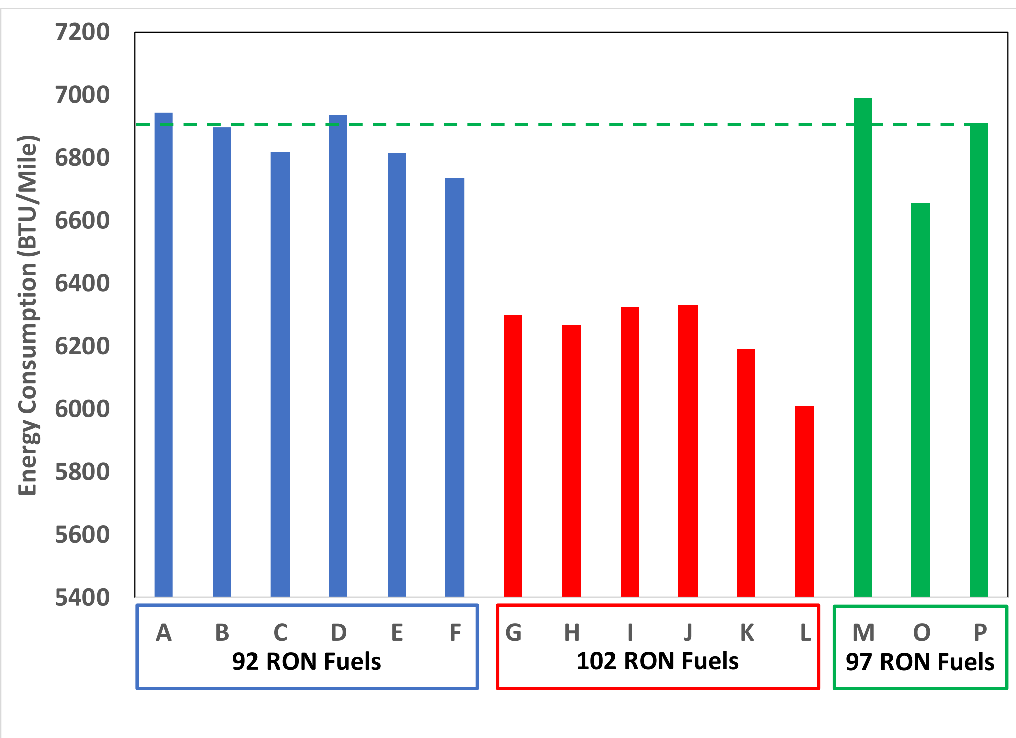

Figure 12. Projected energy consumption results for the advanced engine using study fuels on the city portion of the US06 cycle.

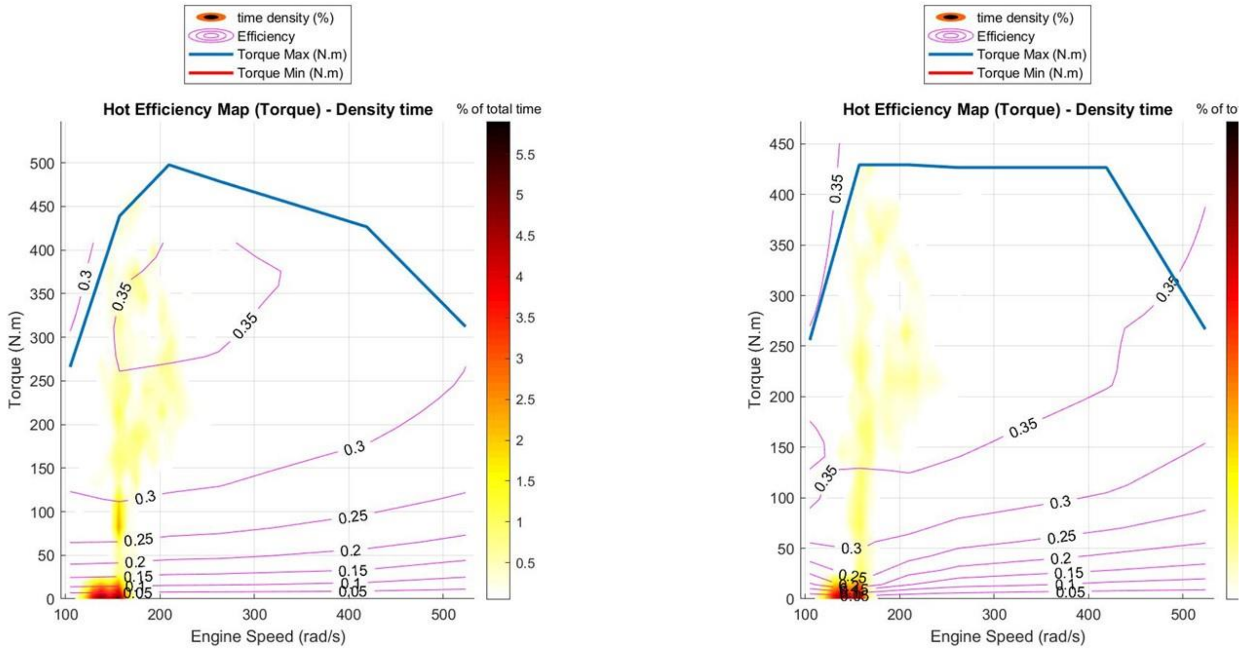

Figure 13. Comparison of the fraction of time spent at each condition for the city portion of the US06 cycle for fuels P (left) and L (right).

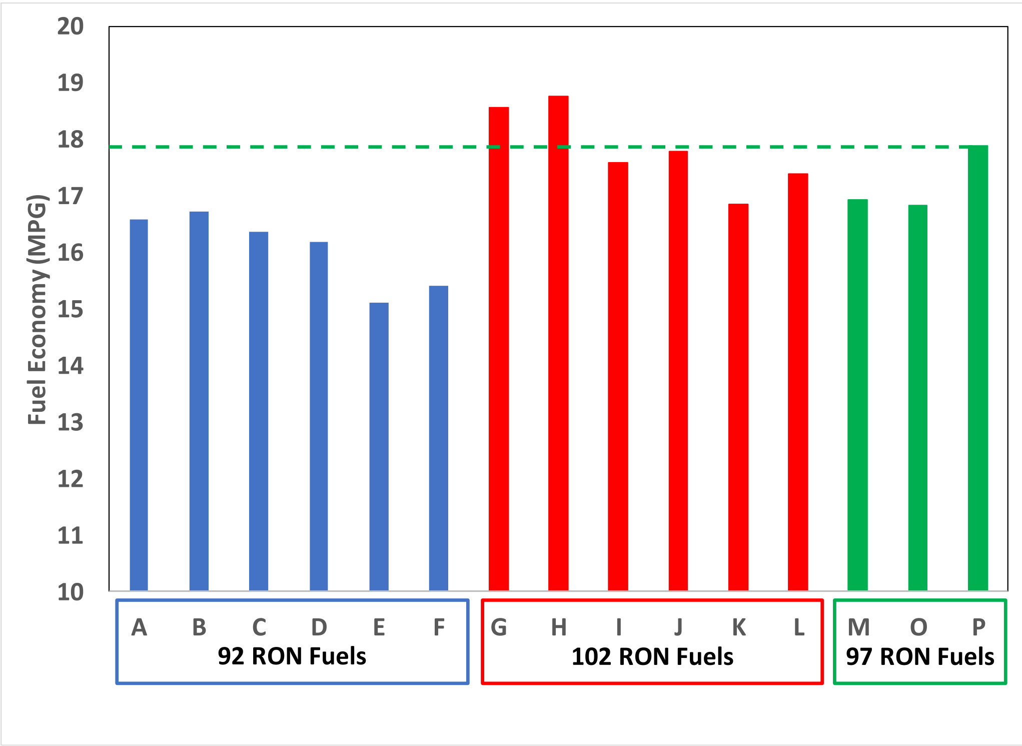

Figure 14. Projected fuel economy results for the advanced engine using the study fuels on the city portion of the US06 cycle.

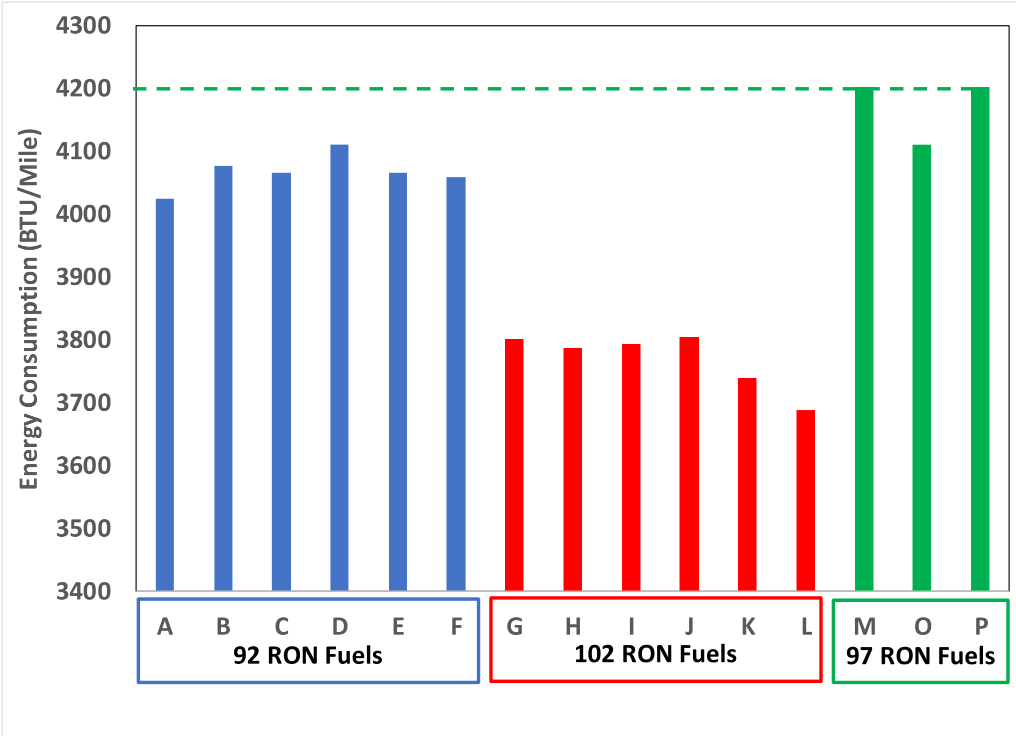

Figure 15. Projected energy consumption for the advanced engine using study fuels on the highway portion of the US06 cycle.

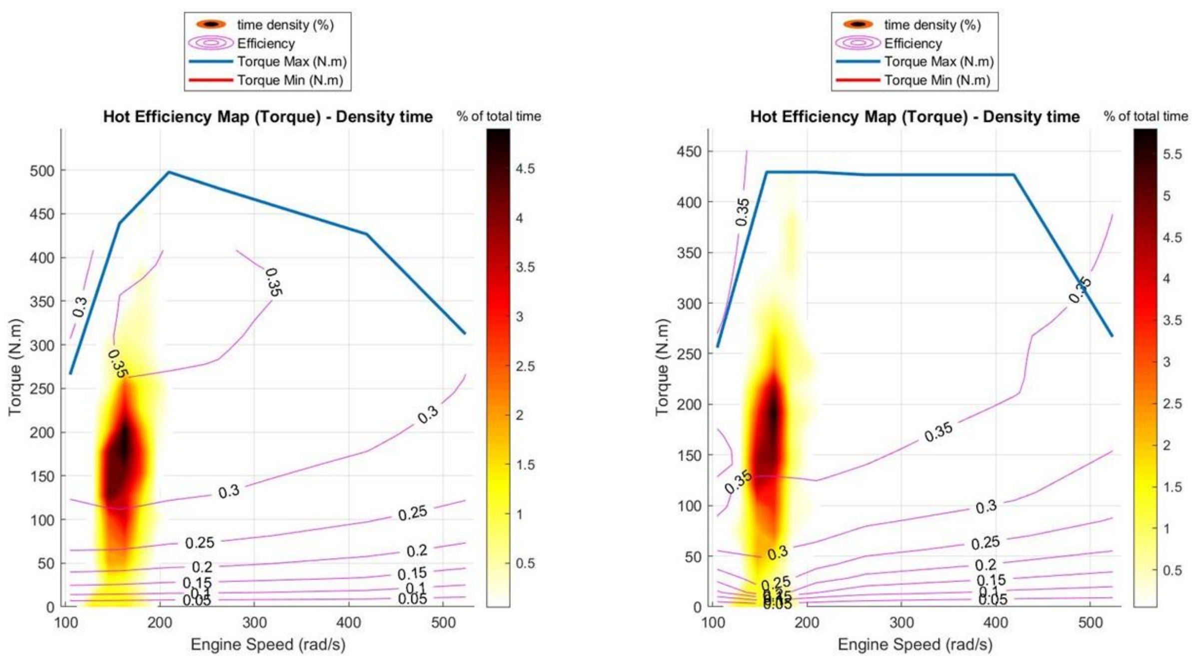

Figure 16. Comparison of the fraction of time spent at each condition for fuels P (left) and L (right) on the highway portion of the US06 cycle.

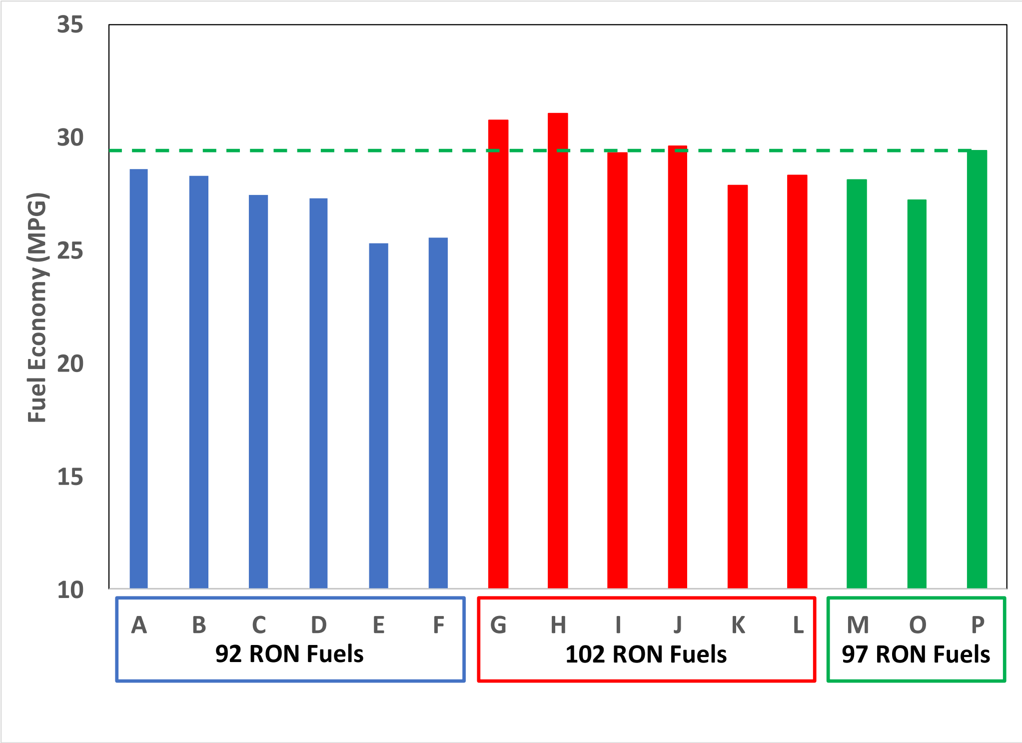

Figure 17. Projected fuel economy for the advanced engine using study fuels on the highway portion of the US06 cycle.

2.3 REDUCTION OF PETROLEUM CONSUMPTION

A goal of this project was to reduce petroleum consumption by 25%. This objective is most likely to be achieved when the energy consumption for all four cycles is reduced significantly in combination with a substantial biofuel blending. The lower the energy consumption for the cycle can be, the less biofuel blending is needed to achieve the goal, and vice versa. Because the larger displacement advanced engine has higher energy consumption than the baseline engine when similar fuels are used, reductions in petroleum consumption are driven primarily by biofuel blending. Virtually all real-world driving combines aspects of the cycles studied. An approximation of the EPA 5-cycle weighting was used to combine the results of all cycles studied to a single petroleum reduction estimate. The approximation of the 5-cycle weighting used the UDDS results in place of all FTP, Cold CO, and SC03 results as was the case in a related study.[8] Figure 18 shows the projected impacts to petroleum consumption for all of the study fuels. Fuels E and F achieve 10% or greater reduction in petroleum consumption, with fuels K and O achieving greater than a 20% reduction. Fuel L achieves greater than 25% reduction, meeting the petroleum reduction target of the project. All of the fuels that achieve 10% or greater reduction in petroleum consumption are 30% ethanol blends.

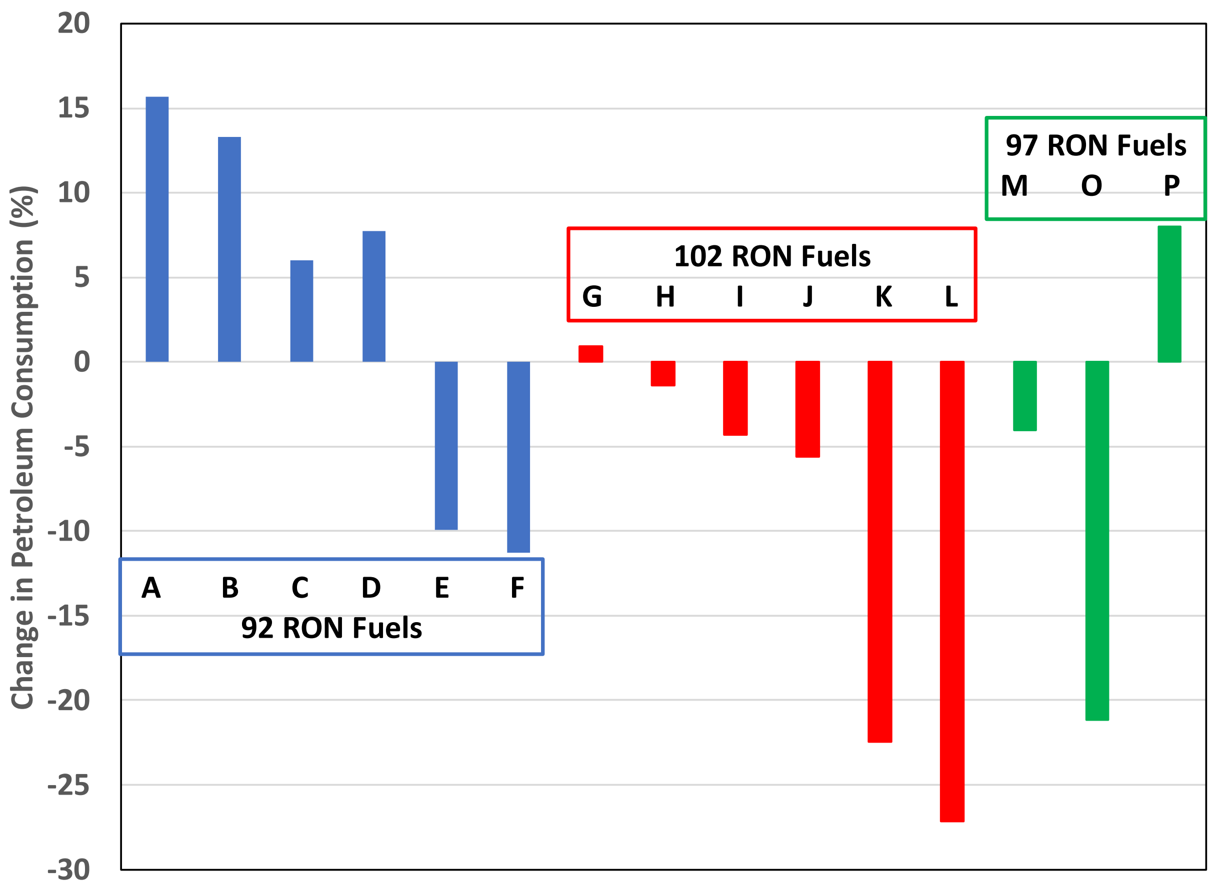

Figure 18. Projected impacts to petroleum consumption for the study fuels. Results are based on a weighted average of the drive cycle results that approximates the EPA 5-cycle weighting method.

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[8] C. Scott Sluder, David E. Smith, James E. Anderson, Thomas G. Leon, and Michael H. Shelby, "U.S. DRIVE Fuels Working Group Engine and Vehicle Modeling Study to Support Life-Cycle Analysis of High-Octane Fuels," February 2019. Available on the web at https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports

3. CONCLUSIONS

- Data collected from calibration of an advanced engine at IAV for a matrix of fuels were used in an Autonomie simulation to project energy consumption and fuel economy results for an industry-average mid-size sedan.
- Use of the larger displacement (2.35L) advanced engine caused the energy consumption of the mid-size sedan to increase relative to the baseline (2.0L) engine on all driving cycles.
- A number of the study fuels enabled reductions in energy consumption for the advanced engine on one or more of the drive cycles compared to the use of Fuel P, which was similar to the EEE fuel used in the baseline engine.
- A 102-RON 30% ethanol blend, fuel L, was projected to provide the lowest energy consumption on all driving cycles. Fuel L does not provide the highest fuel economy, however, because it has a reduced energy content resulting from its 30% ethanol content.
- While high levels of ethanol blending often correlated with improvements in energy consumption for the drive cycles studied, the data do not reveal a consistent trend in this regard.
- The 102-RON fuels consistently provided the lowest energy consumption and the highest fuel economy values for the advanced engine on all four cycles.
- Increasing the final boiling point of the fuel at 102-RON resulted in fuel formulations that had increased energy content and thus improved fuel economy relative to fuels with lower final boiling point at the same ethanol content. This trend was not consistent for the 92-RON fuels.
- 25% reduction in petroleum consumption is projected to be achievable with the advanced engine and fuel L, a 102-RON 30% ethanol fuel, in mixed driving using a combination of the four drive cycles evaluated in this study.

AVFL-26 Calibration Study on Modified GM LTG Engine Using a Matrix of 15 Fuels

IAV Project # USGA-18010
Report Dated: 5/7/2020

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1 List of Acronyms and Abbreviations

ATDC	After Top Dead Center
AVFL	Advanced Vehicle Fuel Lubricants Committee of the Coordinating Research Council
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BSNOx	Brake Specific Nitrogen Oxide
BTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
BTU	British Thermal Units
CA50	Crank Angle Location of 50% Mass Fraction Burned
CAD	Crank Angle Degrees
CAFE	Corporate Average Fuel Economy
CAC	Charge Air Cooler
COV	Coefficient of Variation
cEGR	Externally Cooled Exhaust Gas Recirculation
CR	Compression Ratio
df	Degree of Freedom
E10	10% Ethanol Content Fuel
E25	25% Ethanol Content Fuel
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EtOH	Ethanol
EOI	End of Injection
EOI2_diff	End of Injection Difference Angle
FST	Fuel System Treatment
HC	Hydrocarbon
HP	High Pressure
IAV	Ingenieurgesellschaft für Automobil und Verkehr
iEGR	Internal Exhaust Gas Recirculation
IMEP	Indicated Mean Effective Pressure
KI	Knock Intensity
L	Liter
LBP	Low Boiling Point

LCV	General Motors Corporation 2.5L Engine
LP	Low Pressure
LTG	General Motors Corporation 2.0L Turbocharged Engine
MBT	Maximum Brake Torque
Mdp	Modified Double Pass
MEP	Mean Effective Pressure
MON	Motor Octane Number
N_ACT	Actual Engine Speed
OEM	Original Equipment Manufacturer
ON	Octane Number
P85	Knock intensity threshold based on the 85 % quantile for knocking cylinder pressure
Pmax	Maximum Cylinder Pressure
Peff	Power Effective
PSI	Pound per square inch
RON	Research Octane Number
RPM	Revolutions per Minute
SOI	Start of Injection
Split Factor	Ratio between Primary and Secondary Fuel Injection Mass
STDEV	Standard Deviation
t-cric	t-Critical Value
TtlVol	Total Volume percent of oxygenates
TtlWt	Total Weight percent of oxygen
TWC	Three-way Catalytic Converter

2 Executive Summary

The automotive industry has taken numerous steps to improve overall vehicle fuel efficiency, such as the adoption of downsized turbocharged engines. Downsizing together with other engine technologies like increased compression ratio, sequential boosting, cooled exhaust gas recirculation and multiple injection together with fuel property improvements are enablers to meet future demands of increased fuel efficiency and lower emissions.

The project's objective was to quantify the effects of different fuel properties on the fuel consumption, performance and emissions of a modified engine with calibrations that were specifically optimized for each fuel. The test engine was a GM LTG 2.0 L turbocharged direct injected engine that was modified by GM with the following changes. The GM LTG crankshaft was replaced with a production GM LCV crankshaft which increased the stroke from 86 mm to 101 mm resulting in a displacement increase from 2.0 L to 2.35 L. The geometric compression ratio was increased from 9.5 to 11.5 using stock LTG pistons. A low pressure cooled external EGR system was added and the turbocharger system changed from a single turbo to a two stage sequential. The aforementioned changes although directionally correct for improved engine efficiency, should not be considered optimized as a system. There is a potential that a fully optimized 11.5 CR combustion system with an appropriately matched turbocharger could show better BSFC, BTE and emissions values than in this report. However, the engine as tested is still representative of the general population of down-sized boosted engines and the trends in the data remain valid.

The modified GM LTG engine was calibrated at IAV Automotive Engineering located in Northville, Michigan. Calibration was carried out at steady state conditions at the following speeds; 1000 RPM, 1500 RPM, 2000 RPM, 2500 RPM, 4000 RPM and 5000 RPM. At each speed, engine load was stepped by 2 bar BMEP (equivalent to 37.4 Nm) increments, starting at 2 bar up to a maximum load limited by spark knock, exhaust gas temperature, peak cylinder pressure or engine software. At each steady state point the calibration was optimized to provide the lowest BSFC while maintaining emissions consistent with other production engines of similar displacement and performance. All calibrations were carried out under stoichiometric homogeneous combustion operation.

Variations in RON, ethanol content and boiling point were investigated, forming a fuels matrix comprised of 15 fuel variants (reference ***Figure 1***). The matrix covers three levels of RON; 92, 98 and 102, four levels of ethanol content by percent volume; 0 %, 10 %, 15 % and 30 %, and a high and low final boiling point range of 380-420 °F and 360-385 °F respectively.

Results show that under stoichiometric homogeneous combustion at steady state engine speeds, increased RON decreases the engine's knocking tendency and thus significantly expanding its performance limit to higher loads. With 92 RON fuels the maximum achievable load is limited to 12 bar BMEP due to spark knock from 1500-4000 RPM and exhaust gas temperature limits above 4000 RPM. 98 RON fuels are limited to a peak performance of 16 bar BMEP at 2000 RPM. As engine speed increases from 2000-4000 RPM the performance decreases due to a combination of both spark knock and exhaust gas temperature limits. 102 RON fuels are limited to 16 bar BMEP due to spark knock below 4000 RPM and exhaust gas temperature limits above 4000 RPM. Below 2000 RPM there is a software limitation that does not permit 100% throttle opening under boosted operation, this affects all fuels.

In general the lowest BSFC is attained with E0 fuels where a minimum BSFC ranging from 216-224 g/kWh is obtained from 1500-2000 RPM and 8-10 bar BMEP. This translates to an equivalent maximum BTE range of 37.6-39.3 % in the same map area.

The highest BTE is attained with 102 RON E30 fuels where efficiencies greater than 39.0 0% BTE are achieved in a broad map area ranging from 1500-2500 RPM and from 8 bar BMEP up to the maximum load limit of 16 bar BMEP. Results show that increasing the ethanol content at a fixed RON level increases BSFC by about 4% for each 15% increase in ethanol. This BSFC increase is at a lower rate than the 5% loss in overall fuel energy for each 15% increase in ethanol, thus resulting in improved BTE. As well, increasing RON level decreases knocking tendency thus significantly expands the map area of best efficiency to higher loads and higher speeds.

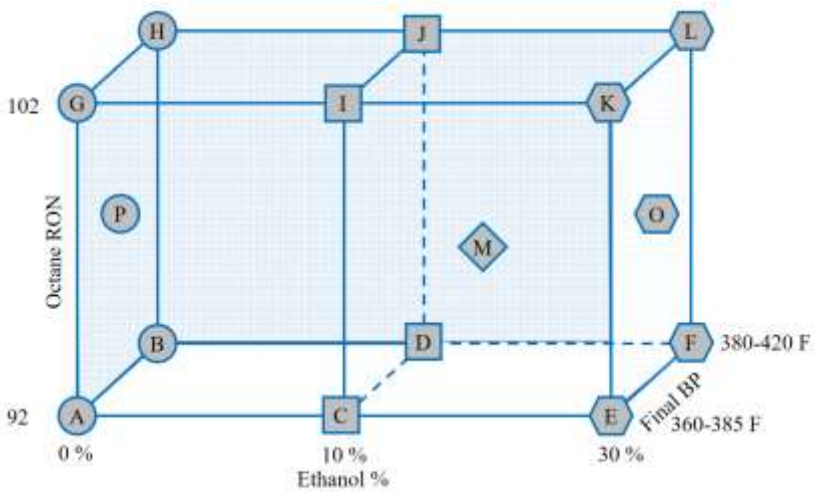

Figure 1: *Fuel Matrix*

3 Calibration Results

3.1 Effects of Ethanol Content

The lowest BSFC is possible with E0 fuels where a minimum BSFC ranging from 216-224 g/kWh is measured equating to BTE of 37.6-39.3 %. However, engine efficiency is highest with E30 fuels where the increased ethanol content improves combustion efficiency through improved charge cooling and a decrease in burn duration allowing for increased EGR dilution while maintaining spark timing close to MBT.

Taking the example at the mid-RON level of 98 RON to quantify the effects of ethanol on BSFC and BTE. It can be shown that increasing the ethanol content results in a corresponding increase in BSFC. On average each 15% increase in ethanol results in an increase of 4.3% in BSFC at the engine's most efficient operating points. However, increasing ethanol also reduces the energy density of the fuel, where a 15% ethanol increase equates to approximately a 6% decrease in heating value (reference ***Table 1***). The loss in energy density that results from increasing ethanol is much greater than the increase in fuel consumption. As a result the area in which the engine operates most efficiently (i.e. area of highest BTE) increases with increasing ethanol content. (Reference ***Figure 2*** and ***Figure 3***).

	Fuel O 98RON E30	Fuel M 98RON E15	Fuel P 98RON E0
Gross Heating Value (MJ/kg)	41.34	43.80	46.32
% Heating Value Difference (Fuel O - Fuel M)/(Fuel O)		-6.0%	
% Heating Value Difference (Fuel M - Fuel P)/(Fuel M)			-5.8%
Lowest BSFC (g/kW*h)	242	231	221
% BSFC Difference (Fuel O - Fuel M)/(Fuel O)		4.5%	
% BSFC Difference (Fuel M - Fuel P)/(Fuel M)			4.3%

Table 1: *Heating Value and BSFC For 98 RON Fuel*

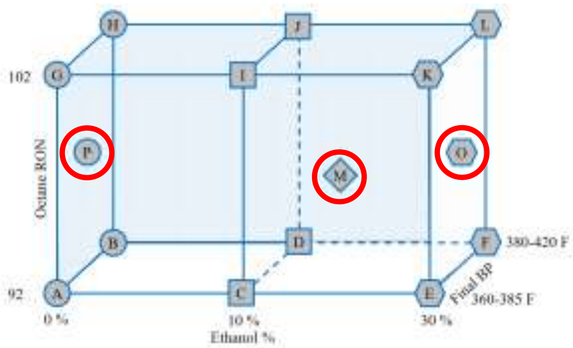

Figure 2: *Fuel Matrix with Ethanol Fuel Comparison Highlighted*

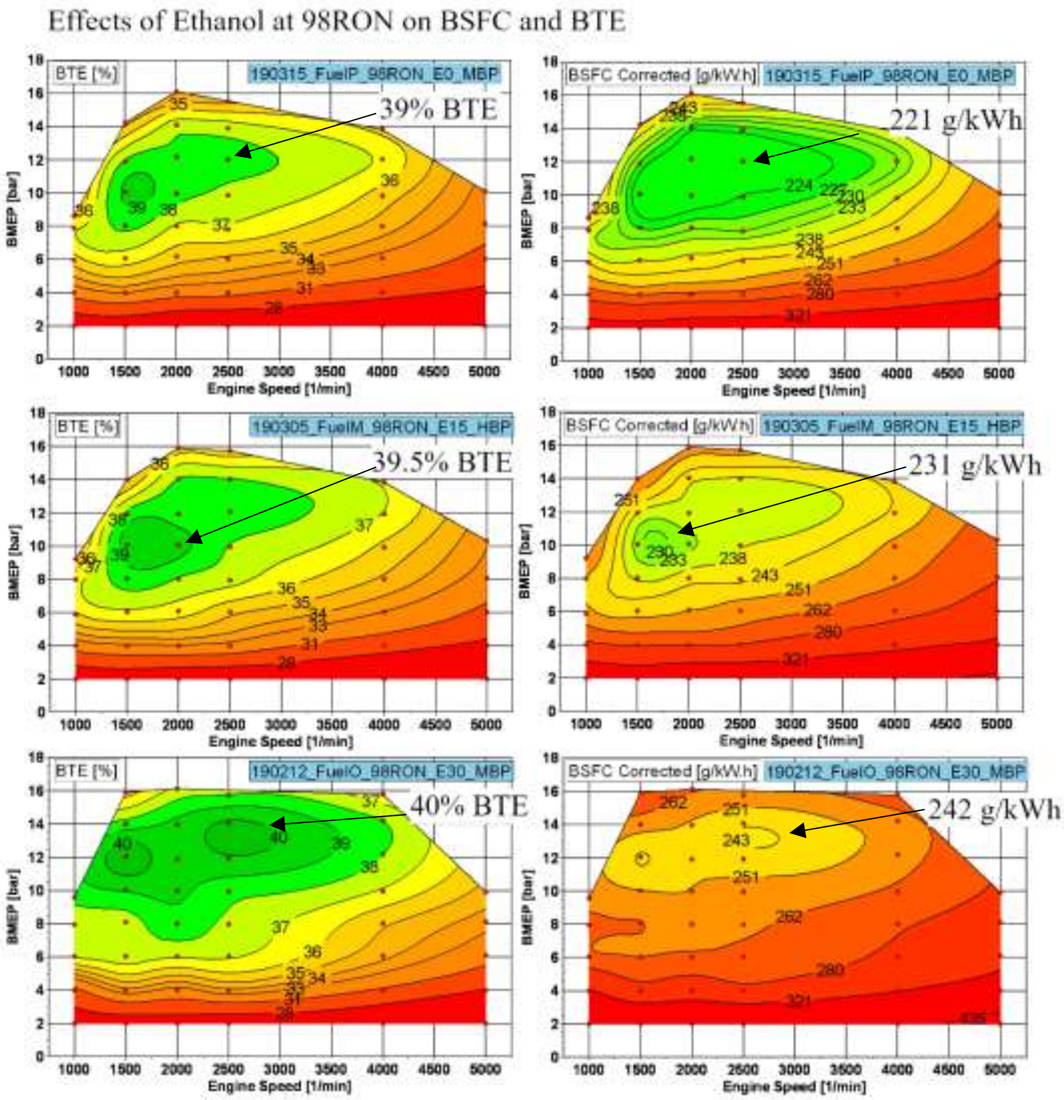

Figure 3*: Effects of Ethanol on BSFC and BTE*

3.2 Effects of RON

Increasing RON increases the engine's knock threshold. This makes it possible to maintain MBT timing at higher loads and speeds. The engine's maximum efficiency is not changed, however the area of best efficiency is greatly expanded. For example a change in RON from 92 to 98 to 102 RON increases the upper efficiency load "limit" from 11 bar to 14 bar to 16 bar respectively (reference ***Figure 4*** and ***Figure 5***).

Spark knock with 92 RON fuel starts at 8 bar BMEP, at which point the 102 RON fuel is already 3-10 g/kWh BSFC lower. At 10 bar BMEP the difference is even greater with the 102 RON fuel being 10-50 g/kWh BSFC lower. 92 RON has its best efficiency from 8-10 bar BMEP with a maximum BMEP of 12 bar. 98 RON has its best efficiency at 10-12 bar BMEP with a maximum BMEP of 16 bar. 102 RON reaches its best efficiency around 10 bar BMEP with a maximum BMEP of 16 bar BMEP. Because 102 RON fuel is less knock prone the engine can run closer to maximum brake torque (MBT) timing across most of the map. Therefore, the optimum BSFC "island" extends from 6 bar BMEP to its maximum load limit of 16 bar BMEP. This can be seen in ***Figure 5***, where the map area that BTE is above 37% increases from 10% for 92 RON to 30% for 98 RON and then to 40 % for 102 RON.

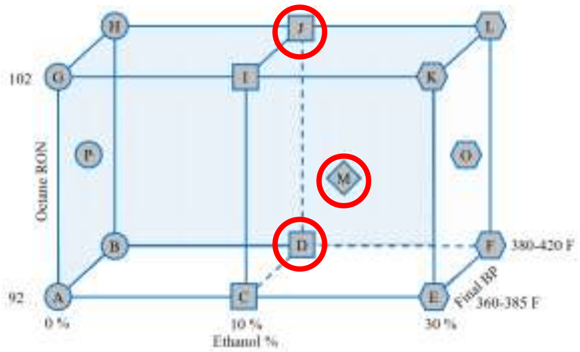

Figure 4: *Fuel Matrix With RON Fuel Comparison Highlighted*

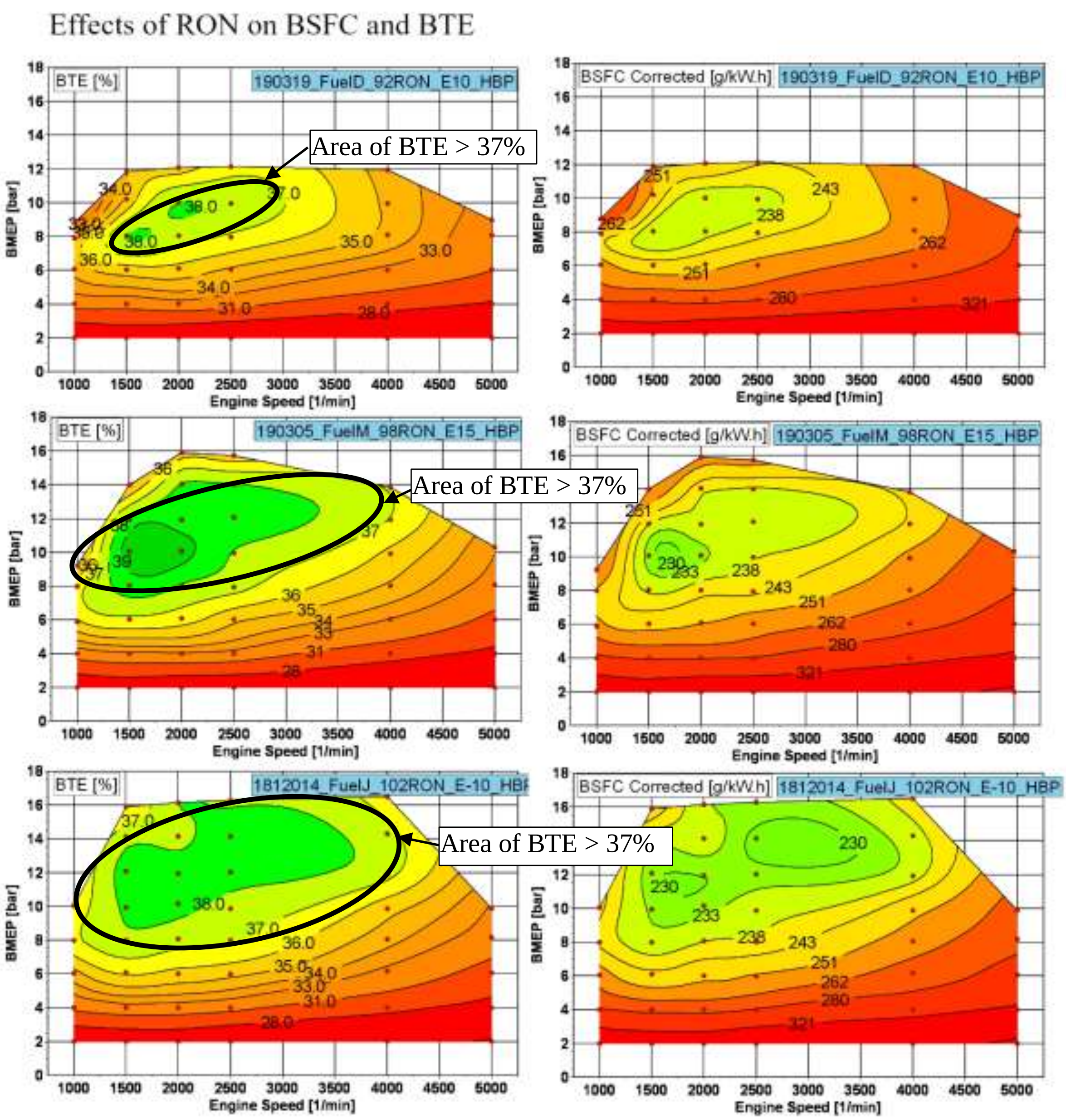

Figure 5*: Effects of RON on BSFC and BTE*

3.3 Effects of Boiling Point Range

Fuels were grouped into two boiling point ranges. The high boiling point fuels had a final boiling point temperature ranging from 380-420 °F and the low boiling point fuels had a temperature ranging from 360-385 °F. In the area of the engine map from 8-16 bar BMEP and 1500-4000 RPM where the engine operates the most efficiently and BSFC measurement accuracy is the highest, the low boiling point fuels are on average 2 g/kWh lower in BSFC than the comparative high boiling point fuels at 0 % and 10 % ethanol. At 30 % ethanol the difference in BSFC between the two boiling point ranges is negligible (reference ***Figure 7***).

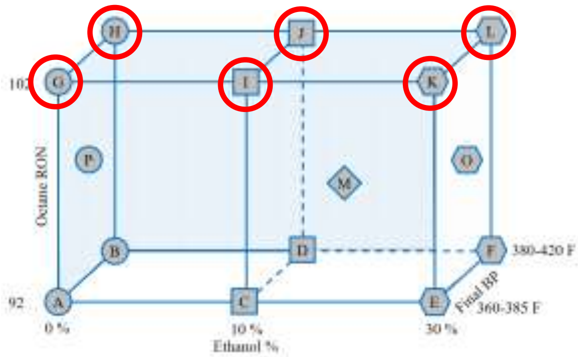

Figure 6*: Fuel Matrix with Boiling Point Range Comparison Highlighted*

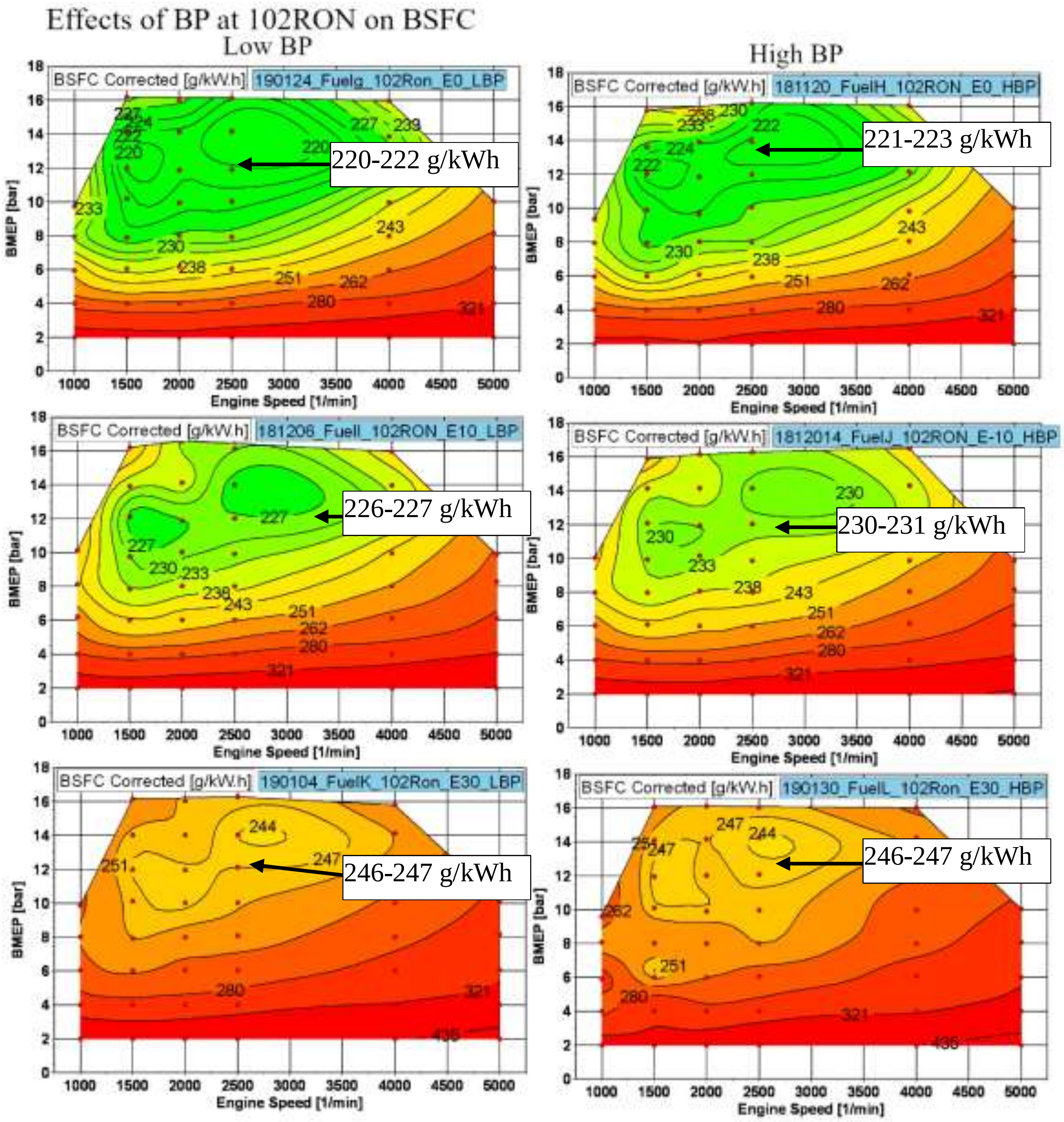

__Figure 7__: Effects of Boiling Point at 102 RON on BSFC and BTE

3.4 Operation Limits

The engine map in ***Figure 8*** summarizes the map area that can be reached with each level of RON fuel. In this study there are four factors that can affect the engine's maximum performance limit; software limiting throttle, spark knock, exhaust gas temperature and turbocharger flow limit. At operating conditions limited by spark knock, sparking timing was retarded from MBT until limited by one of the following; maximum exhaust gas temperature, an inability to maintain torque or combustion stability exceeds 3% COV of IMEP. Cooled external EGR which lowers combustion temperature was also maximized with further increases constrained by an increase in combustion burn duration resulting in combustion stability exceeding 3% COV of IMEP and/or limitations of the compressor efficiency due to the increased mass flow.

Overall, higher RON fuels increase the engine's load limit which could translate to vehicle performance benefits or the possibility of further engine downsizing which improves fuel efficiency. These limitations are further discussed in the following sections.

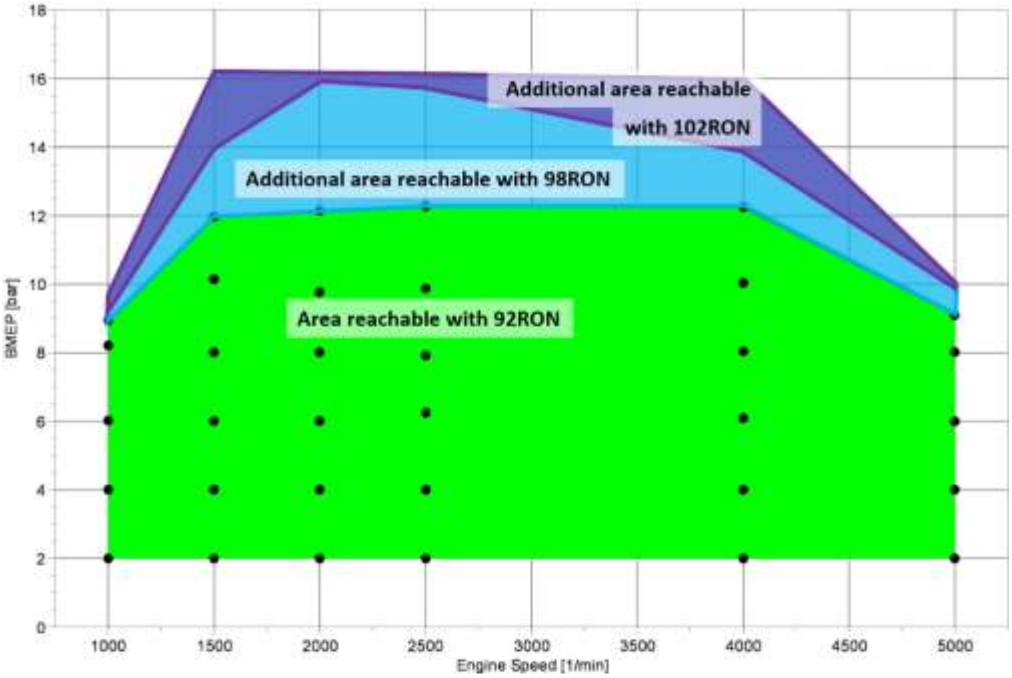

Figure 8*: Reachable Area per RON*

3.4.1 Limitations with 102 RON Fuel

At low speeds and high loads, the production GM software does not permit 100% throttle opening in the boosted region below 1500 RPM. This limitation is highest at 1000 RPM where it is believed to be software related, a result of the increased displacement of the modified engine leading to incorrect air mass calculation in the engine controller. Since a relatively small area of the map is affected and the majority of the region would be knock limited it was mutually agreed to omit this area. The throttle limited area is shaded blue in ***Figure 9***.

From 1500-4000 RPM, the engine is primarily knock limited. Additional factors influencing the maximum load potential in this speed range include boost system limitation due to the compressor sizing being unable to efficiently flow more air and cEGR, as well as the coarse 2 bar BMEP load increment.

Above 4000 RPM the engine is limited by exhaust gas temperature at the high pressure turbocharger inlet (set at 920 °C). Fuel enrichment would lower the exhaust gas temperature, but at the expense of significantly increased BSFC and emissions, therefore enrichment was omitted.

For 102 RON fuels there is no significant effect on maximum engine performance when varying the levels of ethanol content. This may be due to the relatively coarse load step of 2 bar BMEP increments.

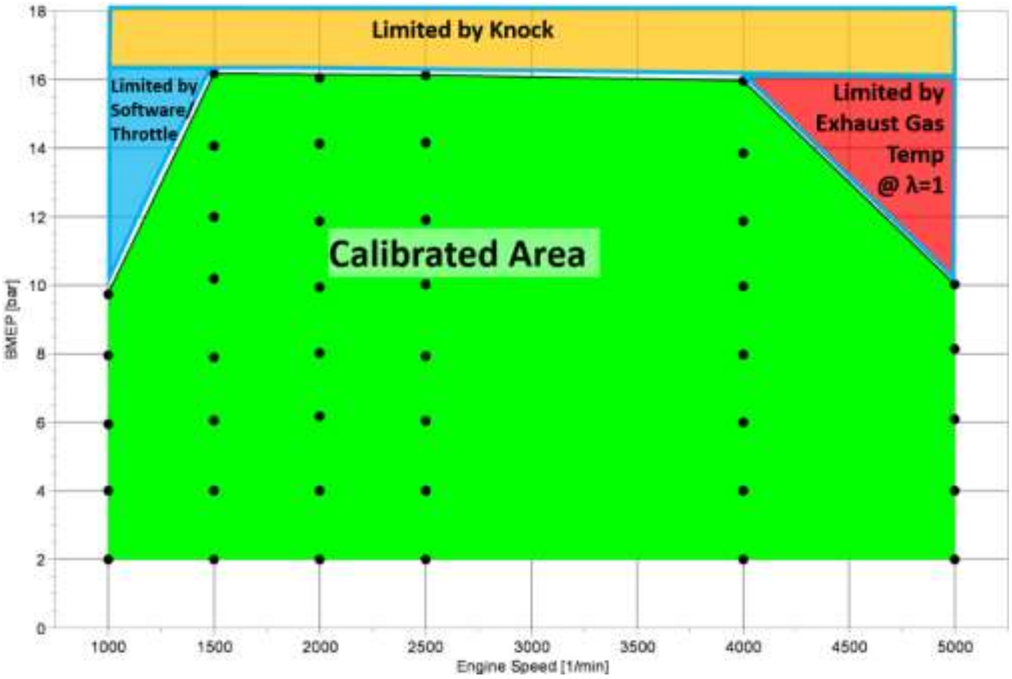

***Figure 9**: Engine Operational Limit with 102 RON Fuel*

3.4.2 Limitations with 98 RON Fuel

The operation limits with 98 RON fuel is shown in ***Figure 10***. From 1000-1500 RPM, maximum performance is limited by engine software affecting the throttle as noted above. Maximum performance between 2000-4000 RPM is limited by spark knock, however since retarding ignition timing to lessen spark knock also has the effect of increasing exhaust gas temperatures, both could be considered limiting factors for operation. Above 4000 RPM further load is limited by maximum exhaust gas temperatures.

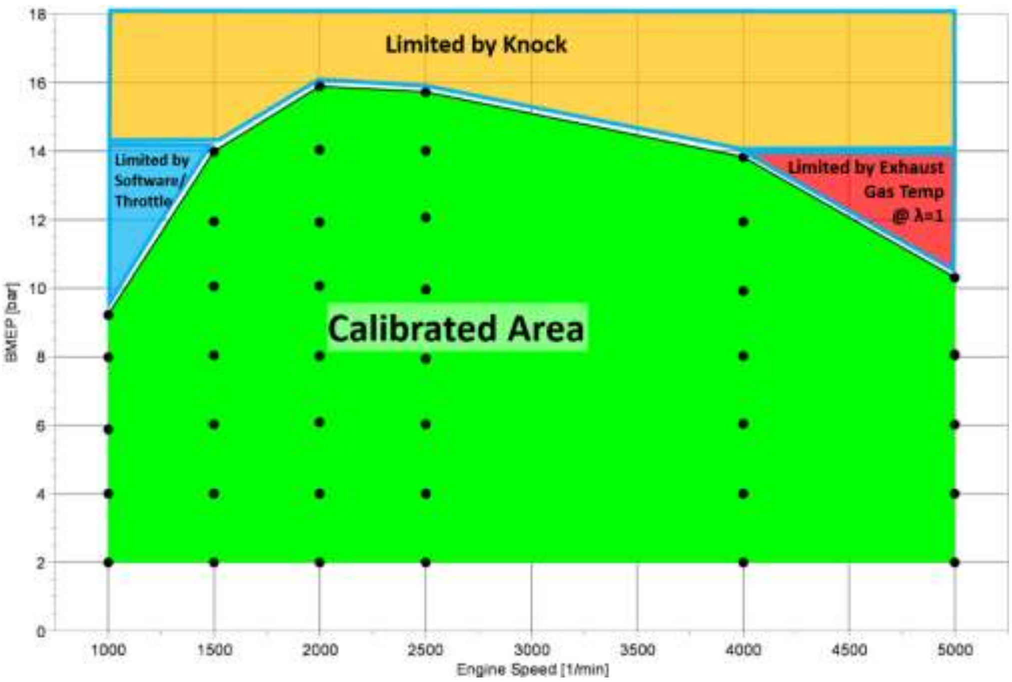

***Figure 10**: Engine Operational Limit with 98 RON Fuel*

3.4.3 Limitations with 92 RON Fuel

From 1000-1500 RPM, maximum performance is limited by the engine software affecting the throttle. From 1000-4000 RPM performance is limited by spark knock. The addition of cEGR reduces the severity of spark knock but has the counter effect of slowing the burn rate which reduces combustion efficiency. Since the engine is operated as homogeneous stoichiometric combustion the load potential at 4000 RPM and above is limited by exhaust gas temperatures.

Similar to 102 RON fuels, there were no measurable effects from the ethanol content on operation limits, due to the coarse 2 bar BMEP load step.

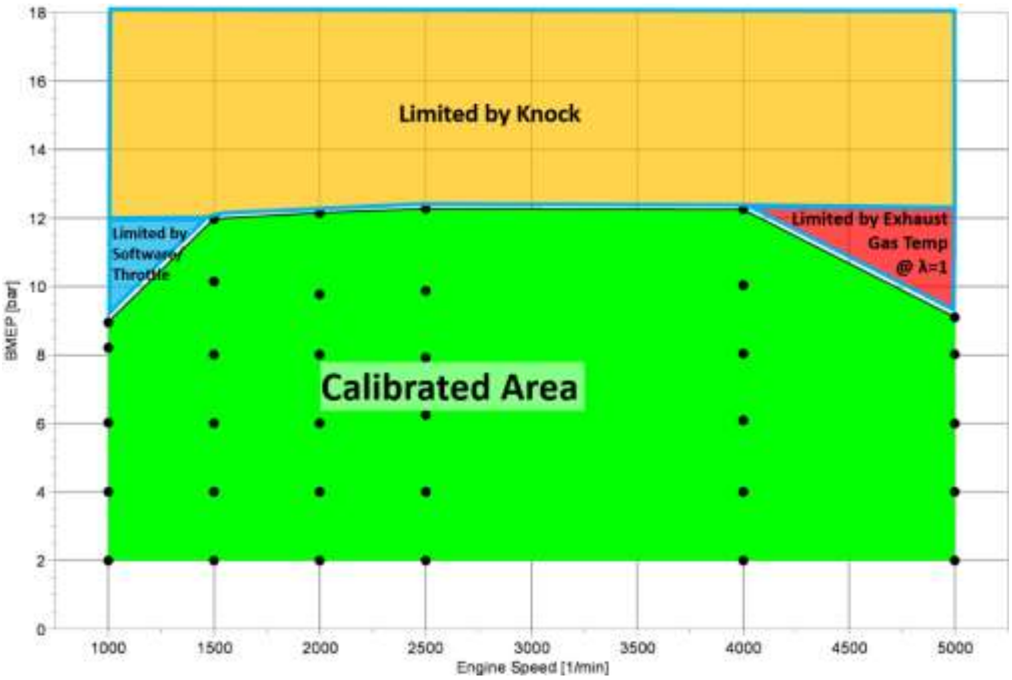

Figure 11*: Engine Operational Limit with 92 RON Fuel*

3.5 Spark Efficiency

At a given air-fuel ratio there exists an optimal ignition or spark timing that result in the maximum brake torque (MBT) and corresponding best engine efficiency. To determine MBT timing the engine was subjected to spark sweeps at multiple speed and loads. While keeping other calibration values constant, spark timing was adjusted in a range around the estimated MBT timing. Plotting torque in BMEP and engine efficiency in BSFC, shows that optimal engine efficiency is achieved at a CA50 of approximately 8 CAD ATDC. ***Figure 12*** shows an example at 2000 RPM and 8 bar BMEP.

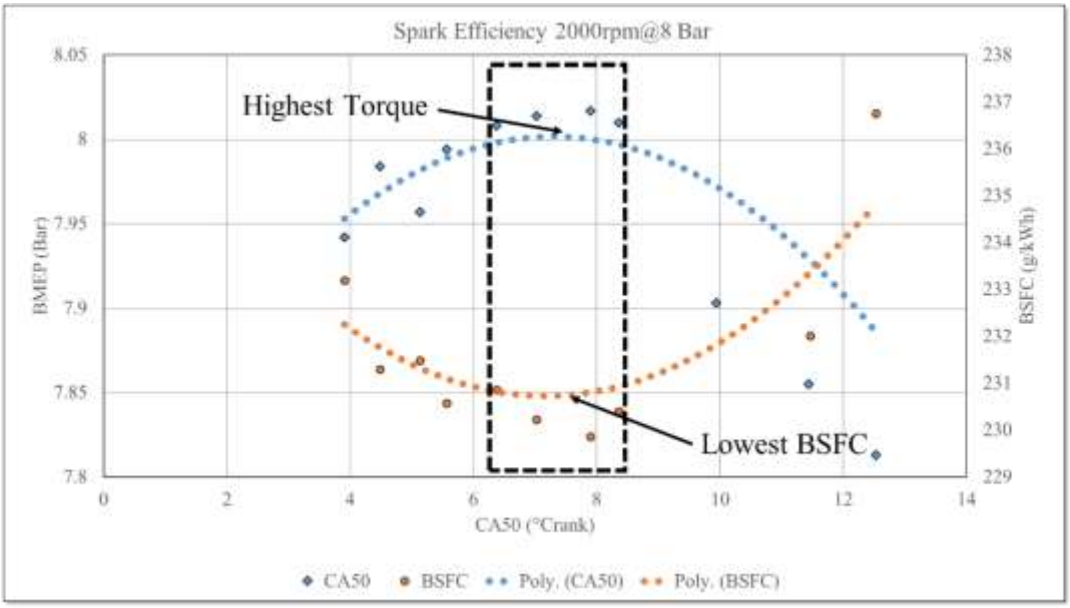

Figure 12: *Spark Efficiency*

3.6 Spark Efficiency Limitation

Figure 13 outlines the area of the map in which MBT timing can be maintained. The portions of the map where MBT timing can be maintained increases with RON. In addition to increasing the torque potential, higher RON fuels shifts the optimal map area towards the lower speed. This benefits applications that make use of the drivability and efficiency gains that come from higher torque at low speeds.

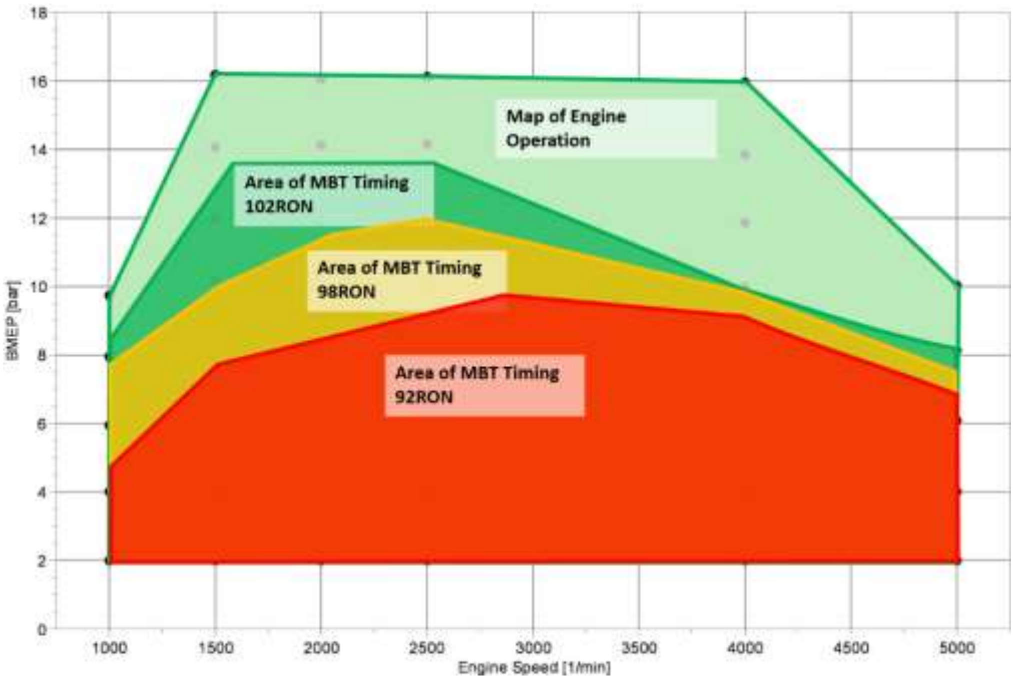

Figure 13*: Area of MBT Operation*

3.6.1 Spark Efficiency Limitation with 102 RON Fuel

With 102 RON fuel a CA50 of 8 CAD ATDC can be maintained up to 14 bar BMEP. Above 14 bar BMEP a CA50 of 8 CAD ATDC is not achievable due to increasing spark knock. Higher cEGR % would help reduce spark knock severity, however below 2500 RPM the boost system is unable to meet the required charge filling with higher levels of cEGR. Above 2500 RPM there is a lower pressure differential across the low pressure cEGR system that results in reduced cEGR flow.

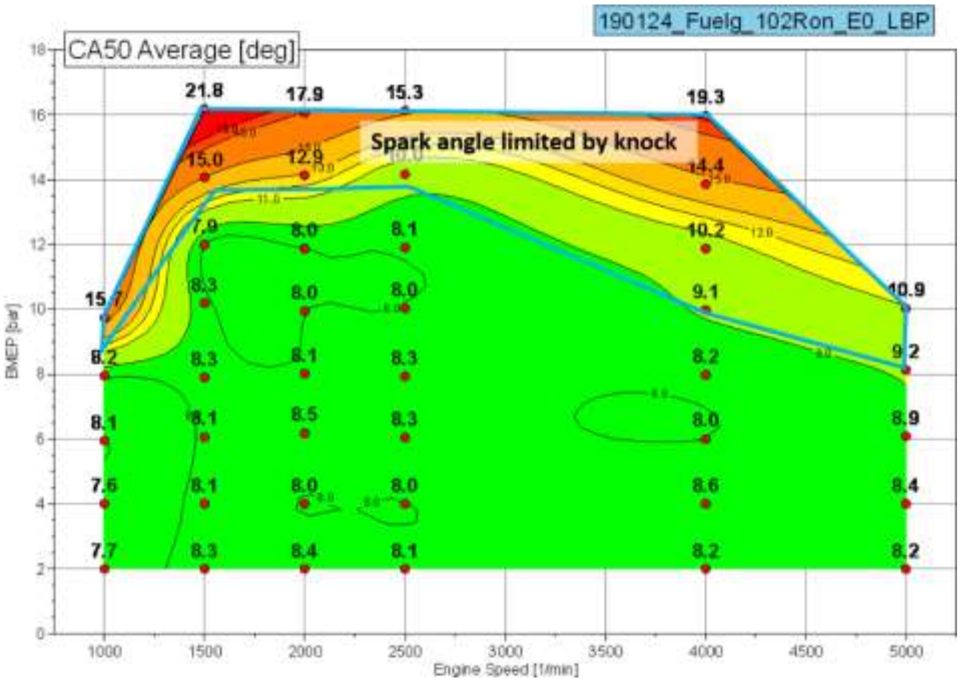

***Figure 14**: Combustion Efficiency 102 RON*

3.6.2 Spark Efficiency Limitation with 92 RON Fuel

The spark timing for 92 RON fuel is mostly limited by knock. The entire boosted region above 10 bar BMEP with 92 RON fuel is spark limited by knock, so MBT timing can only be achieved in the naturally aspirated regions. Increased levels of EGR (externally cooled and internal) does help provide knock relief, but also decreases combustion burn rate. This results in longer burn durations, thus increasing combustion instability which was constrained to 3% maximum COV of IMEP.

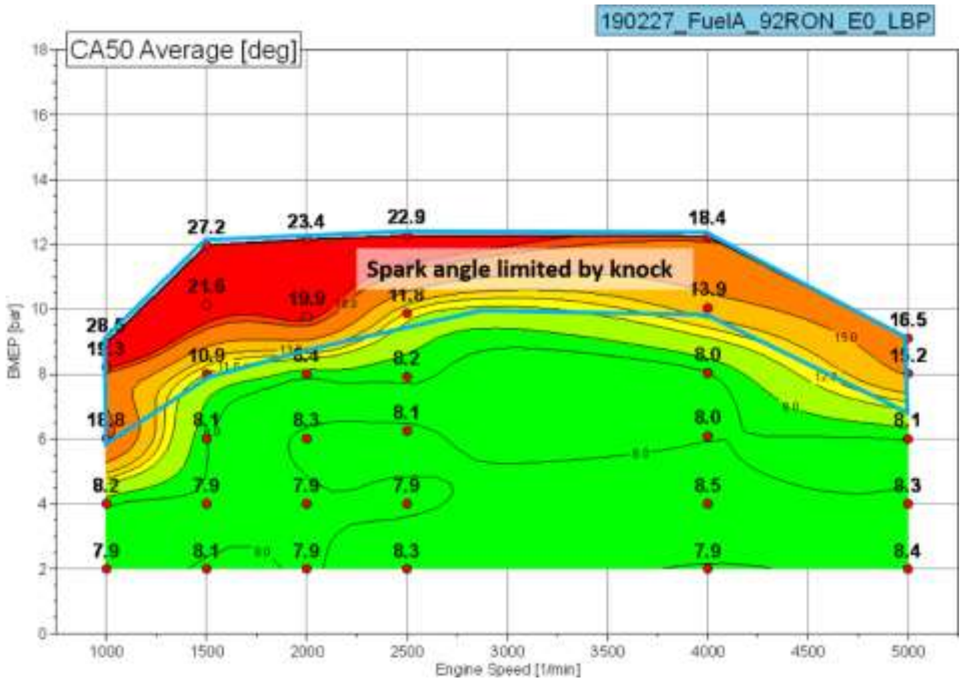

__Figure 15__: Combustion Efficiency 92 RON

3.6.3 Spark Efficiency Limitation with 98 RON Fuel

The spark timing for 98 RON fuel is mostly limited by knock in the boosted region. As is the case with 92 RON and 102 RON, additional cEGR helps but is either limited by COV of IMEP below 14 bar BMEP, or the ability to achieve the required boost pressure at maximum load.

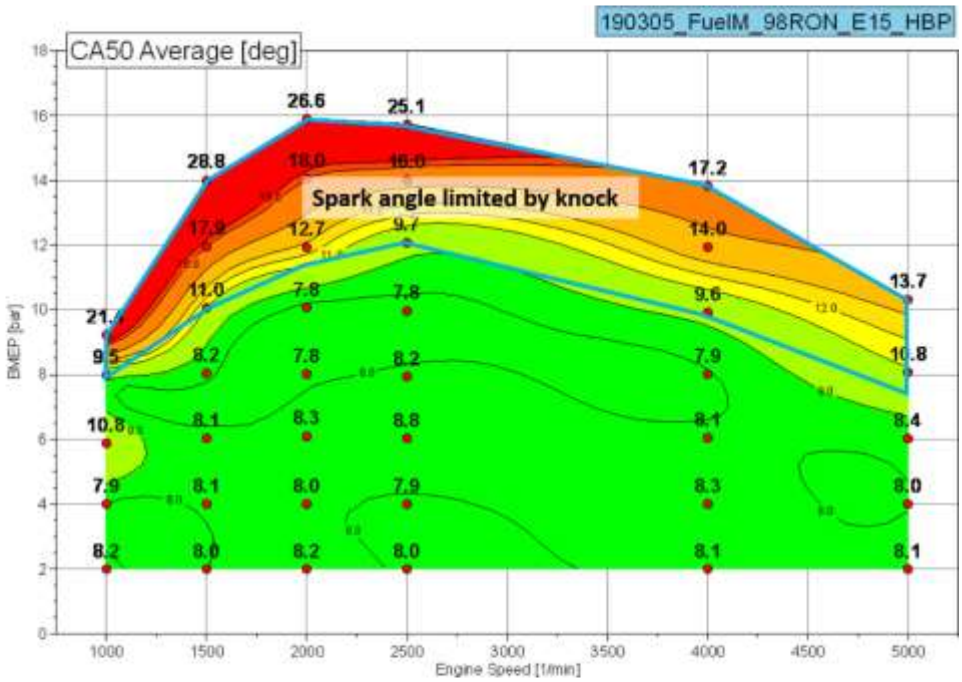

__Figure 16__: Combustion Efficiency 98 RON

3.7 EGR

Two means of exhaust gas recirculation (EGR) were used with this testing: Internal EGR (iEGR) via increased intake and exhaust cam overlap to trap residual gases and cooled external EGR (cEGR) via a low pressure system that pulls from midpoint of the catalyst, through a cooler and valve before feeding back into the induction system upstream of the compressor. Both iEGR and cEGR have their benefits and disadvantages. Internal iEGR has benefits at low load where the increased charge temperature improves breathing efficiency. External cEGR has the most benefits in the knock limited region where the reduced combustion temperatures provide knock relief. The main disadvantage for both iEGR and cEGR is the increase in the burn duration which lowers combustion efficiency or in severe cases increases combustion instability above the limit of 3 % COV of IMEP. Because low pressure cEGR systems feed EGR through the compressor, high load performance can also be negatively impacted because of the additional mass flow.

In general for all the fuels, iEGR at light loads is attained with approximately 25 deg of cam overlap. Additional iEGR is capped because of its negative impact on COV of IMEP. At the mid load range cam overlap increases to 40-45 deg, tapering off to 25 deg at loads above 10 bar BMEP.

When EGR % is stated, it refers to cEGR (reference ***Figure 17***). At 2 bar BMEP combustion stability limits of 3% COV of IMEP negates the use of cEGR. However, at these low loads iEGR is more effective because the increased heat helps fuel vaporization as well as higher air charge temperatures aids breathing efficiency by reducing throttling losses. From there, cEGR levels increase to a maximum at the BSFC "island", where 15-20% cEGR can be achieved. As load is further increased cEGR % then decreases as the engine struggles to meet power demands due to the increased mass flow through the compressor. Although cEGR reduces combustion temperatures which provides spark knock relief, this needs to be balanced with increased burn duration resulting in reduced combustion efficiency.

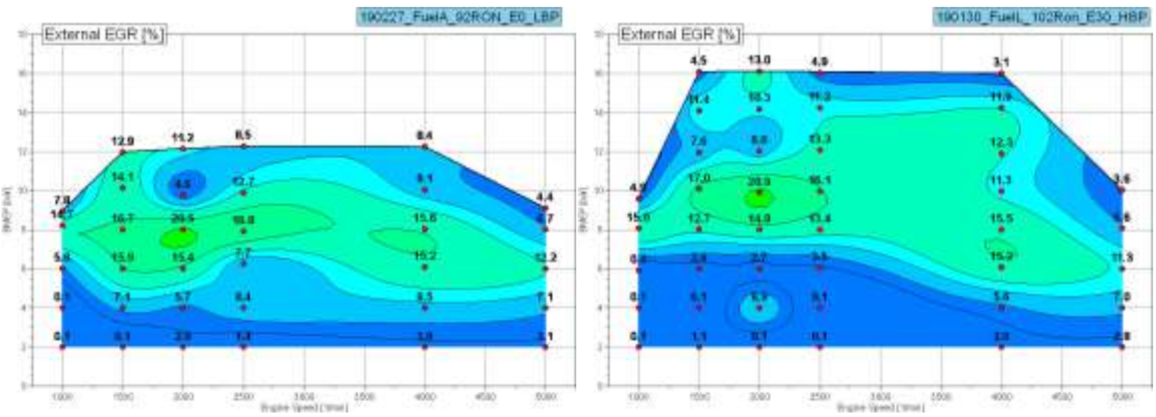

Figure 17*: Fuel A and Fuel L EGR %*

3.8 Brake Specific NOx Results

Overall engine-out brake specific nitrogen oxide (BSNOx) across the map is lower than comparable displacement, turbo-charged, direct injection, production engines. The use of "high" levels of iEGR and cEGR helps in this regard by lowering combustion temperatures.

The highest BSNOx is measured with 102 RON E30 fuel since it achieves both the highest engine load and the highest exhaust gas temperatures. For 102 RON E30 fuel, BSNOx below 10 bar BMEP and 3000 RPM ranges from 2-5 g/kWh. The highest levels are measured at 5000 RPM where BSNOx averages 10 g/kWh with maximum of 17 g/kWh measured at the highest speed and load point. With 92 and 98 RON fuels, BSNOx is on average below 10 g/kWh throughout the map except at the maximum speed of 5000 RPM. An example of BSNOx with 102 RON E30 and 92 RON E0 fuels are shown in ***Figure 18***.

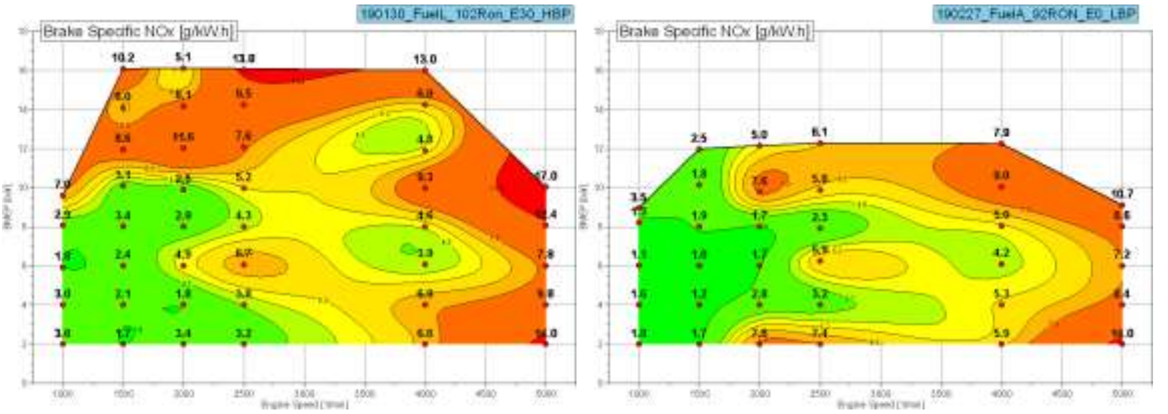

Figure 18*: Fuel L HBP and Fuel A LBP BSNox Comparison*

3.9 Soot

Engine-out soot is lowest at the low load and low speed region of the map for all fuels. Soot density then increases with increasing engine load and engine speed.

To compare soot differences between low boiling point (LBP) and high boiling point (HBP), fuel pairs I and J as well as K and L were compared. Both fuel pairs were tested before there were issues with engine aging.

Fuels I and J are 102 RON E10 fuels where below 10 bar BMEP and 4000 RPM the LBP Fuel I soot levels are 10-50% of the levels of the HBP Fuel J. As loads and speeds are increased, the differences are reduced. Overall, the LBP fuel is lower in soot than the comparable HBP fuel (reference ***Figure 19***).

Fuels K and L are 102 RON E30 fuels where for most of the map the LBP fuel K is on average 50-80 % of the levels of the HBP fuel L. The difference in soot level between is not as pronounced as seen with the lower ethanol 102 RON E10 fuel (reference ***Figure 20***).

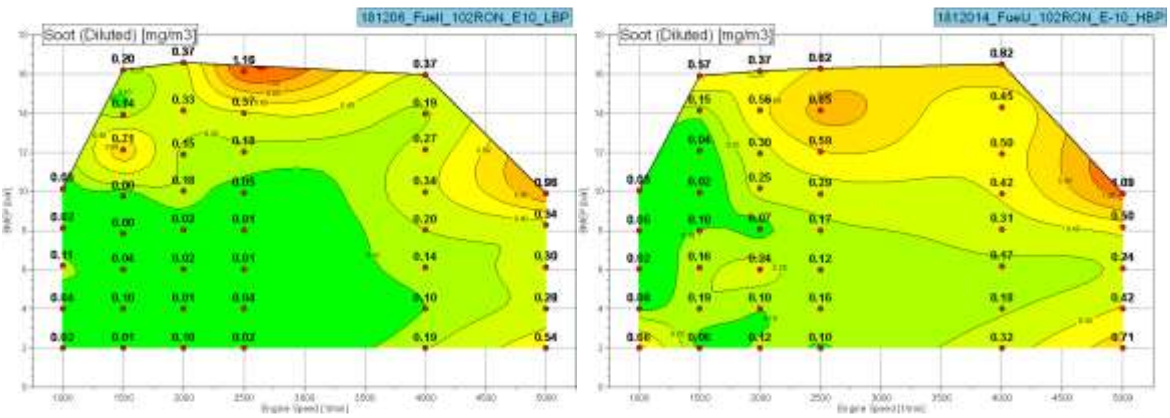

Figure 19*: Boiling Point Soot Comparison I and J*

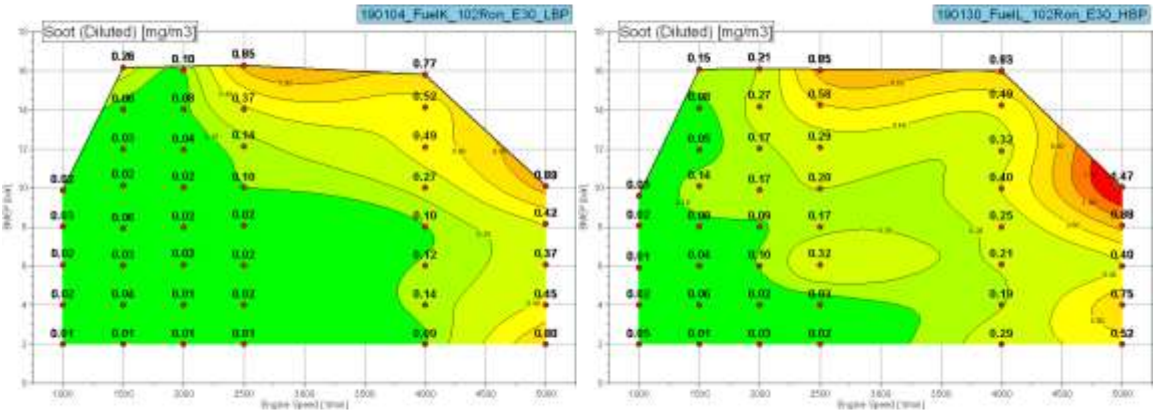

***Figure 20**: Boiling Point Soot Comparison K and L*

Details of engine aging and the corresponding changes in soot are discussed further in section ***5.6.***

4 Instrumentation

4.1 General Instrumentation

The Engine was instrumented with the following channels:

4.1.1 Temperatures

Temperature Coolant Water Engine Out

Temperature Coolant Water Engine In

Temperature Throttle In

Temperature Intake Manifold

Temperature Air HP Compressor In

Temperature Air HP Compressor Out

Temperature Air LP Compressor In

Temperature Air LP Compressor Out

Temperature Fuel Engine In

Temperature Combustion Air

Temperature Oil Sump

Temperature Oil Gallery

Temperature Coolant Water CAC In

Temperature Coolant Water CAC Out

Temperature Exhaust Catalyst In

Temperature Exhaust Tailpipe Out

Temperature Exhaust HP Turbine In

Temperature Exhaust HP Turbine Out

Temperature Exhaust LP Turbine In

Temperature Exhaust LP Turbine Out

Temperature Oil Heat Exchanger Engine Out

Temperature Oil Turbo In

Temperature Oil Heat Exchanger In

Temperature Exhaust Gas EGR Cooler In

Temperature Exhaust Gas EGR Cooler Out

Temperature Coolant EGR Cooler In

Temperature Coolant EGR Cooler Out

Temperature Exhaust Manifold

Exhaust Gas Temp Cylinder 1

Exhaust Gas Temp Cylinder 2

Exhaust Gas Temp Cylinder 3

Exhaust Gas Temp Cylinder 4

Test Cell Air Temperature

4.1.2 Pressures

Pressure in Air Filter

Pressure Fuel Supply

Pressure CAC Water In

Pressure CAC Water Out

Pressure Coolant System (bottle)

Pressure Coolant Water Engine In

Pressure Coolant Water Engine Out

Pressure Turbo Oil Feed Return

Pressure Oil Gallery

Pressure Turbo Oil Feed In

Pressure HP Compressor 1 Inlet

Pressure HP Compressor 1 Outlet

Pressure LP Compressor 1 Inlet

Pressure LP Compressor 1 Outlet

Exhaust Pressure after HP Turbine

Exhaust Pressure before HP Turbine

Exhaust Pressure after LP Turbine

Exhaust Pressure before LP Turbine

Throttle Body Inlet Pressure (Turbine)

COMB Air IN_ABS (Kiel Probe) from Vaisala

Intake Manifold Pressure

Pressure Exhaust after TWC

Pressure before EGR cooler

Pressure EGR valve in

Pressure EGR valve out

Crankcase Pressure

Test Cell Air Pressure
In Cylinder Pressure Cylinder 1
In Cylinder Pressure Cylinder 2
In Cylinder Pressure Cylinder 3
In Cylinder Pressure Cylinder 4

4.1.3 Speeds

Engine speed
High Pressure Turbo speed (Compressor)
Low Pressure Turbo speed (Compressor)

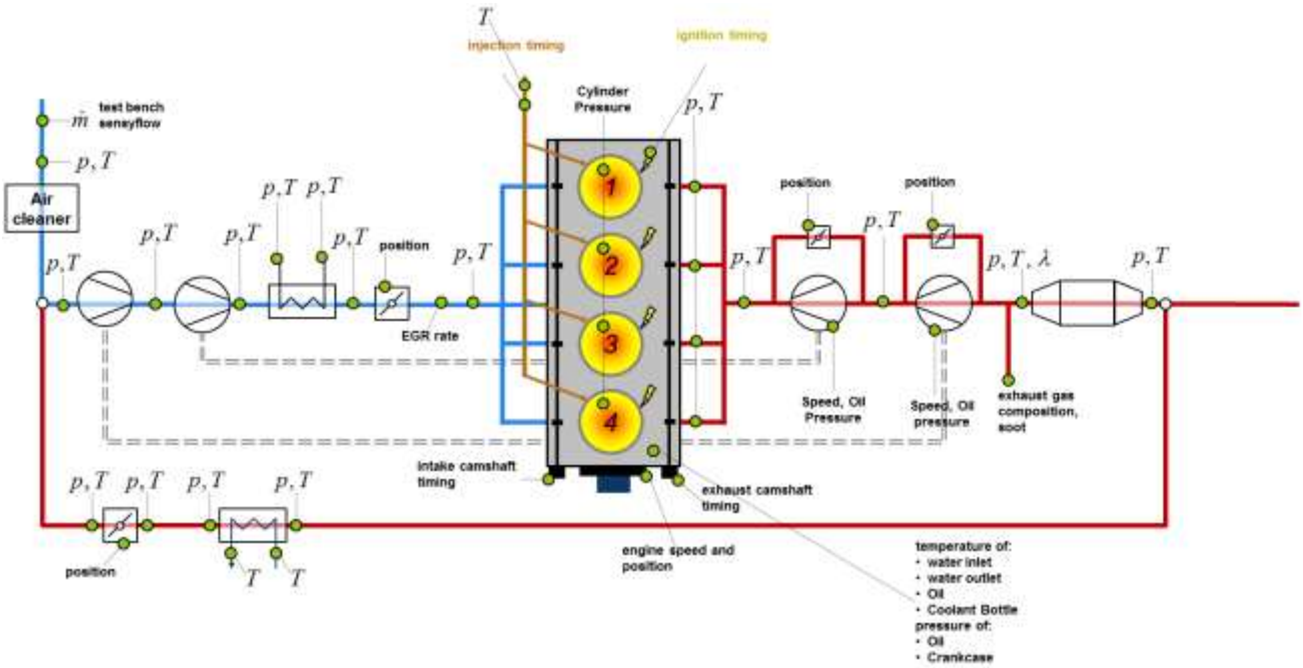

Figure 21*: Instrumentation Setup*

4.2 Knock Indication System

Due to the nature of testing fuels with different RON ratings, an accurate knock detection system was needed to prevent engine damage when calibrating spark advance. KIS4 which is an IAV combustion analysis system was selected for knock detection. KIS4 relies on the measured cylinder pressure data compared against a calculated P85 value to calculate knock intensity. During engine commissioning KIS4 knock intensity results were compared to GM's production knock detection and found to correlate very well. IAV's KIS4 system was also used to capture all combustion metrics.

The first step in determining the knock limit is the measurement of the knock intensity (KI) via the method shown in ***Figure 22***.

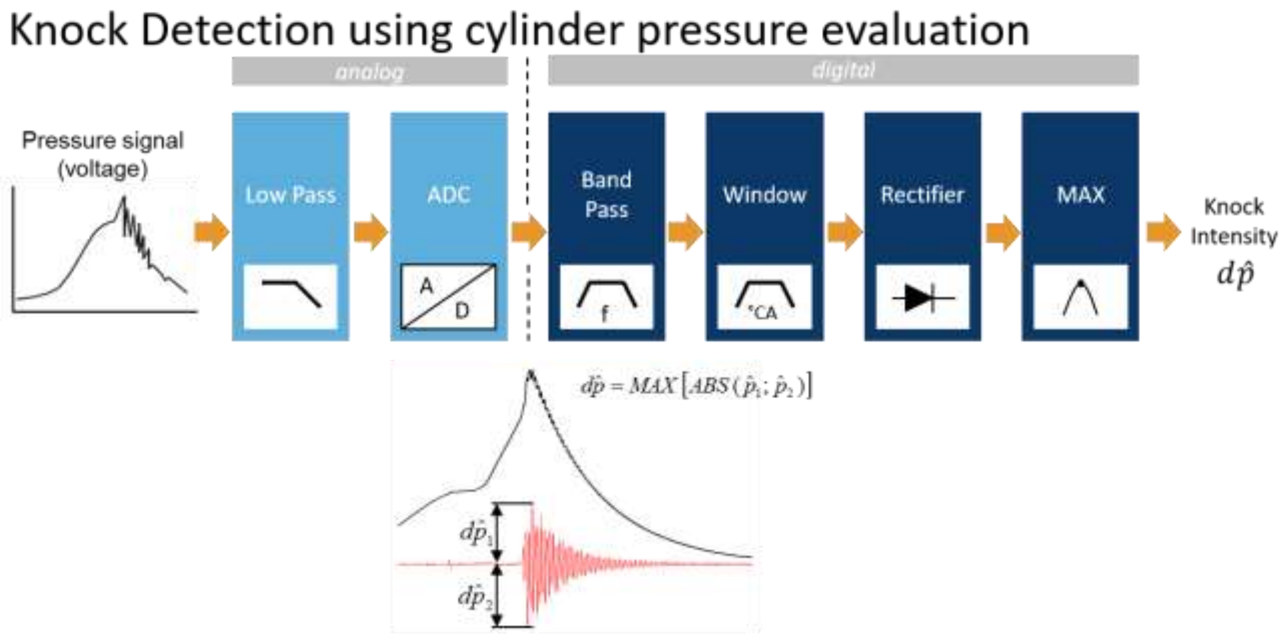

***Figure 22**: Knock Intensity*

Since knock is a stochastic phenomenon, corresponding cycles have different values of knock intensity, making a statistical evaluation of knock intensity necessary. This is what is represented in IAV's P85 value where the knock frequency (or rate) at a given pressure value is not considered, but the pressure value is determined at a given frequency. This is a significant advantage, since this pressure value is easy to determine while the reliable determination of frequencies requires the evaluation of a large number of events. Since the frequency is fixed and the pressure value is variable, the outcome is one continuous characteristic value, which can also be graphically represented by its influencing variables (e.g. ignition angle).

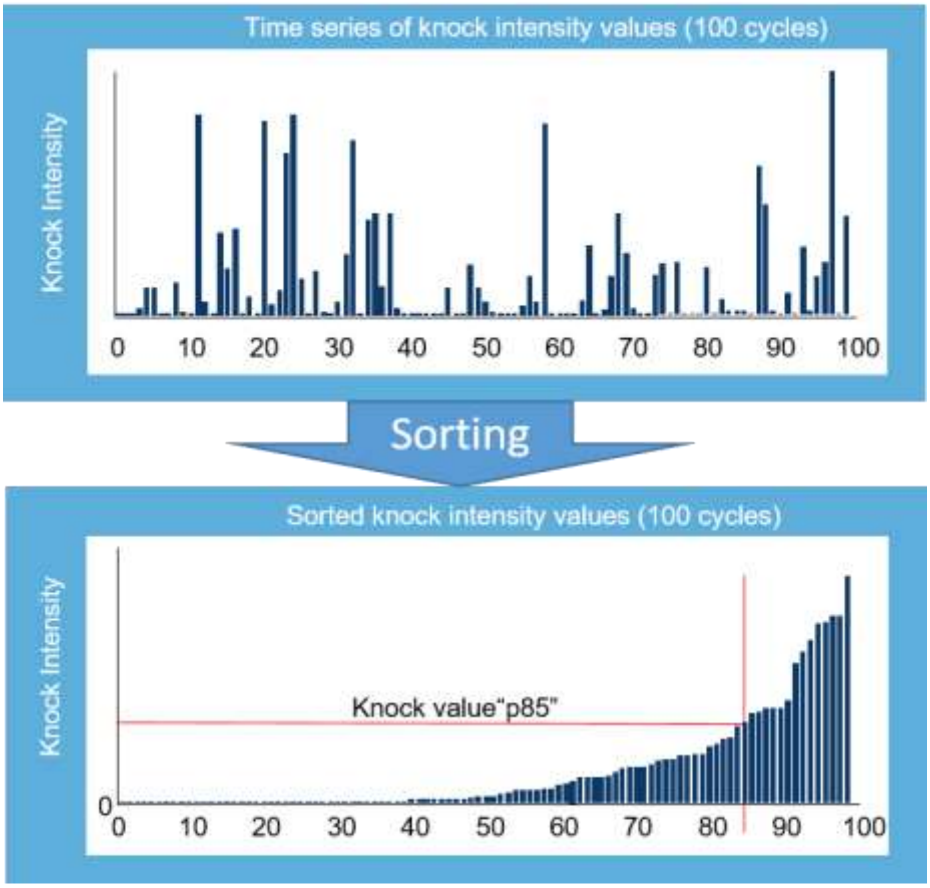

***Figure 23**: P85 Determination*

Using IAV's proprietary P85 knock index curve (reference ***Figure 24***), KIS4 was set up to detect knock severity once the P85 value had been crossed.

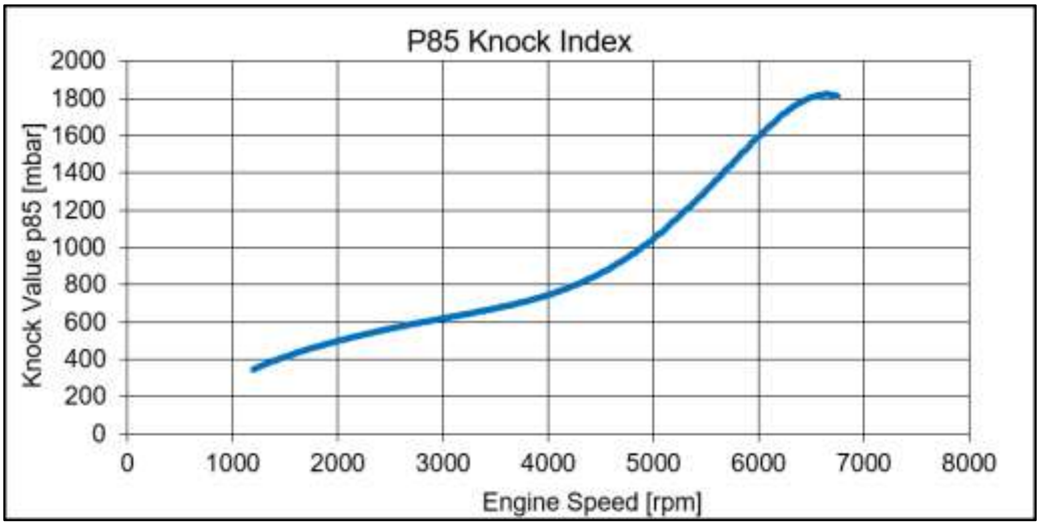

***Figure 24**: P85 Knock Index*

5 Engine Health

5.1 102 RON Health Check

To ensure engine and data consistency and accuracy, the health of the engine was checked during the study at four intervals during the testing; before the start of testing, after the 6th fuel, after the 12th fuel and at the end of test. Health checks were conducted using a 102 RON E25 fuel at predefined speed and load as well as fixed calibration settings shown in ***Table 2.*** The health check is split into three test points, R1 at 2000 RPM 2 bar BMEP, R2 at 3000 RPM 10 bar BMEP, and R3 at 2500 RPM 10 bar BMEP. At each test point the calibration values were set and three data points taken with a recording time of 60 secs each. The three points were then averaged and compared to the prior health check.

Test Points		**R1**	**R2**	**R3**
Variable	Unit	2000/2Bar	3000/10Bar	2500/15Bar
SOI	°BTDC	276	310	310
EOI	°BTDC	-	270	260
Exhaust Cam	°	5	0	5
Intake Cam	°	25	32	14
Rail Pressure	MPa	4	10	10
Split	-	0	0.1	0.1
Wastegate B	%	0	0	86
EGR Valve	-	1	1	1
Spark Timing	°BTDC	36.5	23	13
CA50	°ATDC	8	8	12

Table 2*: 102 RON Checkpoint Calibration Values*

The comparison of the four check points is shown in ***Table 3***. Variability in BSFC is very low at the mid and high load conditions of R2 and R3 respectively. Results at the low load R1 2000 RPM 2 bar condition shows high BSFC variation, which is a result of small deviations in engine operation being magnified by the low load condition.

Gaseous emissions including CO2, CO, NOx, and HC are consistent for all of the four health check points. Note that the emission data for the first health check was unavailable due to an emission's bench error. Soot level shows a large increase after health check 3, which is in line with the data from section ***5.6.***

	Point	Date	PME	Engine Speed	BSFC	PMEP	AFR	CA50	Soot	CO2	CO	HC	NOx	TC1 Exh	Air Mass	P85 Knock	COV
			Bar	rev/min	g/k.W-h	Bar	λ	°A	mg/m3	g/kW.h	g/kW.h	g/kW.h	g/kW.h	°C	kg/h		%
Health Check 1	R1	10/17/2018	2.0	2000	361.2	-0.60	0.991	7.55	0.000	1186	30.0	NA	NA	458	39.0	35.8	1.33
Health Check 2	R1	1/23/2019	2.0	2000	368.6	-0.60	0.988	7.96	0.007	1200	27.5	4.51	4.96	443	39.2	38.6	1.46
Health Check 3	R1	3/12/2019	2.0	1999	374.7	-0.61	0.988	8.29	0.006	1210	28.7	6.15	5.05	449	39.6	34.0	1.63
Health Check 4	R1	3/27/2019	2.0	2000	376.7	-0.61	0.993	7.92	0.008	1233	25.9	5.98	5.10	458	39.3	34.5	1.25
Health Check 1	R2	10/17/2018	10.2	3000	245.0	-0.18	0.997	8.57	0.004	803	17.8	NA	NA	714	192.1	397.8	0.84
Health Check 2	R2	1/23/2019	10.0	3000	246.4	-0.19	0.997	8.23	0.039	800	19.3	1.34	14.98	720	189.6	395.1	0.78
Health Check 3	R2	3/12/2019	10.2	3000	245.9	-0.19	0.997	8.25	0.131	800	19.2	1.81	15.22	719	192.4	367.4	0.80
Health Check 4	R2	3/27/2019	10.1	3000	246.7	-0.18	0.996	8.16	1.159	806	18.9	1.83	15.16	734	191.3	375.2	0.84
Health Check 1	R3	10/17/2018	15.1	2500	239.3	-0.16	0.997	12.06	0.069	780	20.5	NA	NA	740	232.2	412.5	0.96
Health Check 2	R3	1/23/2019	15.0	2500	239.7	-0.14	0.997	11.96	0.186	774	21.9	1.45	15.58	748	230.3	400.3	0.90
Health Check 3	R3	3/12/2019	14.9	2500	241.6	-0.15	0.996	12.27	0.428	780	22.0	1.76	15.55	756	231.4	400.7	0.92
Health Check 4	R3	3/27/2019	15.1	2500	240.5	-0.12	0.996	12.13	0.597	780	22	1.60	15.28	763	235	461	1

Table 3: *102 RON Health Check Data*

5.2 Data Consistency

5.2.1 ECU controlled engine parameters

Some engine actuators were not controlled but left to their default values. This included the oil pump as well as the Lambda control and fuel trim. The production oil pump for the LTG engine is a dual stage pump with a high and low mode. The production setting keeps the pump in low pressure mode in low speed and low load areas and switches to higher pressure at higher speeds and loads. Since the speed, load as well as temperature were tightly controlled during testing, it is not expected to impact test results. All test points of different fuels have comparable oil pressures.

The production closed loop fuel control was left in place to allow most efficient engine operation. The production control accuracy was confirmed with a secondary wideband O_2 sensor.

The throttle was controlled via pedal input and a specific dynamometer calibration that mapped pedal input directly to throttle input. Due to the underlying air mass calculation there was an area where the engine did not allow the throttle to open fully. Only a small region of the map at 1000 and 1500 RPM was effected.

The original vehicle water pump was used with coolant thermostat blocked in the open position. This allowed the coolant temperature to be directly controlled to a specified outlet temperature via the test cell controller. Similarly, the engine oil temperature was controlled via an external heat exchanger.

Intake charge temperature after the charge air cooler was controlled via a water-to-air intercooler setup. A test cell controller was set up to control the outlet temperature of the charge air cooler replicating a vehicle setup. The temperature map was based on vehicle data from a production LTG engine that considered charge air cooler inlet temperature as well as charge air mass flow.

5.2.2 BSFC Repeatability

The *t*-distribution confidence interval for the BSFC results from the 102 RON health check data is shown in ***Table 4.*** At the 10 and 15 bar BMEP load points the 90% confidence interval for BSFC is +/- 1.0 g/kWh. At the low load point of 2 bar BMEP there was a larger variation of +/- 2.3 g/kWh. The larger variation at the low load point is a result of variations in engine operation having a higher impact on BSFC at low BMEP operating points (small fuel variation divided by a low torque value). The 2000 RPM 2 bar point had been corrected for BSFC deviations based on the method outlined in section ***6.1***.

t-distribution	BSFC (g/kW·h)		
	90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	365.4	244.89	239.4
Data #2	366.1	244.82	239.29
Data #3	365.3	245.32	239.27
Data #4	368.9	246.2	239.78
Data #5	373.1	246.6	239.63
Data #6	370.5	246.4	239.57
Data #7	375.3	245.4	241.43
Data #8	373.3	246.13	241.84
Data #9	375.4	246.28	241.5
Data #10	374.0	241.47	238.17
Data #11	377.3	249.68	238.91
Data #12	377.5	243.76	244.57
Average	371.8	245.6	240.3
STDEV	4.50	1.93	1.76
COV	0.01	0.01	0.01
Sample Size	12	12	12
df =	11	11	11
t cric	1.80	1.80	1.80
Est STD for mean	1.3	0.6	0.5
One side interval	2.3	1.0	0.9
Upper Limit	374.2	246.6	241.2
Lower Limit	369.5	244.6	239.4

***Table 4**: BSFC Confidence Interval*

5.2.3 BMEP Control Accuracy

The ability to control the engine to a set load in the test cell is shown in Table 5**.** As can be seen, the control is extremely accurate with a maximum deviation of less than +/- 0.05 bar BMEP at all load conditions.

t-distribution	BMEP (bar)		
	90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	2.02	10.17	15.10
Data #2	2.03	10.17	15.13
Data #3	2.03	10.17	15.12
Data #4	2.01	10.03	14.97
Data #5	2.02	10.02	14.98

Data #6	2.00	10.02	14.99
Data #7	2.01	10.20	14.92
Data #8	2.01	10.20	14.92
Data #9	2.00	10.17	14.94
Data #10	2.00	9.96	15.10
Data #11	2.01	9.96	15.09
Data #12	2.00	9.98	15.10
Ave	2.01	10.09	15.03
STD	0.01	0.10	0.08
COV	0.01	0.01	0.01
Sample Size	12	12	12
df =	11	11	11
t cric	1.80	1.80	1.80
Est STD for mean	0.00	0.03	0.02
One side interval	0.01	0.05	0.04
Upper Limit	2.02	10.14	15.07
Lower Limit	2.01	10.04	14.99

***Table 5:** BMEP Confidence Interval*

5.2.4 Repeatability of Emissions

There is good repeatability of the emissions result for all but microsoot concentration. Test to test variation of brake specific CO2 and CO is less than 1% of the average as shown in Table 6 and Table 7 respectively. Variation in brake specific HC emission is less than 8% of the average as shown in Table 8 and for brake specific NOx it's less than 1.2% of the average as shown in ***Table 9***. Microsoot concentration show the highest test to test variation, as much as 68% of the average as shown in ***Table 10***. The microsoot emissions and to a certain degree the HC emissions have a larger test to test variation due to the increased blow-by as the engine ages.

Note that for all emission measurements, data #1-3 which are from the first test are unavailable due to an error with the emission bench.

t-distribution	**Brake Specific CO2 (g/kW·h)**		
	90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	n/a	n/a	n/a
Data #2	n/a	n/a	n/a
Data #3	n/a	n/a	n/a
Data #4	1198.65	798.68	774.67
Data #5	1196.84	800.76	773.63
Data #6	1203.32	799.82	773.28
Data #7	1206.65	798.39	779.73
Data #8	1215.14	800.40	780.99

Data #9	1208.87	802.35	779.35
Data #10	1225.74	790.94	770.41
Data #11	1233.40	818.10	775.68
Data #12	1240.60	798.85	793.63
Ave	1214.36	800.92	777.93
stdev	15.60	7.19	6.83
COV	0.01	0.01	0.01
Sample Size	9	9	9
df =	8	8	8
t cric	1.86	1.86	1.86
Est STD for mean	5.20	2.40	2.28
One side interval	9.67	4.46	4.24
Upper Limit	1224.03	805.38	782.17
Lower Limit	1204.68	796.46	773.69

Table 6: *Brake Specific CO2 Confidence Interval*

t-distribution	**Brake Specific CO (g/kW·h)** 90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	n/a	n/a	n/a
Data #2	n/a	n/a	n/a
Data #3	n/a	n/a	n/a
Data #4	26.77	19.25	21.94
Data #5	27.97	19.43	21.94
Data #6	27.72	19.26	21.80
Data #7	29.05	19.31	22.13
Data #8	28.97	19.22	21.91
Data #9	28.14	19.17	21.85
Data #10	27.14	17.31	21.96
Data #11	26.10	17.97	22.09
Data #12	24.57	17.51	22.38
Ave	27.38	18.71	22.00
stdev	1.43	0.86	0.18
COV	0.05	0.05	0.01
Sample Size	12	12	12
df =	11	11	11
t cric	1.86	1.86	1.86
Est STD for mean	0.41	0.25	0.05
One side interval	0.77	0.46	0.09
Upper Limit	28.15	19.17	22.09
Lower Limit	26.61	18.25	21.90

Table 7: *Brake Specific CO Confidence Interval*

t-distribution	Brake Specific HC (g/kW·h)		
	90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	n/a	n/a	n/a
Data #2	n/a	n/a	n/a
Data #3	n/a	n/a	n/a
Data #4	4.52	1.33	1.46
Data #5	4.48	1.33	1.47
Data #6	4.55	1.35	1.43
Data #7	6.19	1.79	1.77
Data #8	6.15	1.81	1.76
Data #9	6.11	1.81	1.76
Data #10	5.90	1.84	1.60
Data #11	6.01	1.91	1.58
Data #12	6.05	1.81	1.61
Ave	5.55	1.67	1.60
stdev	0.78	0.25	0.13
COV	0.14	0.15	0.08
Sample Size	12	12	12
df =	11	11	11
t cric	1.86	1.86	1.86
Est STD for mean	0.23	0.07	0.04
One side interval	0.42	0.13	0.07
Upper Limit	5.97	1.80	1.68
Lower Limit	5.13	1.53	1.53

Table 8: *Brake Specific HC Confidence Interval*

t-distribution	Brake Specific NOx (g/kW·h)		
	90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	n/a	n/a	n/a
Data #2	n/a	n/a	n/a
Data #3	n/a	n/a	n/a
Data #4	5.06	15.01	15.65
Data #5	4.95	14.97	15.54
Data #6	4.88	14.96	15.53
Data #7	5.19	15.19	15.49
Data #8	4.95	15.21	15.59

Data #9	5.02	15.26	15.58
Data #10	4.97	14.86	15.08
Data #11	5.18	15.34	15.22
Data #12	5.15	15.02	15.53
Ave	5.04	15.09	15.47
stdev	0.11	0.16	0.19
COV	0.02	0.01	0.01
Sample Size	12	12	12
df =	11	11	11
t cric	1.86	1.86	1.86
Est STD for mean	0.03	0.05	0.05
One side interval	0.06	0.09	0.10
Upper Limit	5.10	15.18	15.57
Lower Limit	4.98	15.00	15.37

Table 9: *Brake Specific NOx Confidence Interval*

t-distribution	**Microsoot (mg/m^3)** 90% Confidence Interval		
	2000 RPM @ 2 bar	2500 RPM @ 15 bar	3000 RPM @ 10 bar
Data #1	n/a	n/a	n/a
Data #2	n/a	n/a	n/a
Data #3	n/a	n/a	n/a
Data #4	0.009	0.032	0.199
Data #5	0.006	0.040	0.174
Data #6	0.007	0.046	0.186
Data #7	0.006	0.156	0.528
Data #8	0.006	0.124	0.406
Data #9	0.007	0.112	0.349
Data #10	0.006	0.987	0.569
Data #11	0.008	1.330	0.634
Data #12	0.009	0.948	0.589
Ave	0.007	0.419	0.404
stdev	0.001	0.514	0.185
COV	0.178	1.226	0.459
Sample Size	12	12	12
df =	11	11	11
t cric	1.860	1.860	1.860
Est STD for mean	0.000	0.148	0.054
One side interval	0.001	0.276	0.100
Upper Limit	0.008	0.696	0.503
Lower Limit	0.006	0.143	0.304

Table 10: *Microsoot Confidence Interval*

5.3 Engine History

At the start of the testing for this project, the engine had 391 hours of run time from a prior calibration study.

A notable event during the project was the catalyst failure on 10/22/2018. This was the result of an engine communication software issue and did not affect any of the calibration test results. The catalyst was replaced on 10/29/2018 with new substrate packed into the original can. To ensure consistent engine operation after the catalyst replacement, exhaust backpressure at multiple locations and engine conditions were matched to the original operating settings.

Another notable change was the PCV system adjustment made on 12/13/2018, when an external oil catch can was installed and the PCV rerouted through an AVL 442 blow-by meter. This resulted in a minor change in the crank case pressure.

The complete testing history including changes to the engine setup is summarized in the table below.

Event	Engine Hours	Date
102 RON Check1	391	10/17/2018
Fuel C	392	10/18/2018
Catalyst Change	397	10/22/18-10/29/18
Fuel H	464	11/20/2018
Fuel I	481	12/6/2018
PCV System Change	479	12/13/2019
Fuel J	501	12/17/2018
Fuel K	521	1/8/2019
Fuel B	536.4	1/16/2019
102 RON Check 2	553	1/23/2019
Fuel G	560.2	1/24/2019
Fuel L	572.6	1/30/2019
Fuel O	607.1	2/14/2019
Fuel E	616	2/18/2019
Fuel A	640	2/27/2019
Fuel M	660	3/5/2019
102 RON Check 3	673	3/08/2019
Fuel P	686	3/15/2019
Fuel D	698	3/19/2019
Fuel F	712	3/22/2019
102 RON Check 4	726	3/27/2019
End of Test	726.4	3/27/2019

***Table 11**: Engine History*

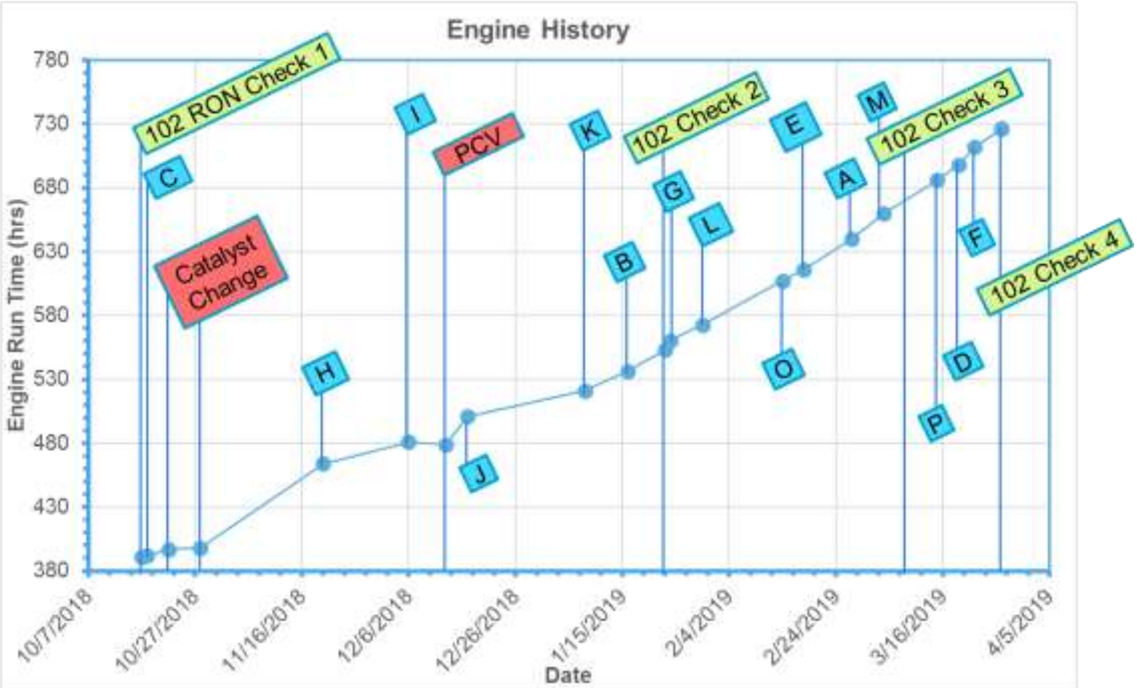

Figure 25*: Engine History*

5.4 Injector Baseline

To define the injector baseline cleanliness the engine was ran at a 3000 RPM 10 bar BMEP point with a fixed calibration setting that included no cEGR. The baseline test was ran in six steps as shown in the table below. An engine-out soot density threshold of 0.04 mg/m^3 was used to define the acceptable injector cleanliness level, and served as the baseline for subsequent injection cleaning.

Step	Run Time hrs	Description	Data
1	1	E25 102 Ron at 3000rpm/10bar (optimized calibration, no cegr)	1 minute intervals, 30 second average
2	1	98 RON Top Tier BIPO fuel at 3000rpm/10bar (optimized calibration without cEGR)	1 minute intervals, 30 second average
3	10	98 RON Top Tier BIPO fuel with ACDelco FST Plus at 3000rpm/10bar	1 minute intervals, 30 second average
4	NA	Oil and Filter Change	
5	1	E25 102 RON at 3000rpm/10bar (optimized calibration without cEGR)	1 minute intervals, 30 second average
6	NA	Oil and Filter Change	

Table 12*: Injector Cleaning Baseline Test*

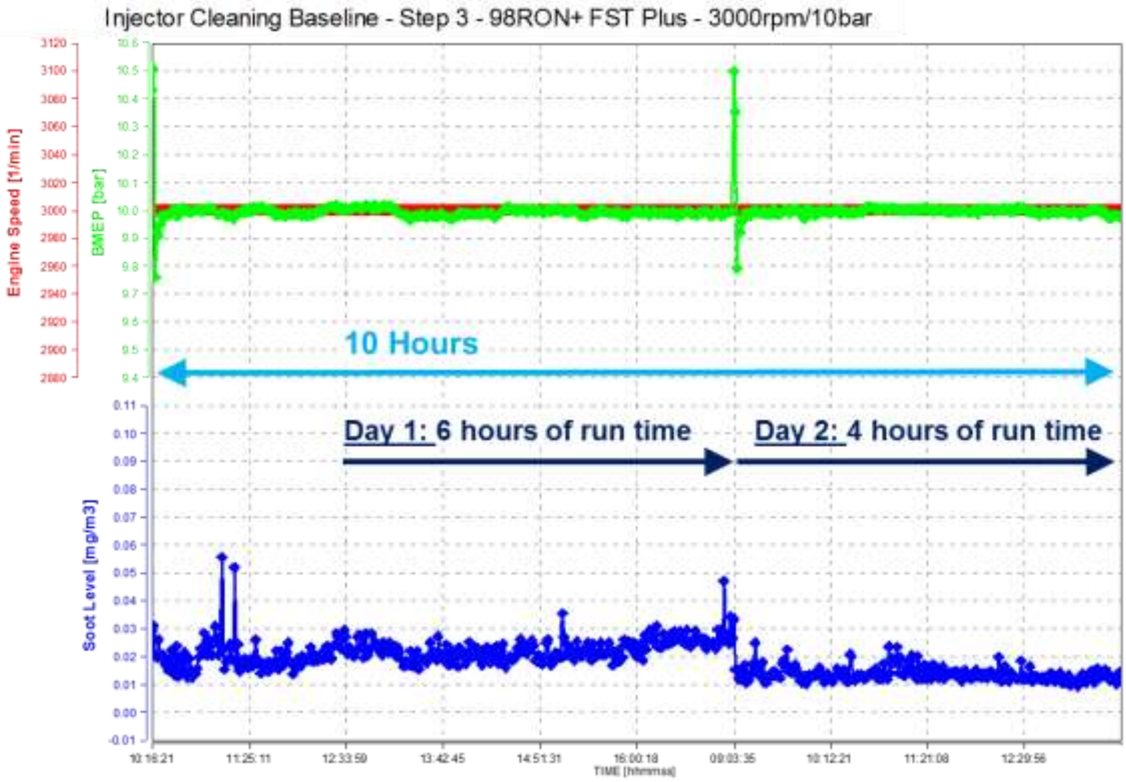

Figure 26: *Injector Cleaning Baseline*

5.5 Routine Maintenance

A number of steps were followed to ensure consistent engine condition at the start of calibration of each fuel. Between each calibration fuel, the engine went through a two-step cleaning process involving GM specified AC Delco Top Engine Cleaner (Part Number: AC-DELCO 10-3015) followed by running with fuel dosed with AC Delco Fuel System Treatment (Part Number: AC-DELCO 10-3004).

The initial cleaning step was with the Top Engine Cleaner. Using the GM specified tool, two bottles of AC Delco Top Engine Cleaner were applied through the intake while the engine was ran at 2000 RPM 5 bar BMEP with 98 RON Top Tier fuel. This was followed by an oil and filter change. The next step was running the injector cleaning, whereby the engine was ran at 3000 RPM 10 bar BMEP for an hour with 98 RON Top Tier fuel dosed with AC Delco Fuel System Treatment. During both the top engine cleaning and the injector cleaning steps the engine runs at a predefined calibration setting as shown below in ***Table 13***. After the injector cleaning was completed another oil and filter change was done before running the next test fuel. The target value for injector cleaning was to have less than 0.04 mg/m^3 of soot density.

	Intake Cam	Exhuast Cam	SOI	EOI	Spark Advance	Split	Wasgate	Egr Valve	Fuel Pressure	CA50
	°	°	°	°	°	-	%	%	Bar	°
2000/5 Bar	25	15	310	-	31.5	0	0	1	7	12
3000/10 Bar	32	0	310	270	22.5	0.1	0	1	10	12

Table 13: *Maintenance Calibration Values*

5.6 Soot Levels

It was noticed during testing that over time the injector cleaning was taking much more time than the expected one hour to achieve soot levels below the targeted 0.04 mg/m^3 soot density. During the third 102 RON health check point, the engine was inspected for abnormal wear which included a compression check and a leak down test performed on all cylinders. The compression test on cylinder 4 revealed a drop in compression from 210 PSI to 190 PSI on a cold engine and the leak down was shown to be 19% higher than the average of the other cylinders, this is summarized in ***Table 14***. By listening for air leakage at exit points of the cylinder, it was determined during the leak down that air was leaking past the piston rings, indicating a worn bore or damaged ring. Using a borescope, pictures were taken of the bore and included below in ***Figure 27***. The borescope pictures show vertical scratches along the cylinder wall. These scratches allow oil and air past the rings causing increase oil consumption and a drop in compression. It is believed that repeated top engine cleaning may have caused damage to the bores as the high consumption of the cleaning solvent can wash the bores of the oil film allowing debris to scratch the surface.

Engine Inspection- 673.30 hour				
Test\Cylinder	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Compresson Test	210 PSI	210 PSI	210 PSI	190 PSI
Leak Down Test	15.00%	12.00%	15%	35%

Table 14*: Engine Inspection*

Figure 27*: Wear on Cylinder Four*

To verify consistency of data, the 102 RON checkpoint was compared to previous data. It showed higher soot than expected as seen in ***Table 3*** above in section 5.4. Because the BSFC at the checkpoint was well within the expected values and combustion metrics showed the engine to be healthy, the soot difference became the main concern.

To see the effect of engine wear on soot over time, measured soot density was plotted for the first 60 points of each injector cleaning since the start of testing. This is shown in ***Figure 28*** where the level of soot during injector cleaning starts to become an issue around the time of Fuel E. After Fuel E the injector cleaning process could no consistently bring soot levels down to the targeted level of 0.04 mg/m^3 (reference ***Figure 29*** and ***Figure 30***).

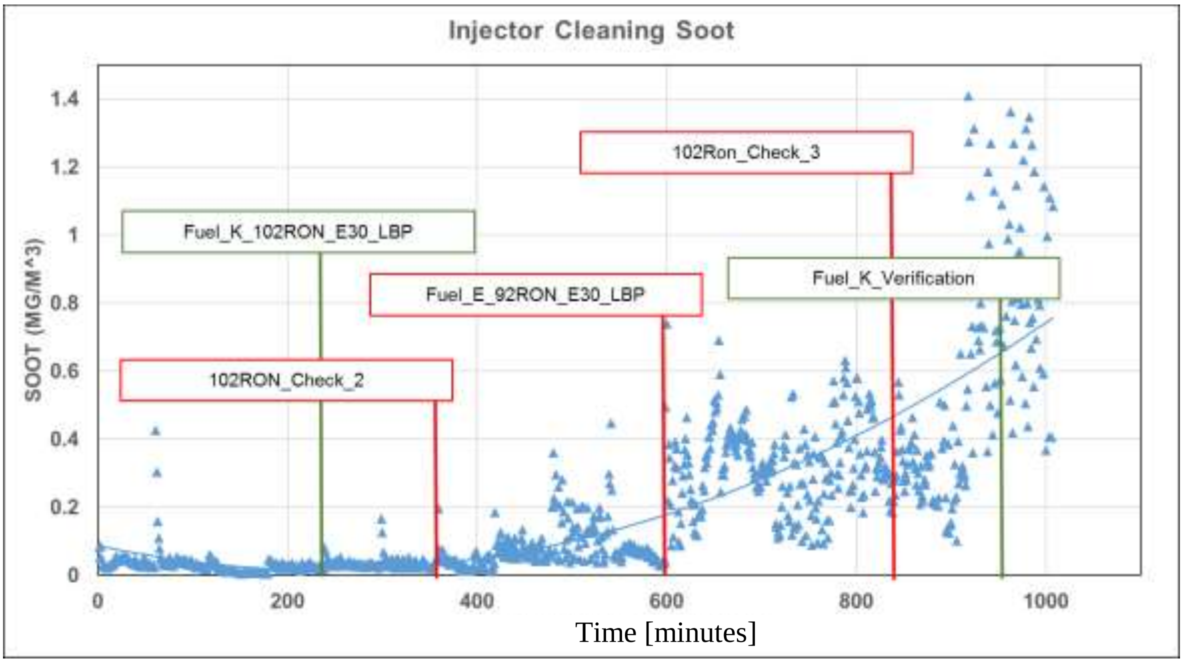

Figure 28*: Injector Cleaning Soot*

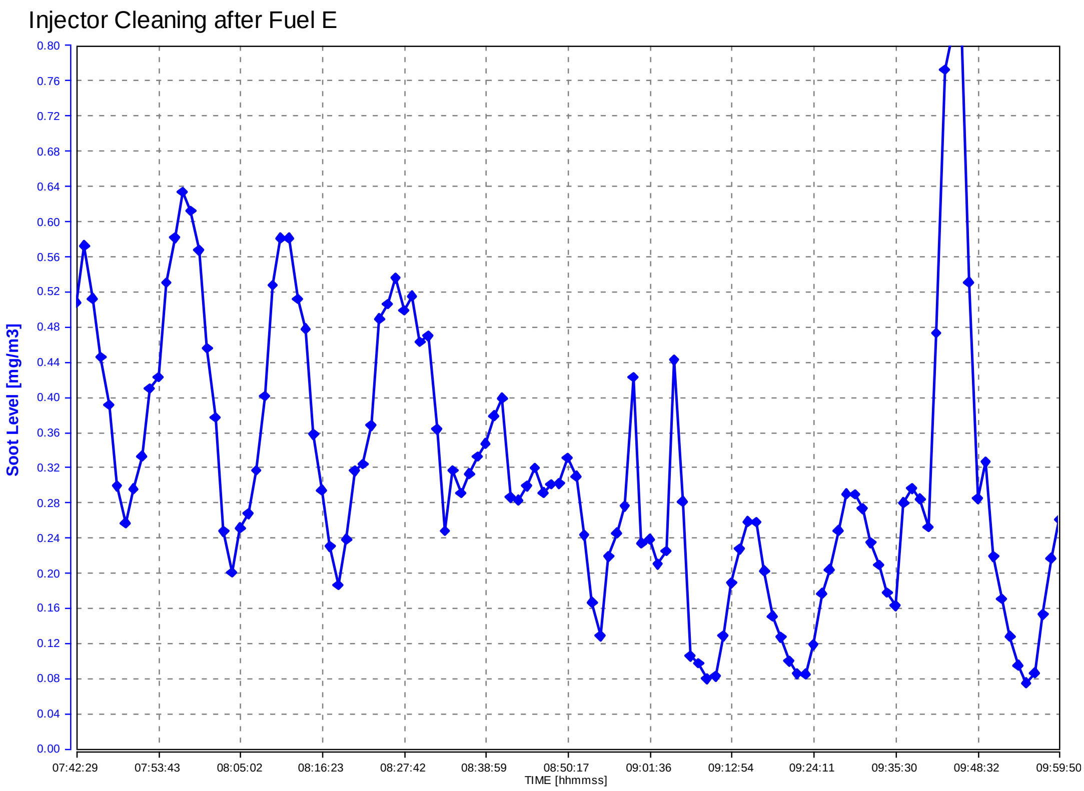

Figure 29*: Injector Cleaning After Fuel E*

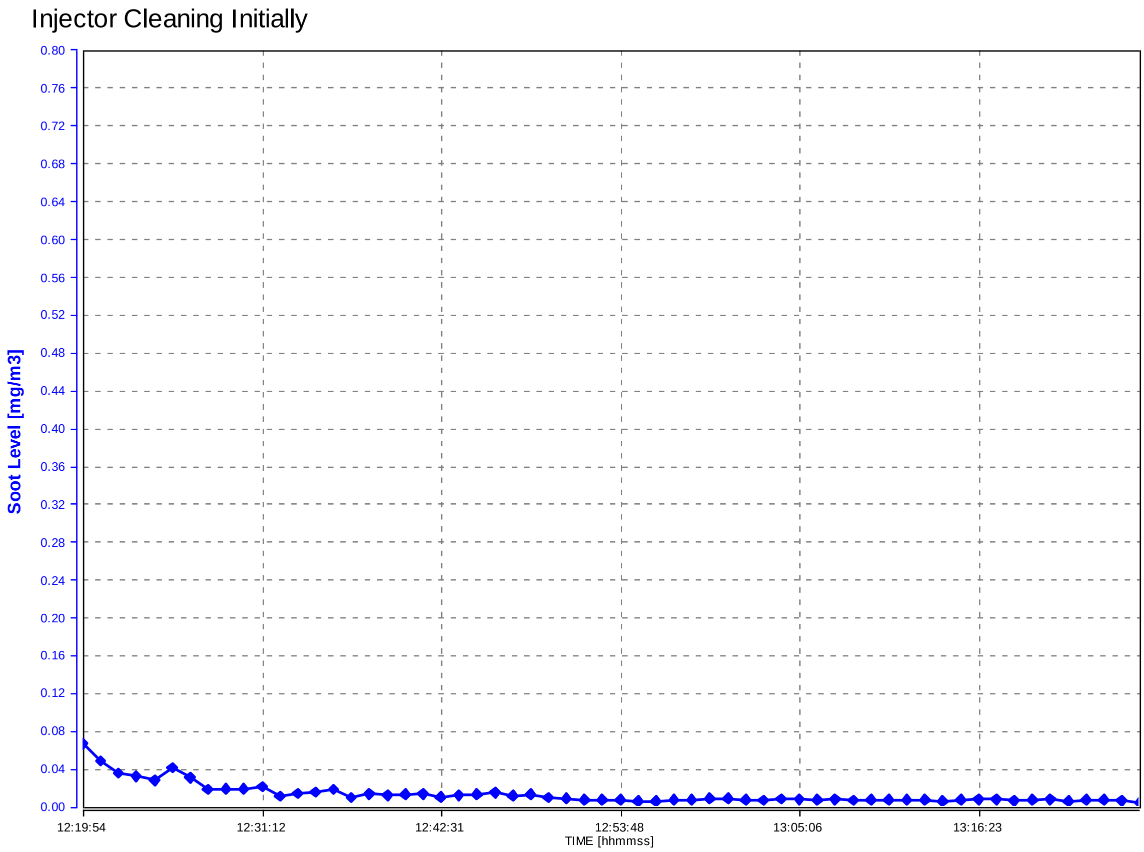

***Figure 30:** Standard Injector Cleaning*

5.6.1 Fuel K Verification

To further investigate the soot issue, Fuel K was reran at specific load and speed points and results compared with earlier data (reference ***Table 15*** and ***Table 16***). The results show a significant increase in soot of 500-1200 % (***Figure 31***). Increases in BSHC was much less at approximately 10% (***Figure 32***). Importantly, BSFC and BSNOx had not changed and remained consistent with the original data (***Figure 33*** and ***Figure 34***).

	PME	Engine Speed	BSFC	PMEP	AFR	CA50	CA10-90	Spark Advance	Soot	CO2	CO	HC	NOx	TC1 Exhaust Temp Inlet	Air Mass	COV
	Bar	1/min	g/k.W-h	bar	-	°A	°A	°A	mg/m3	g/kW.h	g/kW.h	g/kW.h	g/kW.h	°C	kg/h	%
Fuel K Soot Check	6.0	2000	265.8	-0.24	0.993	8.15	33.7	37.5	0.222	890	23.2	3.57	5.42	553.4	81.4	1.50
Fuel K Soot Check	10.0	2500	250.6	-0.17	0.995	7.96	32.9	27.75	1.229	843	19.2	3.98	7.14	646.2	155.4	0.92
Fuel K Soot Check	13.8	2500	244.1	-0.13	0.995	9.90	31.8	21.75	0.815	822	17.6	3.15	8.97	690.9	208.4	1.19
Fuel K Soot Check	10.0	4000	265.5	-0.76	0.995	7.92	34.6	25.5	1.013	898	16.1	3.02	12.27	767.8	265.6	1.10

***Table 15**: New Fuel K Data*

	PME	Engine Speed	BSFC	PMEP	AFR	CA50	CA10-90	Spark Advance	Soot	CO2	CO	HC	NOx	TC1 Exhaust Temp Inlet	Air Mass	COV
	Bar	1/min	g/k.W-h	bar	-	°A	°A	°A	mg/m3	g/kW.h	g/kW.h	g/kW.h	g/kW.h	°C	kg/h	%
Fuel K Original	6.1	2001	267.0	-0.28	0.992	8.41	32.37	38	0.019	898	24.2	3.13	5.24	547.1	81.3	1.54
Fuel K Original	10.0	2500	250.3	-0.16	0.996	8.15	32.39	28	0.098	845	18.9	3.43	6.93	640.2	153.1	1.00
Fuel K Original	14.0	2500	244.0	-0.13	0.996	9.09	31.37	23	0.368	826	18.2	2.73	9.27	687.8	210.4	0.85
Fuel K Original	10.0	4000	265.4	-0.76	0.996	8.00	34.59	28.25	0.270	904	16.3	2.86	10.24	748.7	262.4	1.06

***Table 16**: Original Fuel K Data*

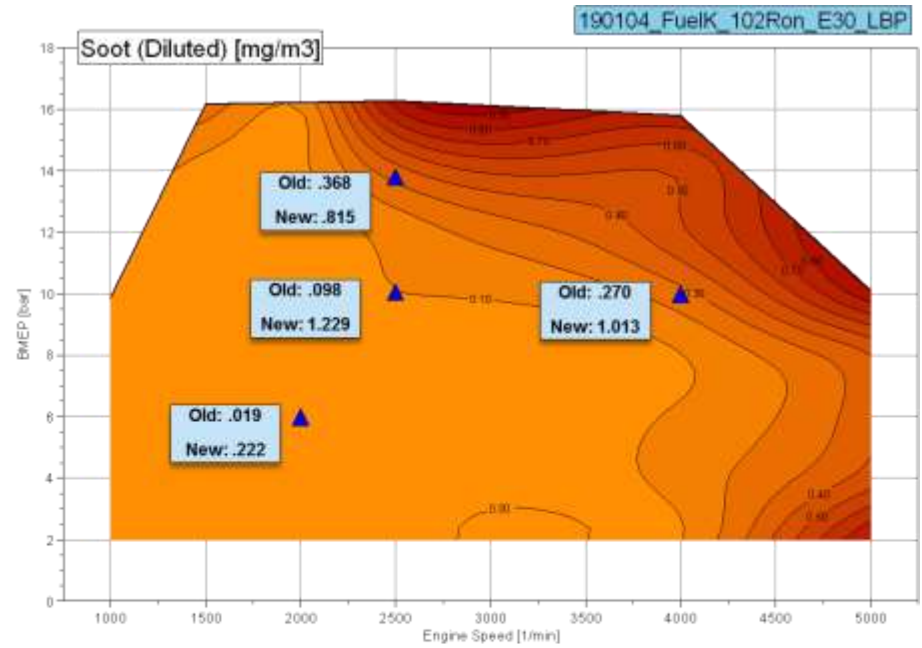

***Figure 31**: Fuel K Soot Comparison*

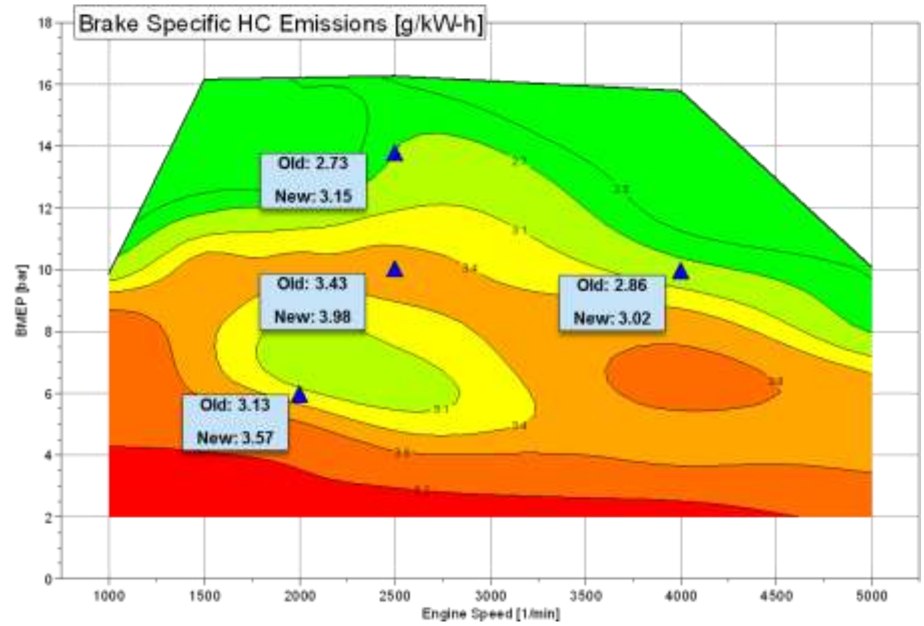

***Figure 32**: Fuel K HC Comparison*

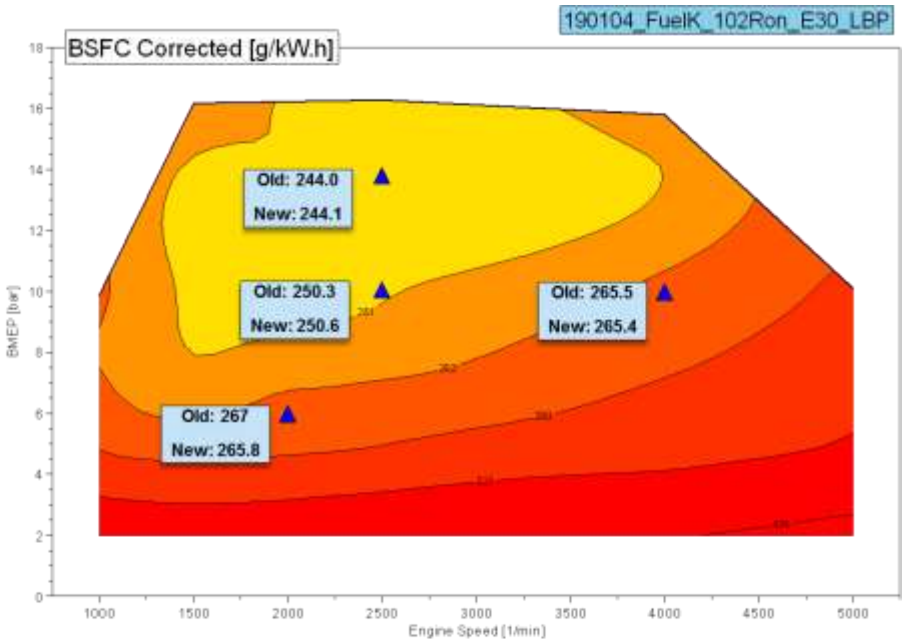

__Figure 33__: Fuel K BSFC Comparison

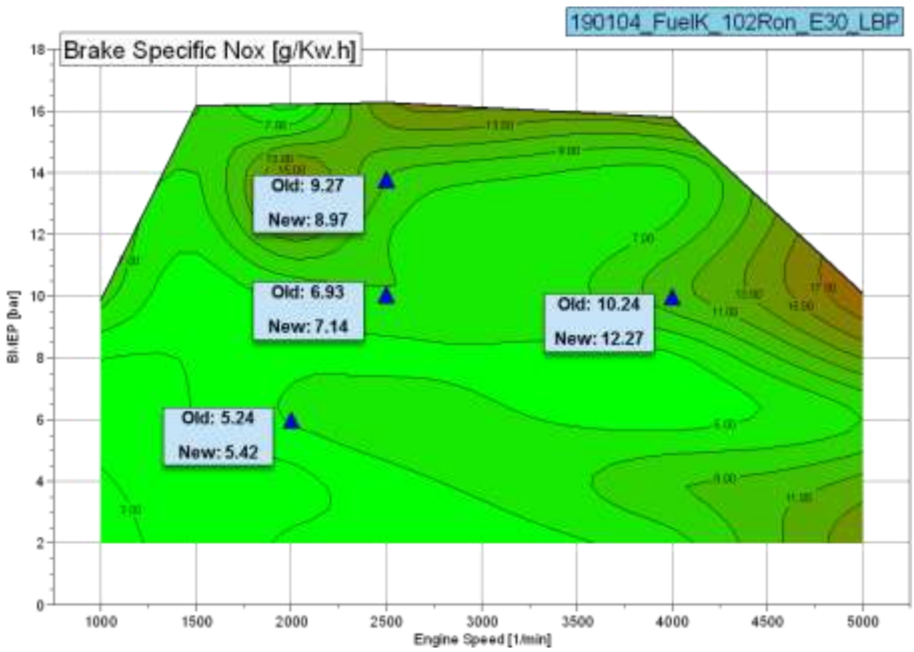

__Figure 34__: Fuel K NOx Comparison

6 Correction of Low Speed Points

6.1 BSFC Correction

Due to the nature of the study, low speed and low load points are very important because of their primary use in test cycles. The engine is less consistent at the low speed/load points. This instability makes it difficult for the dynamometer control to target the low load points to the precision required. To correct for small errors in load, data was gathered using 0.1 bar BMEP increments around the targeted loads keeping all calibration values the same. This created a trend on how small changes in load effect BSFC. Best fit trend lines were then fitted to the BSFC data using polynomial trend lines. This data was then normalized using the expected BSFC at each test point giving a correction factor. This was deemed only necessary for the 2 bar and 4 bar load points due the effect small changes in load have at these points.

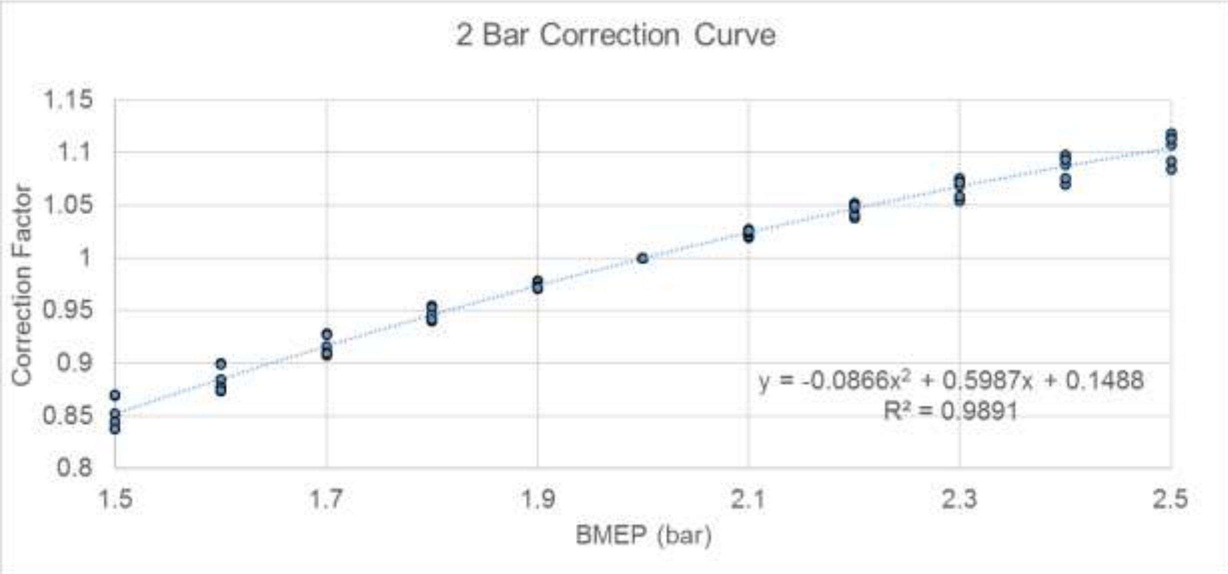

Figure 35: *Normalized BSFC Correction Curve*

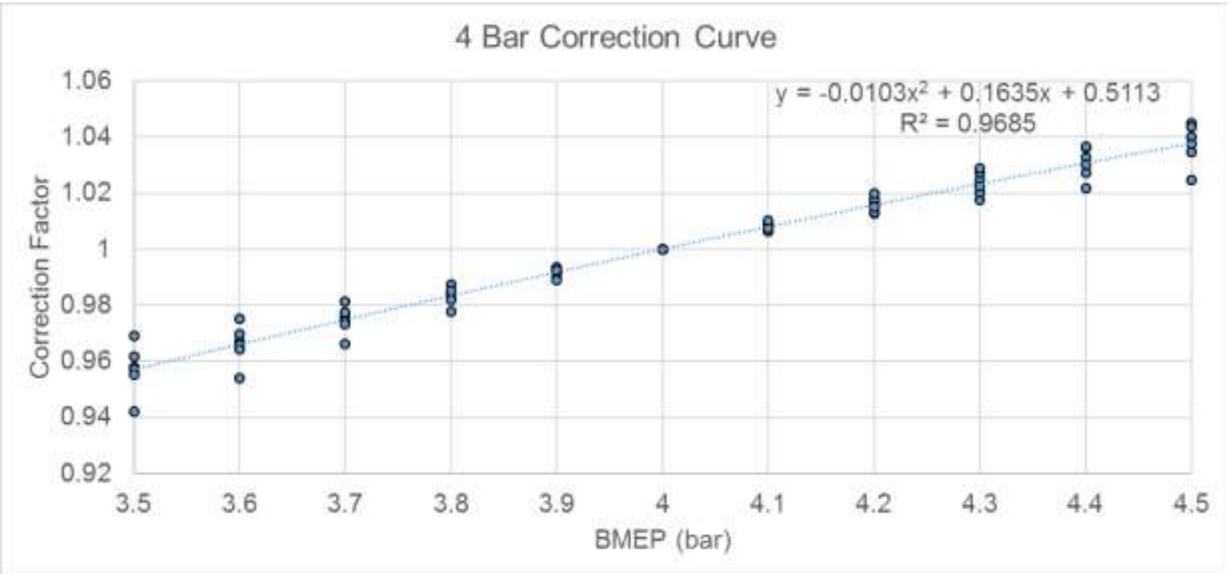

Figure 36: *Normalized BSFC Correction Curve*

6.2 BTE Correction

The same process used above was done for the Brake Thermal Efficiency to correct for small load changes.

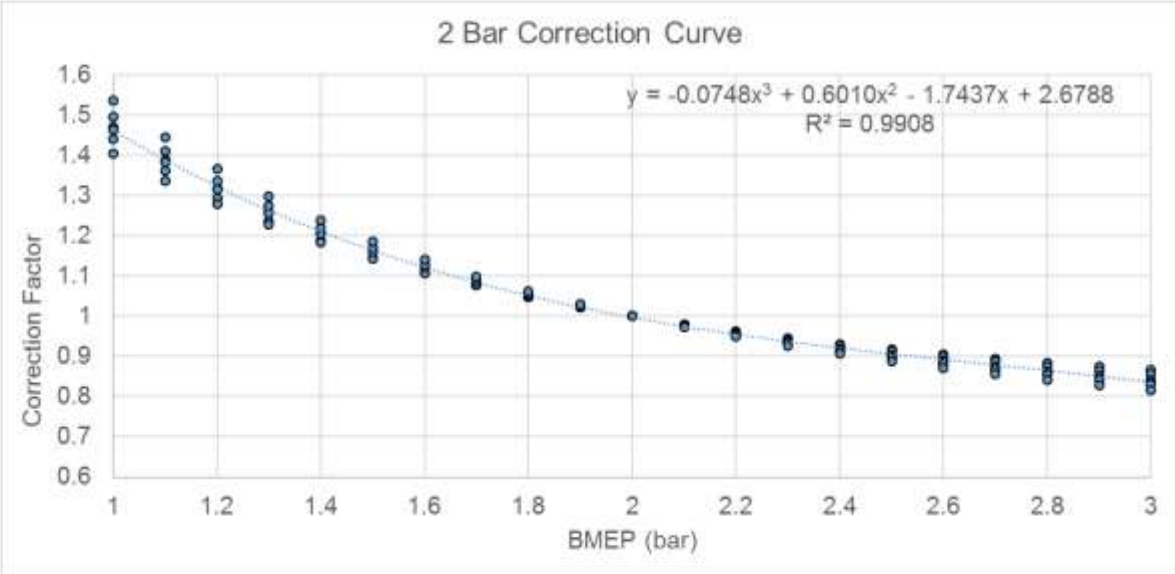

__Figure 37:__ Normalized BTE Correction Curve

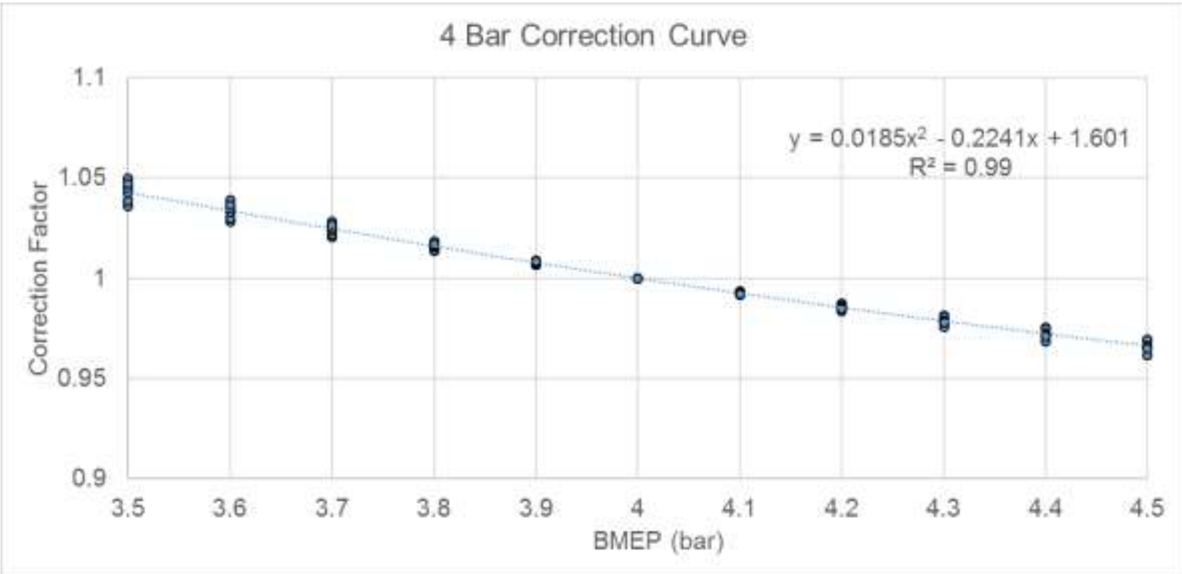

__Figure 38:__ Normalized BTE Correction Curve

6.3 Fuel Flow Correction

This method was also applied to the fuel flow using data from the fuel flow bench in the data channel Fuel_MS. This correction factor is shown in the figures below.

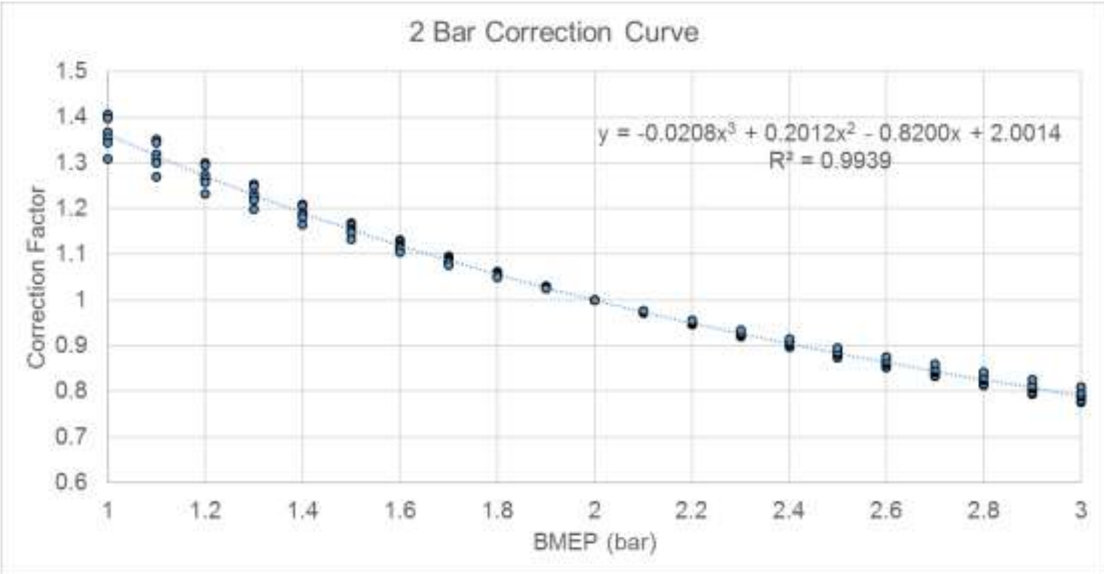

Figure 39: *Normalized Fuel Flow Correction Curve*

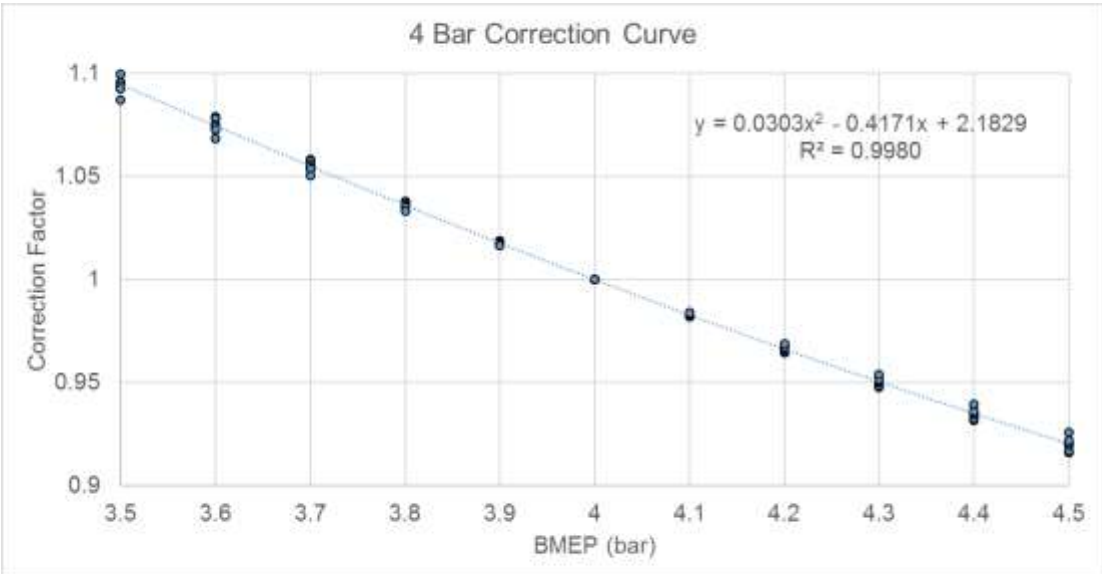

Figure 40: *Normalized Fuel Flow Correction Curve*

Fuel Properties

APPENDIX A: Fuel Specifications

	ProjName		ODDB	ODDB	ODDB	ODDB	ODDB	ODDB
	LabNum		33784	33785	33786	33787	33788	33789
	Sample Code		A	B	C	D	E	F
D5191	RVP	psi	8.08	8.06	7.82	8.21	8.07	7.98
	Ptot	psi	8.81	8.79	8.54	8.95	8.80	8.71
	DVPE	psi	7.95	7.93	7.69	8.09	7.94	7.86
	CARVP	psi	7.85	7.83	7.59	7.98	7.84	7.75
D1319	Aromatic	%	21.2	22.1	23.8	31.0	12.1	17.3
	Olefins	%	7.7	8.5	6.3	8.5	36.2	32.6
	Saturate	%	71.1	69.4	69.9	60.5	51.7	50.1
	CorrArom	%			21.48	28.05	8.53	12.20
	CorrOlef	%			5.69	7.69	25.51	22.99
	CorrSat	%			63.10	54.74	36.44	35.33
D2699Mdp	RON	ON	91.9	92	92.6	92.3	92.5	92.4
D2700Mdp	MON	ON	84.8	84.8	85.0	84.0	83.9	83.6
D4052	API@60°F		60.8	60.2	57.8	56.5	57.7	55.6
	SPGr@60°F		0.7360	0.7380	0.7473	0.7528	0.7478	0.7561
	Dens@15°C	g/ml	0.7358	0.7378	0.7471	0.7526	0.7476	0.7559
D4809 Net	BTUHeat	BTU/lb	18742	18720	17886	17858	16494	16435
	MJHeat	MJ/kg	43.594	43.542	41.602	41.538	38.365	38.228
	CALHeat	cal/g	10412.2	10399.9	9936.6	9921.1	9163.3	9130.6
D5291 CH	Carbon	wt%	86.08	86.3	82.74	82.95	74.86	74.98
	Hydrogen	wt%	14.10	14.14	13.78	13.63	13.87	13.50
D5453	Sulfur	ppmw	1.3	1.5	0.9	0.7	0.8	0.9
	SulfurWtPct	%	0.00013	0.00015	0.00009	0.00007	0.00008	0.00009
D5599	EtOHVol	Vol%			9.73	9.52	29.52	29.48
	EtOHWt	Wt%			10.34	10.04	31.34	30.96
	TtlVol	Vol%			9.73	9.52	29.52	29.48
	TtlWt	Wt%			3.59	3.48	10.88	10.74
PMI Calculation			1.096093357	2.47112591	1.29657742	2.607811152	0.761355814	1.865918608
D86	IBP	degF	98.9	94.5	104.0	100.9	102.0	104.7
	Evap_5	degF	123.8	122.0	126.3	123.5	127.1	128.0
	Evap_10	degF	133.8	131.7	133.0	130.6	136.9	137.5
	Evap_15	degF	141.3	138.8	137.0	135.1	142.2	143.7
	Evap_20	degF	148.2	145.5	141.0	139.6	147.3	148.2
	Evap_30	degF	162.1	158.7	148.0	147.7	153.7	154.9
	Evap_40	degF	177.9	173.9	153.8	154.6	158.9	160.4
	Evap_50	degF	198.2	193.3	201.9	206.8	163.3	165.0
	Evap_60	degF	222.8	217.4	235.1	245.8	167.5	168.8
	Evap_70	degF	245.5	242.3	259.6	270.2	170.9	173.5
	Evap_80	degF	269.0	271.7	276.8	297.3	276.9	298.4
	Evap_90	degF	307.7	350.1	301.2	342.7	303.7	339.1
	Evap_95	degF	330.0	385.1	323.5	376.7	330.4	371.0
	FBP	degF	365.6	430.6	373.4	427.1	362.7	423.5
	Recoverd	%	98.5	98.3	98.5	98.5	98.2	97.8
	Residue	%	0.7	0.9	0.9	0.8	0.8	1.0
	Loss	%	0.8	0.8	0.6	0.7	1.0	1.2

	ProjName		ODDB	ODDB	ODDB	ODDB	ODDB	ODDB
	LabNum		33790	33791	33792	33793	33794	33795
	Sample Code		G	H	I	J	K	L
D5191	**RVP**	**psi**	7.86	7.76	7.81	7.58	8.47	8.74
	Ptot	**psi**	8.58	8.48	8.53	8.29	9.22	9.5
	DVPE	**psi**	7.73	7.64	7.68	7.45	8.35	8.62
	CARVP	**psi**	7.62	7.53	7.58	7.34	8.25	8.52
D1319	**Aromatic**	**%**	38.1	39.9	26.8	30.5	24.3	22.7
	Olefins	**%**	2.4	1.6	4.2	3.7	3.8	3.5
	Saturate	**%**	59.5	58.5	69.0	65.8	71.9	73.8
	CorrArom	**%**			24.22	27.57	17.14	15.96
	CorrOlef	**%**			3.80	3.34	2.68	2.46
	CorrSat	**%**			62.35	59.48	50.72	51.87
D2699Mdp	**RON**	**ON**	102.6	102.7	102.6	102.7	102.7	102.6
D2700Mdp	**MON**	**ON**	90.7	90.4	90.6	90.4	89.9	90.2
D4052	**API@60°F**		55.6	53.6	58.1	55.8	54.2	53.9
	SPGr@60°F		0.7563	0.7645	0.7464	0.7553	0.7621	0.7633
	Dens@15°C	**g/ml**	0.756	0.7643	0.7462	0.755	0.7619	0.7631
D4809 Net	**BTUHeat**	**BTU/lb**	18524	18418	17840	17858	16390	16400
	MJHeat	**MJ/kg**	43.087	42.839	41.495	41.537	38.123	38.147
	CALHeat	**cal/g**	10291.1	10231.9	9910.8	9920.8	9105.5	9111.2
D5291 CH	**Carbon**	**wt%**	87.22	87.36	82.90	82.72	75.23	75.20
	Hydrogen	**wt%**	13.03	13.04	13.74	13.58	13.28	13.34
D5453	**Sulfur**	**ppmw**	0.4	0.4	0.9	1.0	1.1	1.5
	SulfurWtPct	**%**	0.00004	0.00004	0.00009	0.0001	0.00011	0.00015
D5599	**EtOHVol**	**Vol%**			9.64	9.61	29.46	29.71
	EtOHWt	**Wt%**			10.26	10.10	30.69	30.90
	TtlVol	**Vol%**			9.64	9.61	29.46	29.71
	TtlWt	**Wt%**			3.56	3.51	10.65	10.73
PMI Calculation			1.539649883	2.899802203	1.180477076	2.682385448	0.958133898	2.160810812
D86	**IBP**	**degF**	92.6	93.9	105.0	104.4	103.2	99.1
	Evap_5	**degF**	118.8	118.8	128.5	128.5	129.7	122.9
	Evap_10	**degF**	132.8	132.1	135.6	136.3	142.1	138.6
	Evap_15	**degF**	144.1	143.2	140.4	140.9	150.4	147.3
	Evap_20	**degF**	154.9	154.5	144.7	146.2	155.9	153.7
	Evap_30	**degF**	180.2	179.3	151.8	153.9	162.7	160.9
	Evap_40	**degF**	206.2	205.4	161.2	167.6	166.2	164.8
	Evap_50	**degF**	224.4	226.3	205.6	212.8	168.6	167.3
	Evap_60	**degF**	236.3	239.4	216.4	230.4	170.2	169.5
	Evap_70	**degF**	247.5	256.1	233.0	245.5	243.3	241.2
	Evap_80	**degF**	267.7	290.7	255.4	280.6	270.6	287.6
	Evap_90	**degF**	307.3	346.9	304.4	345.2	304.2	341.8
	Evap_95	**degF**	335.3	373.8	331.8	377.2	331.2	371.2
	FBP	**degF**	370.8	427.2	367.2	438.0	371.4	422.5
	Recoverd	**%**	98.3	98.3	98.5	97.9	98.4	97.2
	Residue	**%**	0.5	0.7	0.6	0.6	0.5	1.0
	Loss	**%**	1.2	1.0	0.9	1.5	1.1	1.8

	ProjName		ODDB	ODDB	ODDB
	LabNum		33796	33797	33798
	Sample Code		M	O	P
D5191	**RVP**	**psi**	7.57	7.78	8
	Ptot	**psi**	8.28	8.5	8.73
	DVPE	**psi**	7.44	7.65	7.88
	CARVP	**psi**	7.33	7.55	7.77
D1319	**Aromatic**	**%**	25	19.2	29.2
	Olefins	**%**	5.7	19.1	5.5
	Saturate	**%**	69.3	61.7	65.3
	CorrArom	**%**	21.24	13.46	
	CorrOlef	**%**	4.84	13.39	
	CorrSat	**%**	58.88	43.26	
D2699Mdp	**RON**	**inch-lbs**	98.0	98.2	97.9
D2700Mdp	**MON**	**Inch-lbs**	87.9	87.0	88.0
D4052	**API@60F**		56.5	55.9	58.7
	SPGr@60F		0.7525	0.7552	0.7441
	Dens@15C	**g/ml**	0.7522	0.7549	0.7438
D4809 Net	**BTUHeat**	**BTU/lb**	17456	16387	18553
	MJHeat	**MJ/kg**	40.603	38.117	43.155
	CALHeat	**cal/g**	9697.9	9104.1	10307.3
D5291 CH	**Carbon**	**wt%**	80.58	74.84	86.78
	Hydrogen	**wt%**	13.50	13.65	13.56
D5453	**Sulfur**	**ppm**	2.2	1.2	0.7
	SulfurWtPct	**%**	0.00022	0.00012	0.00007
D5599	**EtOHVol**	**Vol%**	15.03	29.88	
	EtOHWt	**Wt%**	15.86	31.41	
	TtlVol	**Vol%**	15.03	29.88	
	TtlWt	**Wt%**	5.5	10.9	
PMI Calculation			1.45827104	1.305691079	1.634877658
D86	**IBP**	**deg F**	102.0	103.3	94.9
	Evap_5	**degF**	130.1	129.0	119.3
	Evap_10	**degF**	139.2	140.0	131.2
	Evap_15	**degF**	144.6	146.3	140.1
	Evap_20	**degF**	148.8	150.8	148.4
	Evap_30	**degF**	155.6	157.3	165.3
	Evap_40	**degF**	160.6	161.6	184.0
	Evap_50	**degF**	180.1	165.2	203.8
	Evap_60	**degF**	233.6	168.0	222.7
	Evap_70	**degF**	244.3	171.2	236.9
	Evap_80	**degF**	266.9	271.3	254.7
	Evap_90	**degF**	306.6	312.1	295.5
	Evap_95	**degF**	343.9	344.8	333.4
	FBP	**degF**	399.7	396.7	397.0
	Recoverd	**mL**	98.1	97.8	98.1
	Residue	**mL**	1.0	1.0	0.8
	Loss	**mL**	0.9	1.2	1.1

Notes.

1. Mdp - Modified Double Pass
2. TtlVol – Total Volume percent of oxygenates in the sample.
3. TtlWt – Total Weight percent of the oxygen in the sample, calculated from the individual oxygenates oxygen weight %.
4. D1319 reports out the results in volume %. The CorrArom, CorrOlef, and CorrSat are the volume percent of the hydrocarbon type corrected for the ethanol content. In the FIA method, the oxygenated components are separated from the rest of the sample so the hydrocarbon types measured are on an oxygenate free basis. The correction is done to present the hydrocarbon types on a total samples basis. TtlVol + CorrArom+CorrOlef+CorrSat = 100 volume %
5. The prefix "Corr" indicates the sample has been corrected for ethanol, since oxygenates are not accounted for in the analysis technique. For the other fuel property measurements, the oxygenates are taken in to account so no correction is needed.
6. D5191
    i. RVP is the vapor pressure calculated from the Ptot using the EPA equation cited in 40 CFR §80.46(c)
    ii. Ptot is the total measured pressure
    iii. DVPE is the vapor pressure calculated from the Ptot using the ASTM equation found in D5191
    iv. CARVP is the vapor pressure calculated from the Ptot using the equation cited by the California Air Resources Board.

Fuel B Calibration Results

92 Ron 0% Ethanol High Boiling Point

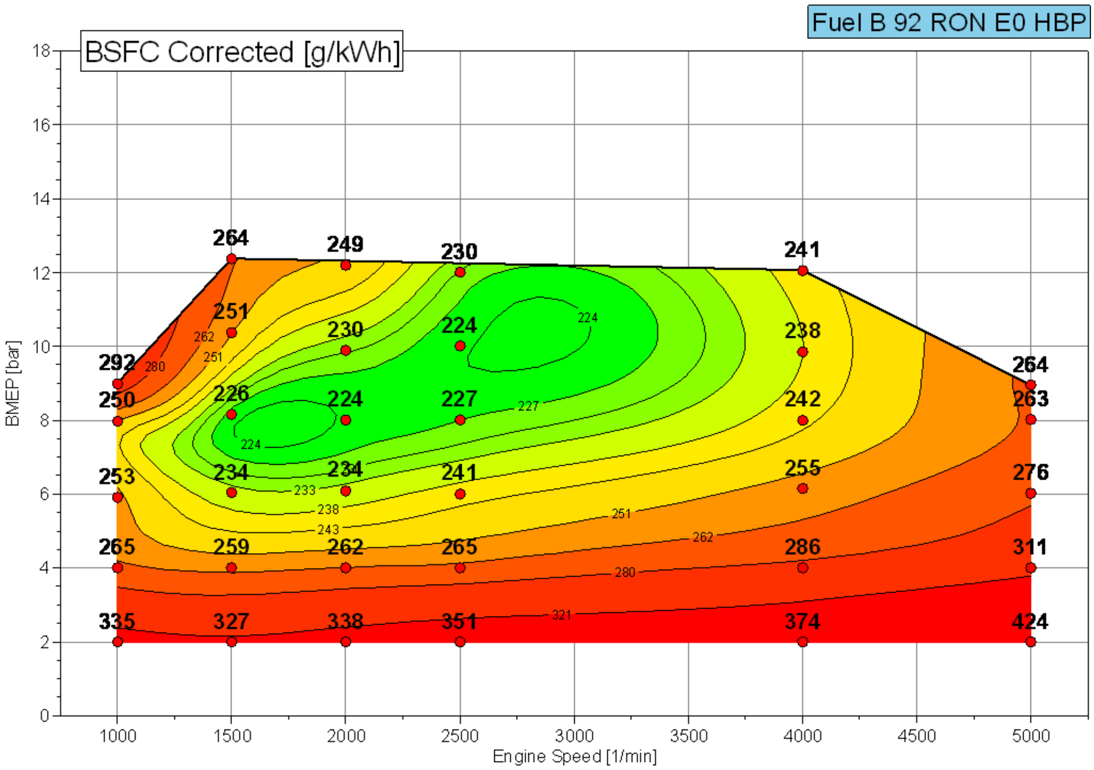

Figure 1: Brake Specific Fuel Consumption

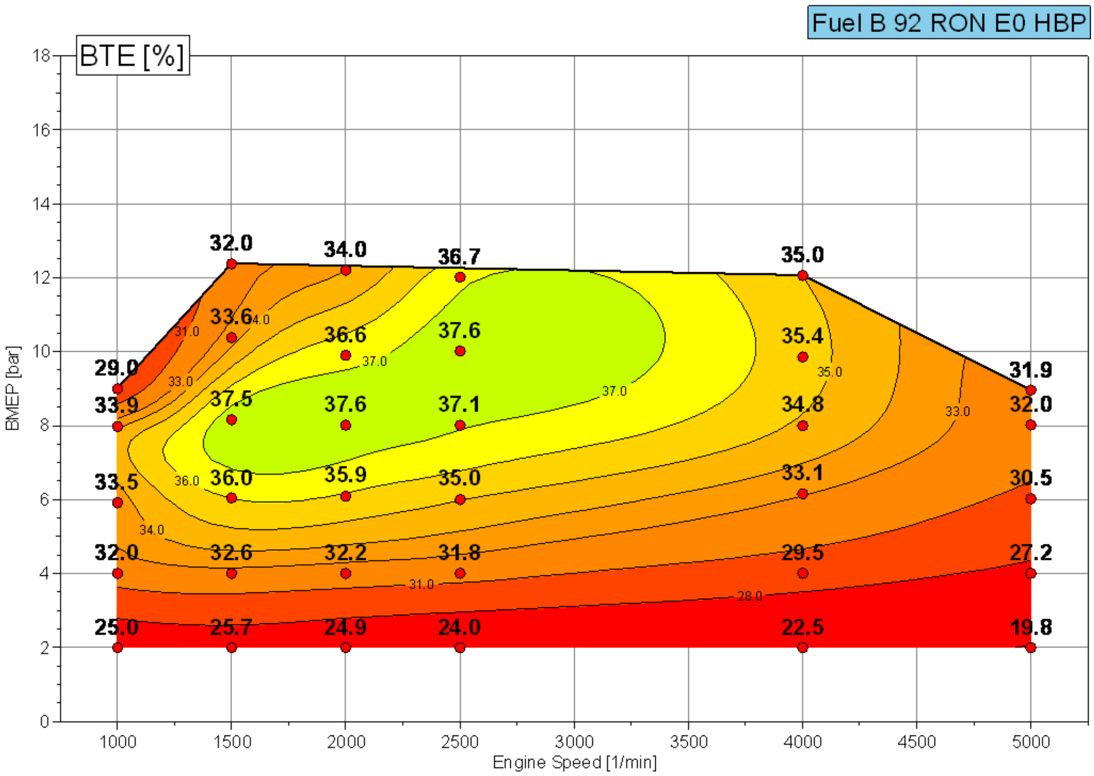

Figure 2: Brake Thermal Efficiency

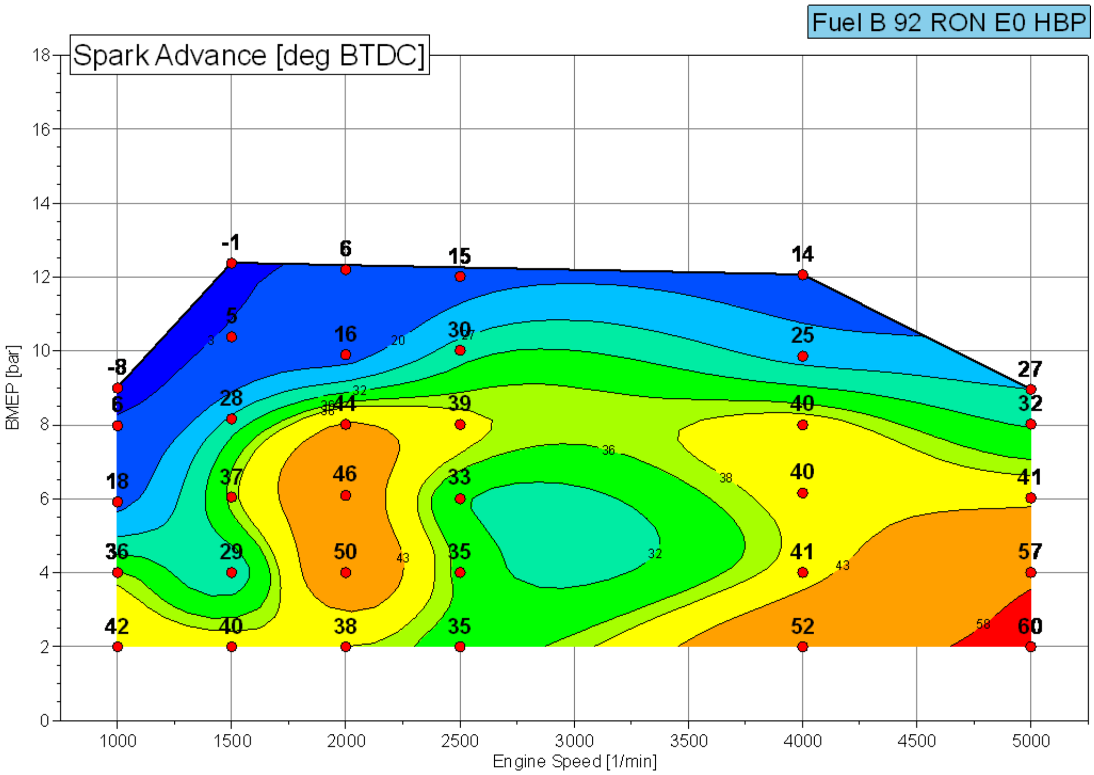

Figure 3: Spark Advance

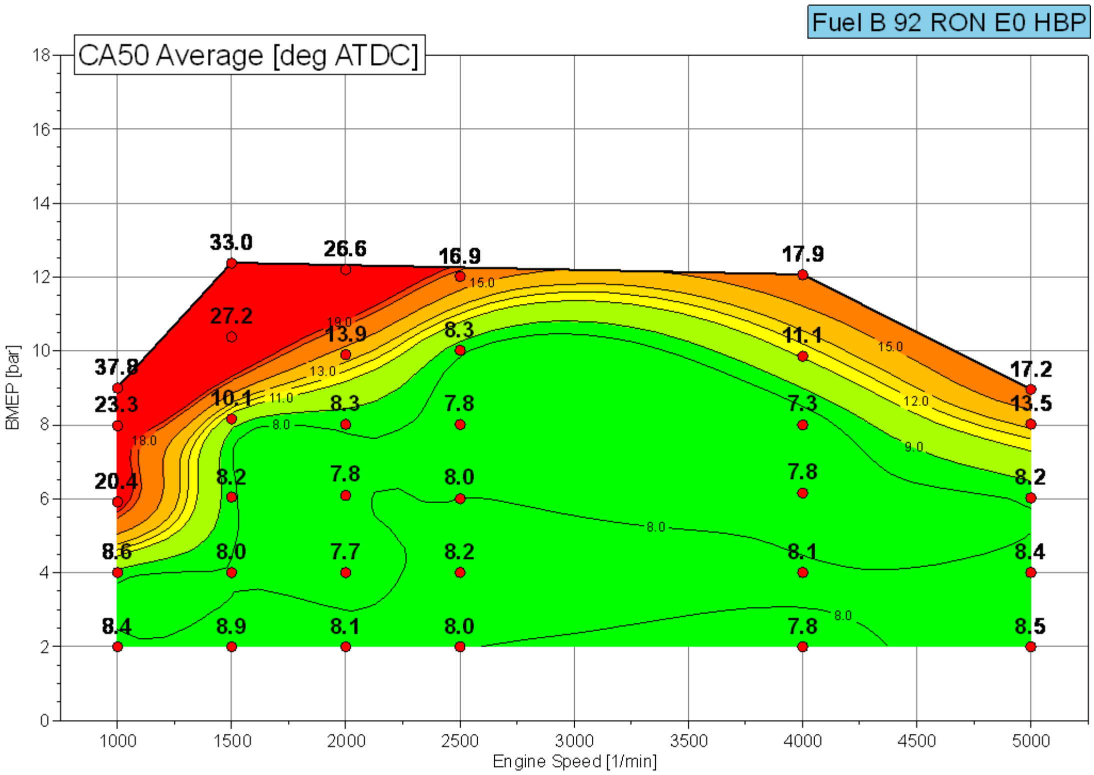

Figure 4: CA50 Average of Cylinders 1-4

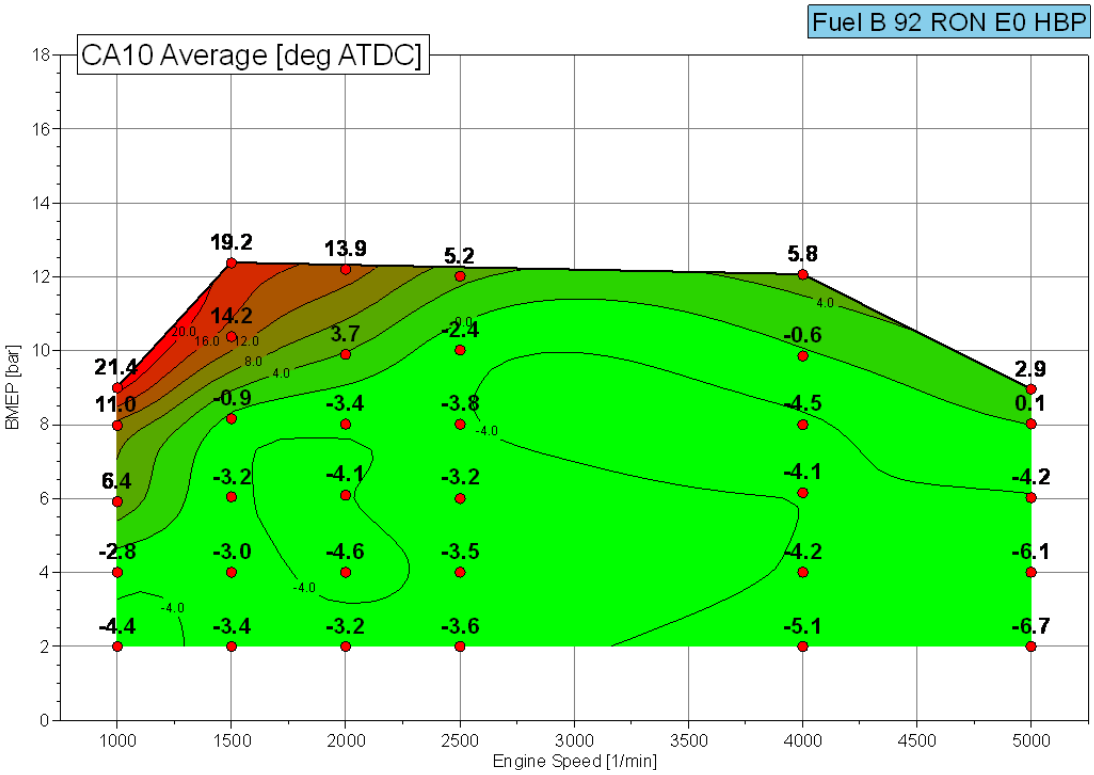

Figure 5: CA10 Average of Cylinders 1-4

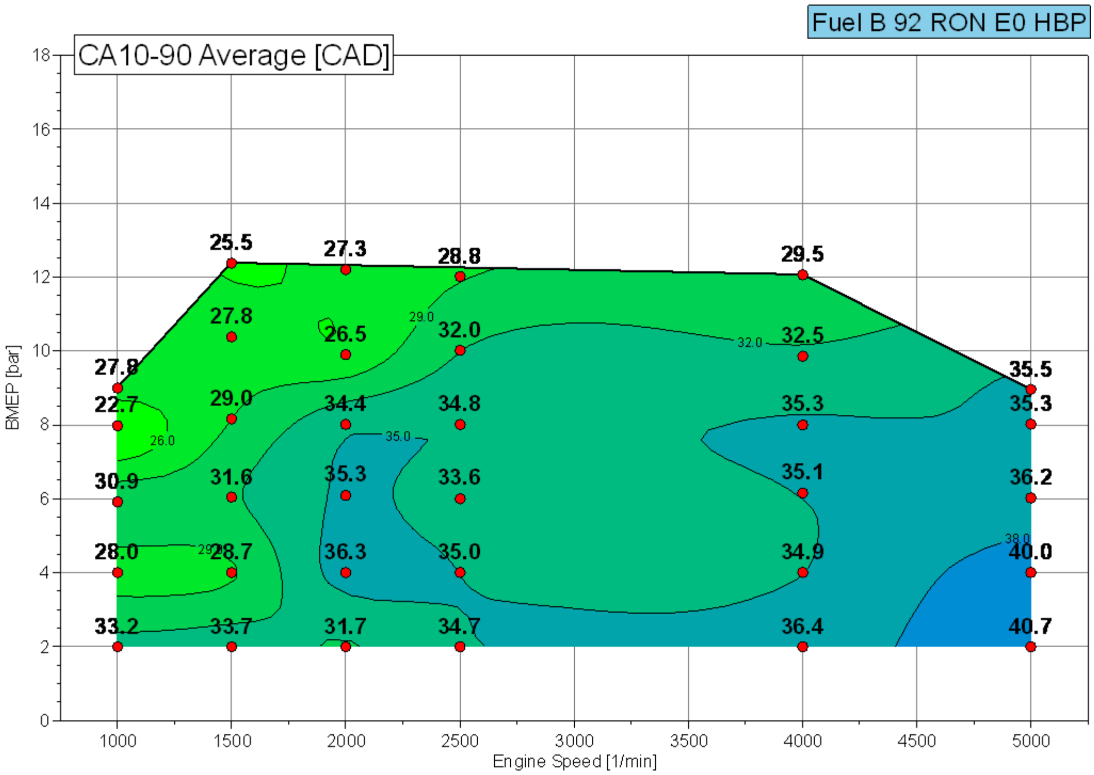

Figure **6:** CA10-90 Average of Cylinders 1-4

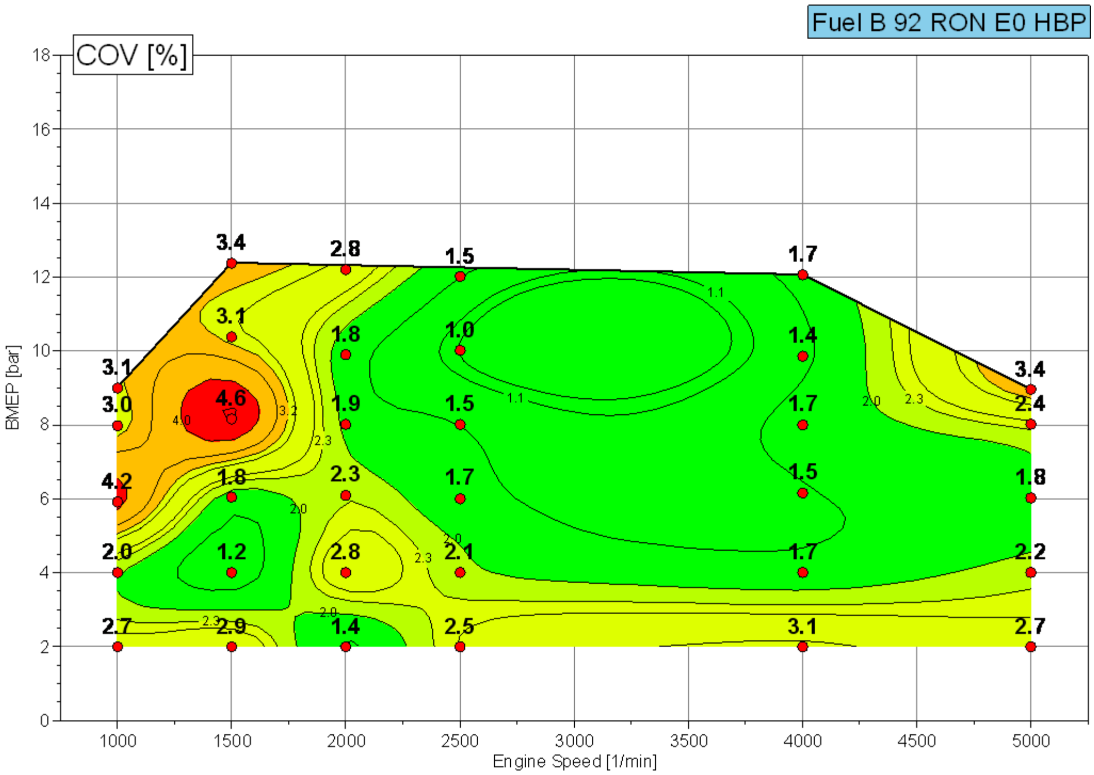

Figure 7: Coefficient of Variation Average of Cylinders 1-4

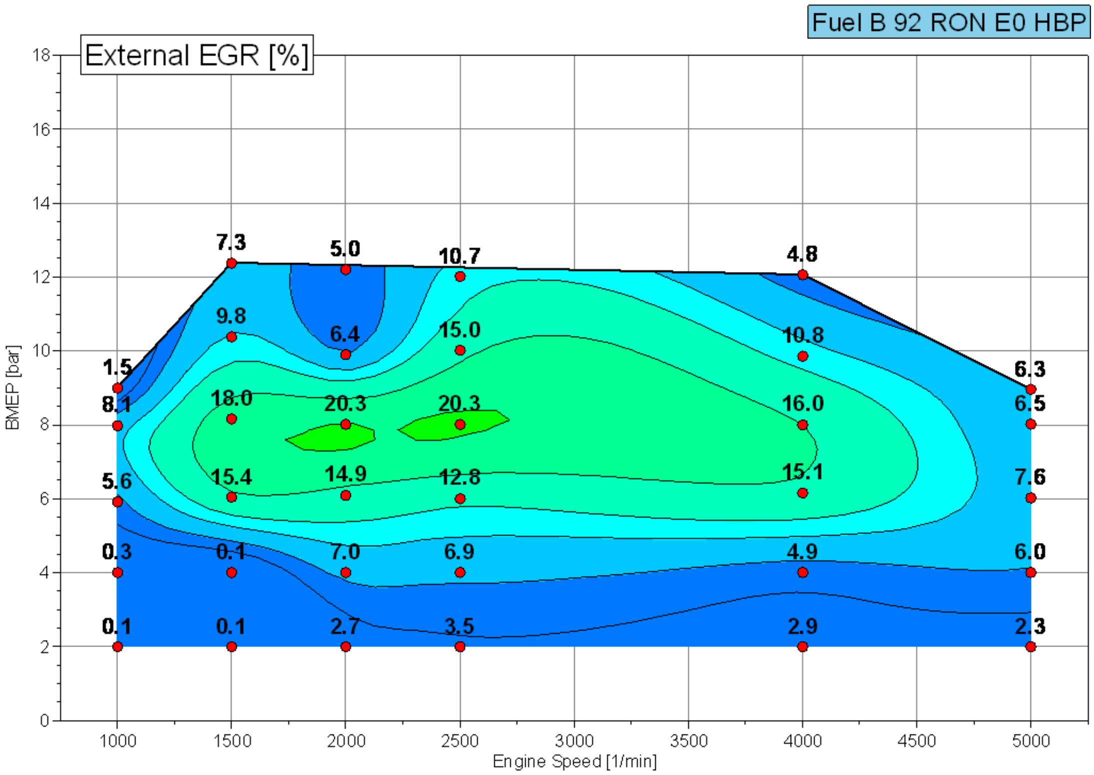

Figure 8: External EGR Percent of Intake Air

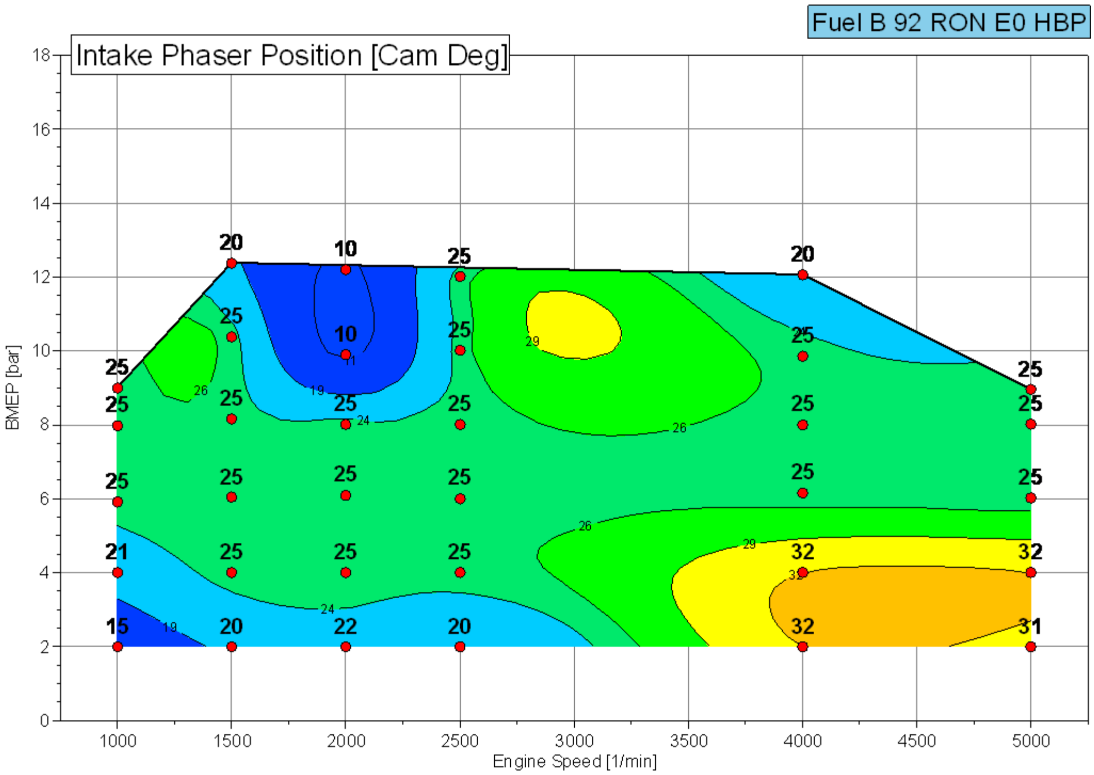

Figure 9: Intake Camshaft Phaser Position

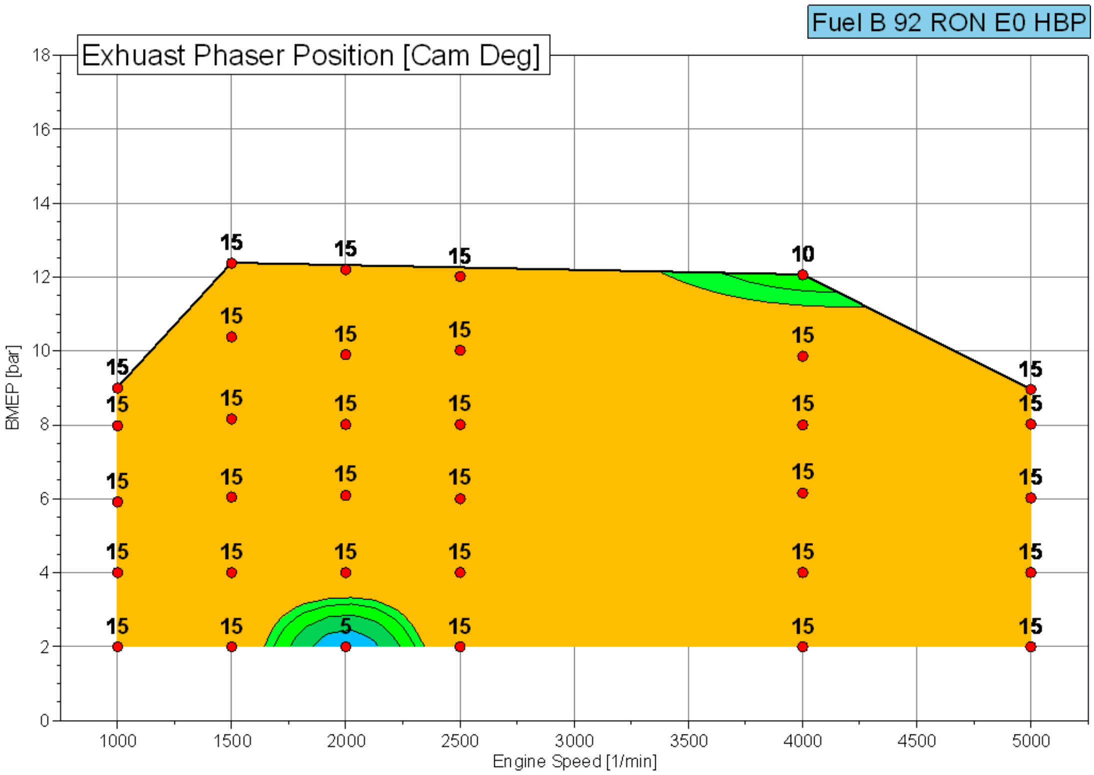

Figure 10: Exhaust Camshaft Phaser Position

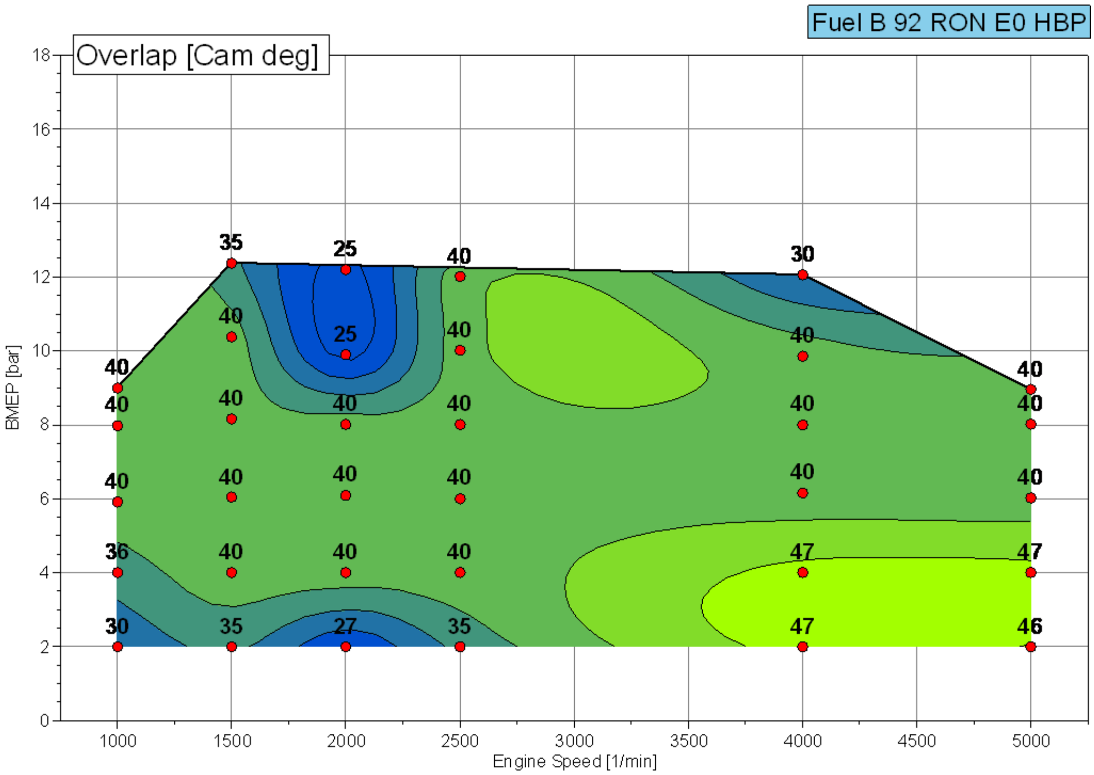

Figure 11: Camshaft Overlap

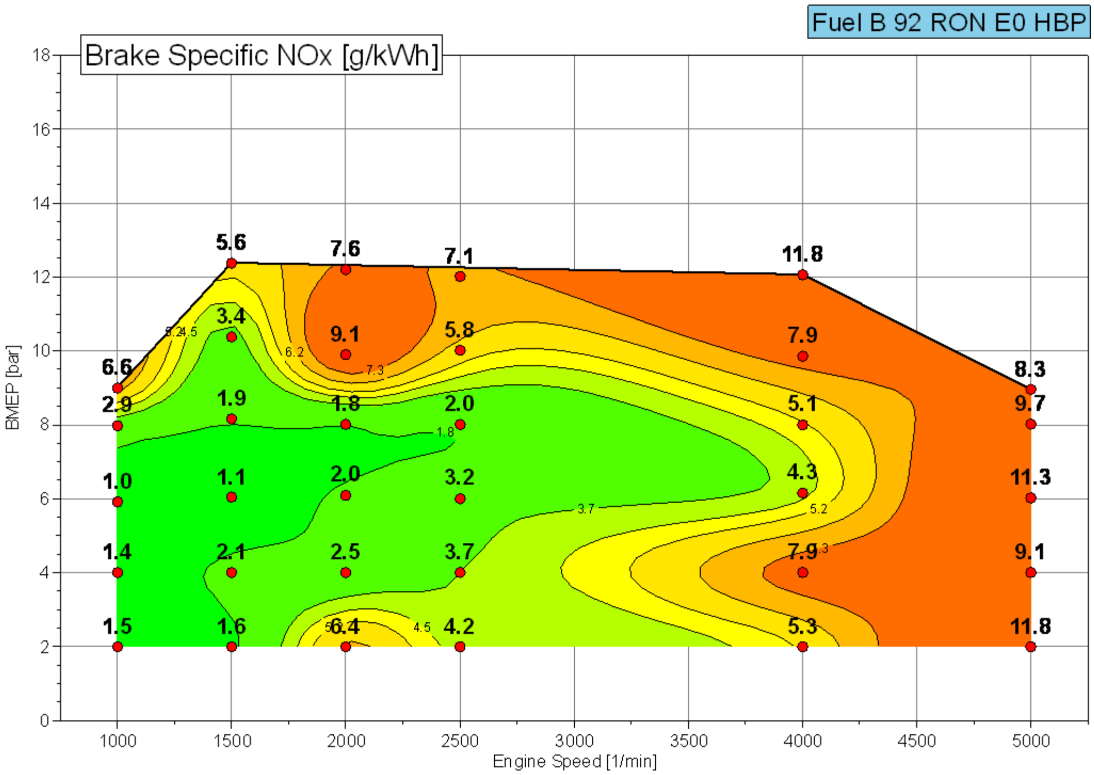

Figure 12: Brake Specific NOx Emissions

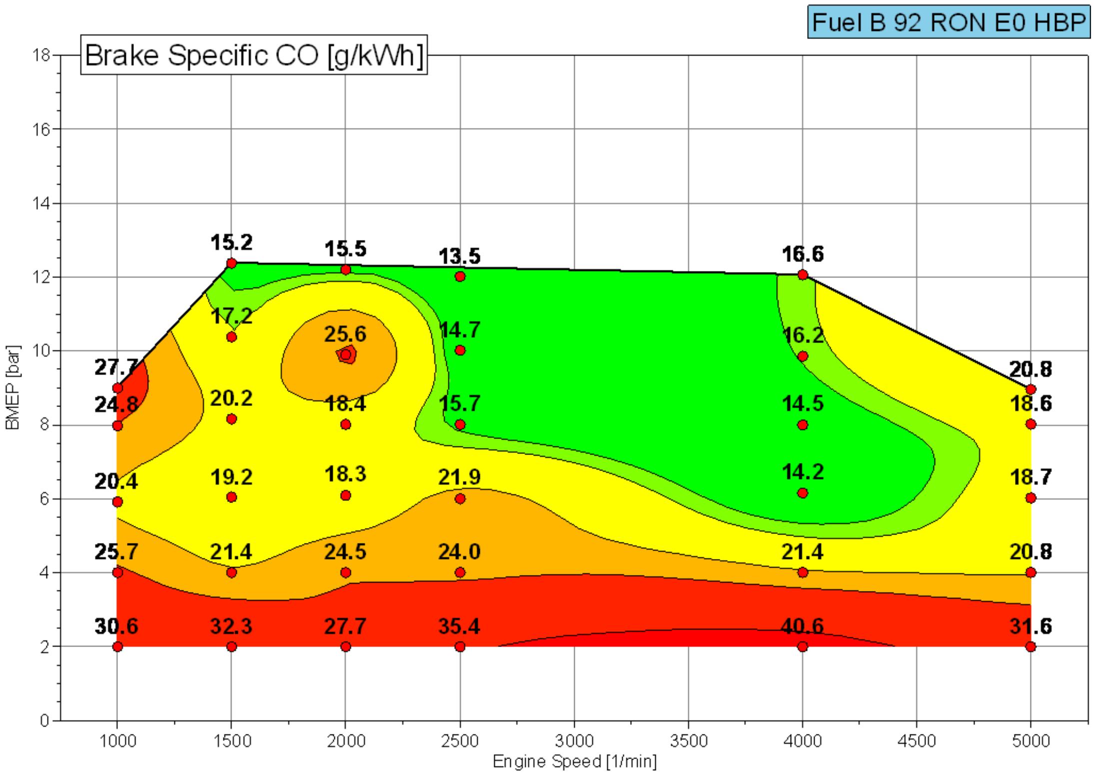

Figure 13: Brake Specific Carbon Monoxide Emissions

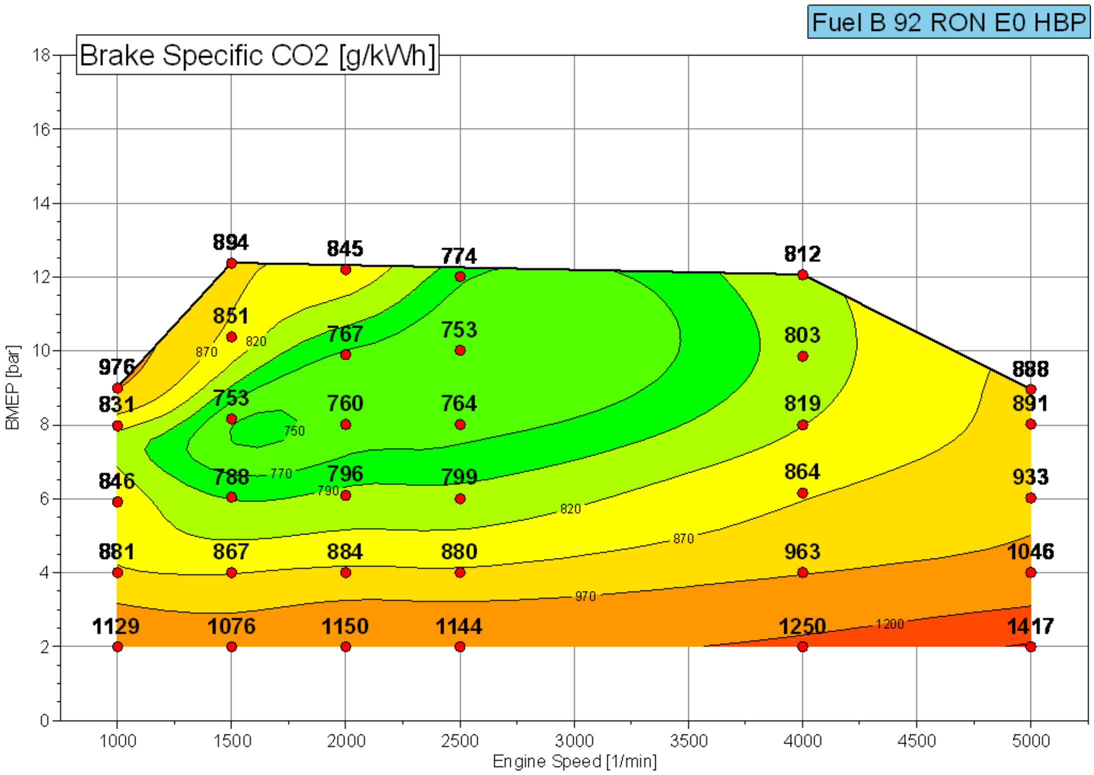

Figure 14: Brake Specific Carbon Dioxide Emissions

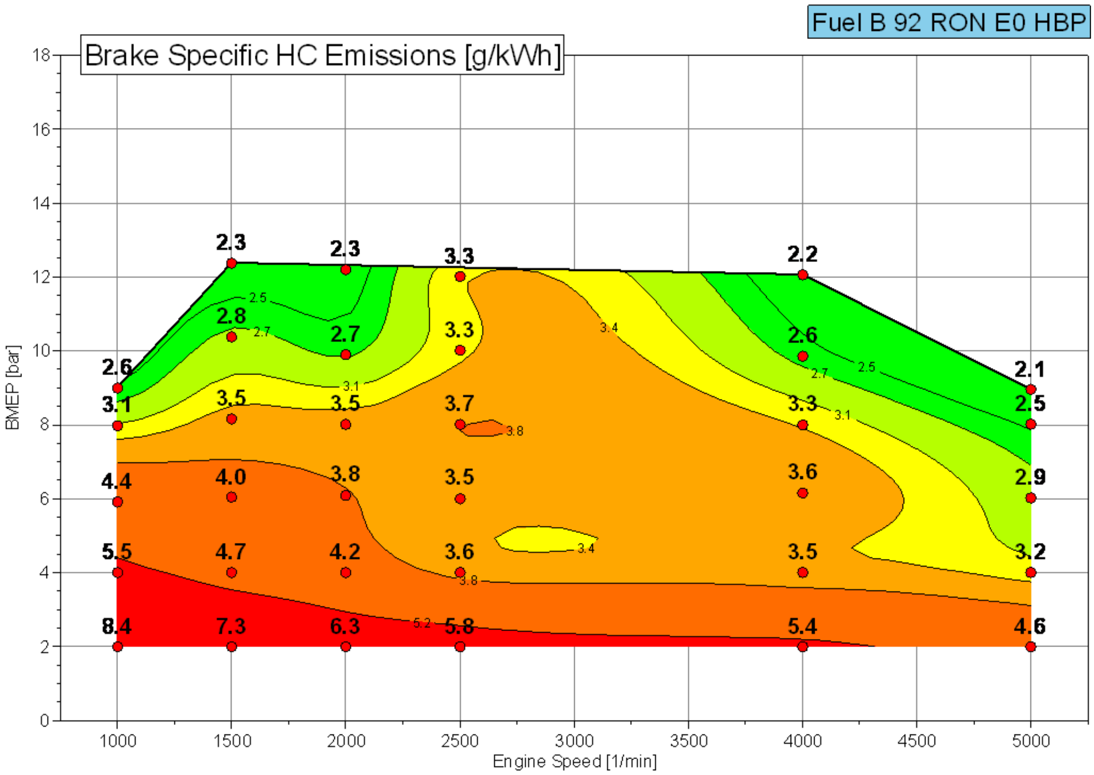

Figure 15: Brake Specific Hydrocarbon Emissions

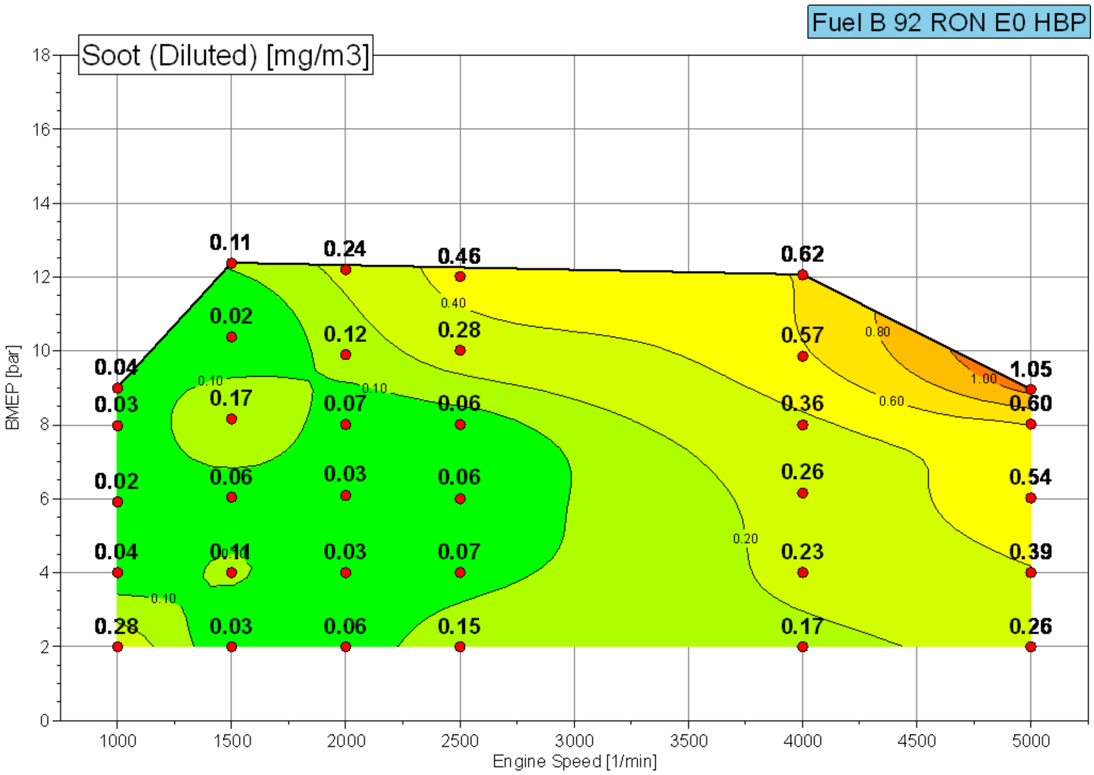

Figure 16: Particulate Soot Emissions

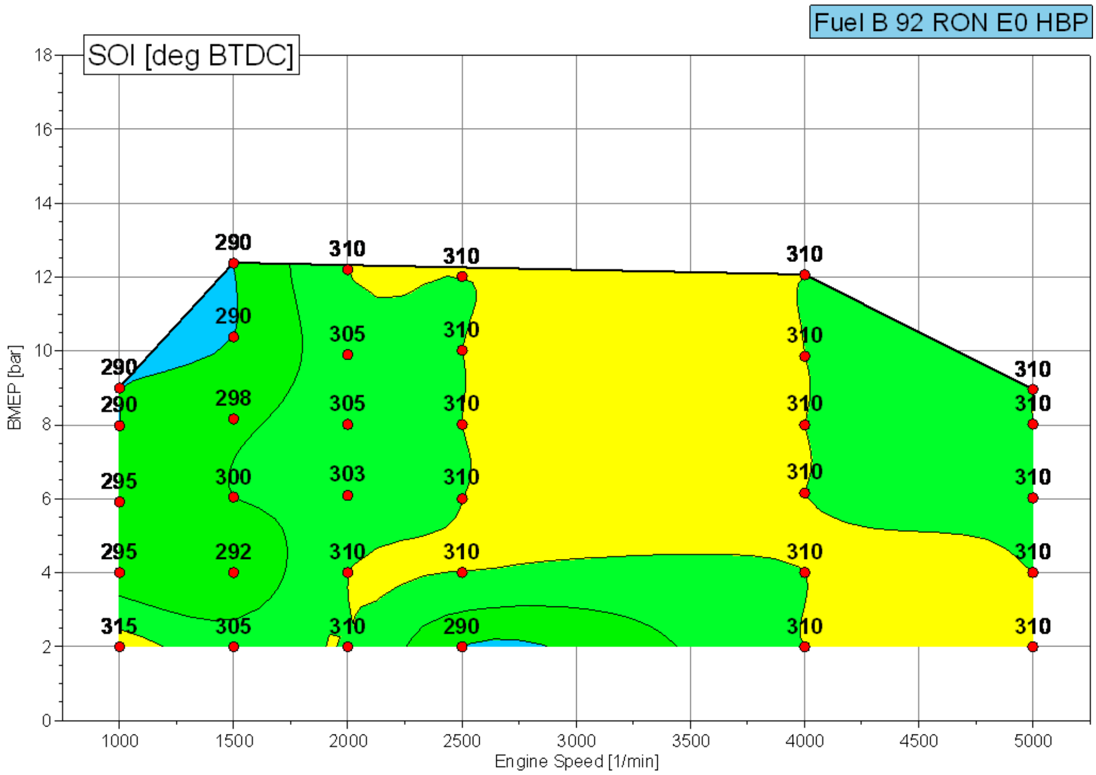

Figure 17: Start of Injection

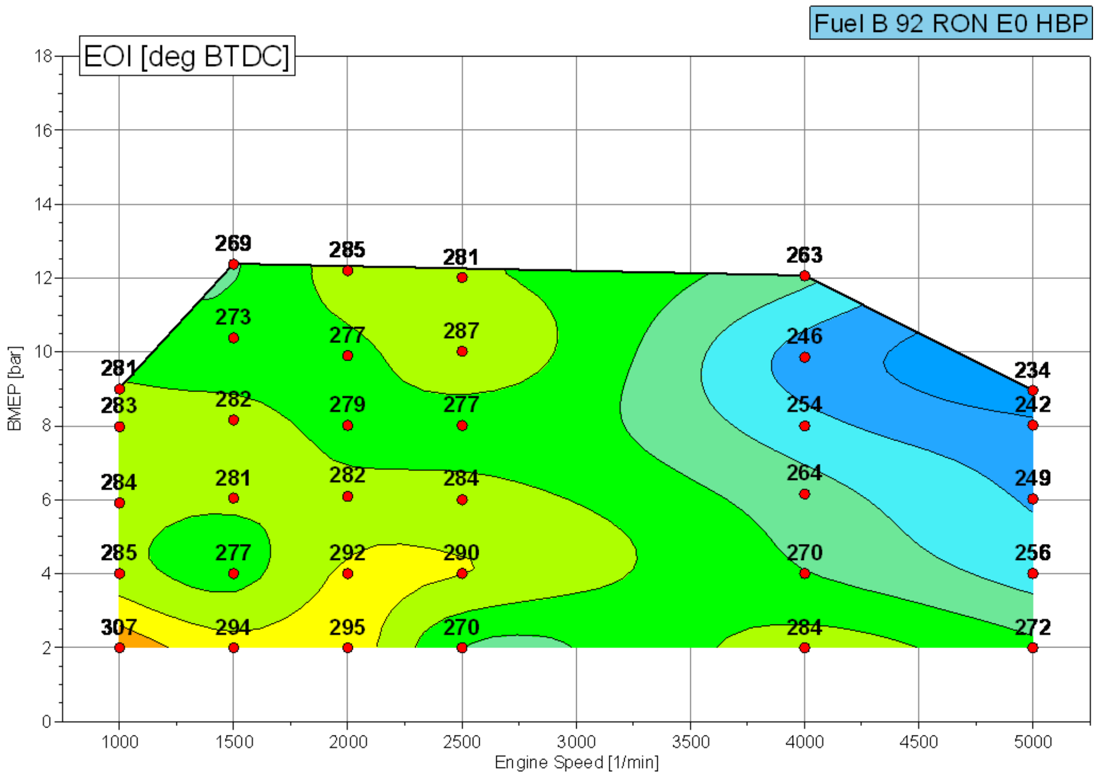

Figure 18: End of Injection

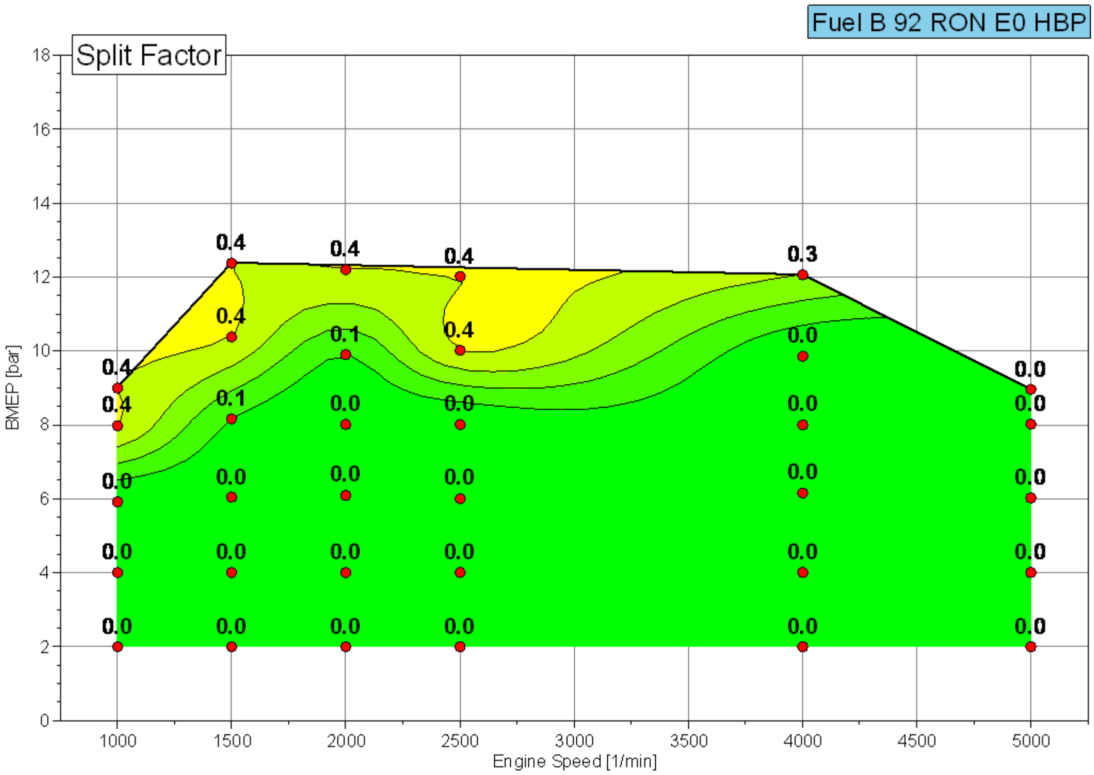

Figure 19: Injection Split Factor

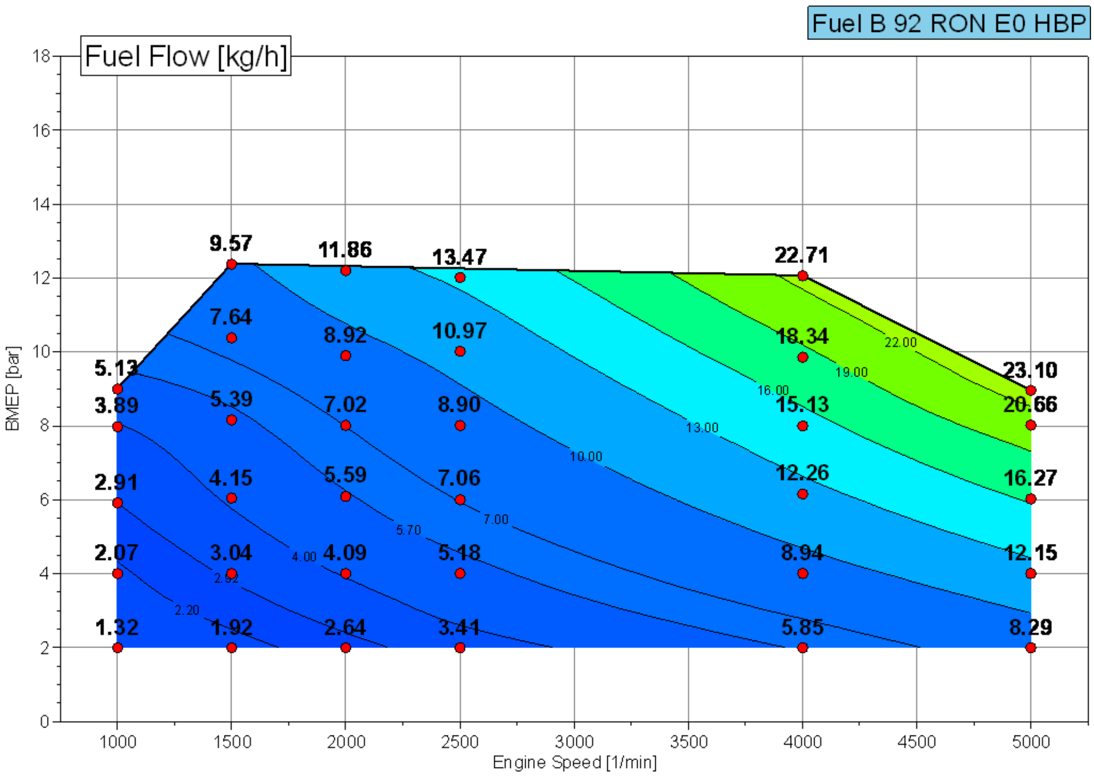

Figure 20: Fuel Flow

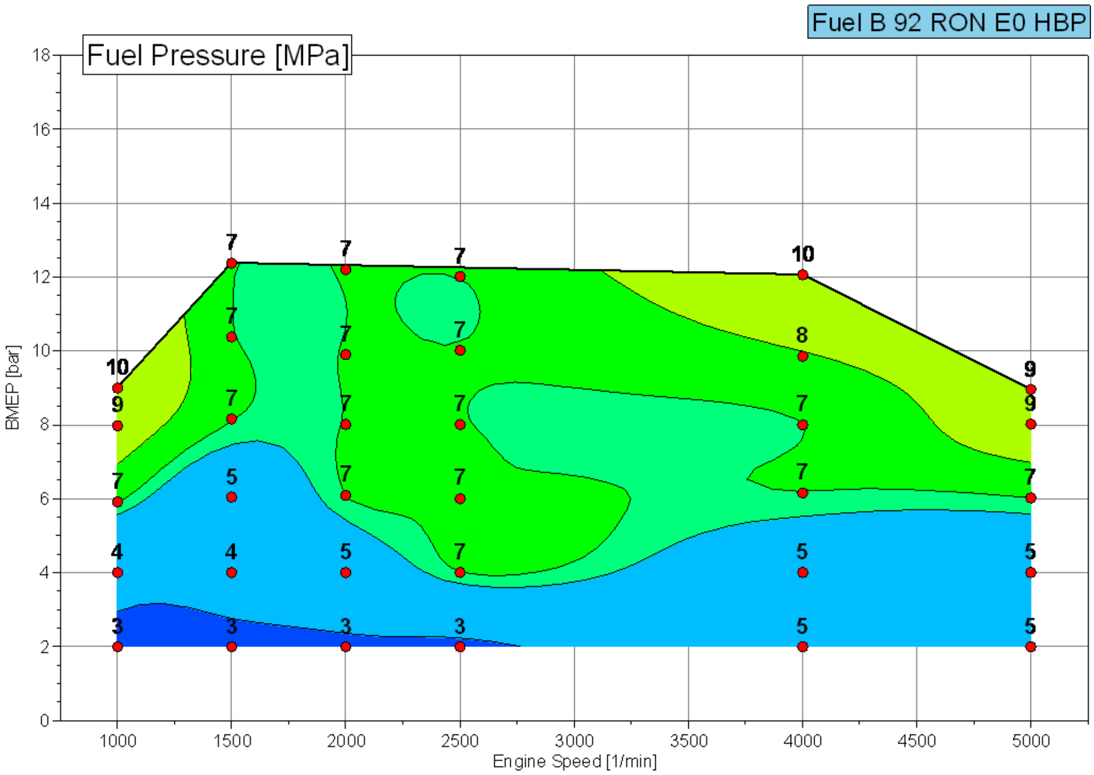

Figure 21: Fuel Rail Pressure

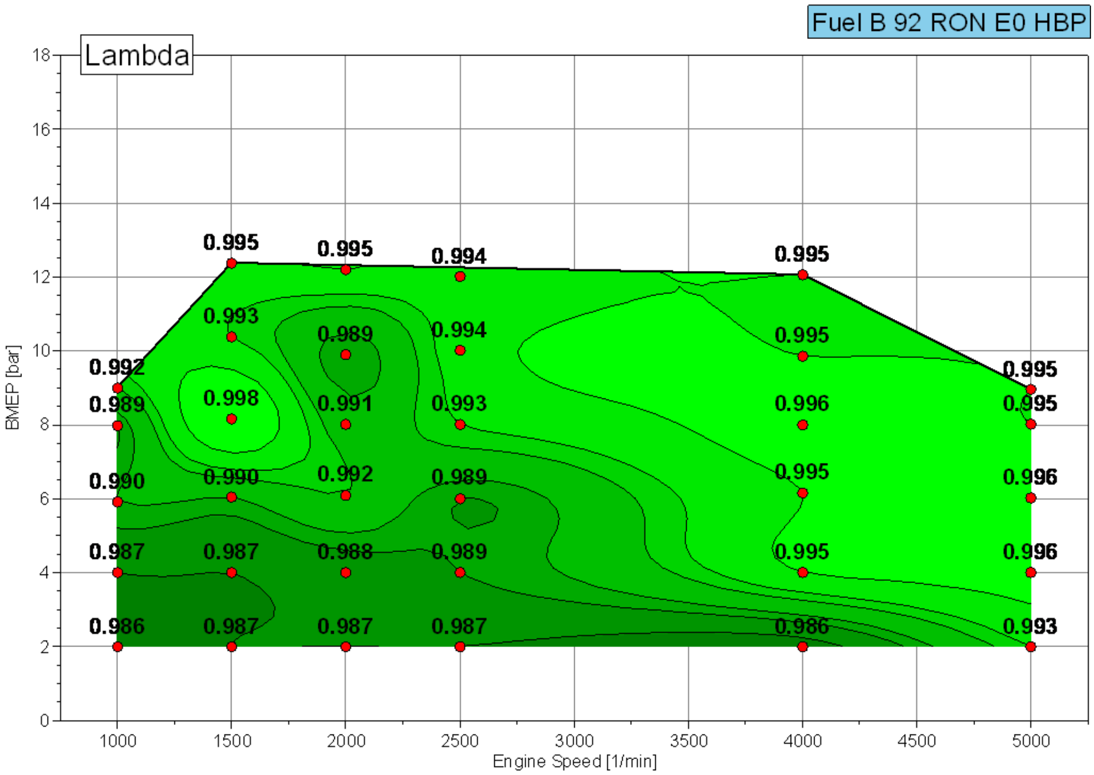

Figure 22: Lambda

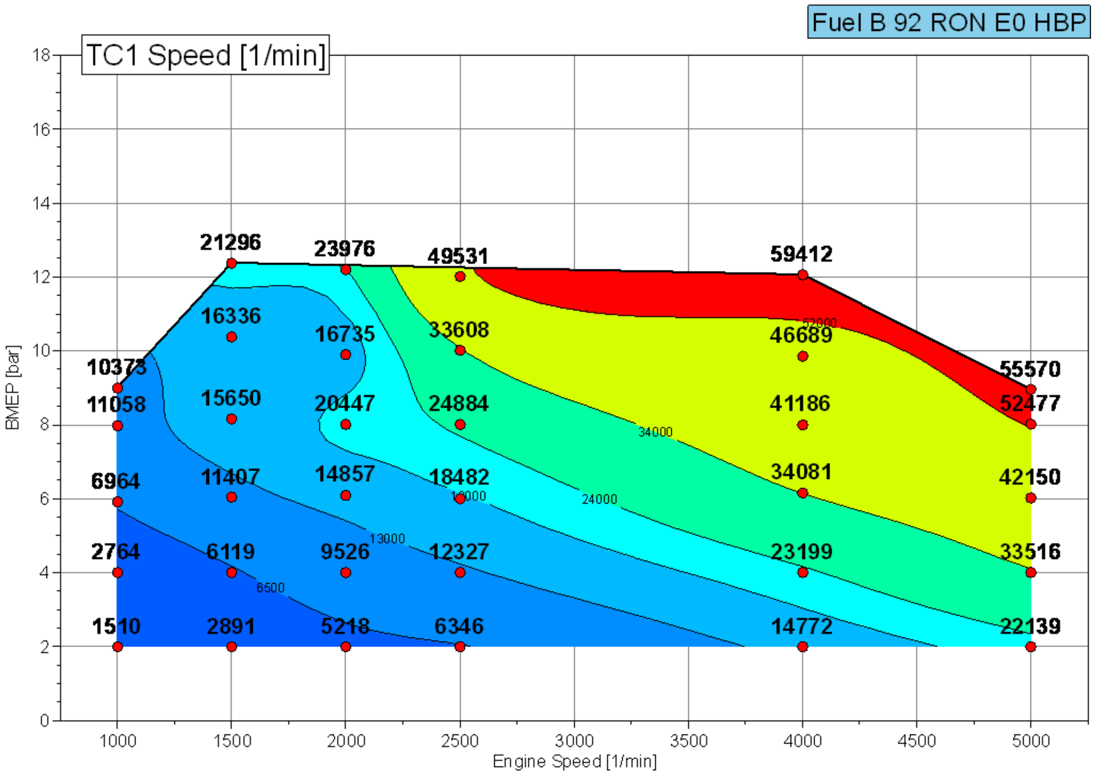

Figure 23: Low Pressure Turbocharger Speed

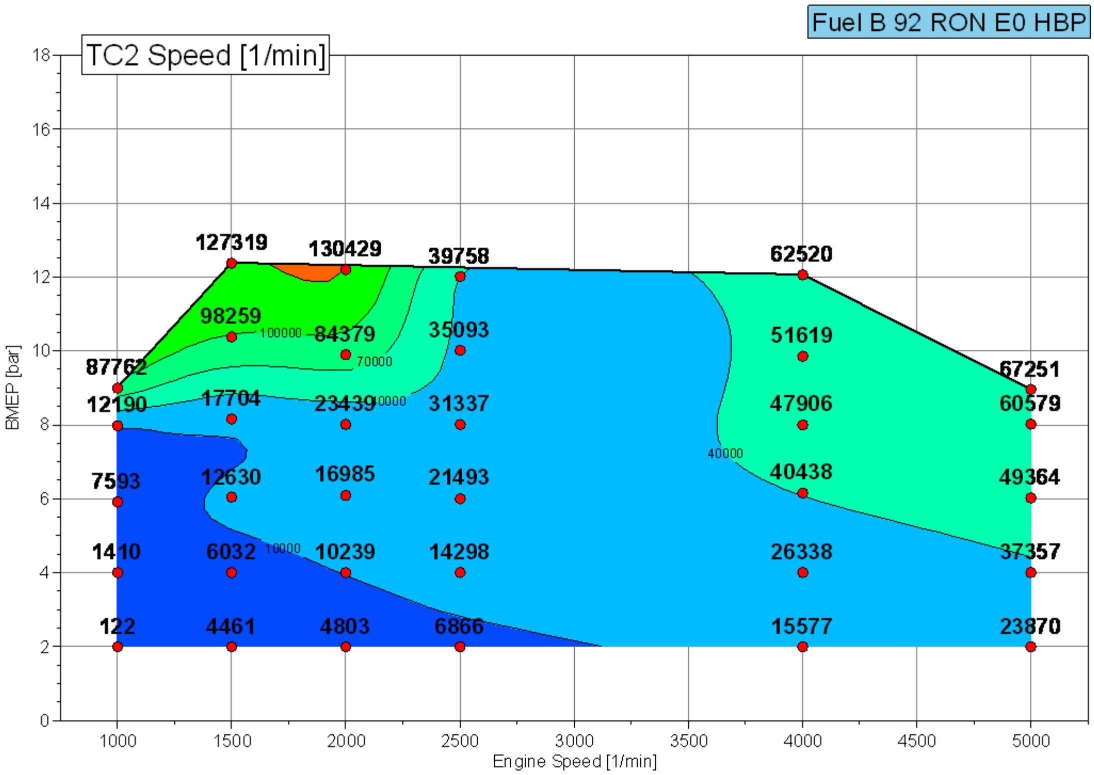

Figure 24: High Pressure Turbocharge Speed

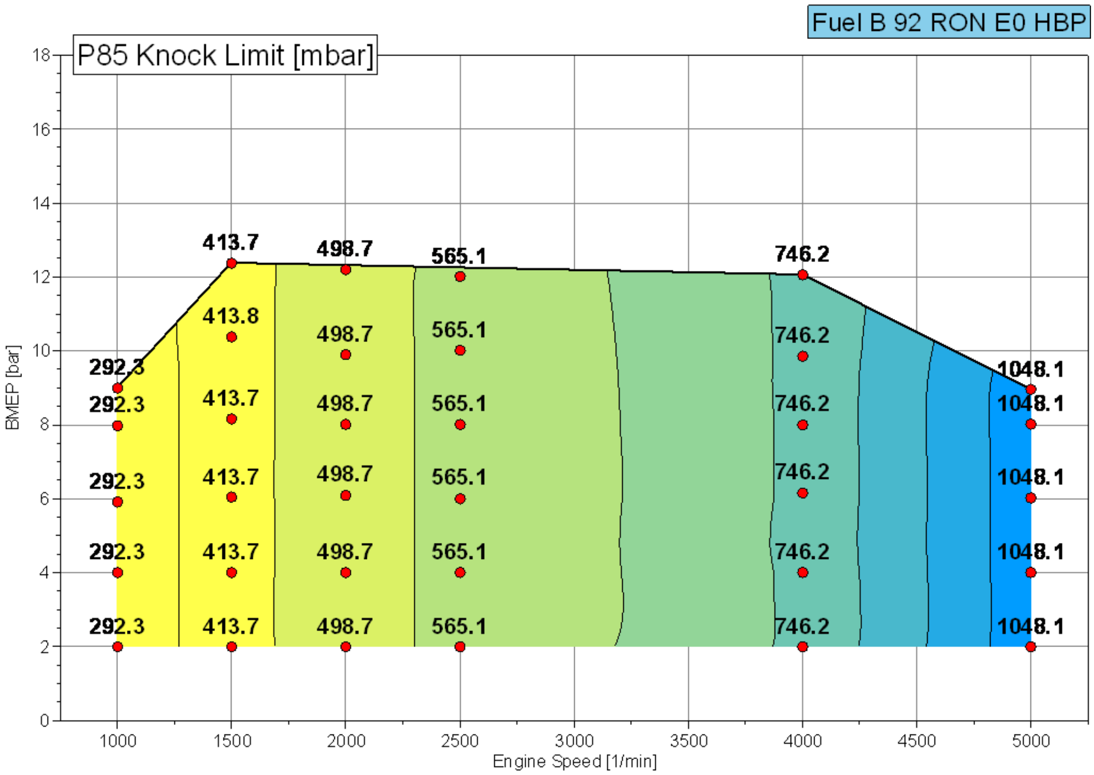

Figure 25: P85 Knock Limit

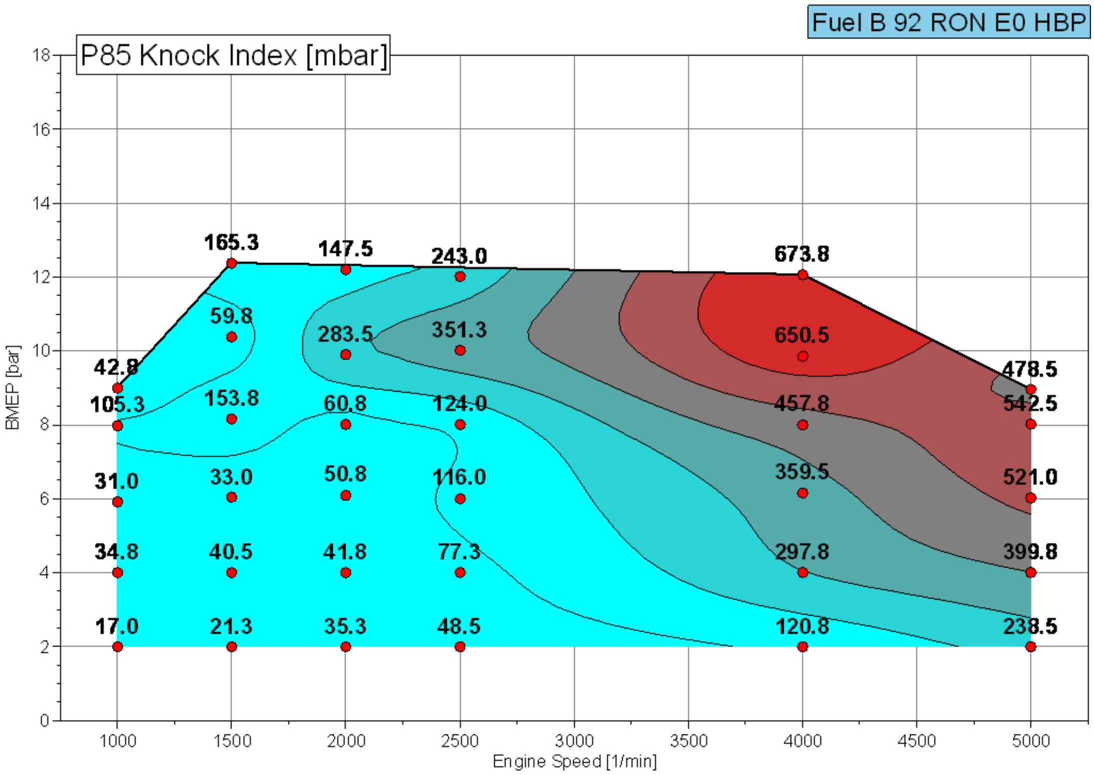

Figure 26: Averaged P85 Knock Index

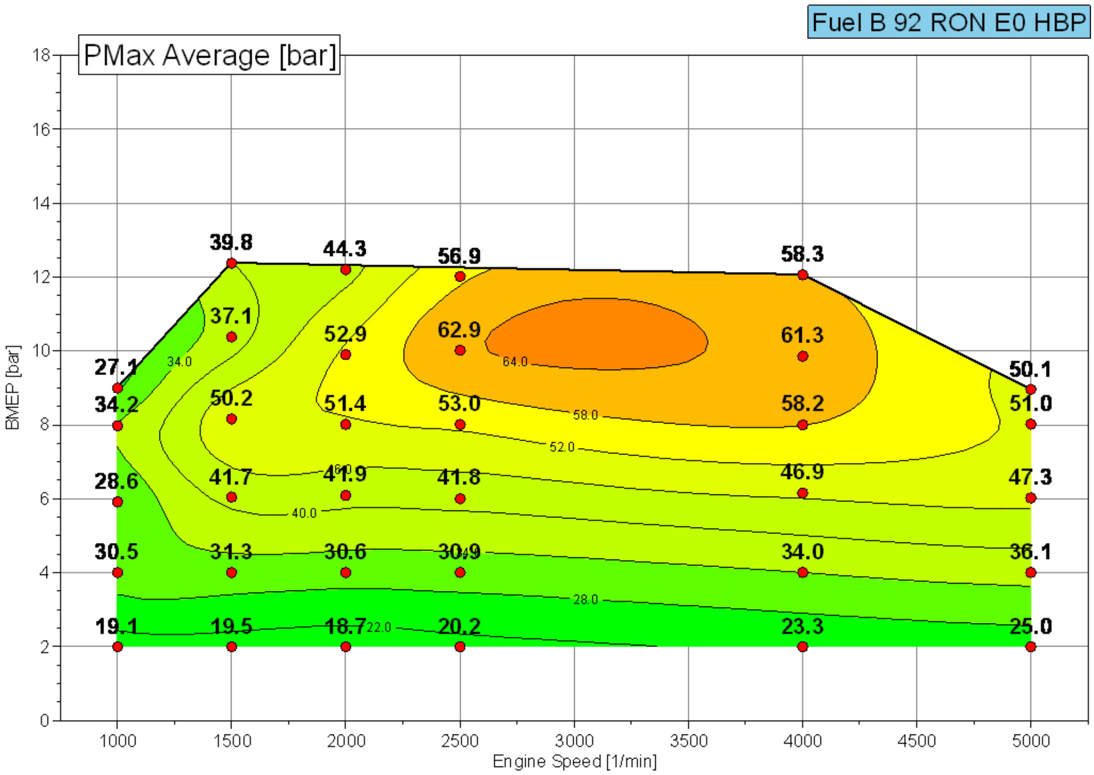

Figure 27: Averaged Max Pressure for Cylinders 1-4

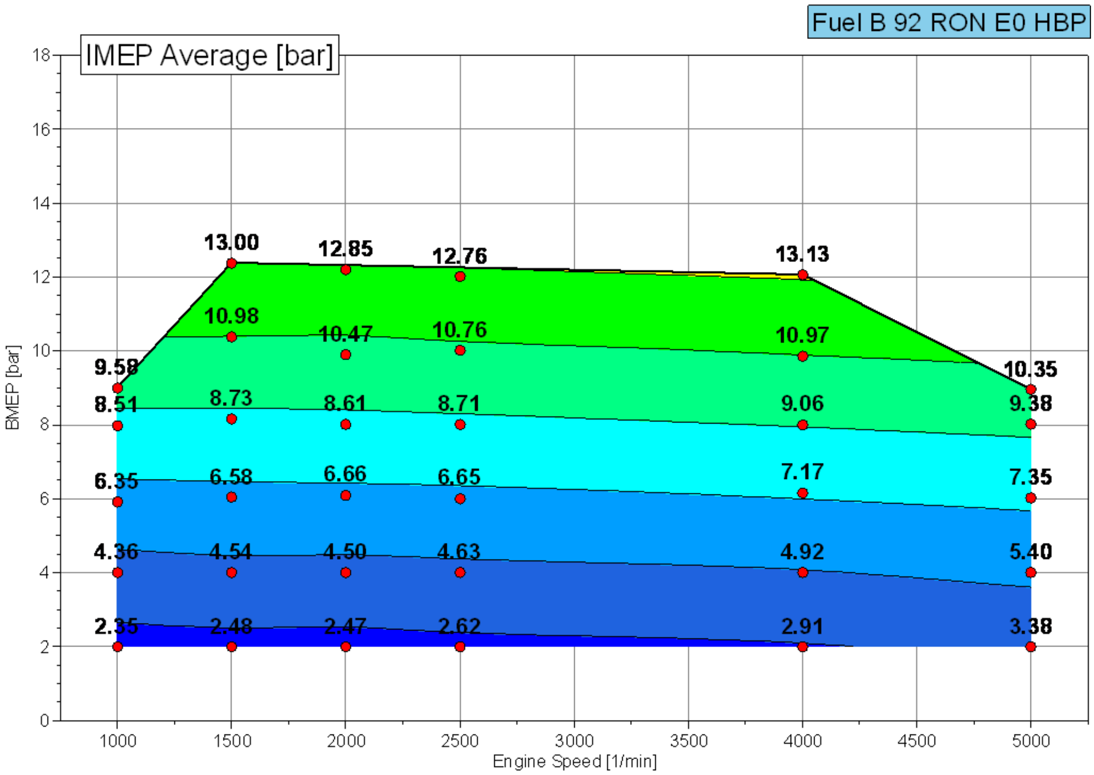

Figure 28: Indicated Mean Effective Pressure

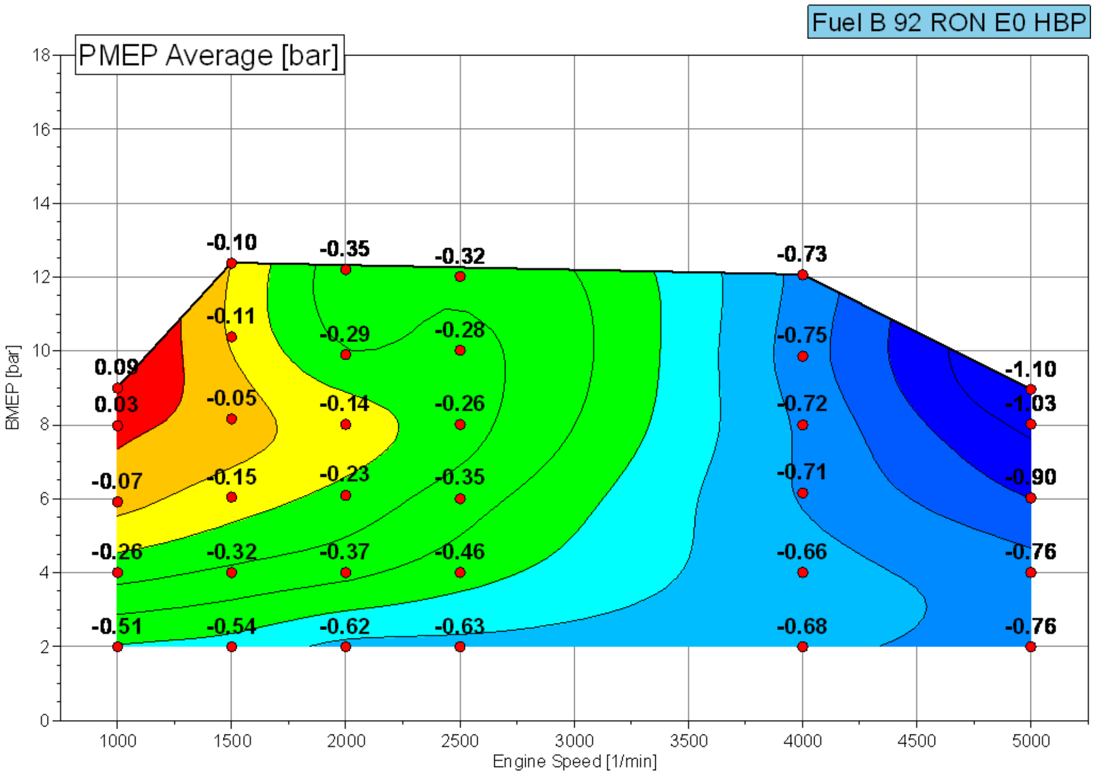

Figure 29: Pumping Mean Effective Pressure

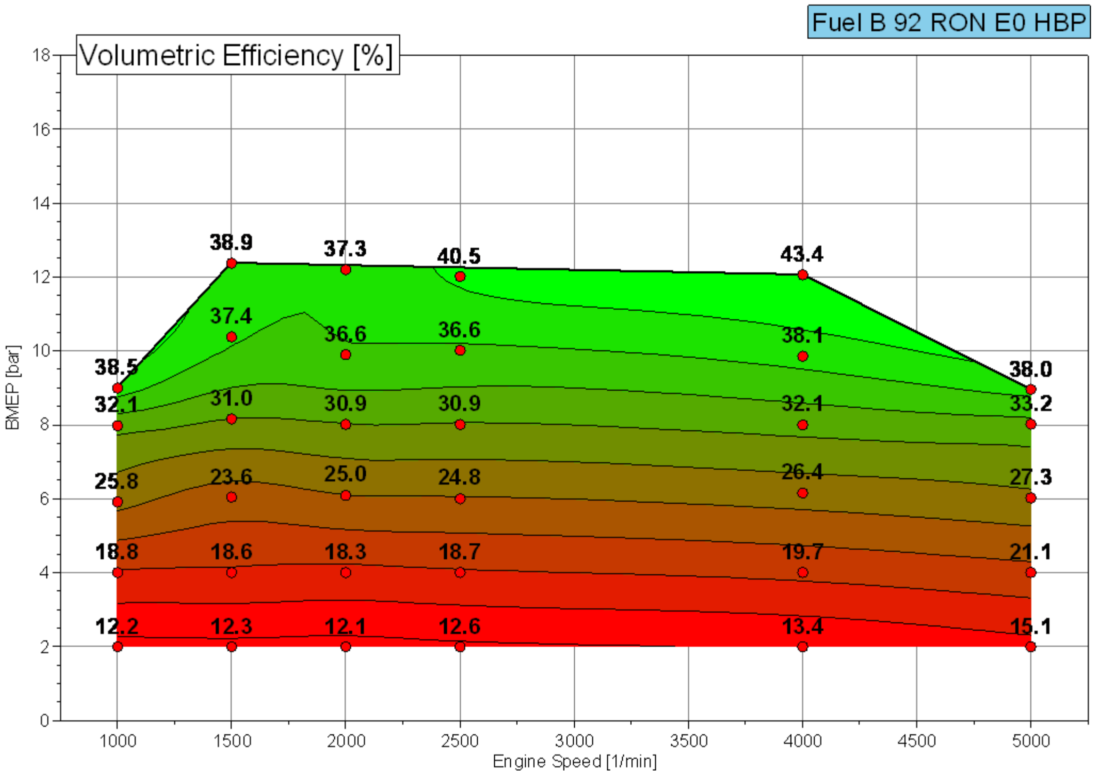

Figure 30: Calculated Volumetric Efficiency

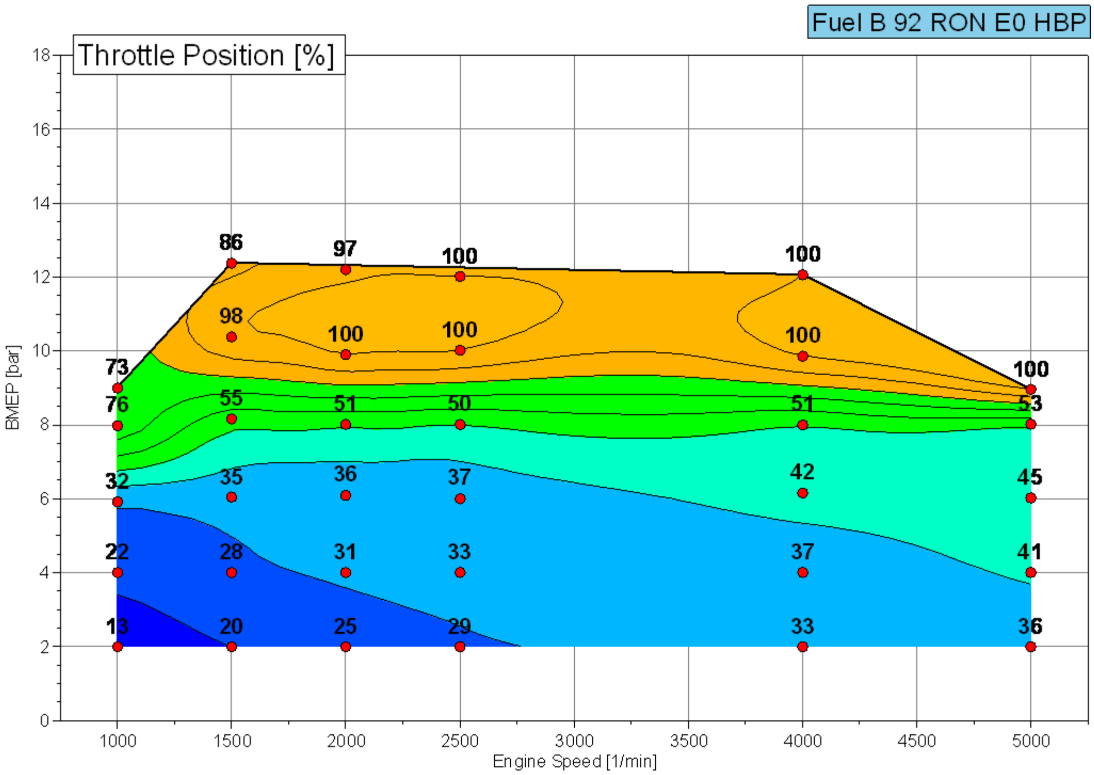

Figure 31: Throttle Position

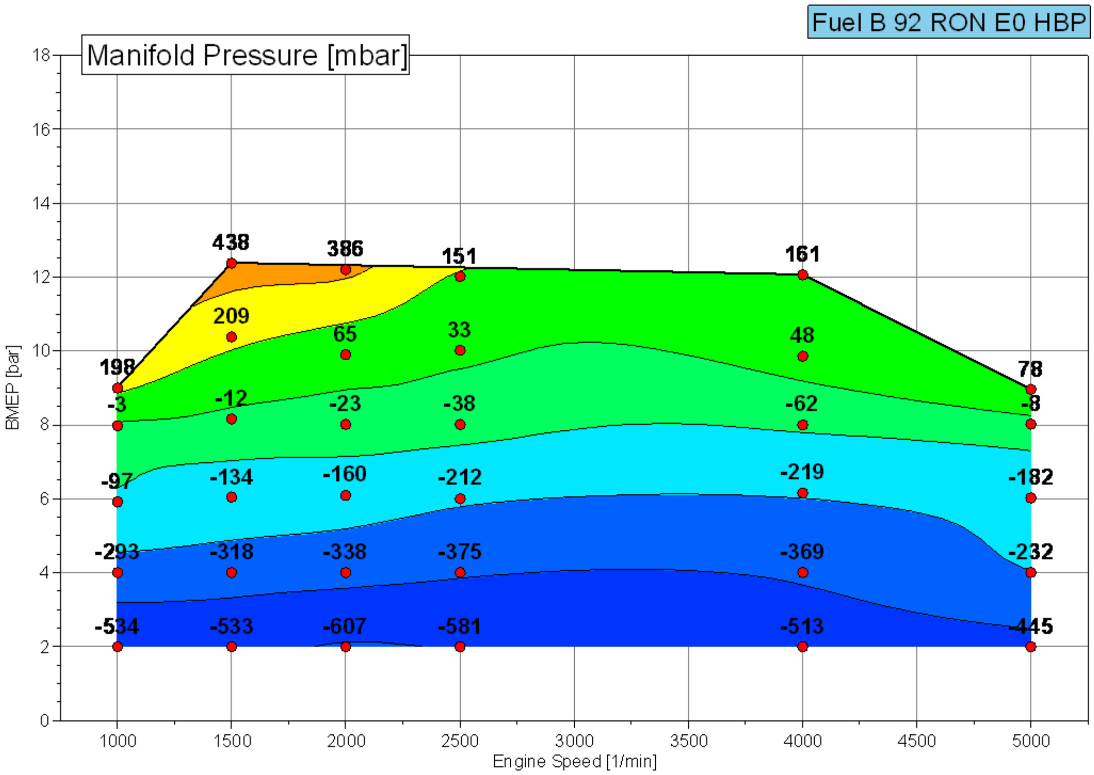

Figure 32: Intake Manifold Pressure

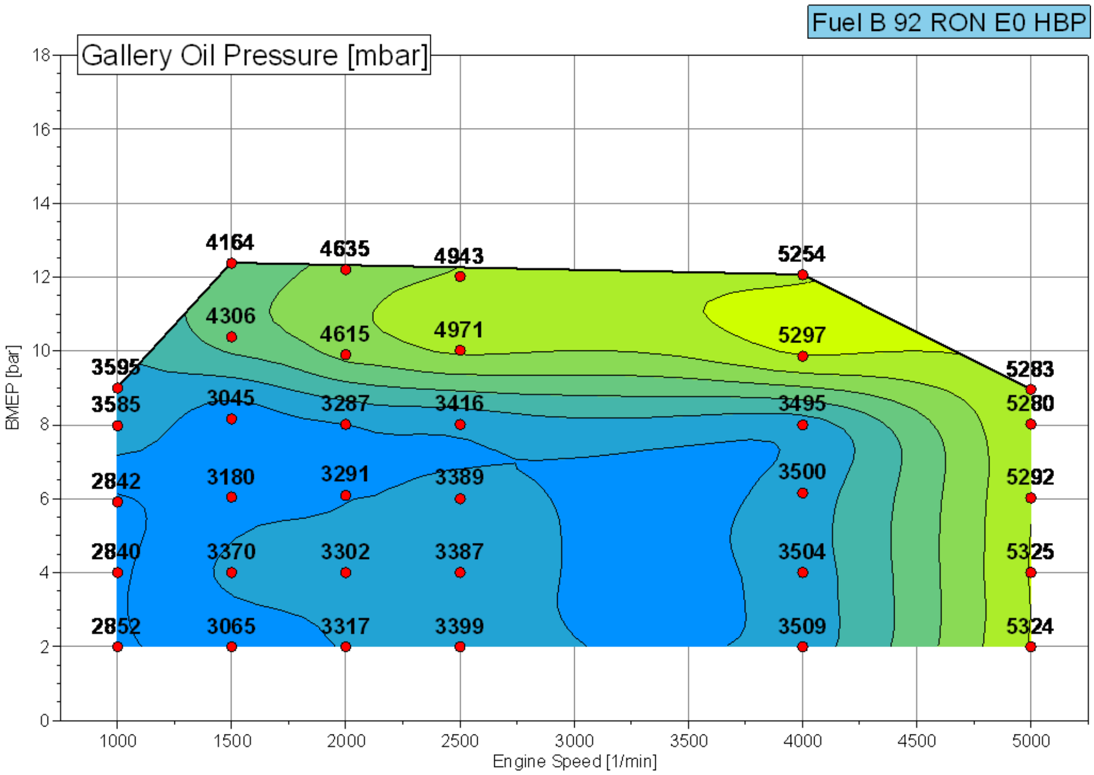

Figure 33: Gallery Oil Pressure

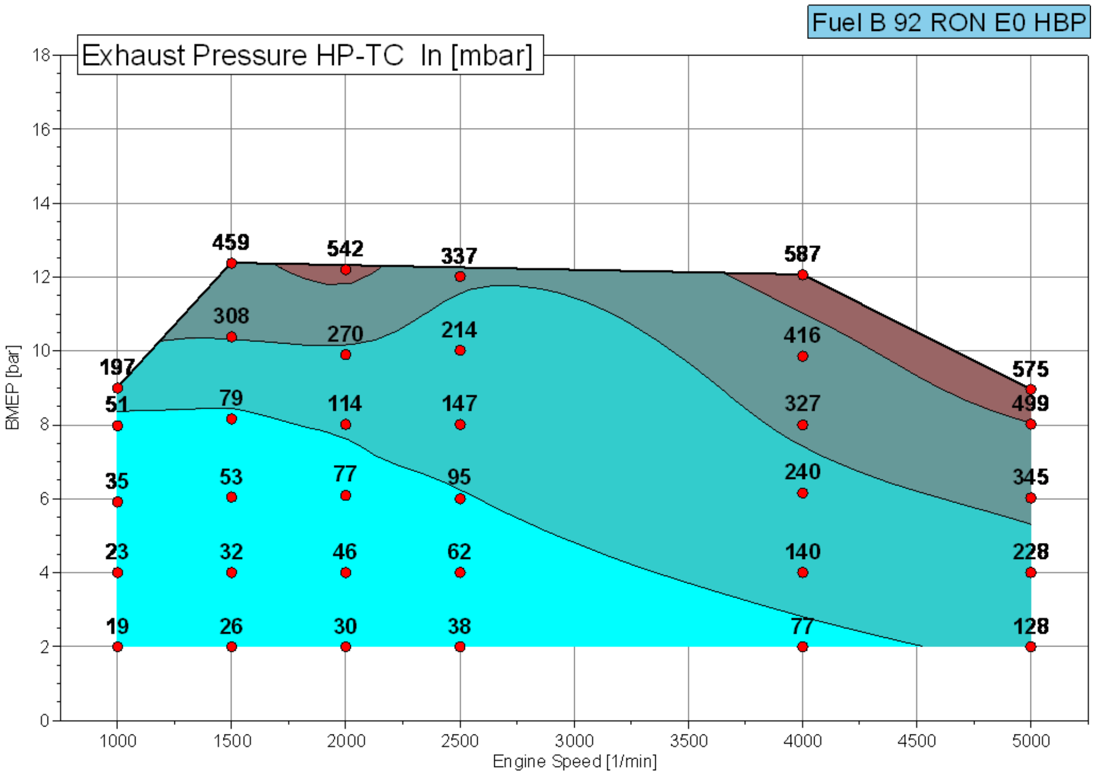

Figure 34: Exhaust Pressure High Pressure Turbocharger In

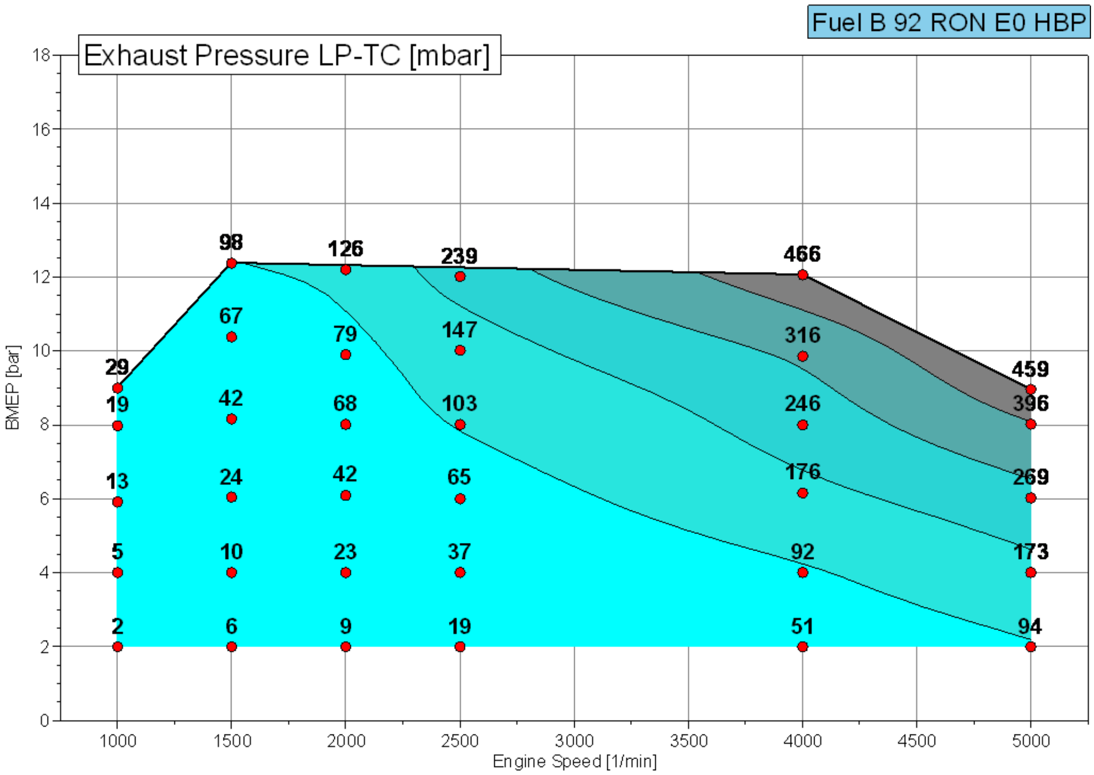

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

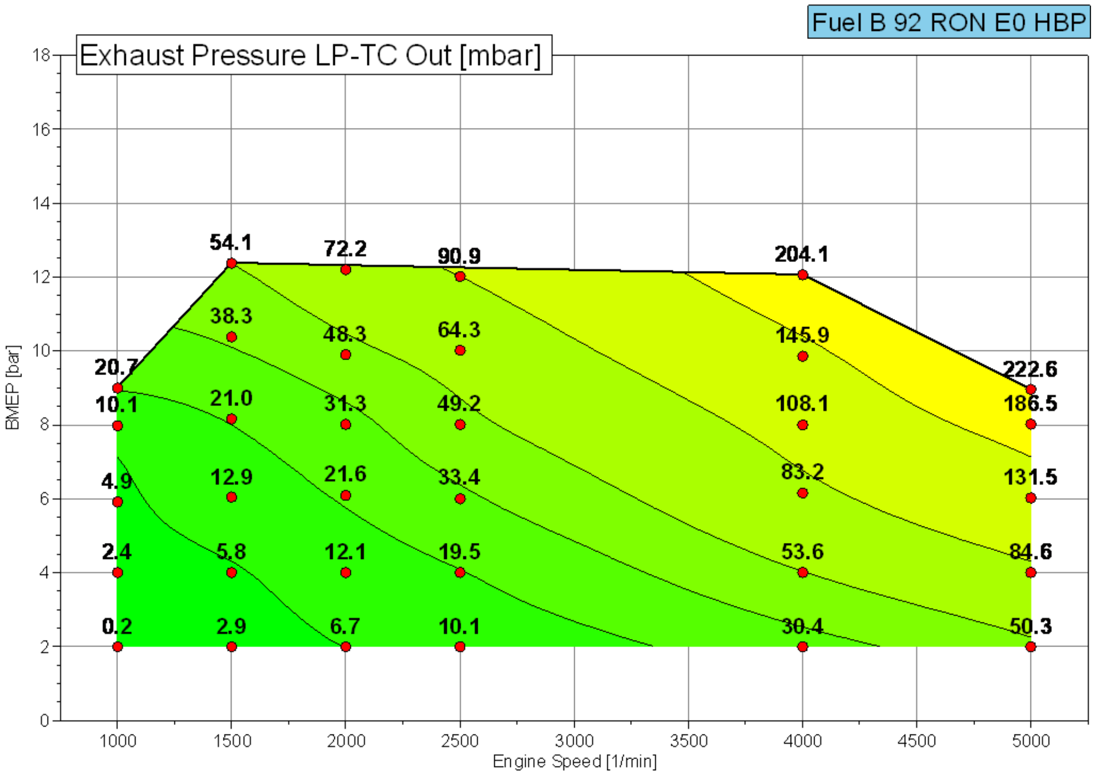

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

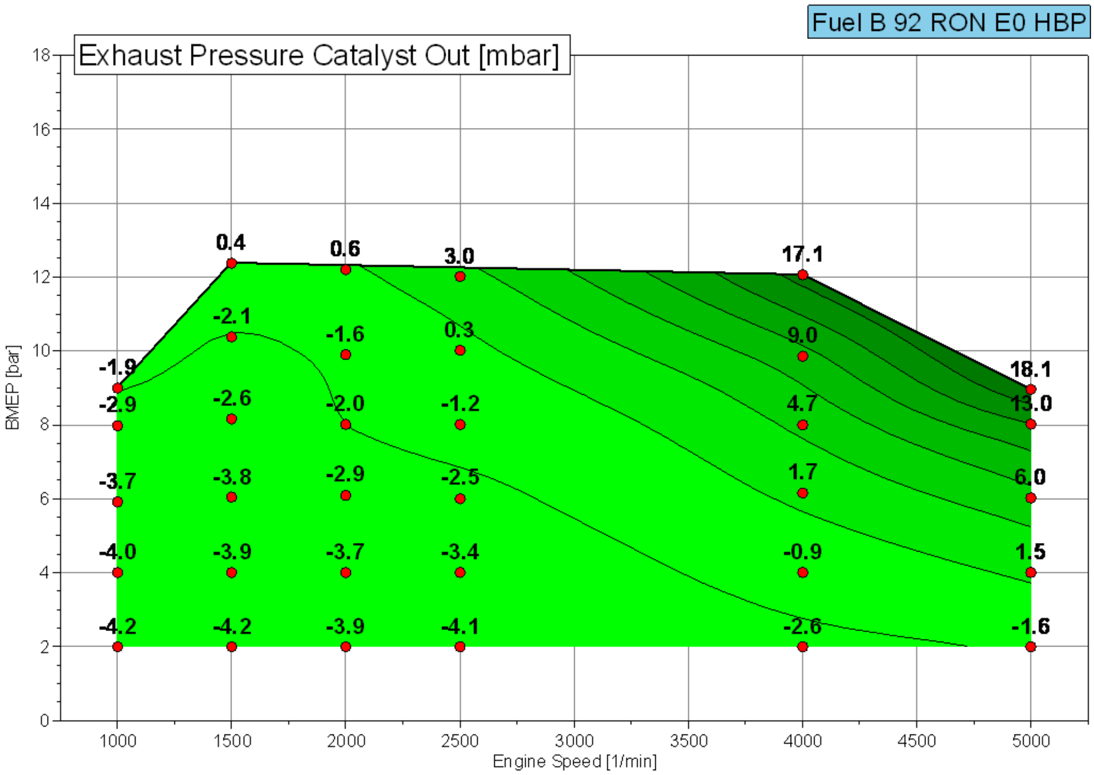

Figure 37: Exhaust Pressure Catalyst Out

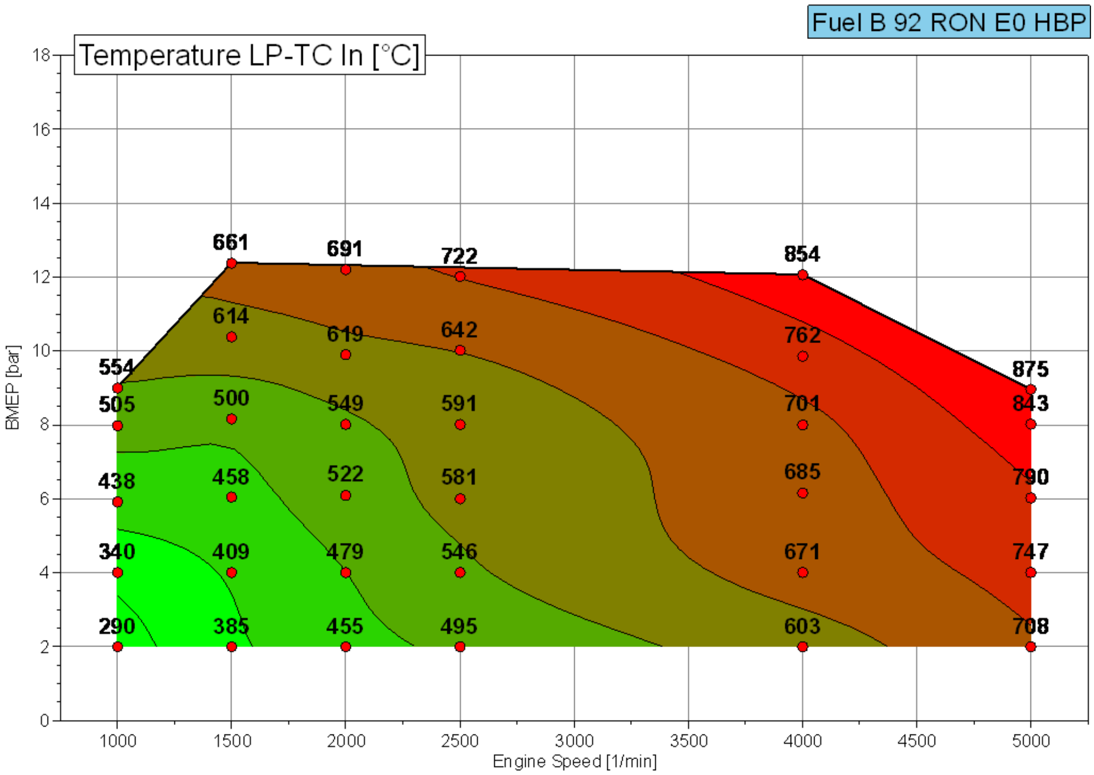

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

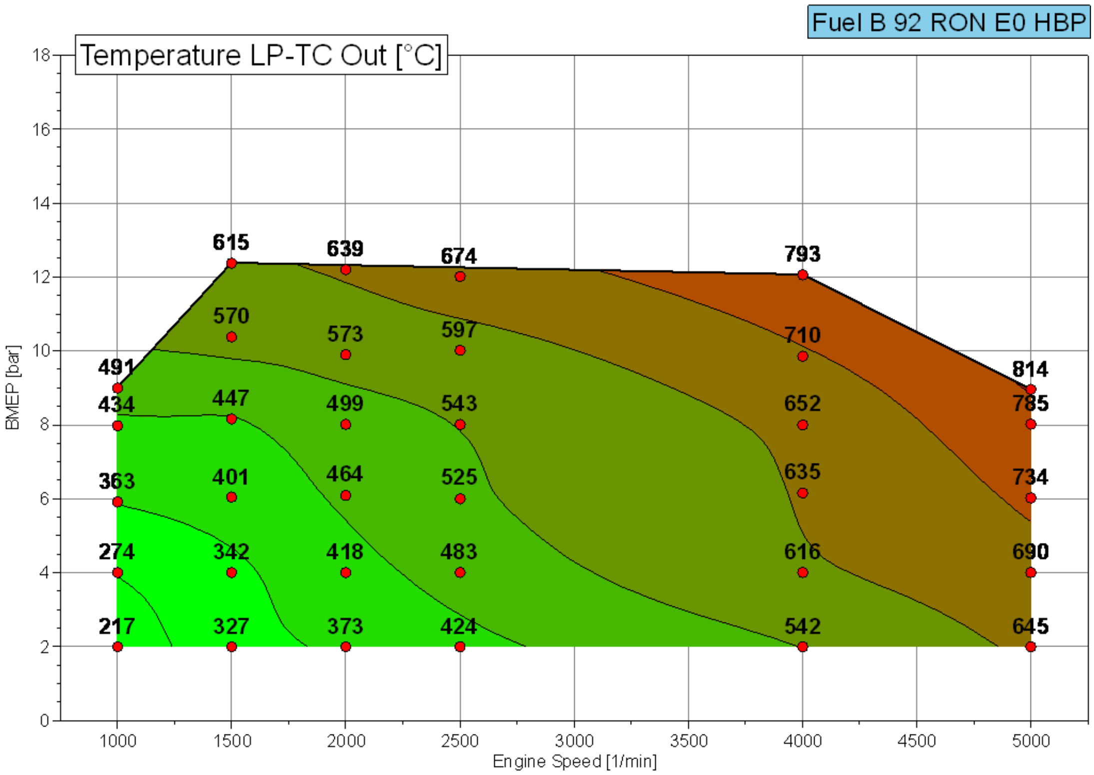

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

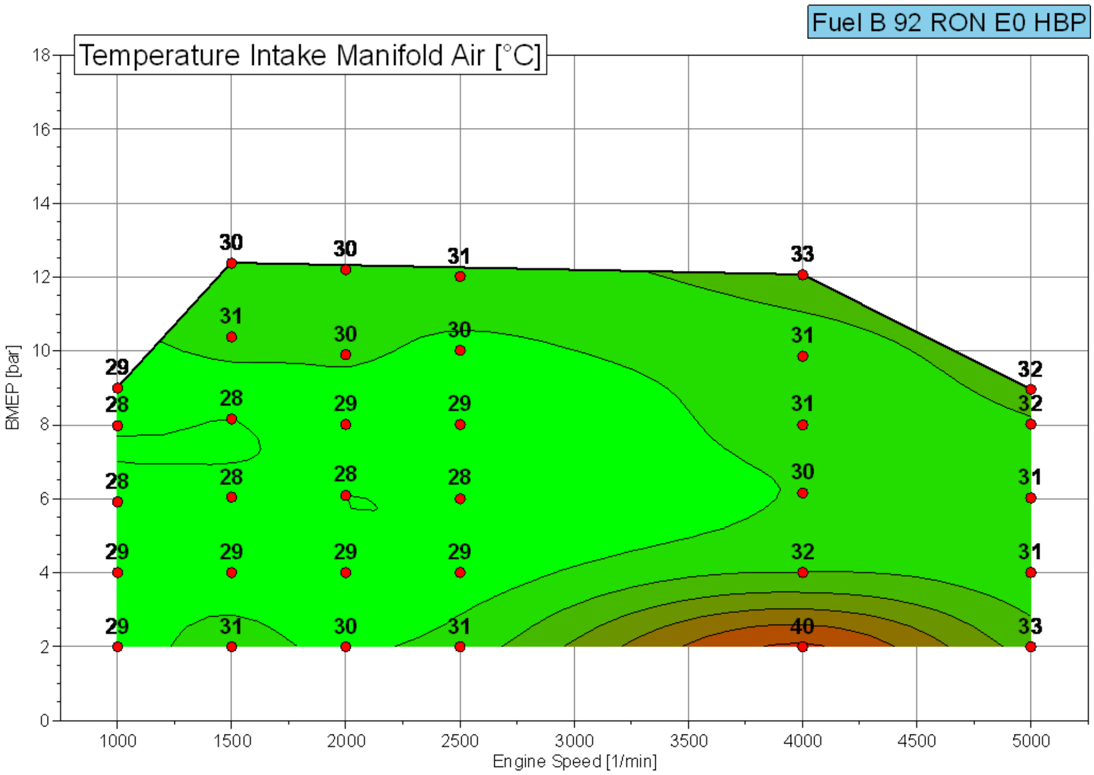

Figure 40: Intake Manifold Air Temperature

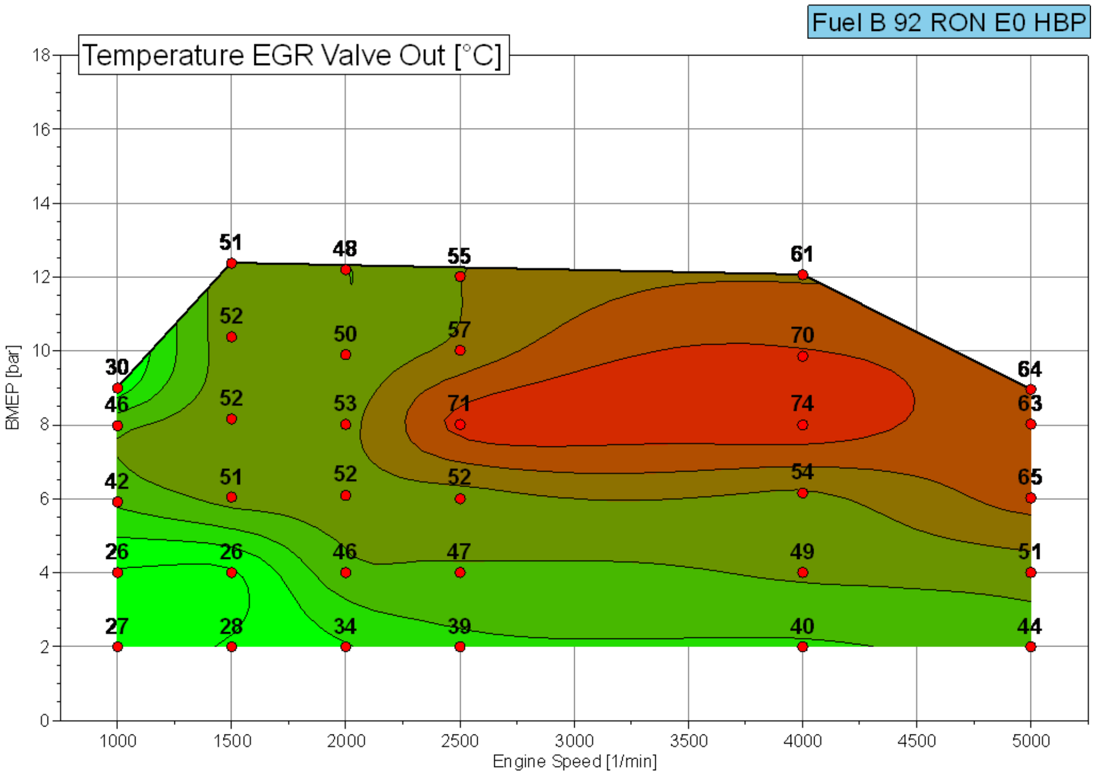

Figure 41: EGR Valve Out Temperature

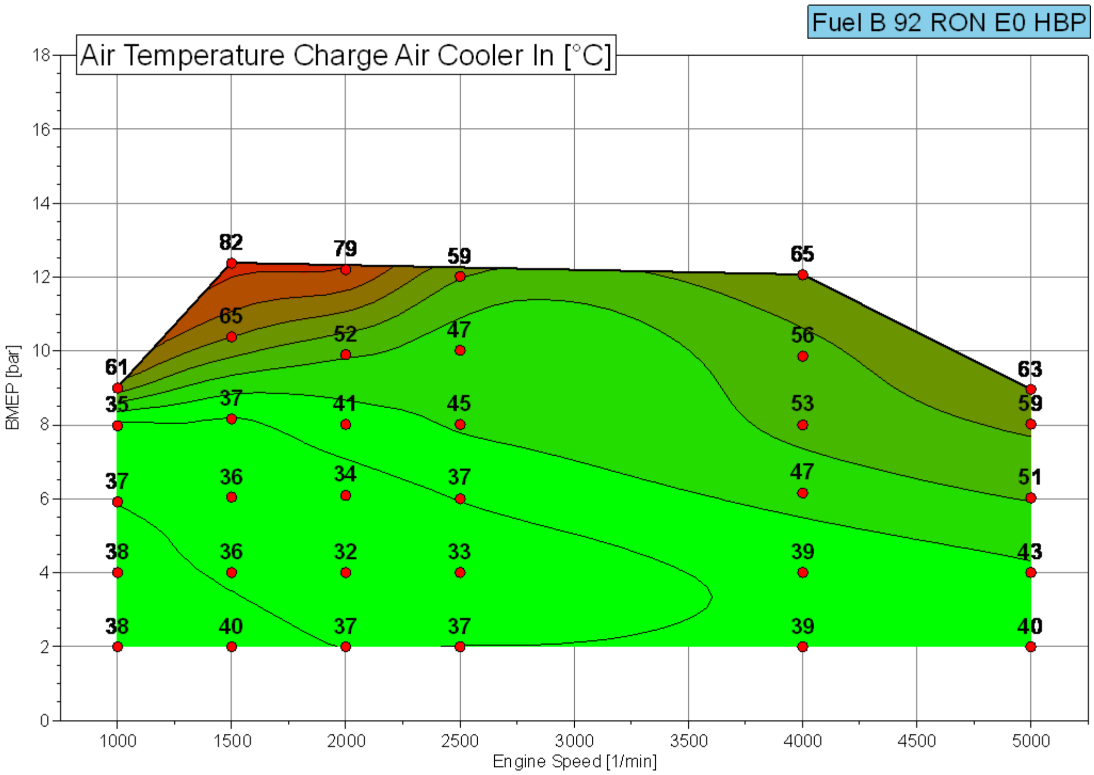

Figure 42: Charge Air Cooler Inlet Air Temperature

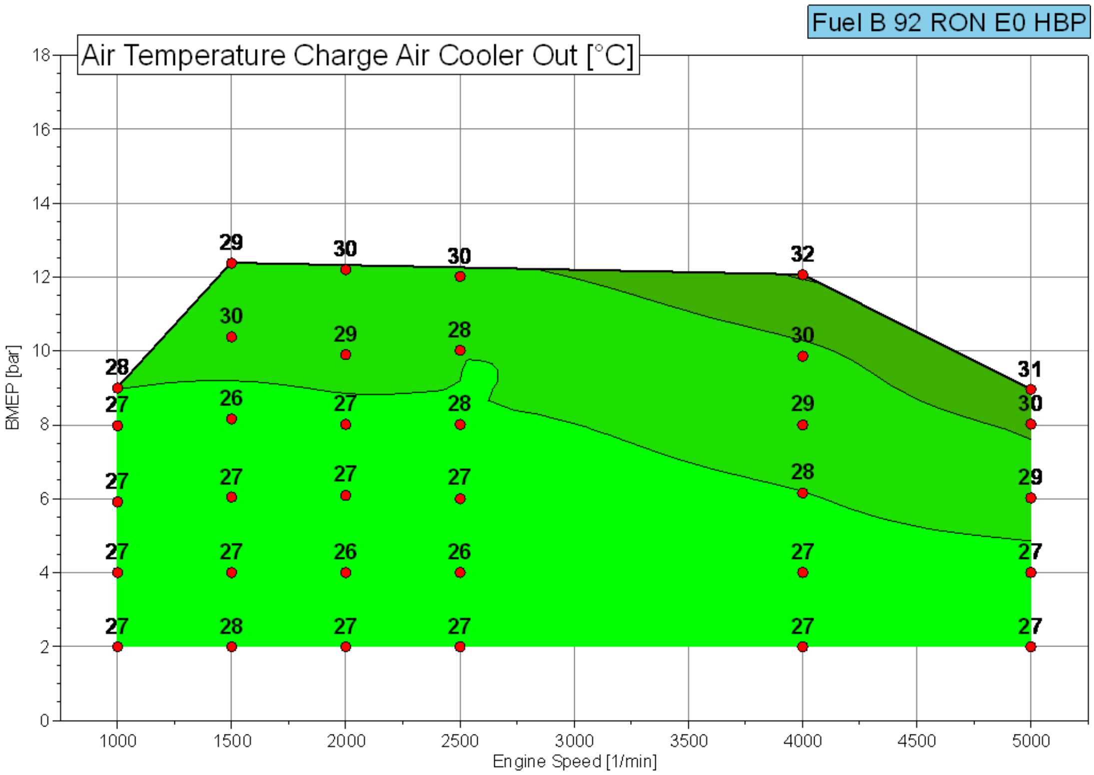

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel A Calibration Results

92 Ron 0% Ethanol Low Boiling Point

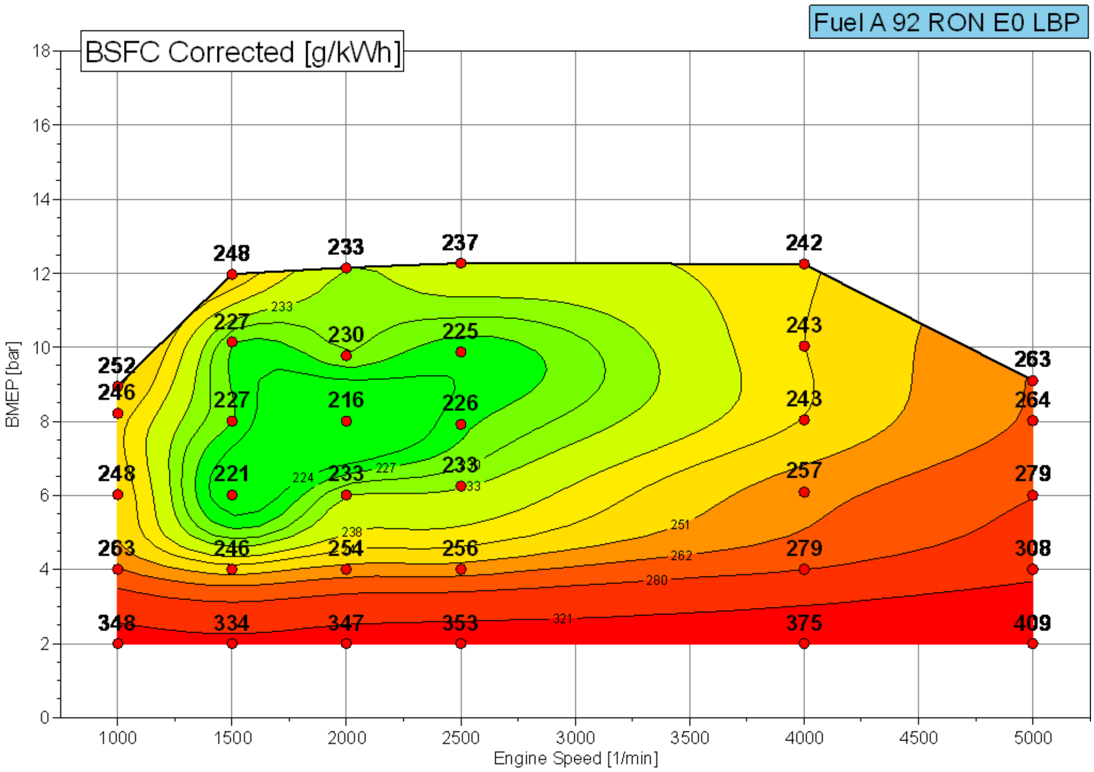

Figure 1: Brake Specific Fuel Consumption

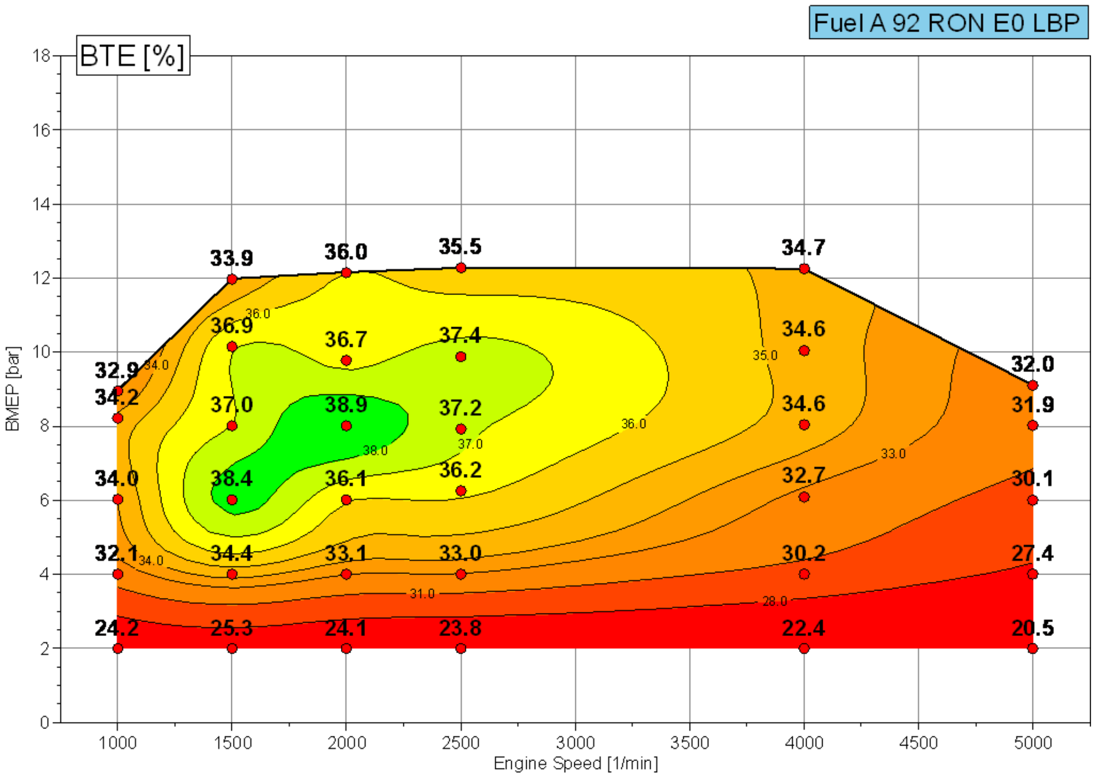

Figure 2: Brake Thermal Efficiency

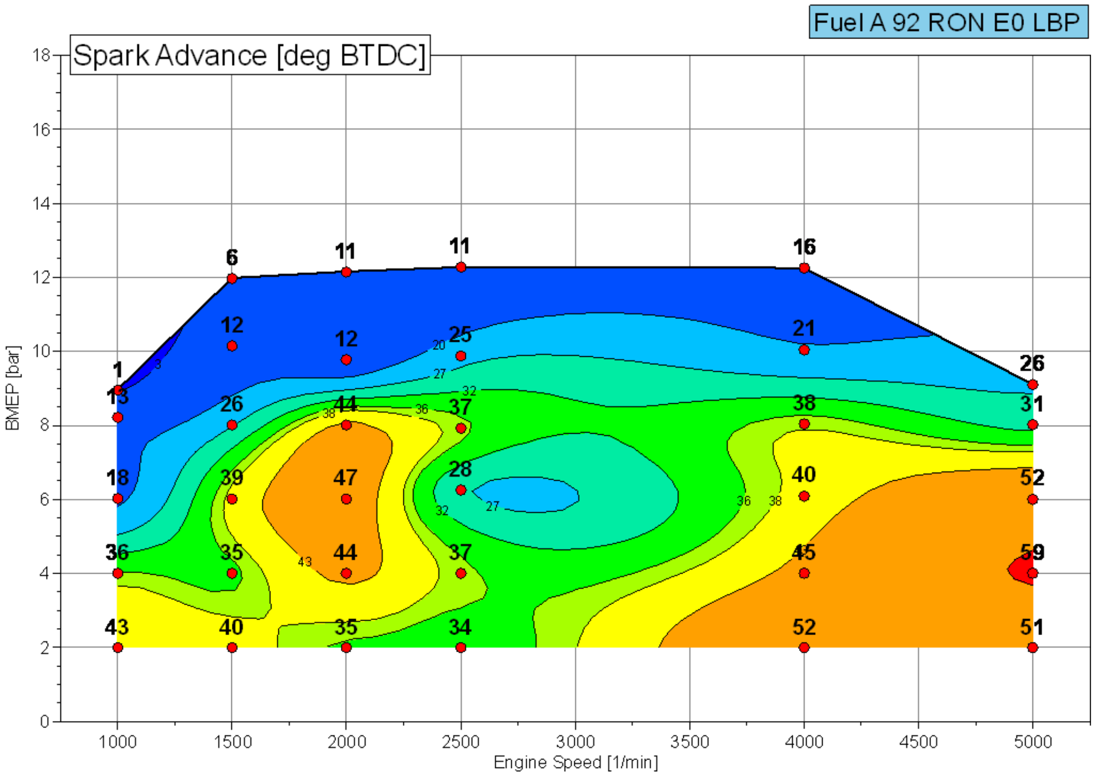

Figure 3: Spark Advance

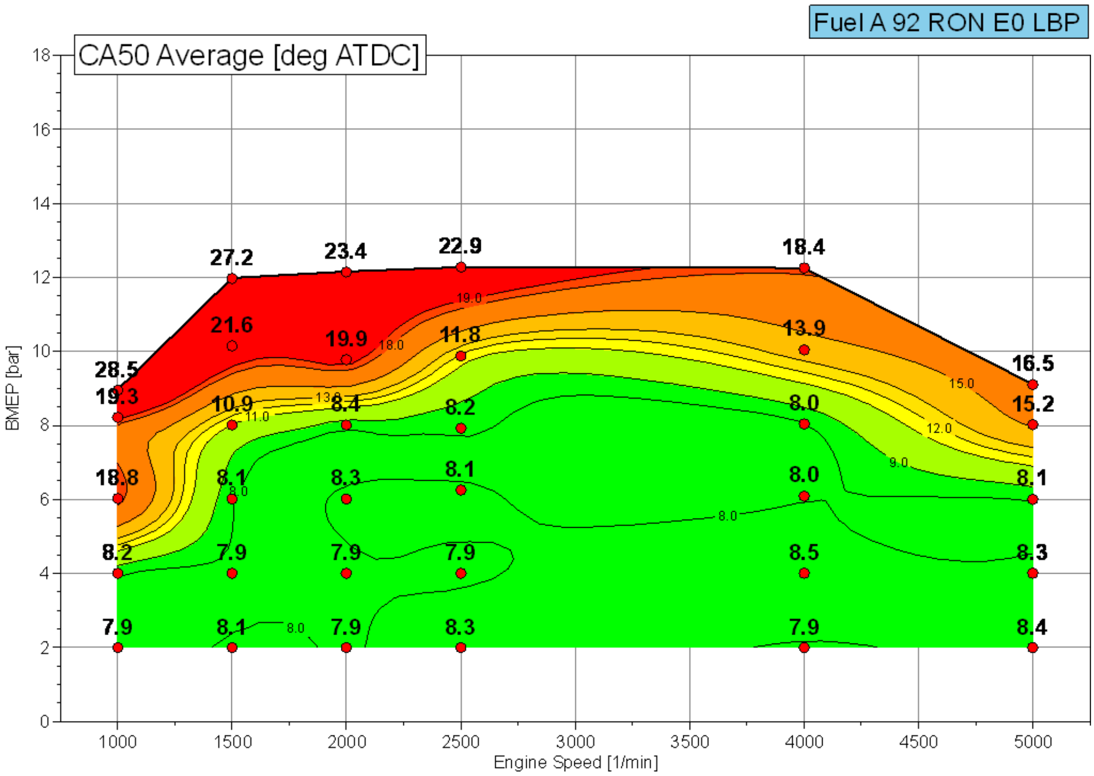

Figure 4: CA50 Average of Cylinders 1-4

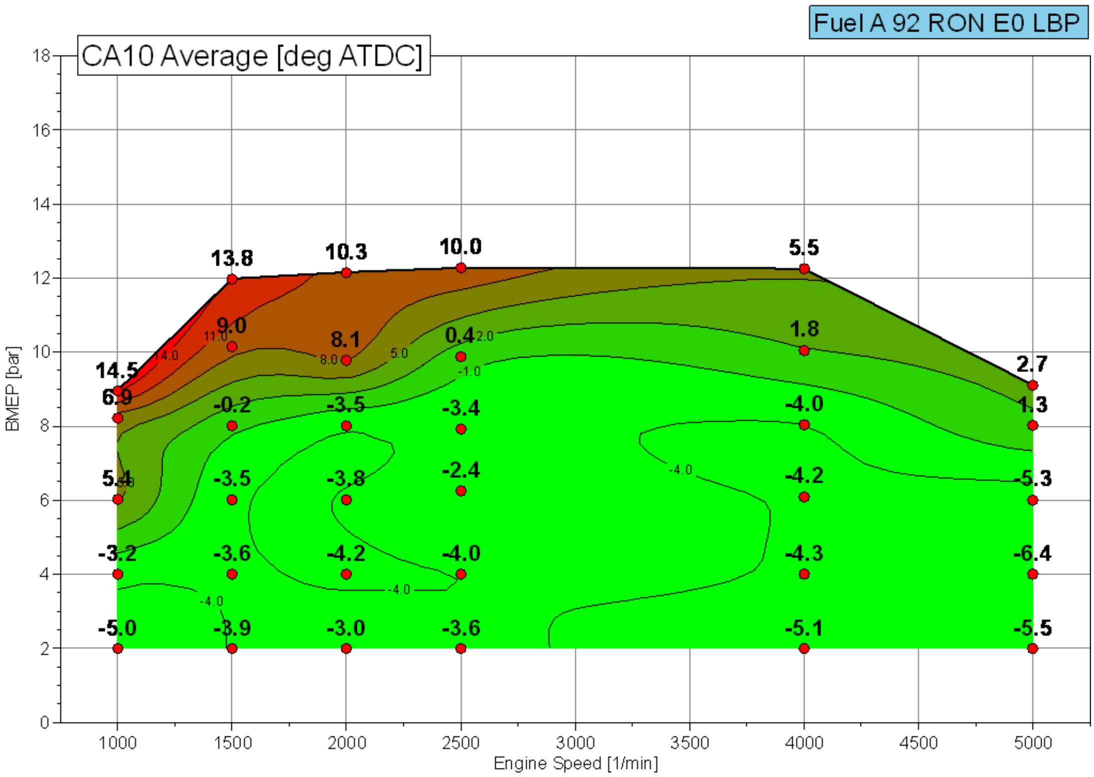

Figure 5: CA10 Average of Cylinders 1-4

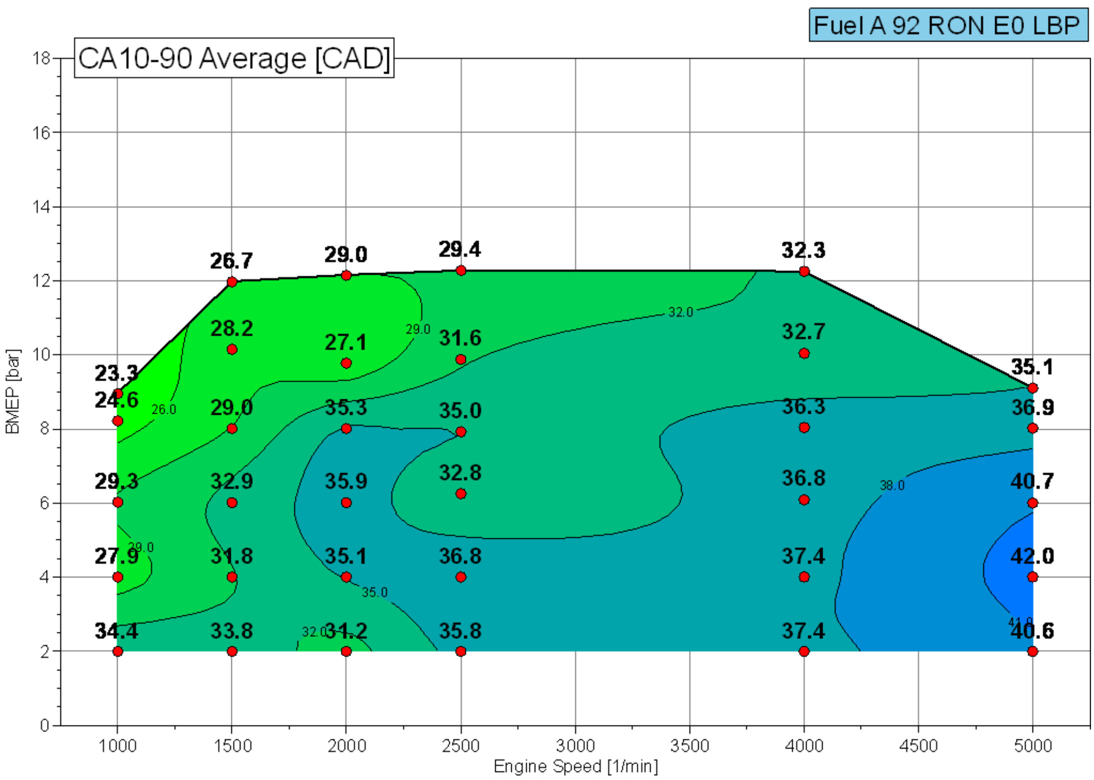

Figure 6: CA10-90 Average of Cylinders 1-4

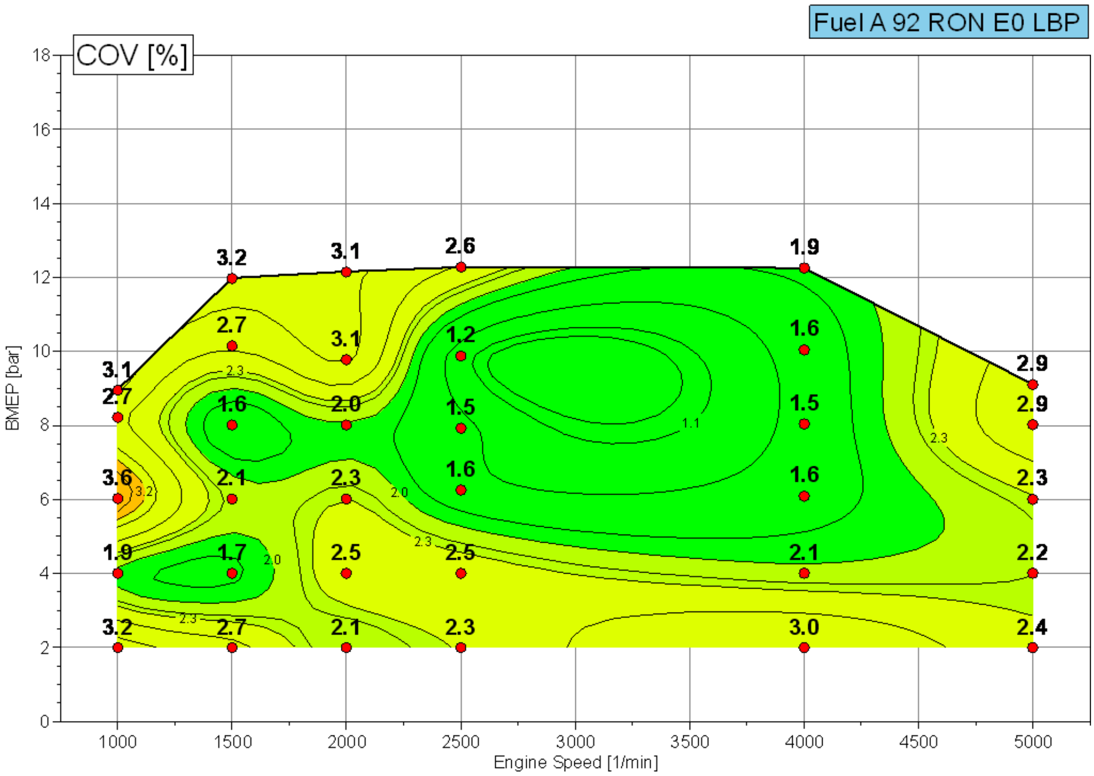

Figure 7: Coefficient of Variation Average of Cylinders 1-4

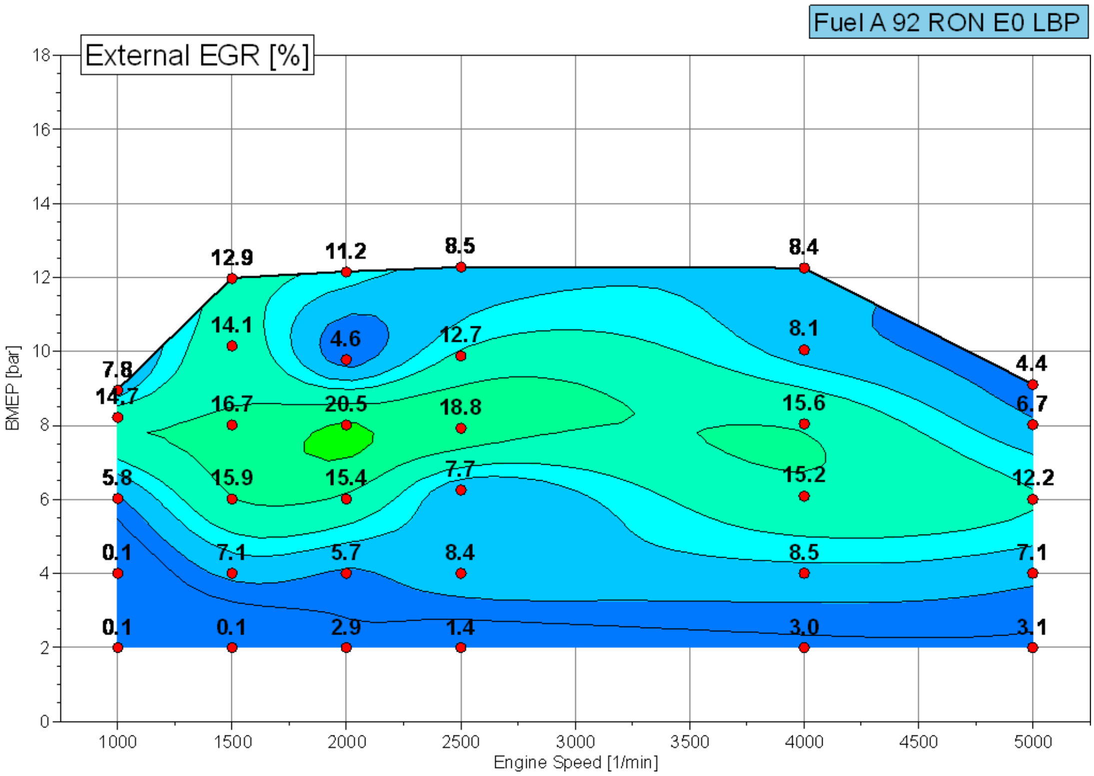

Figure 8: External EGR Percent of Intake Air

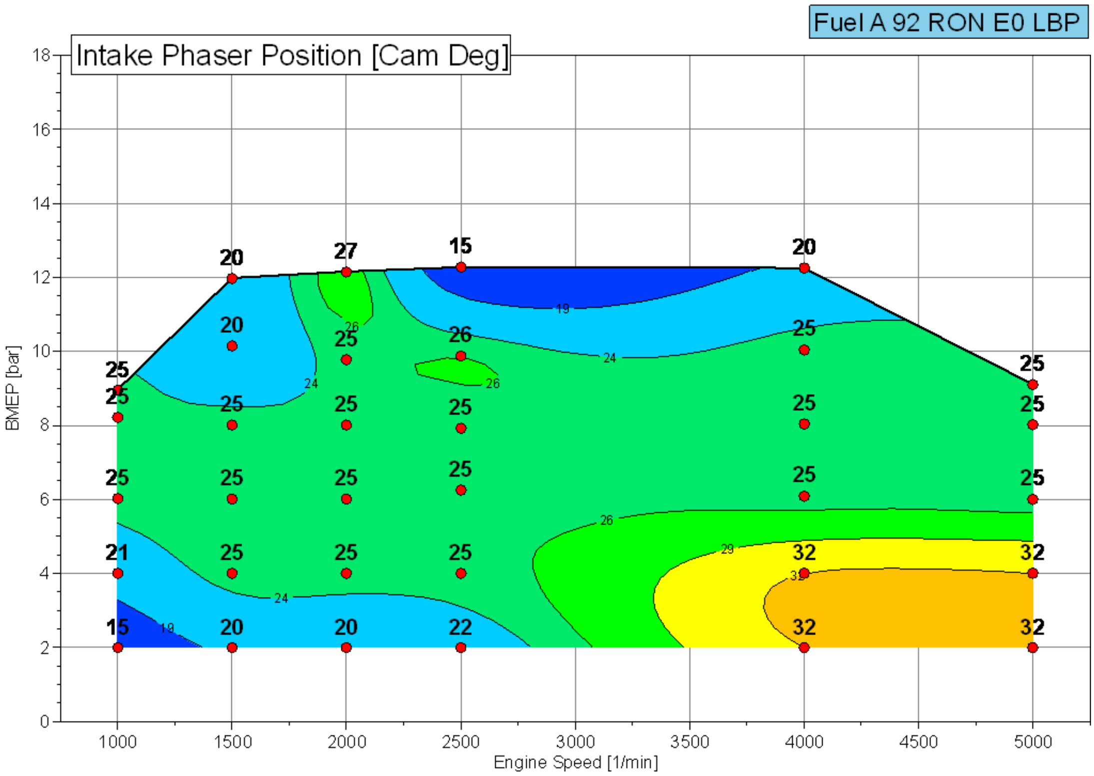

Figure 9: Intake Camshaft Position

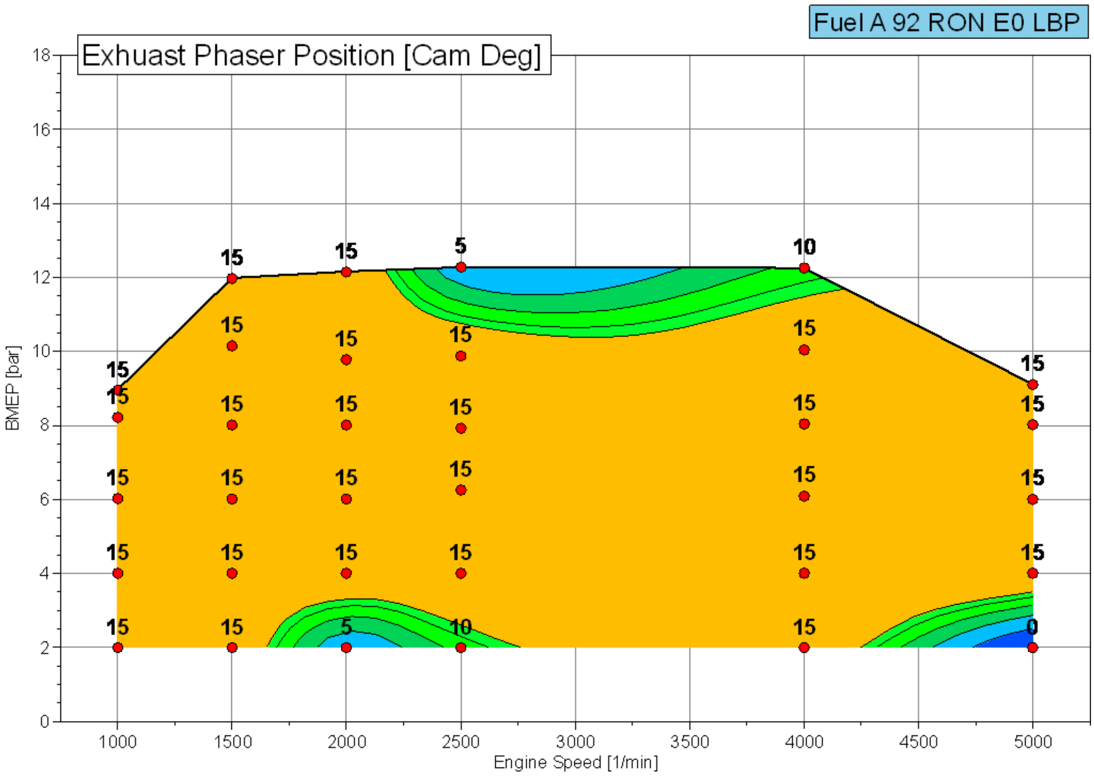

Figure 10: Exhaust Camshaft Position

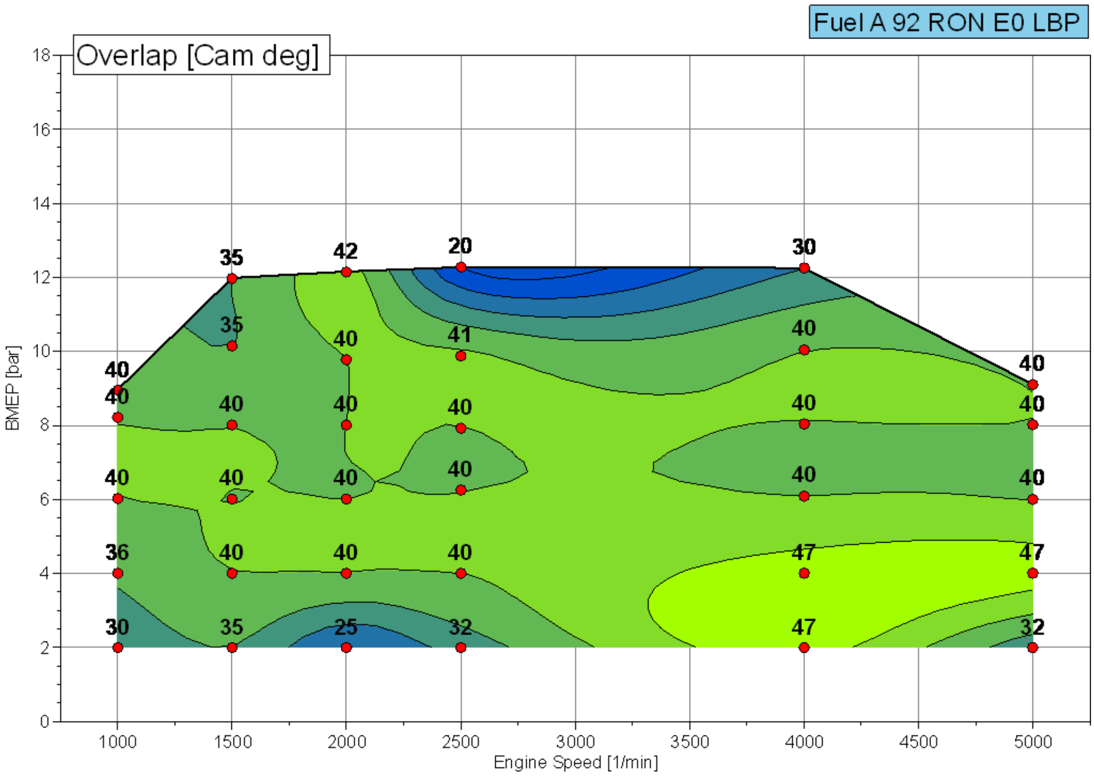

Figure 11: Camshaft Overlap

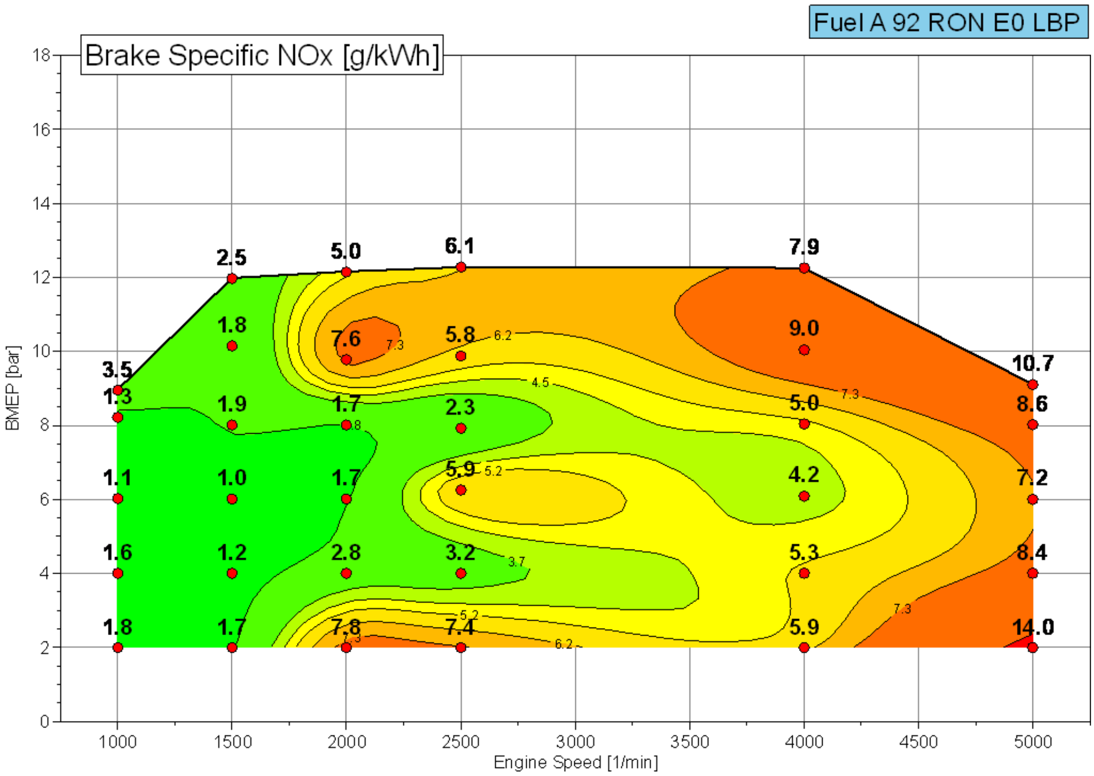

Figure 12: Brake Specific NOx Emissions

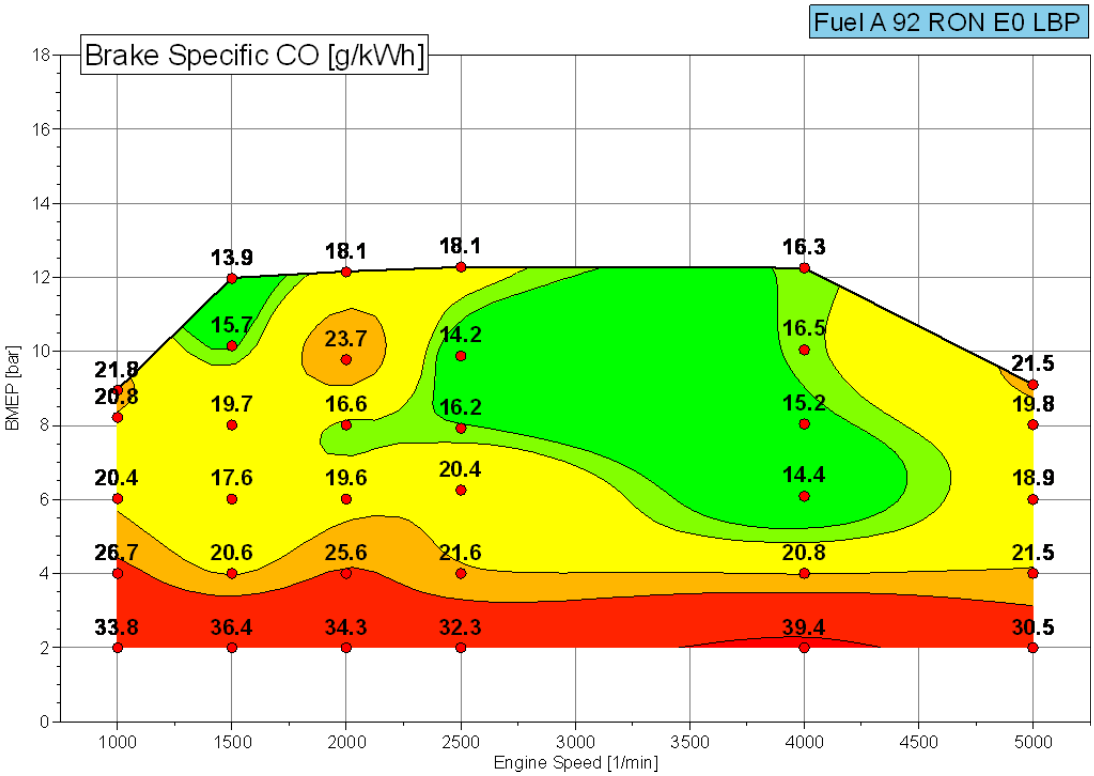

Figure 13: Brake Specific Carbon Monoxide Emissions

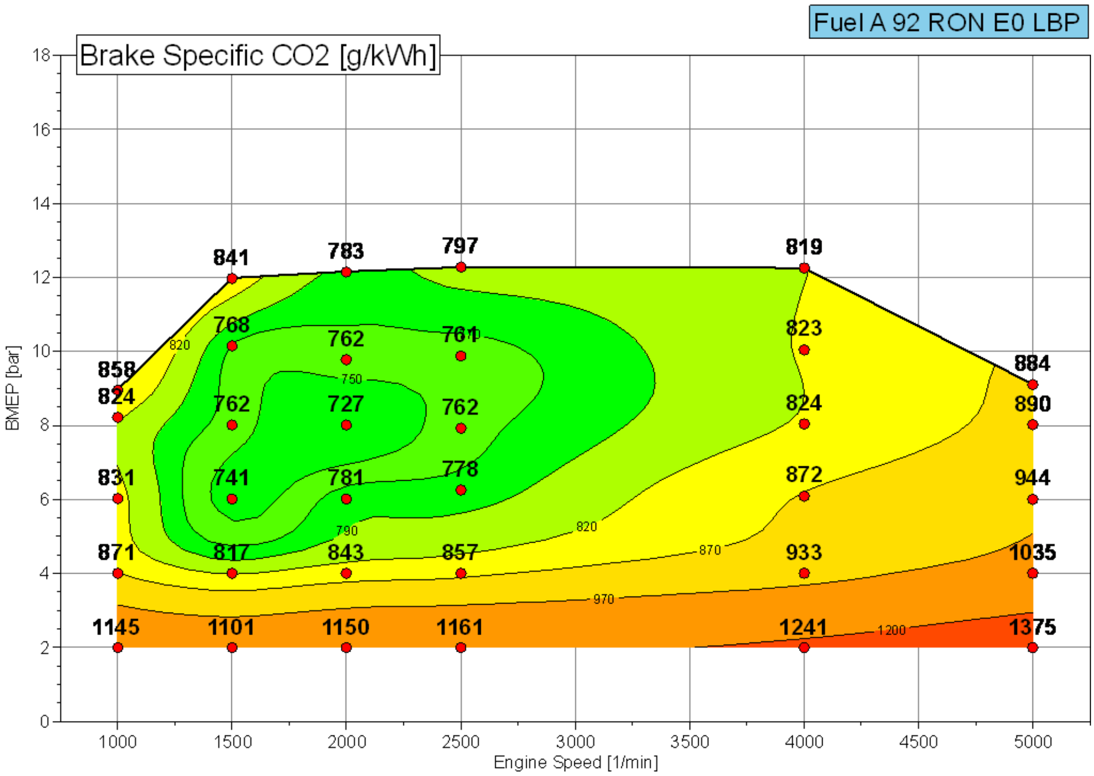

Figure 14: Brake Specific Carbon Dioxide Emissions

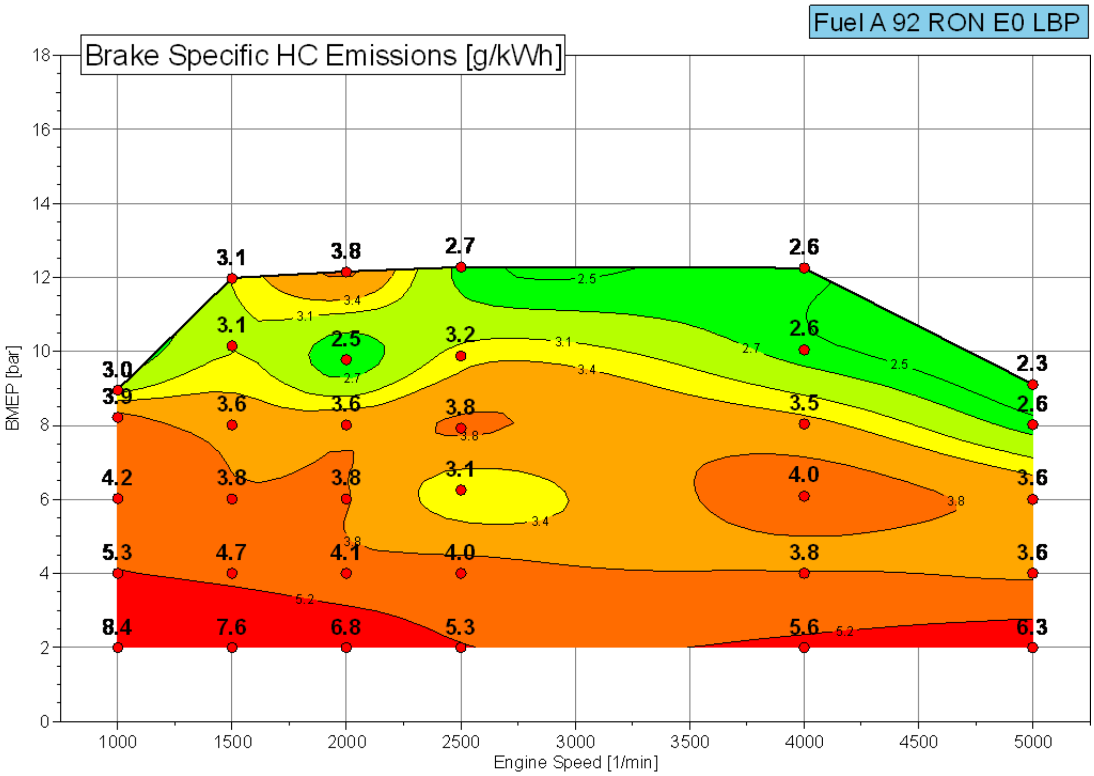

Figure 15: Brake Specific Hydrocarbon Emissions

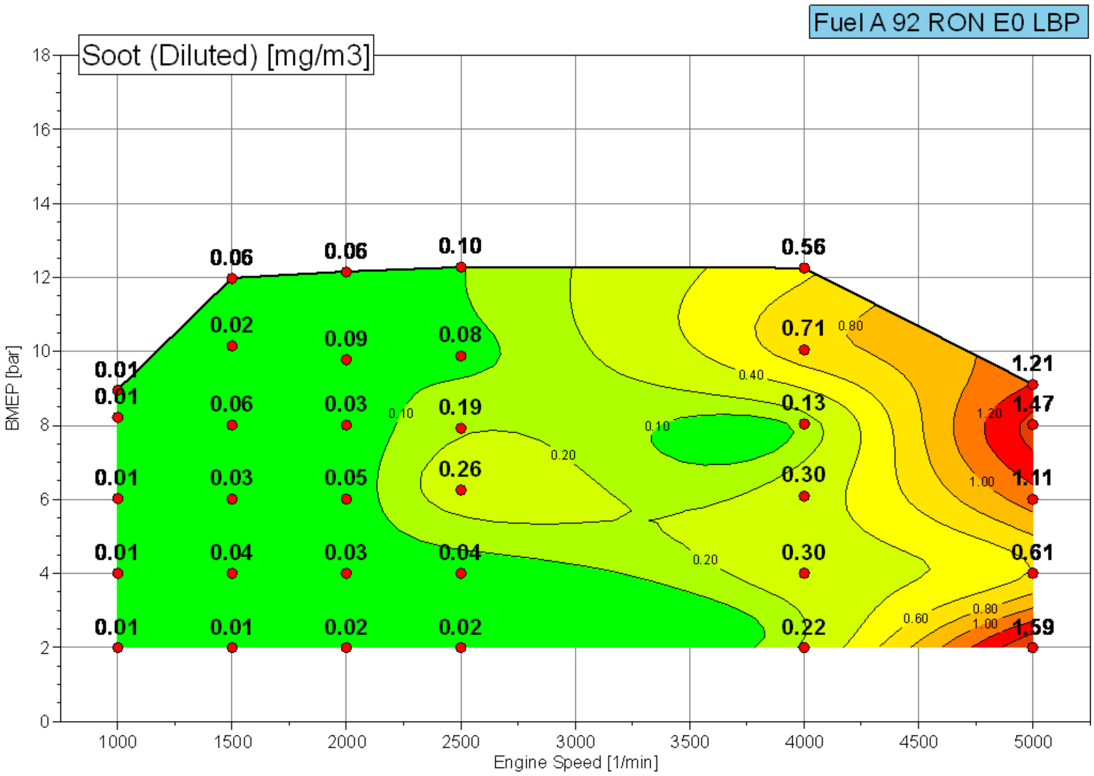

Figure 16: Particulate Soot Emissions

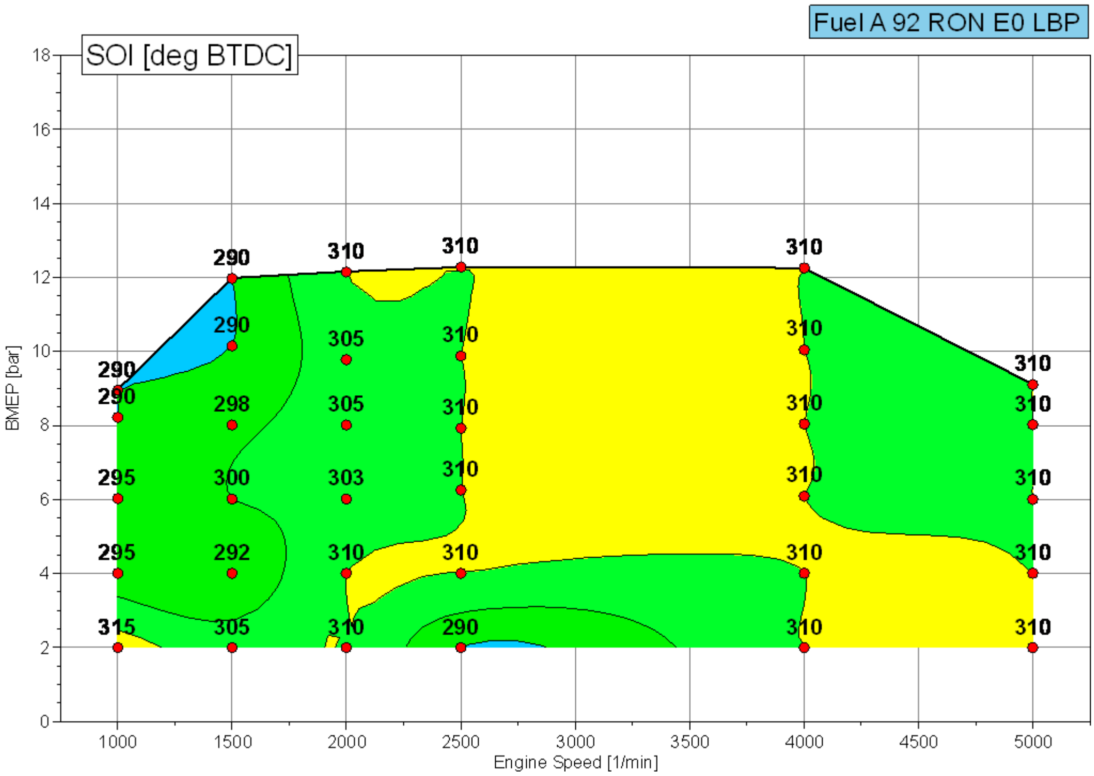

Figure 17: Start of Injection

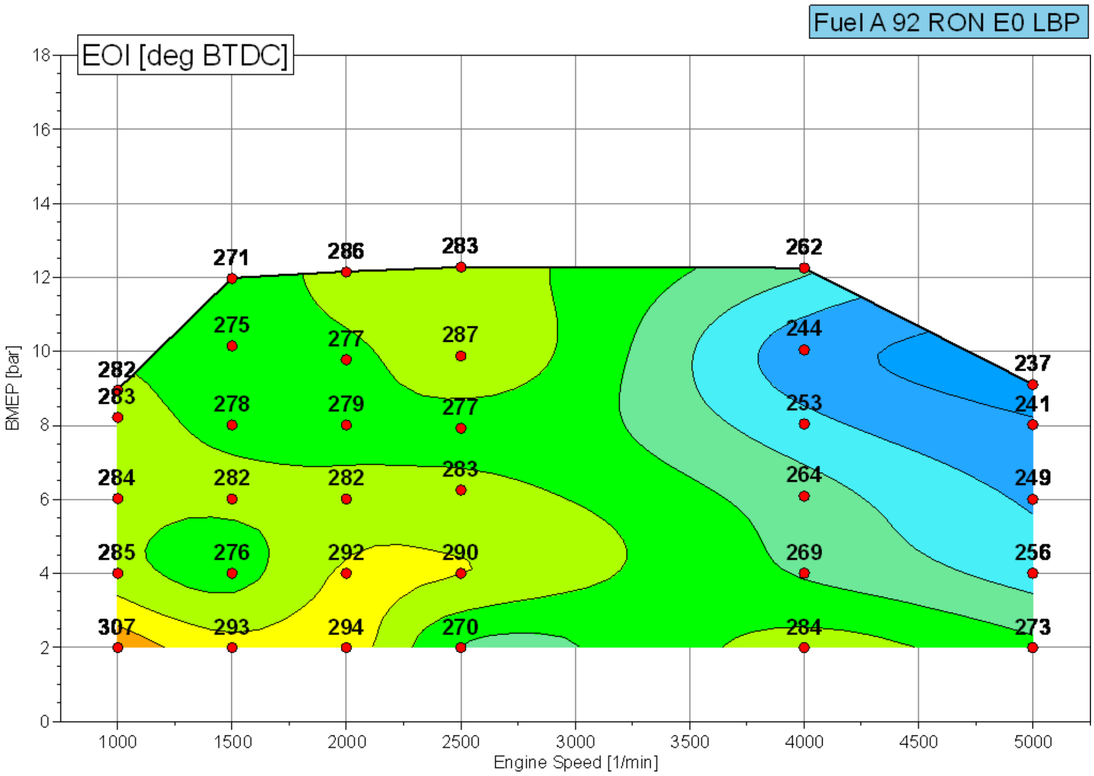

Figure 18: End of Injection

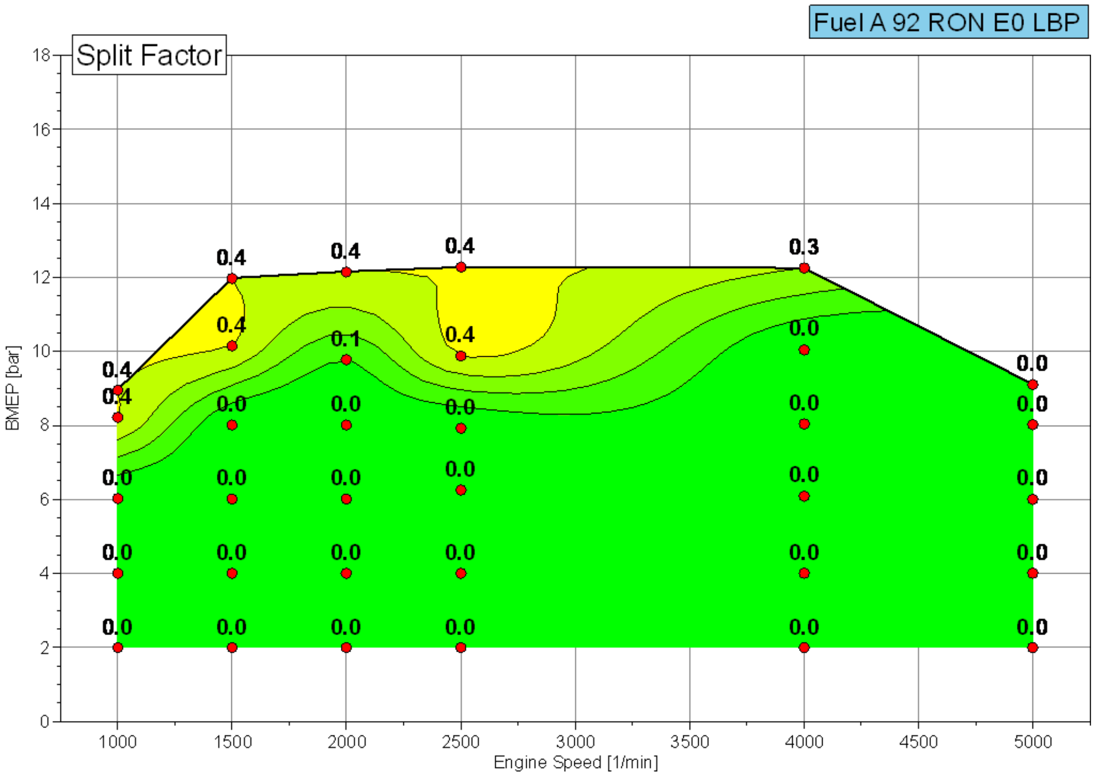

Figure 19: Injection Split Factor

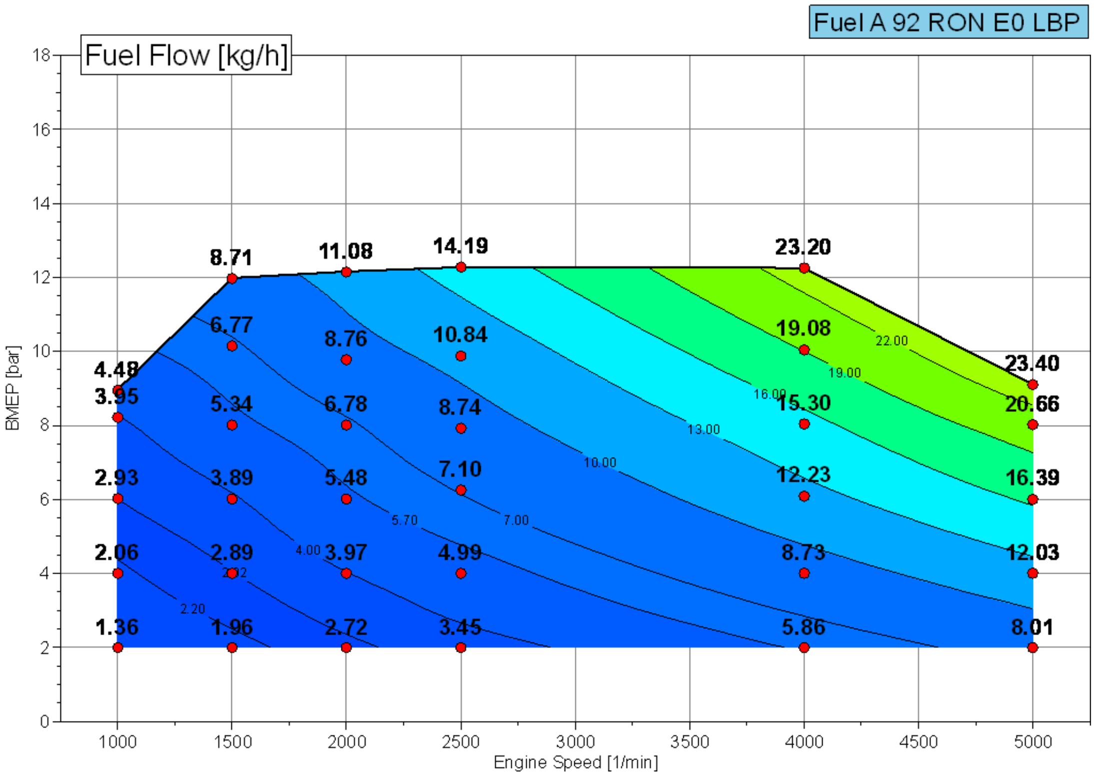

Figure 20: Fuel Flow

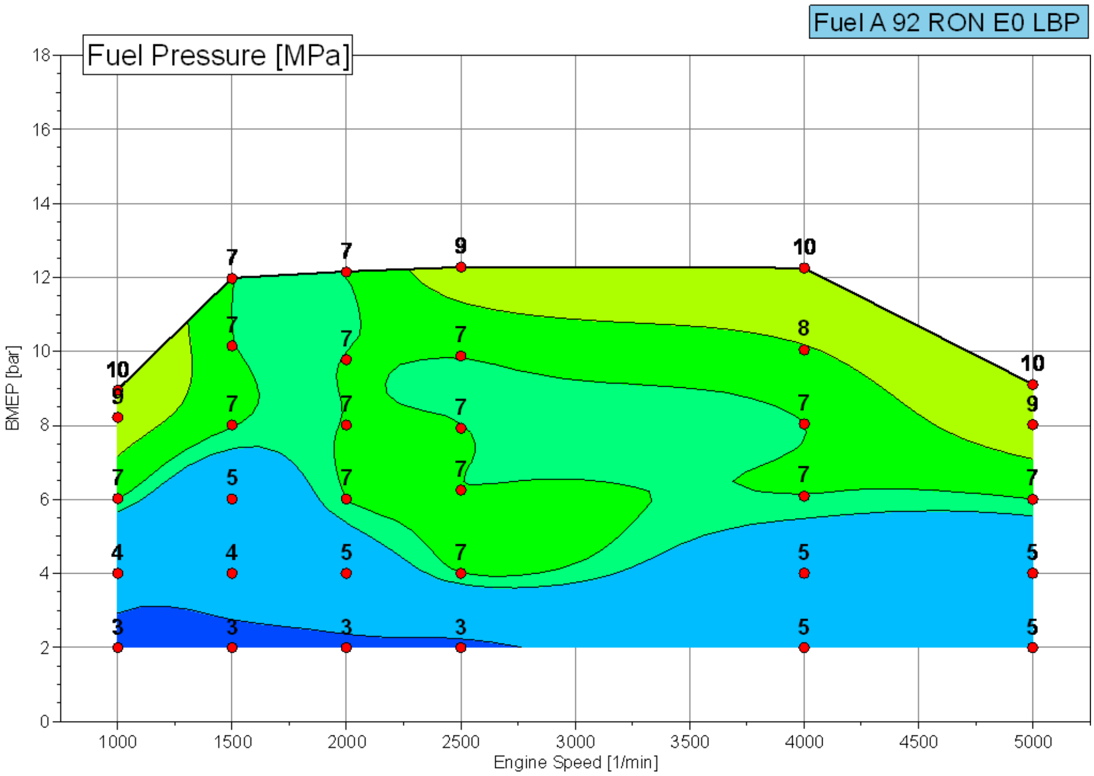

Figure 21: Fuel Rail Pressure

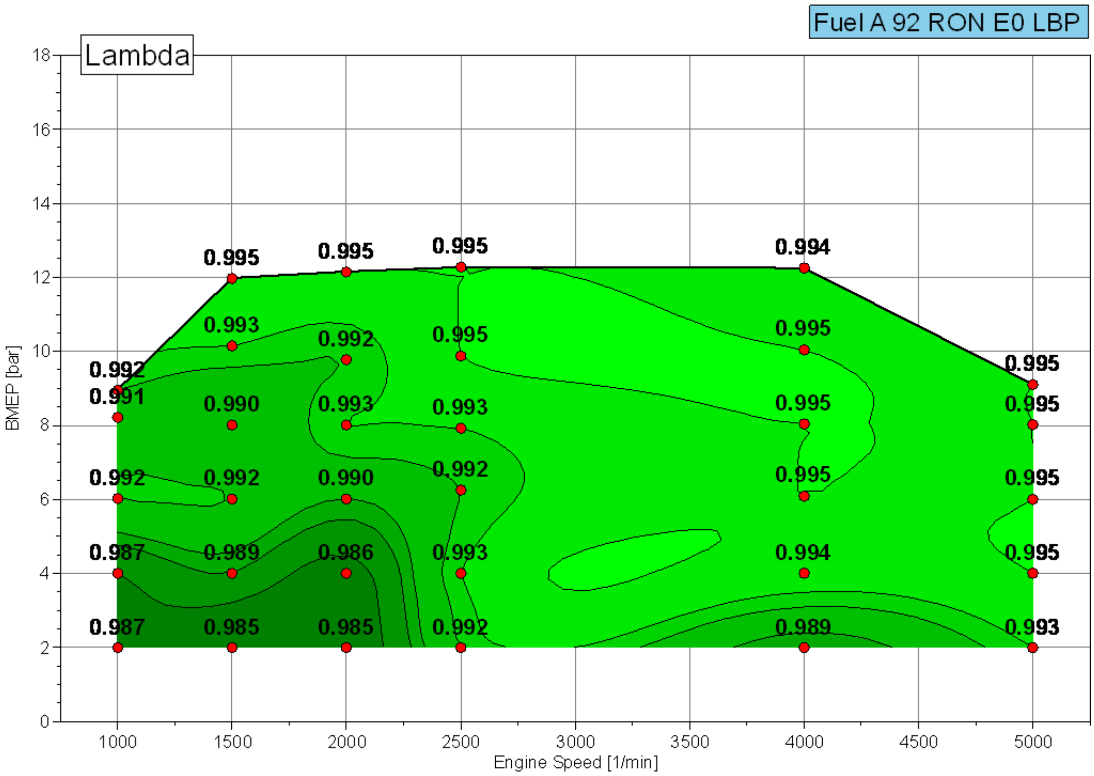

Figure 22: Lambda

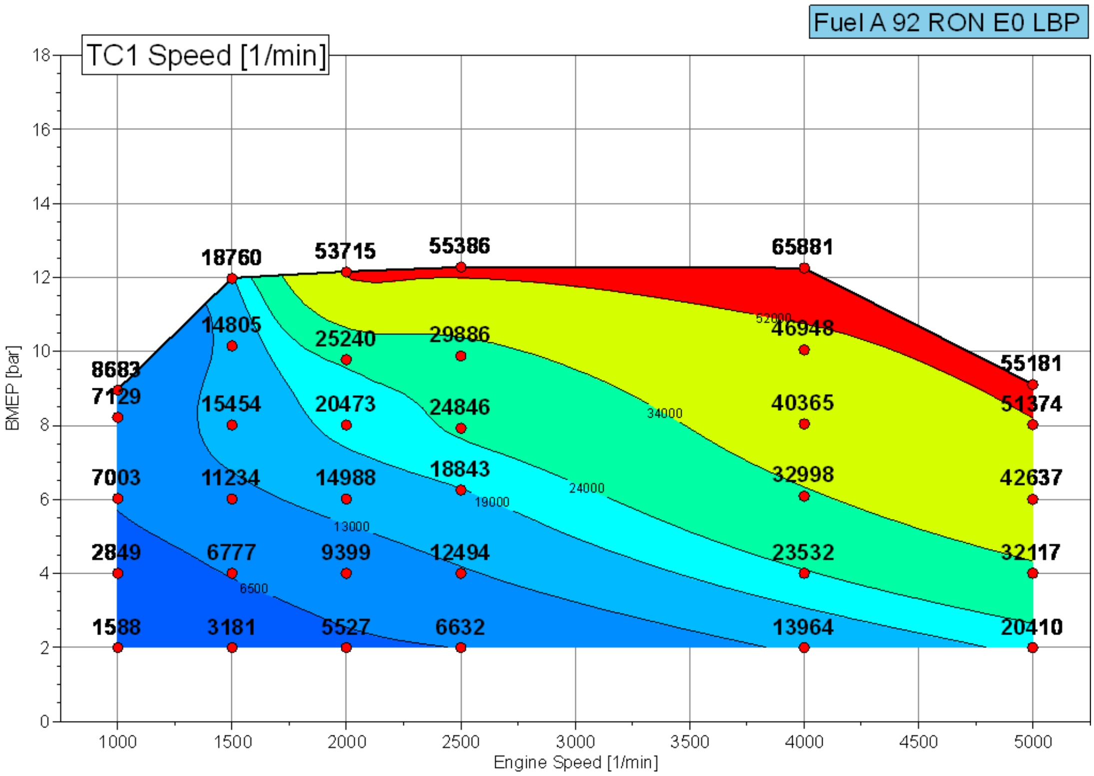

Figure 23: Low Pressure Turbocharger Speed

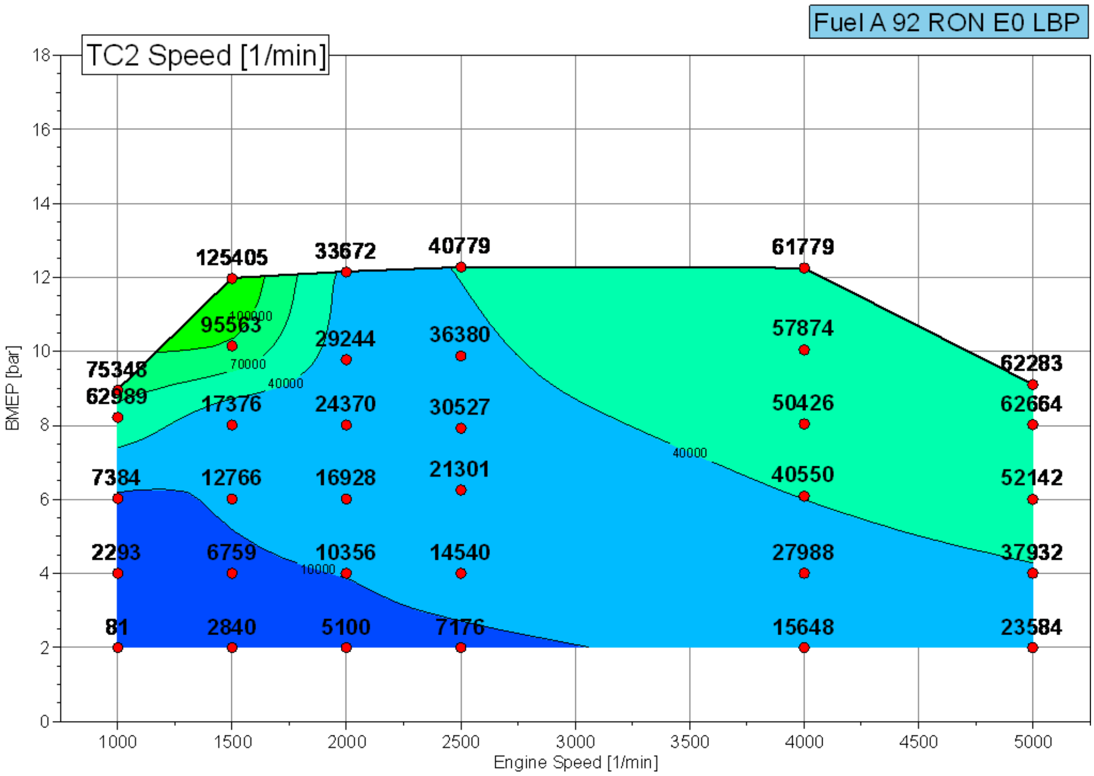

Figure 24: High Pressure Turbocharge Speed

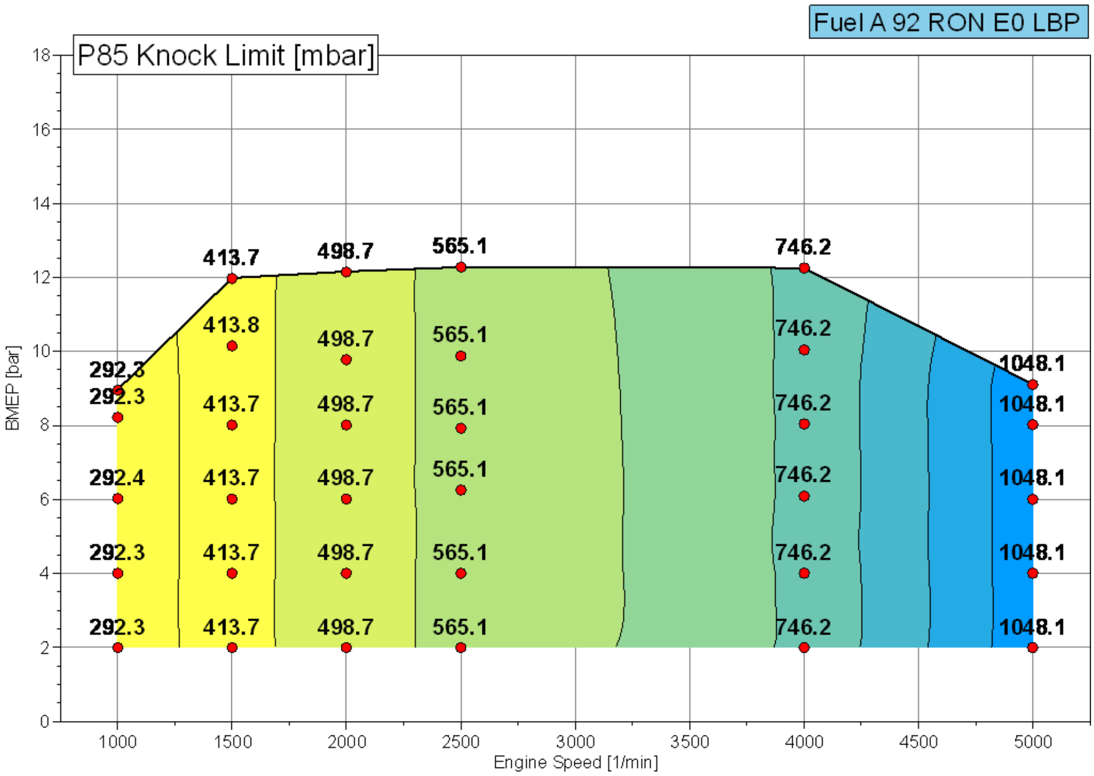

Figure 25: P85 Knock Limit

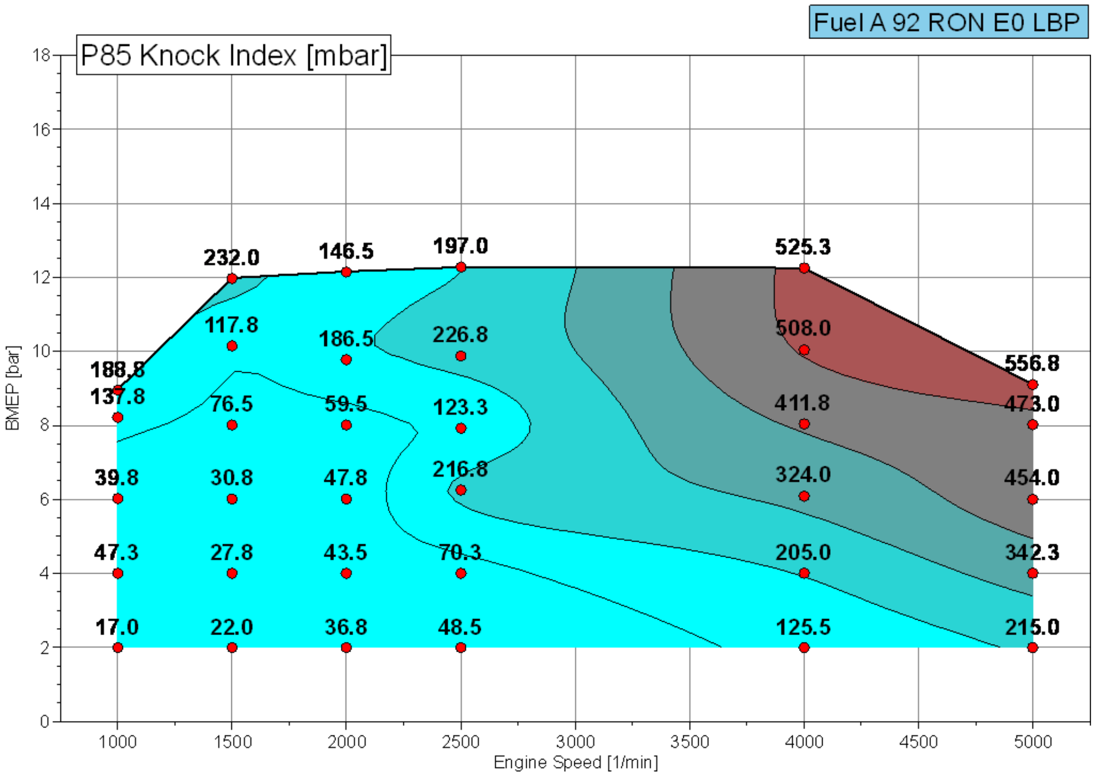

Figure 26: Averaged P85 Knock Index

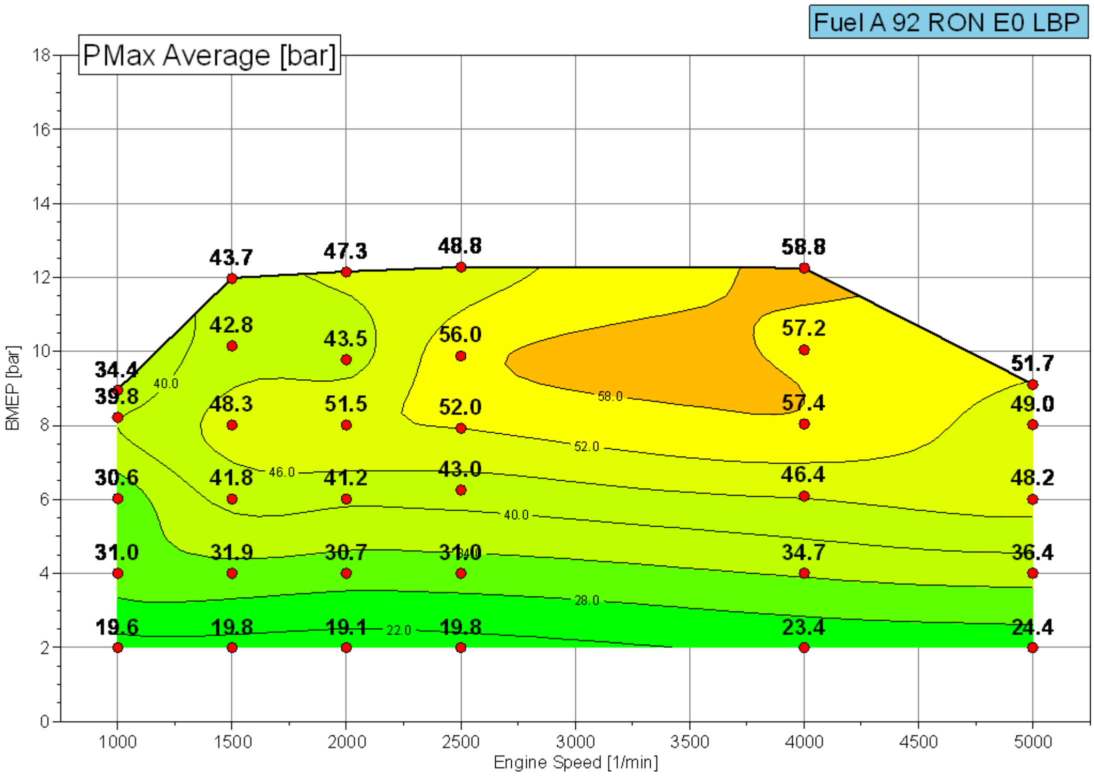

Figure 27: Averaged Max Pressure for Cylinders 1-4

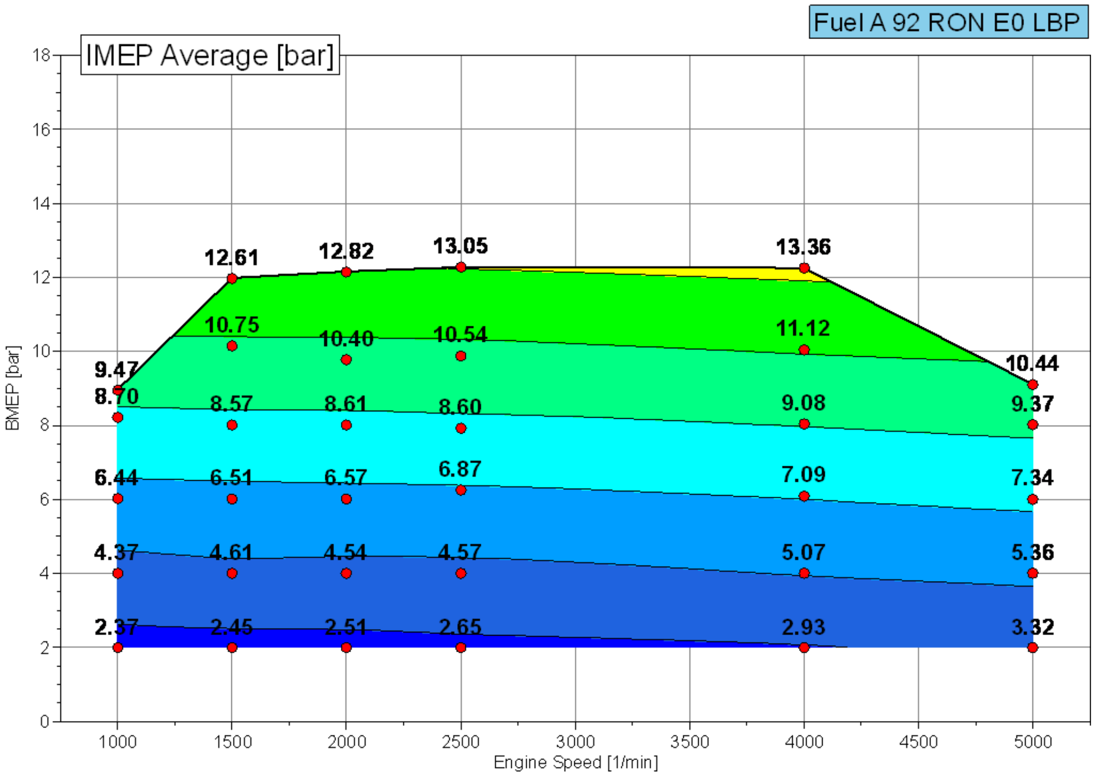

Figure 28: Indicated Mean Effective Pressure

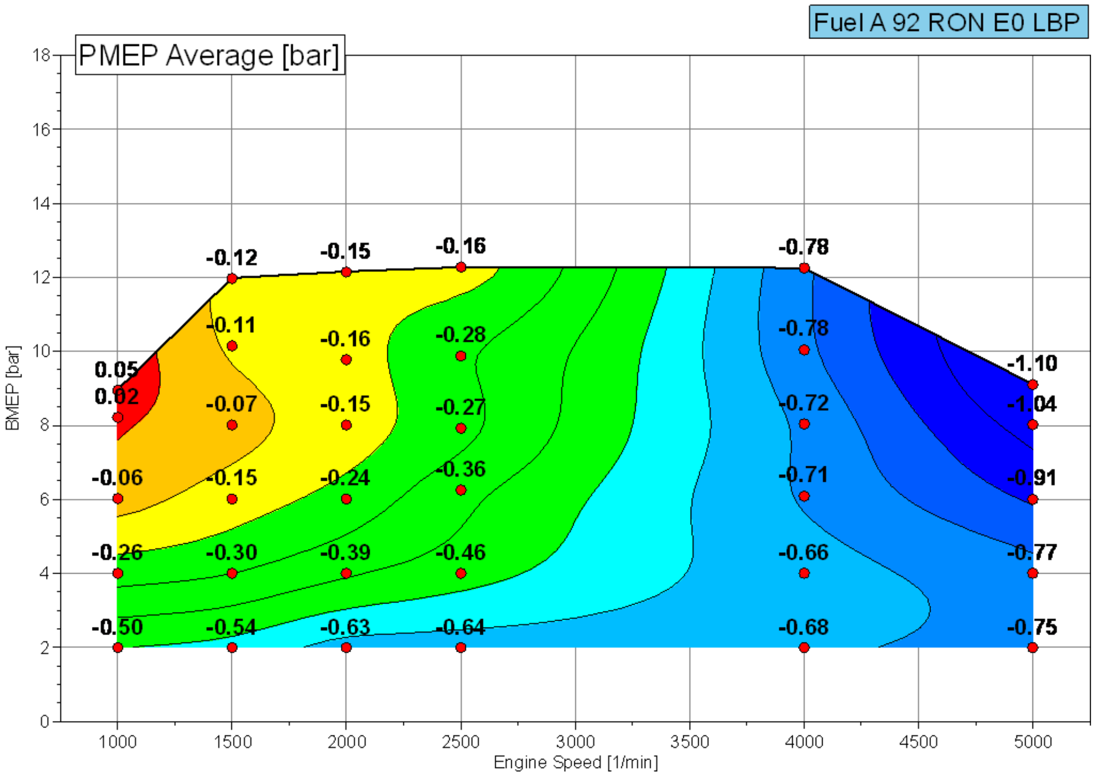

Figure 29: Pumping Mean Effective Pressure

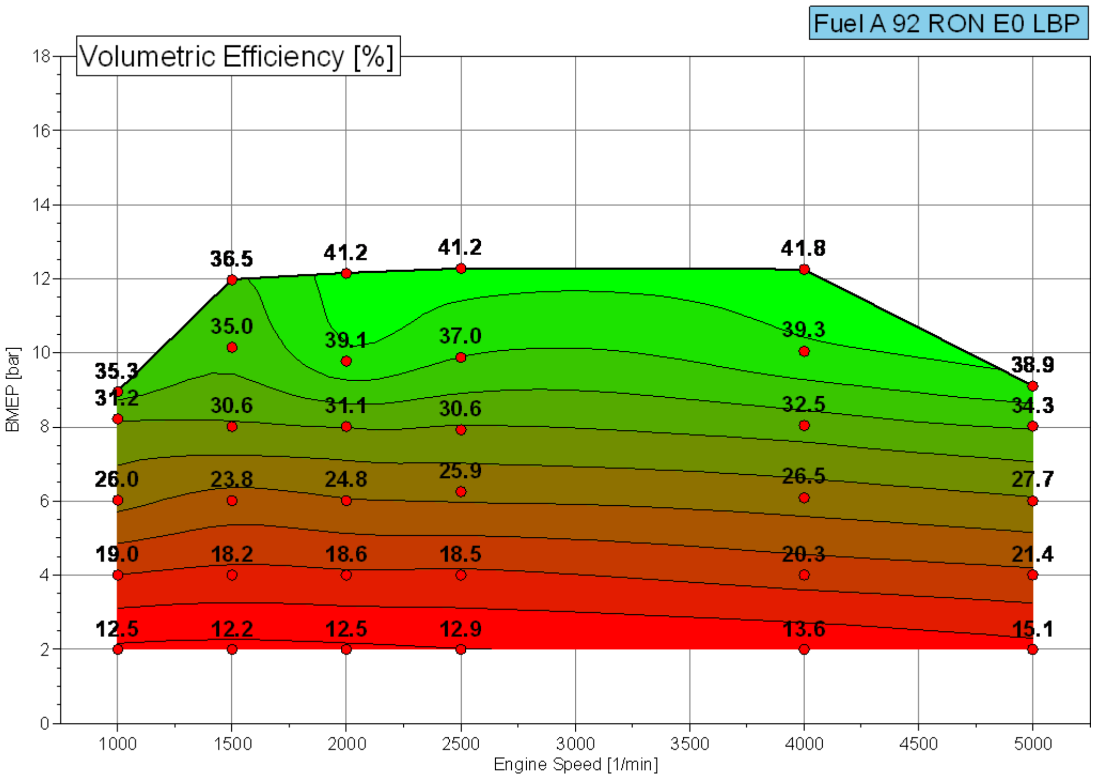

Figure 30: Calculated Volumetric Efficiency

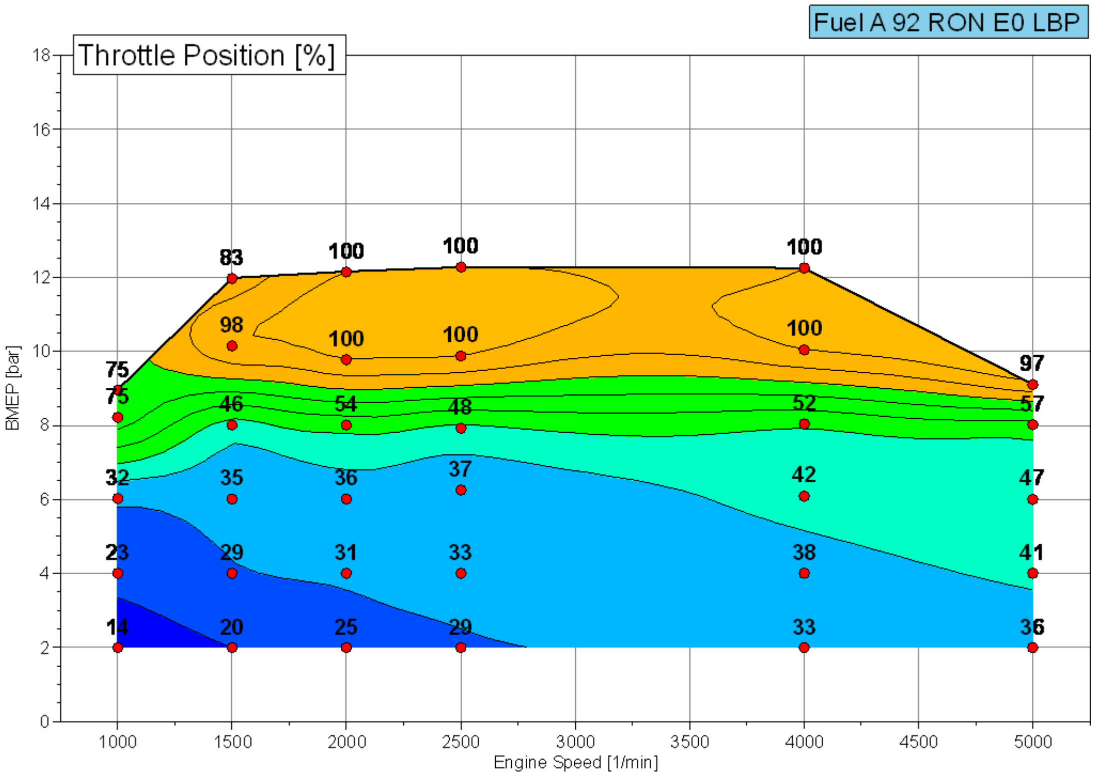

Figure 31: Throttle Position

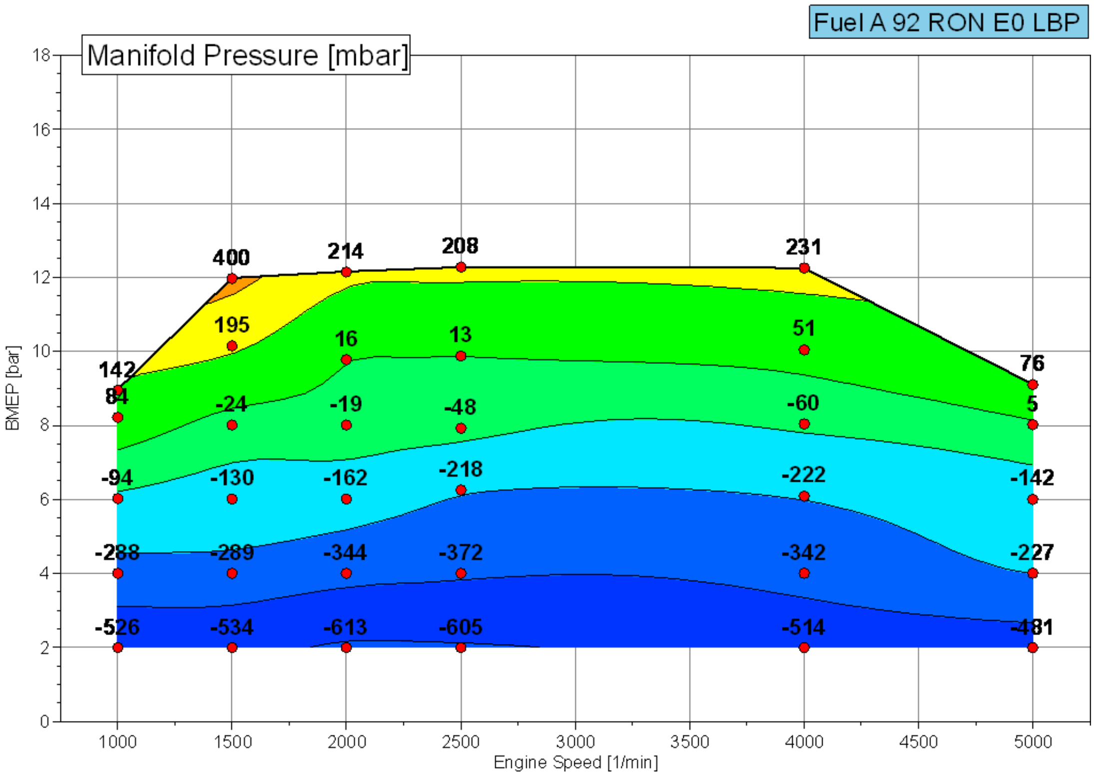

Figure 32: Intake Manifold Pressure

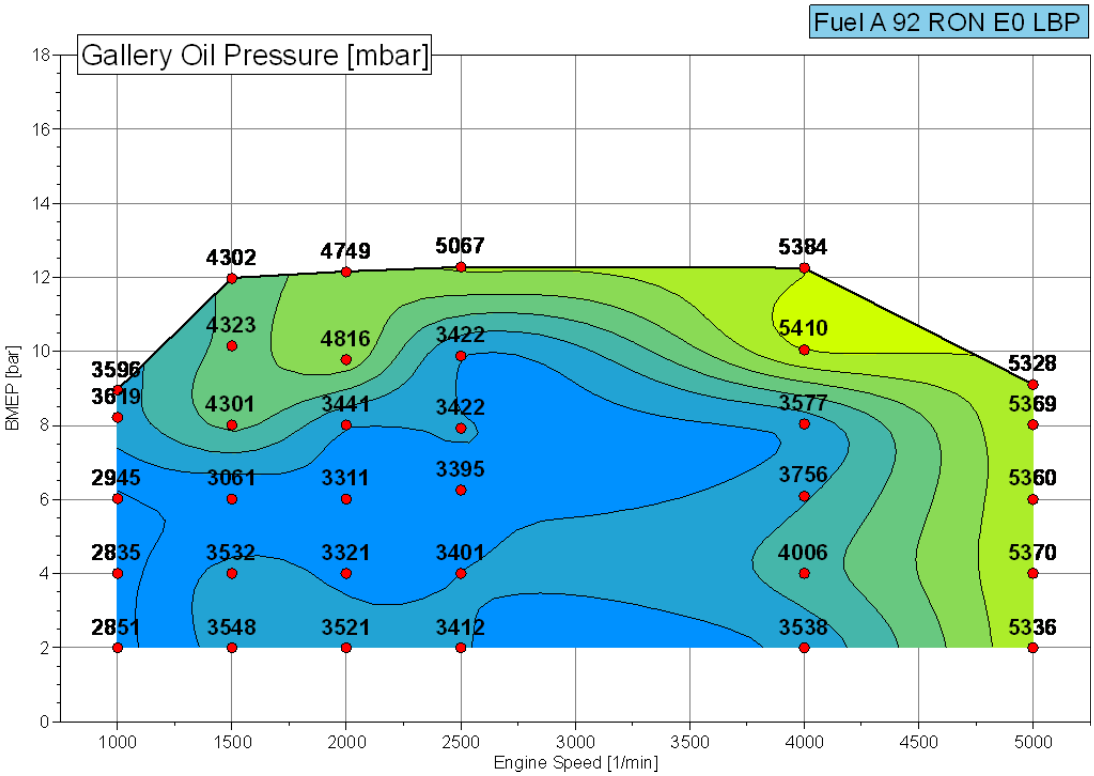

Figure 33: Gallery Oil Pressure

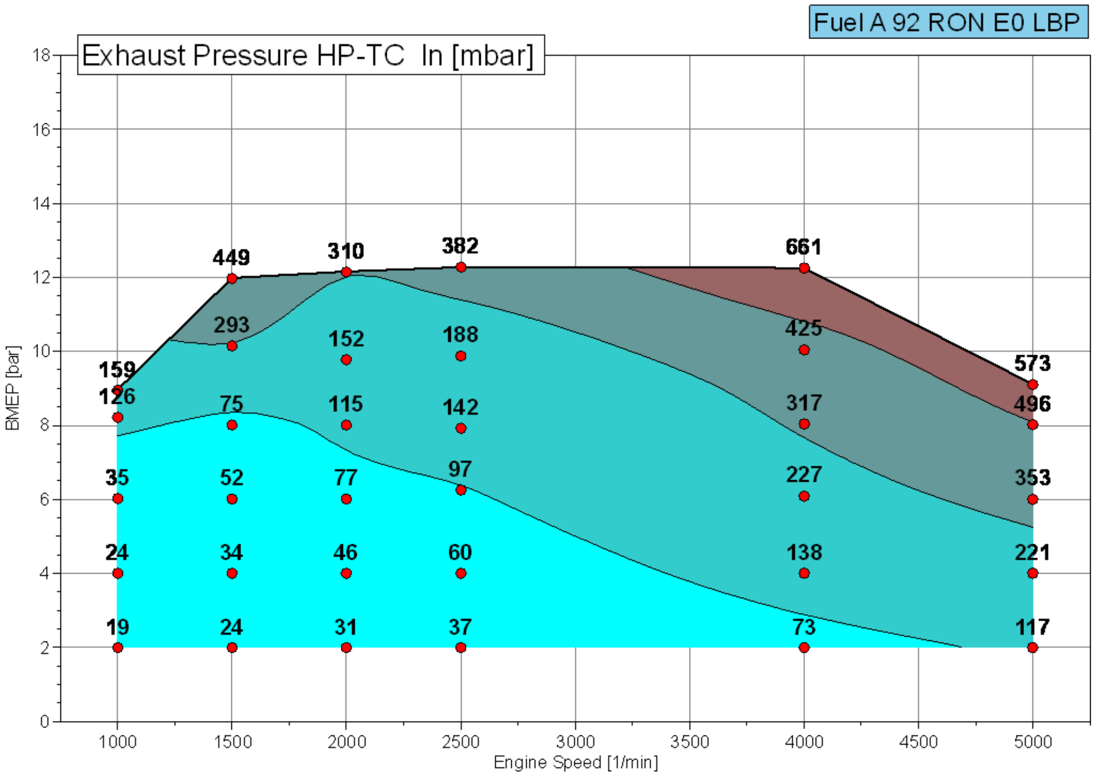

Figure 34: Exhaust Pressure High Pressure Turbocharger In

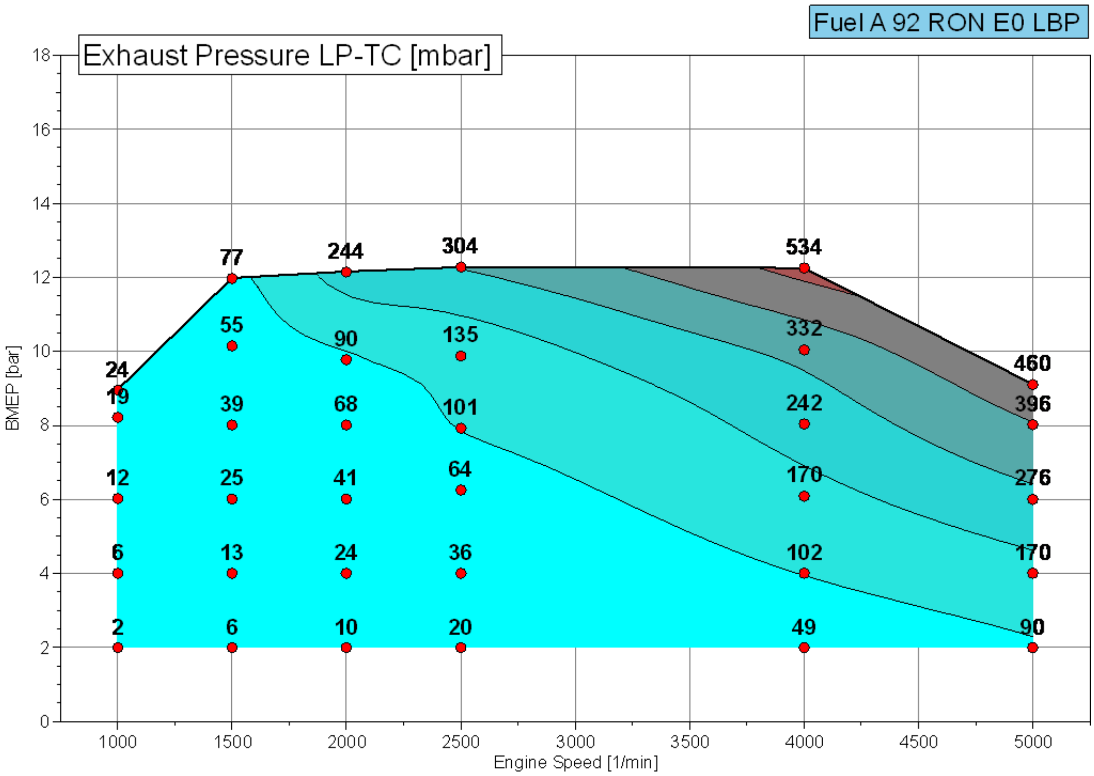

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

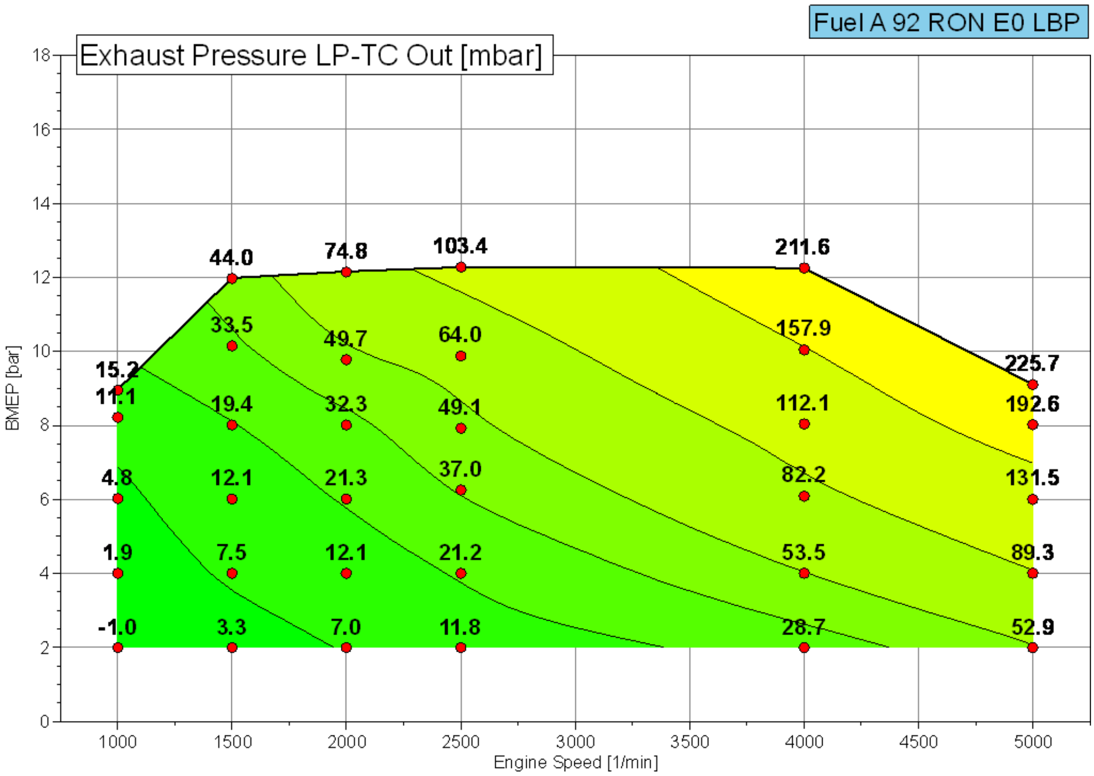

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

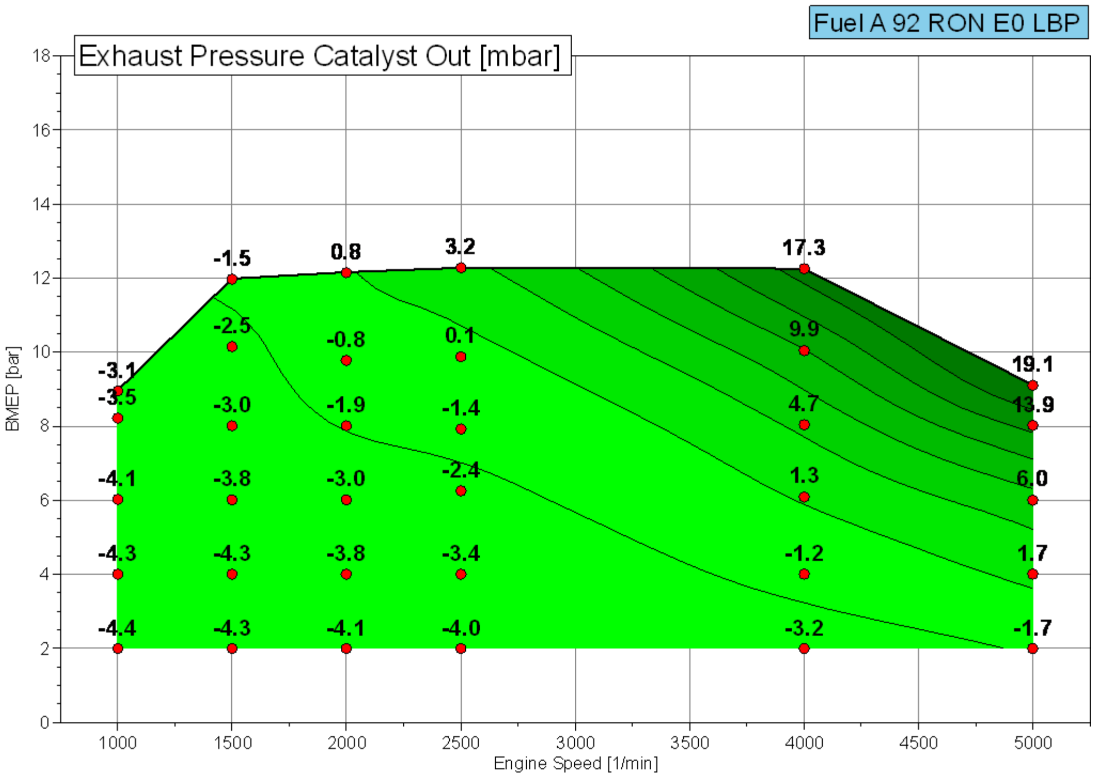

Figure 37: Exhaust Pressure Catalyst Out

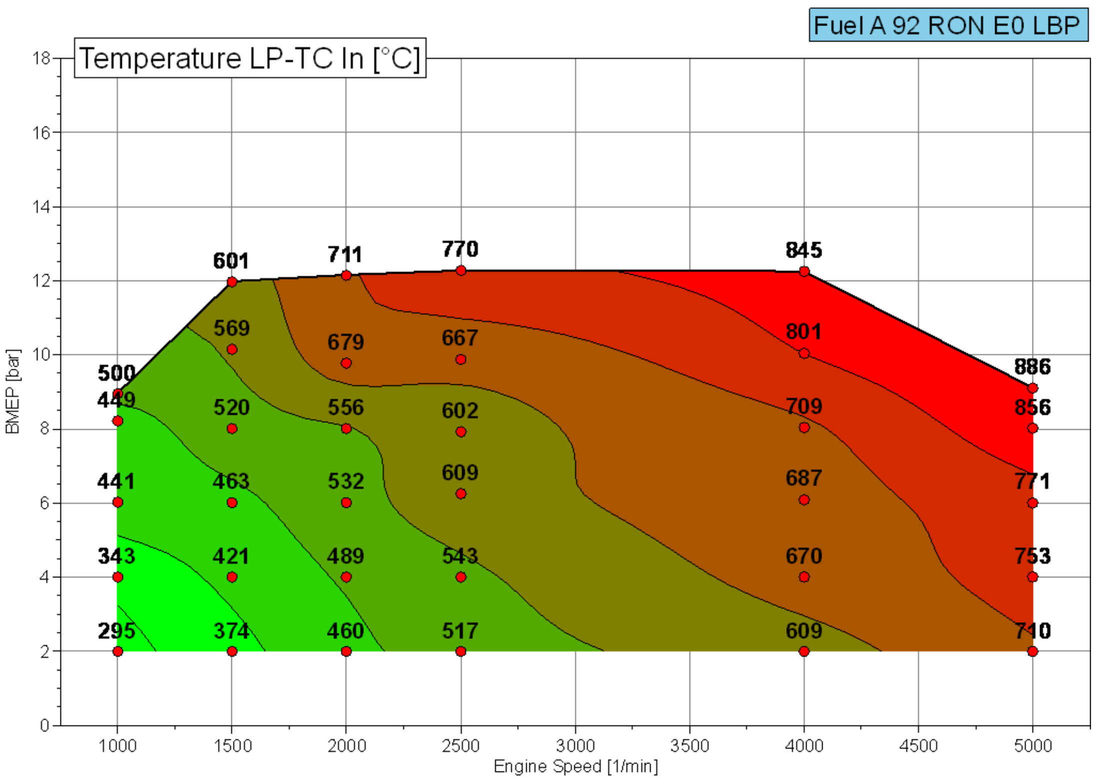

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

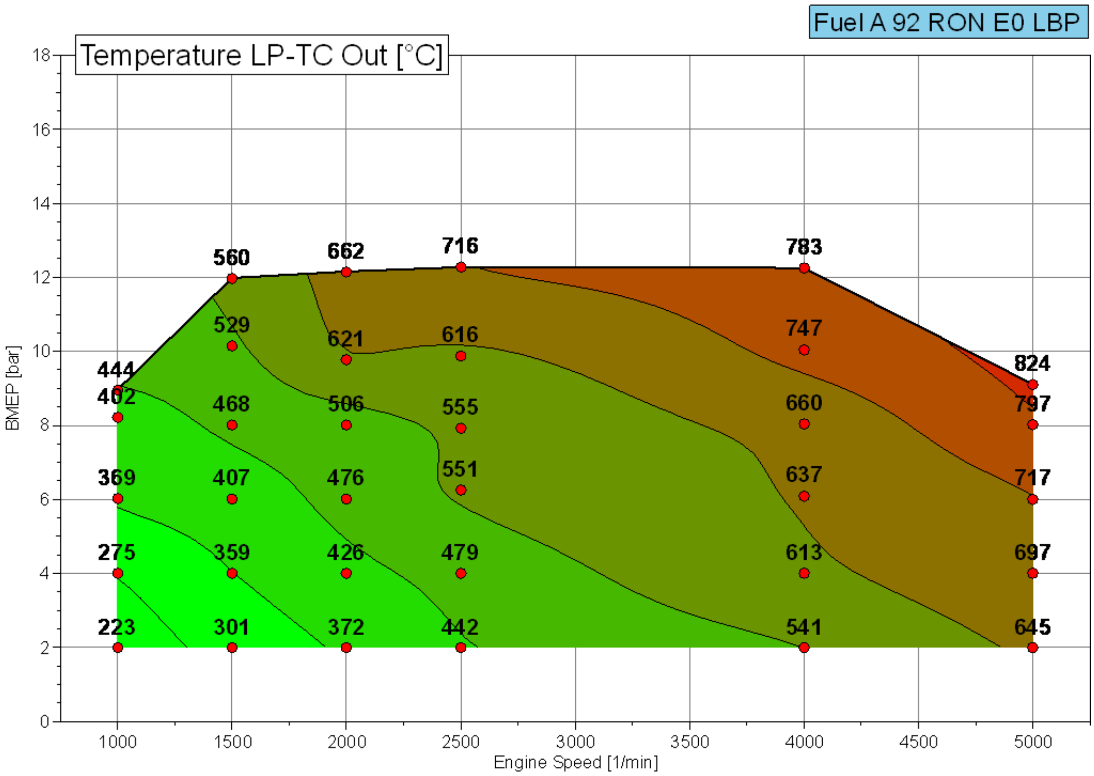

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

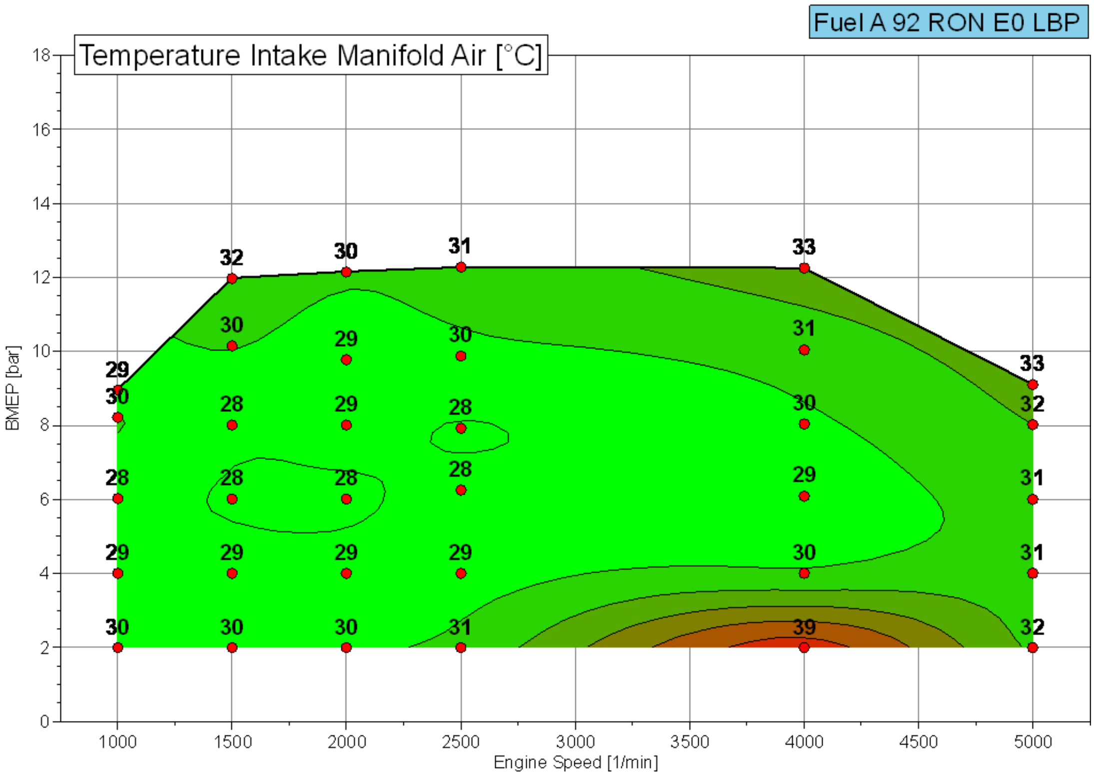

Figure 40: Intake Manifold Air Temperature

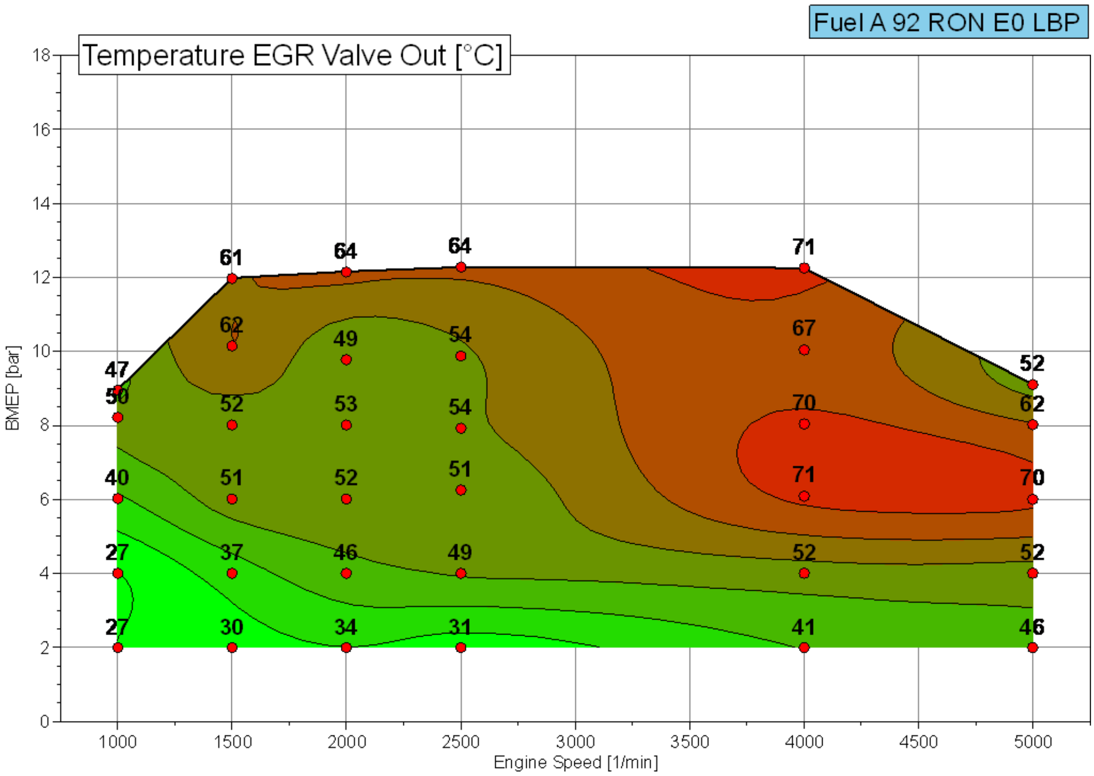

Figure 41: EGR Valve Out Temperature

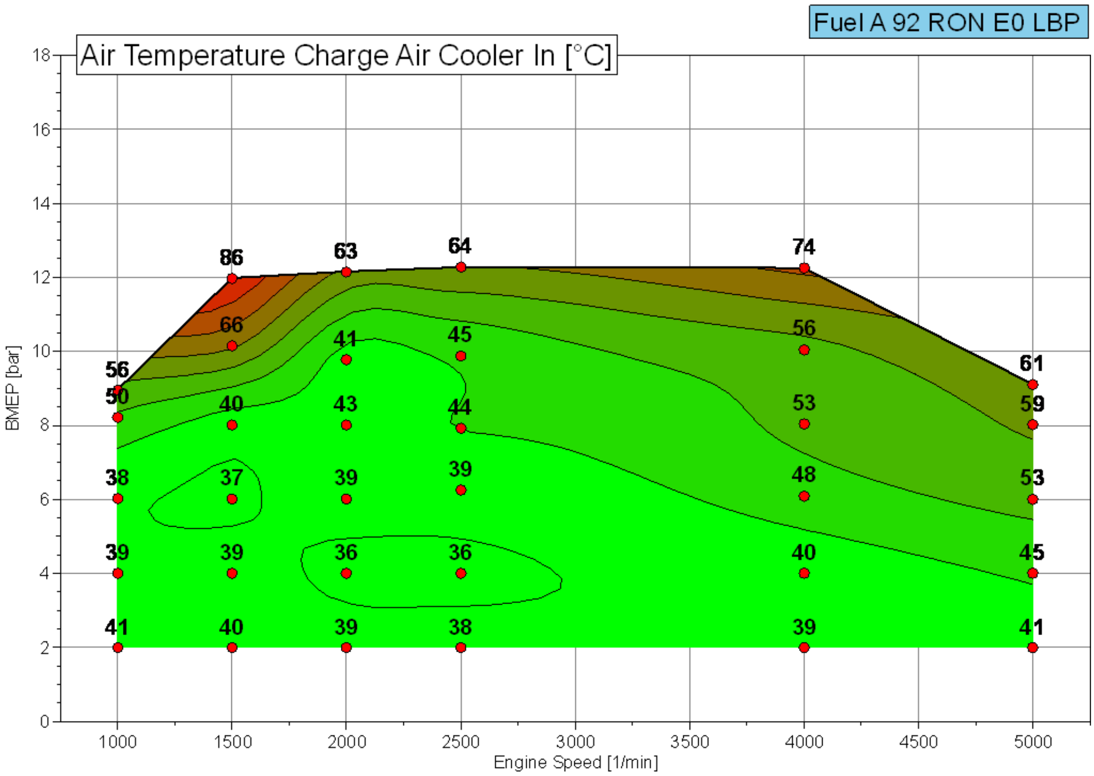

Figure 42: Charge Air Cooler Inlet Air Temperature

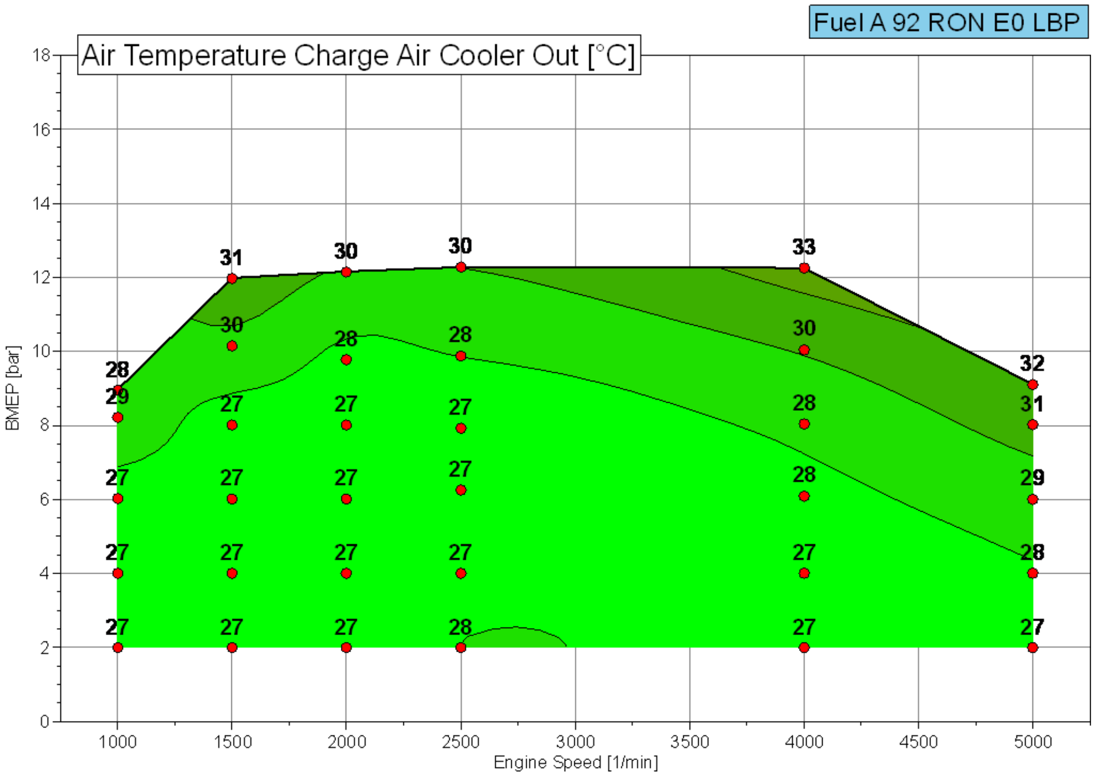

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel C Calibration Results

92 Ron 10% Ethanol Low Boiling Point

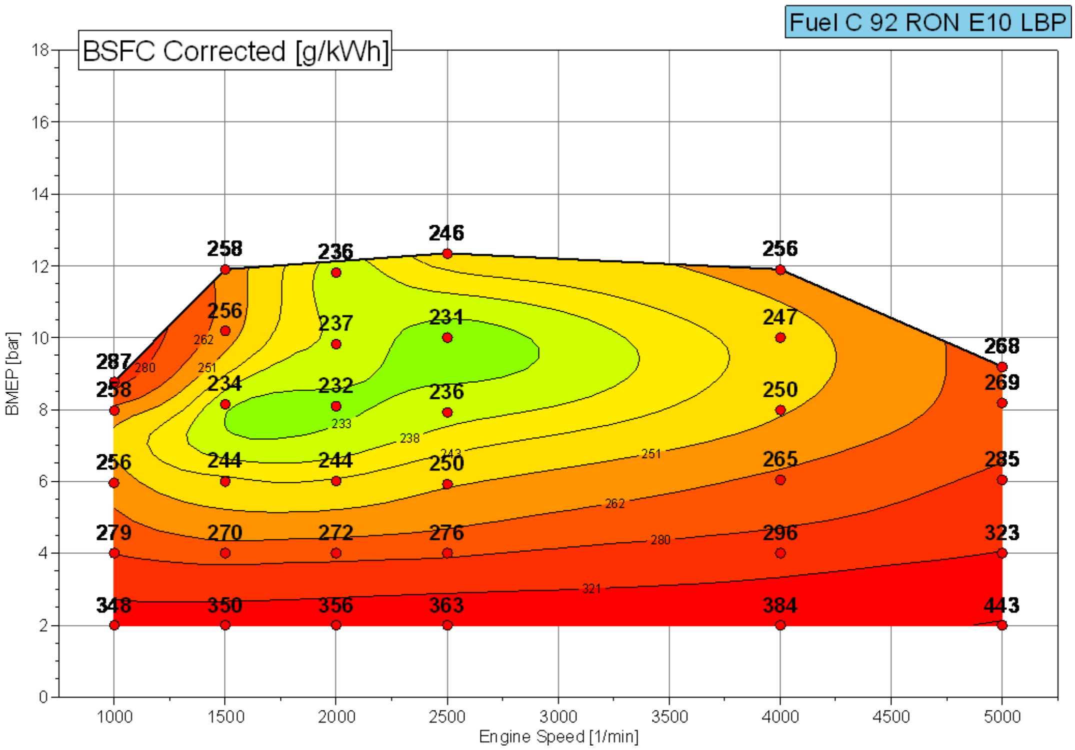

Figure 1: Brake Specific Fuel Consumption

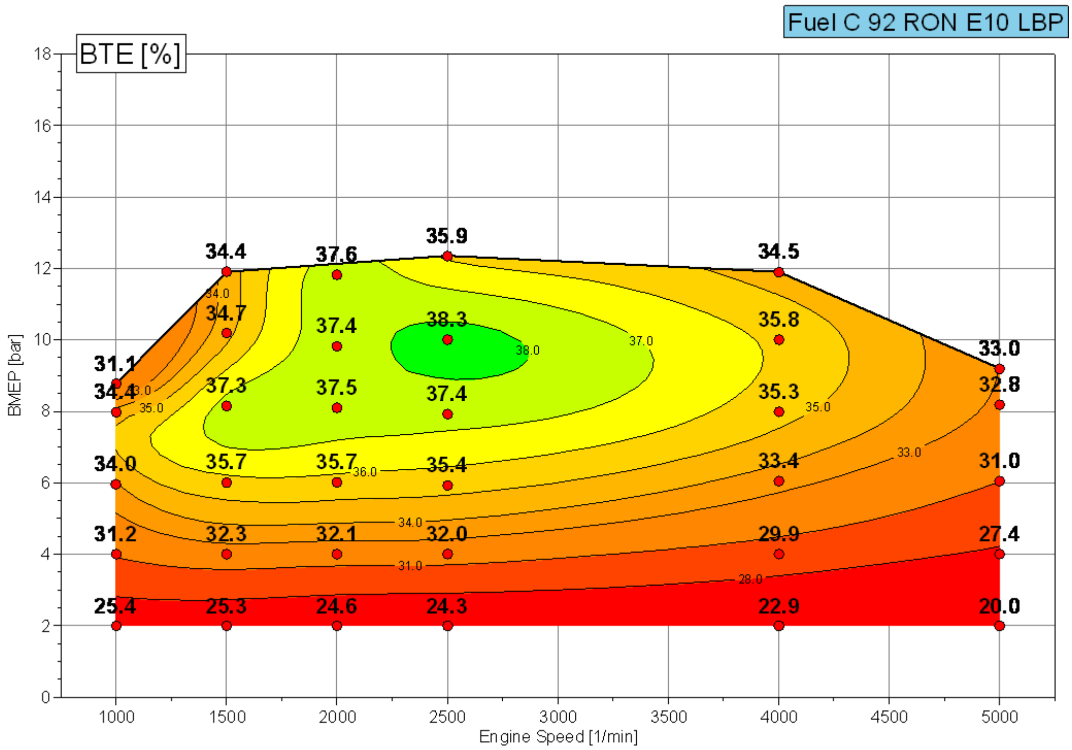

Figure 2: Brake Thermal Efficiency

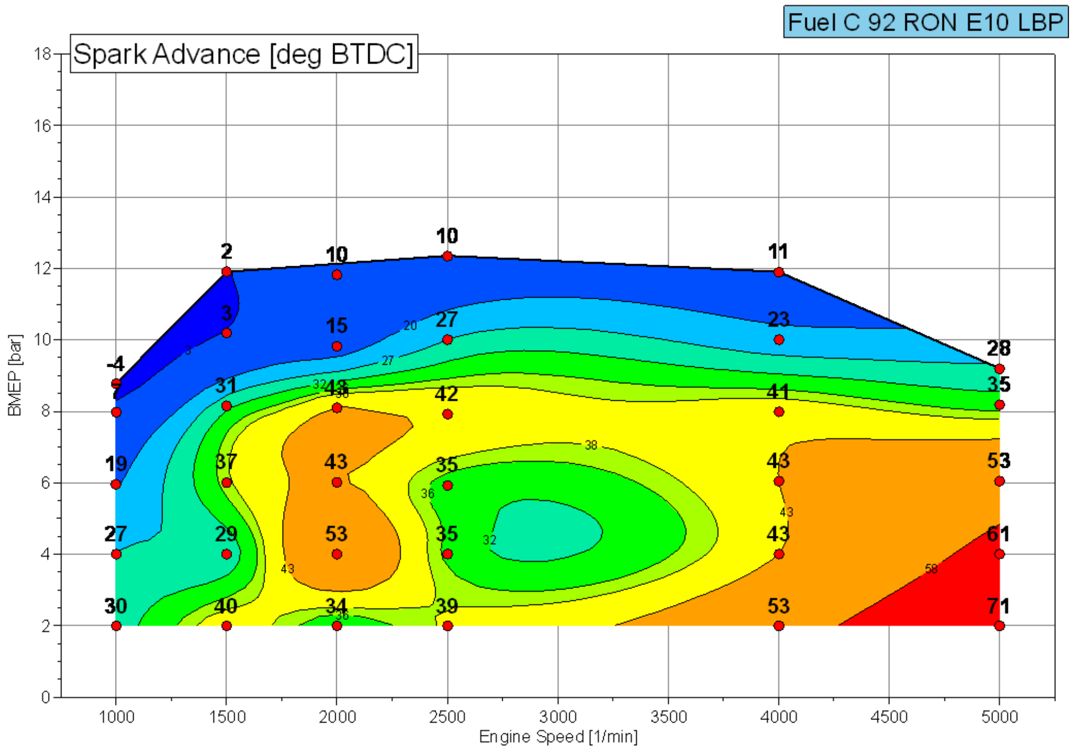

Figure 3: Spark Advance

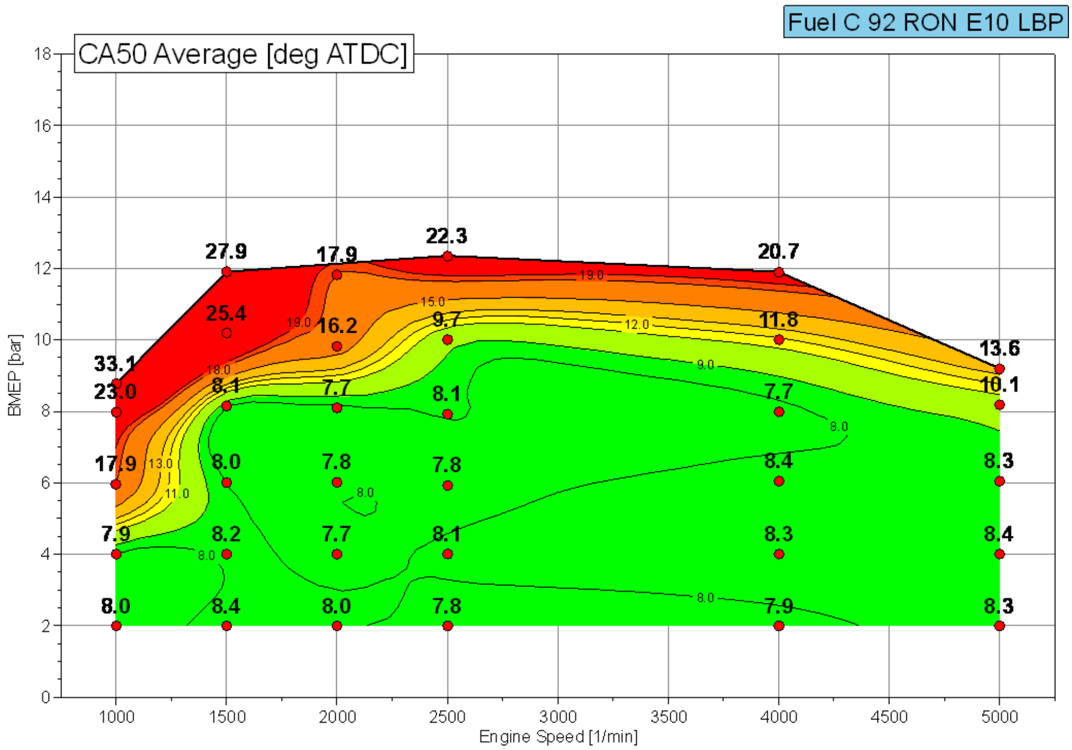

Figure 4: CA50 Average of Cylinders 1-4

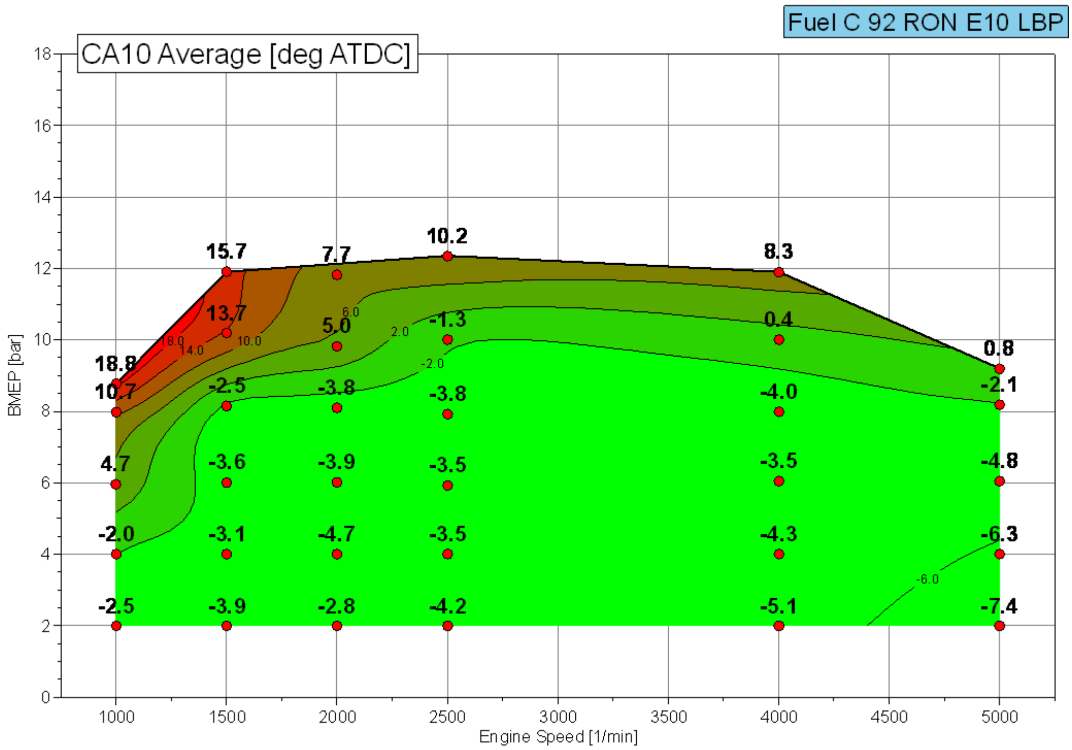

Figure 5: CA10 Average of Cylinders 1-4

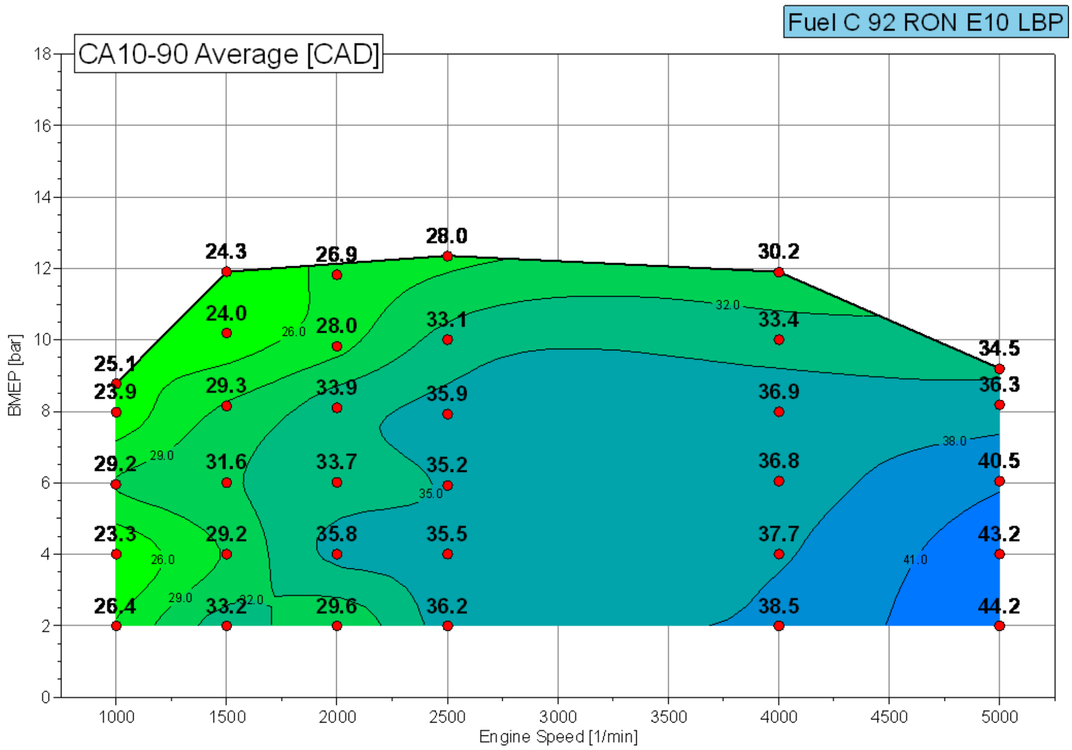

Figure **6:** CA10-90 Average of Cylinders 1-4

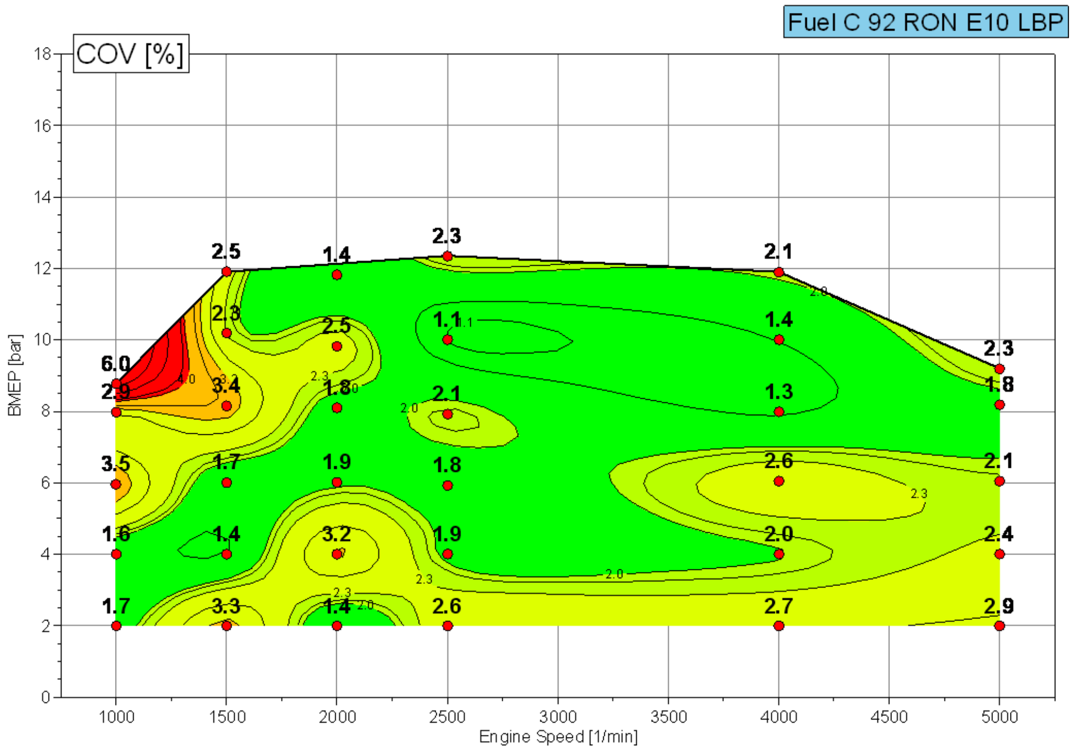

Figure 7: Coefficient of Variation Average of Cylinders 1-4

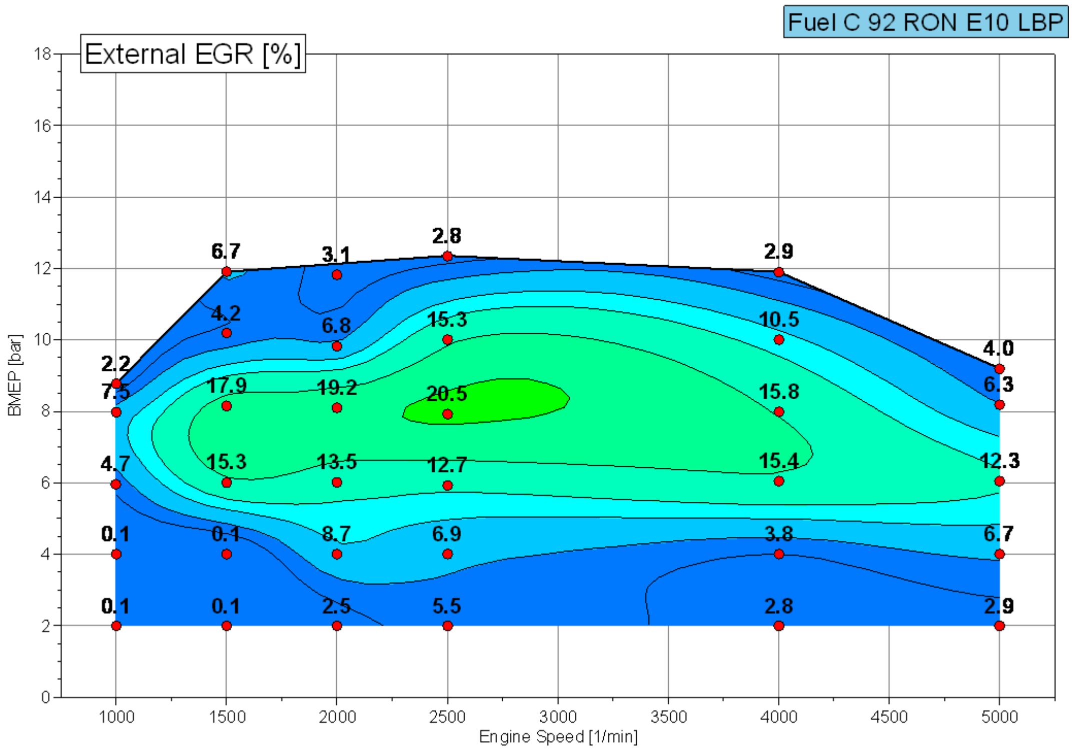

Figure 8: External EGR Percent of Intake Air

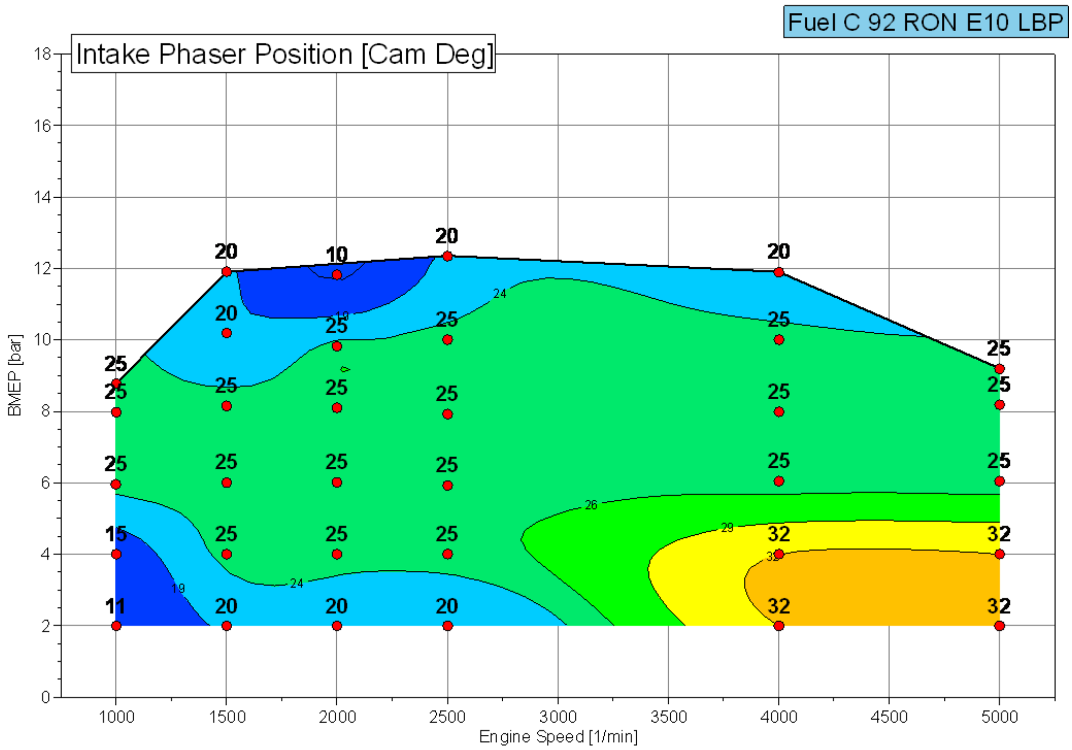

Figure 9: Intake Camshaft Phaser Position

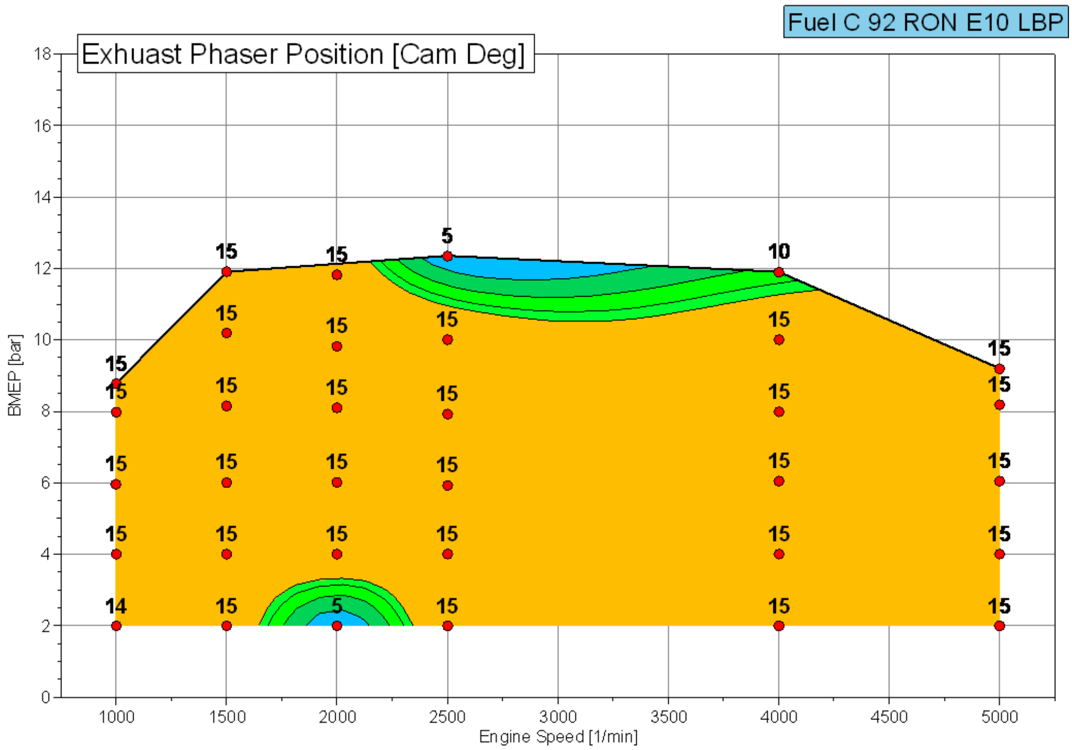

Figure 10: Exhaust Camshaft Phaser Position

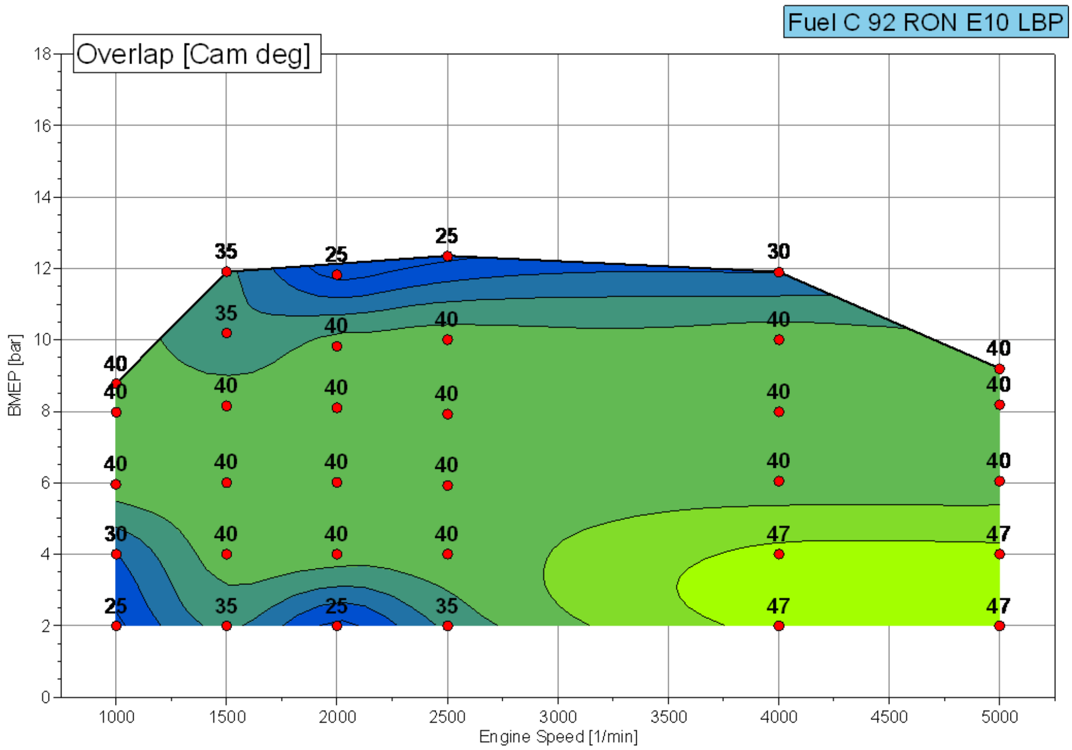

Figure 11: Camshaft Overlap

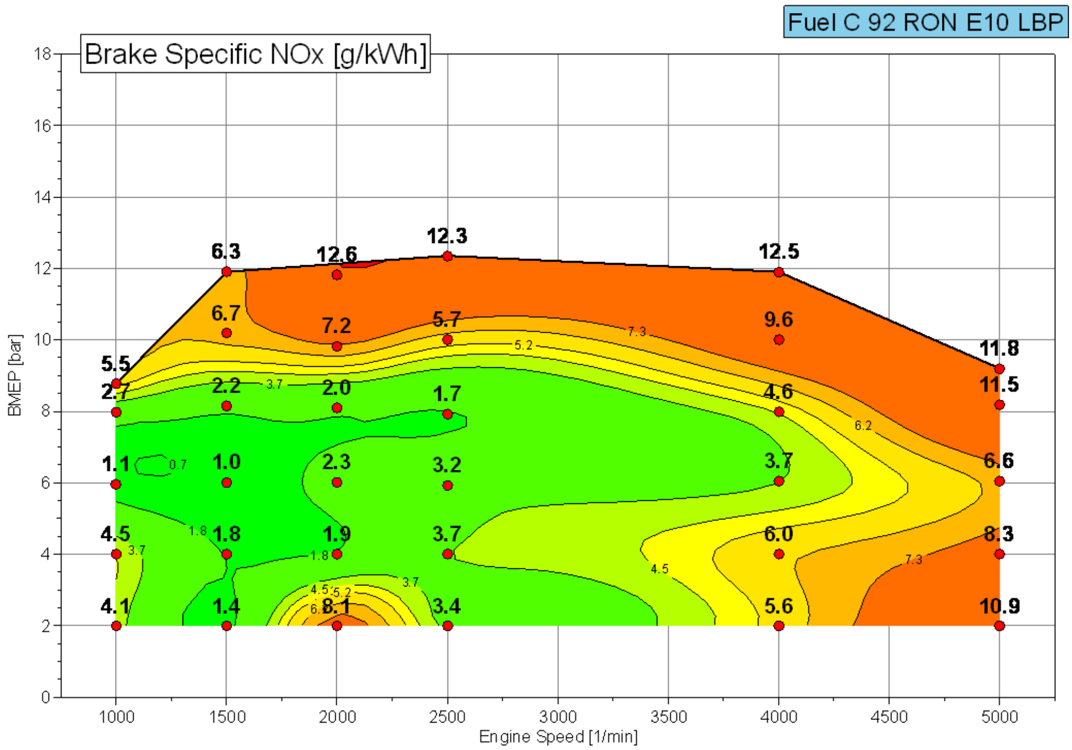

Figure 12: Brake Specific NOx Emissions

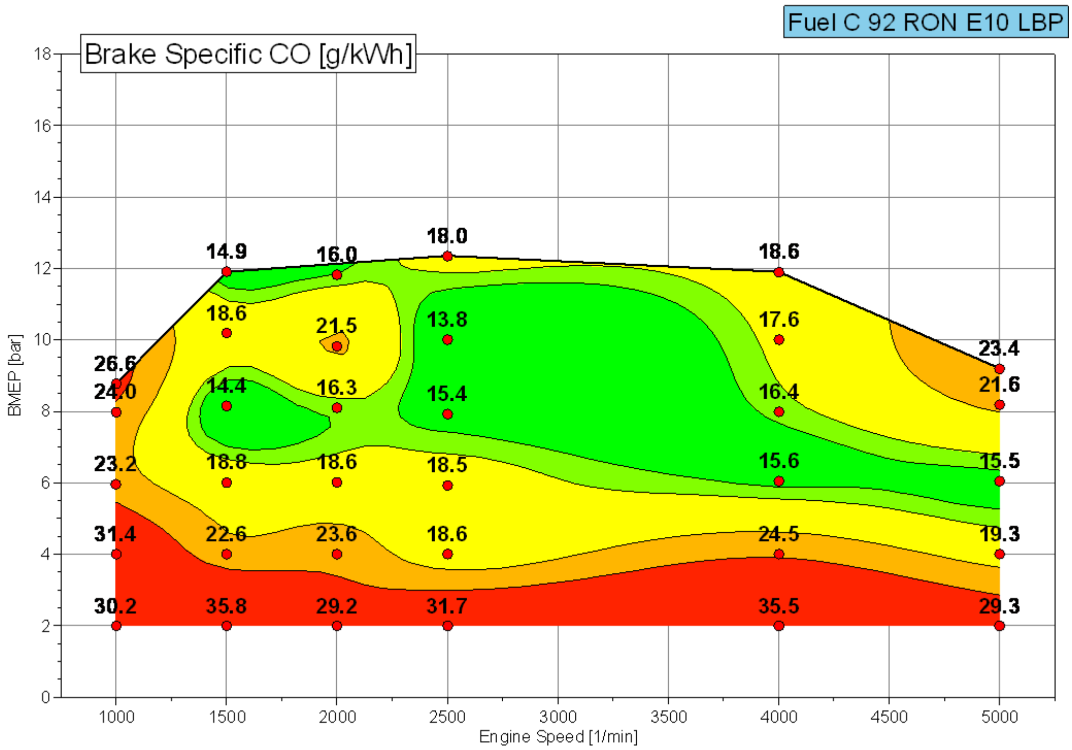

Figure 13: Brake Specific Carbon Monoxide Emissions

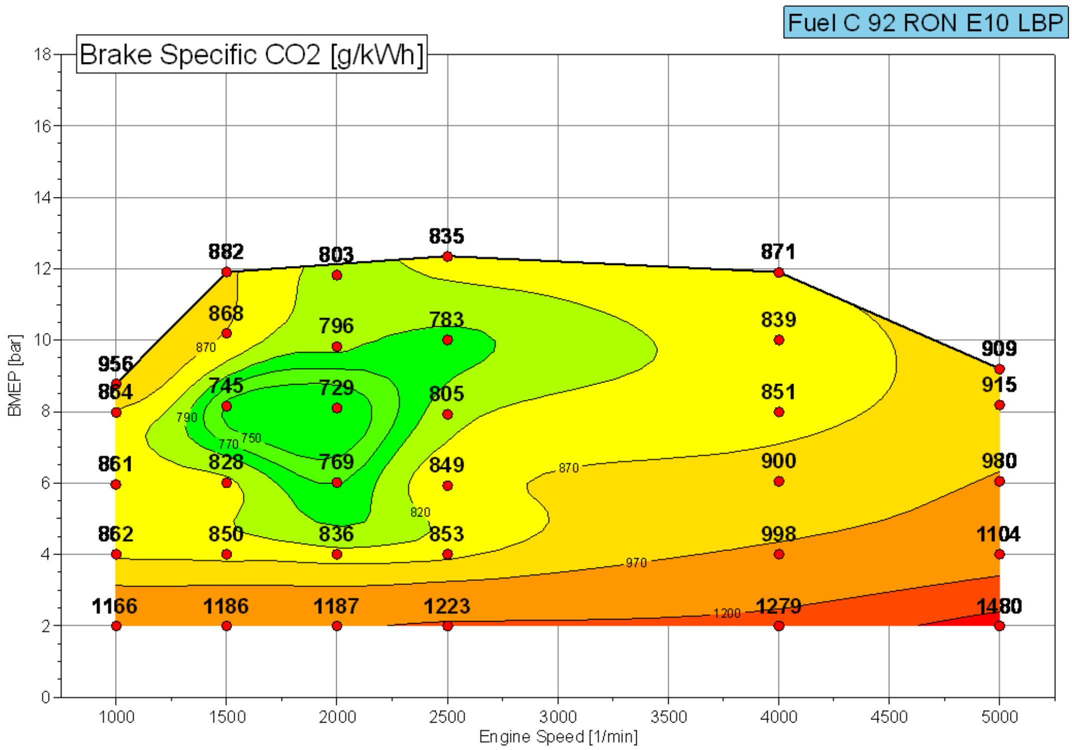

Figure 14: Brake Specific Carbon Dioxide Emissions

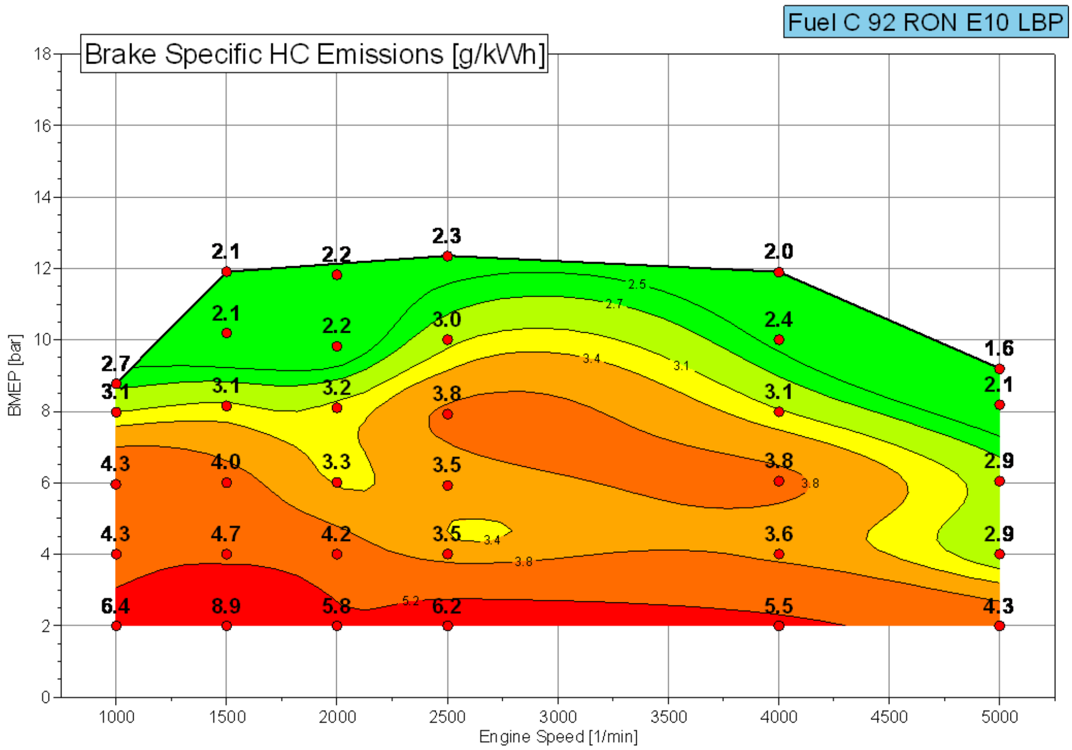

Figure 15: Brake Specific Hydrocarbon Emissions

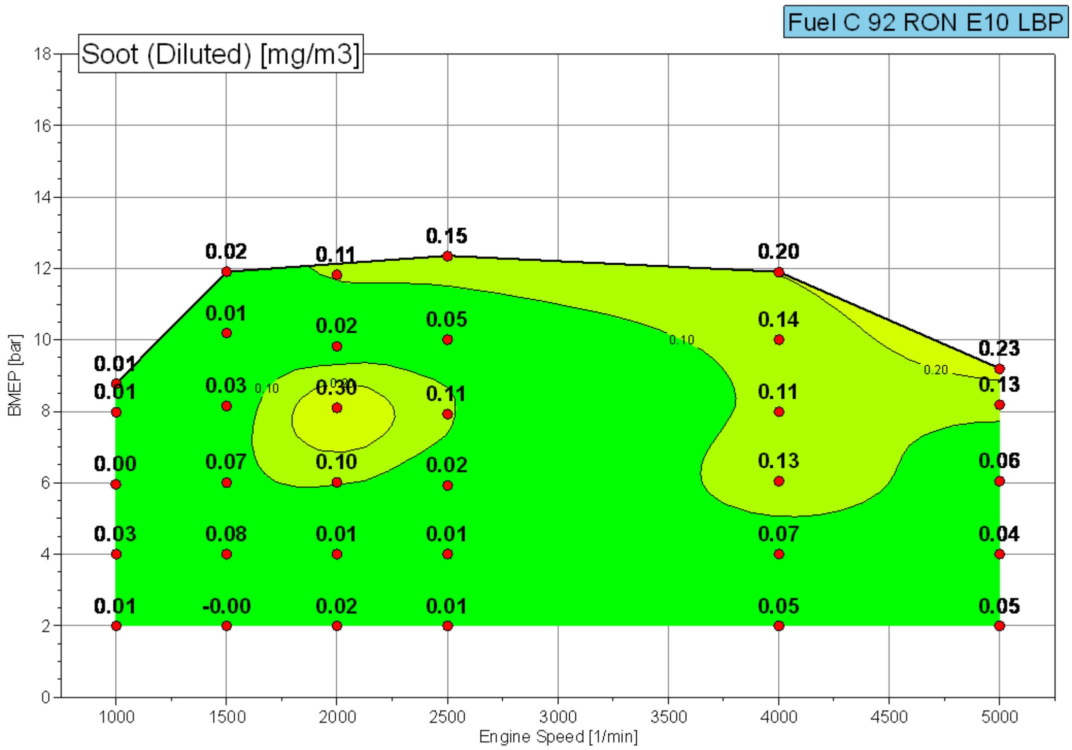

Figure 16: Particulate Soot Emissions

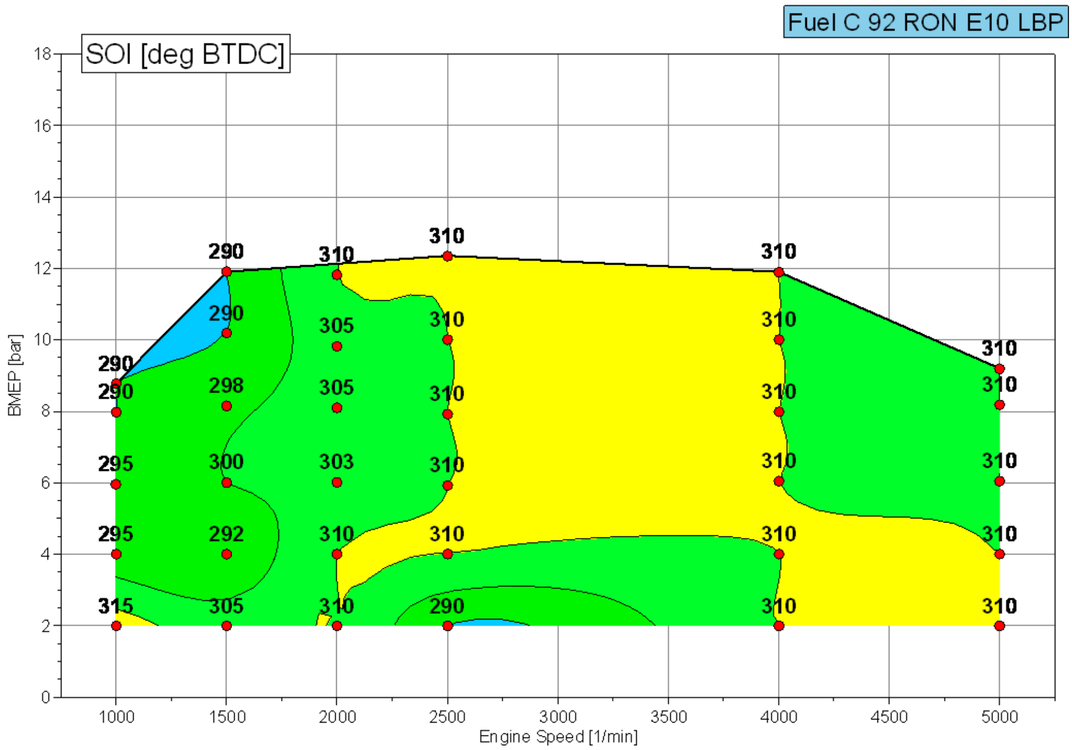

Figure 17: Start of Injection

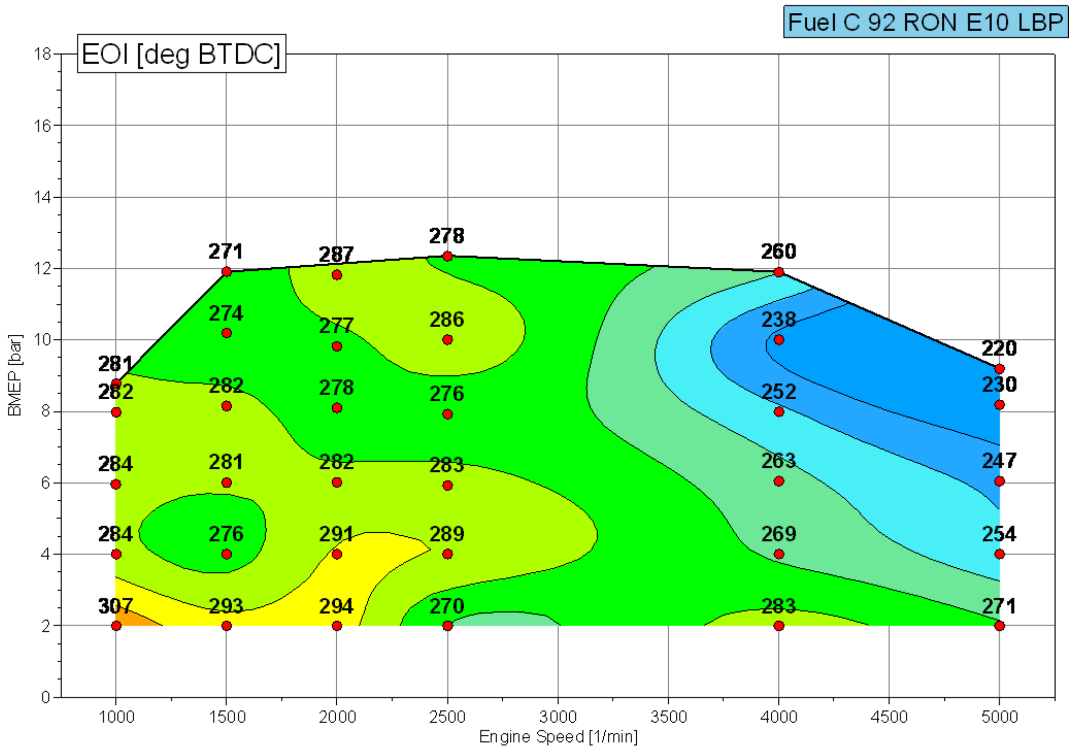

Figure 18: End of Injection

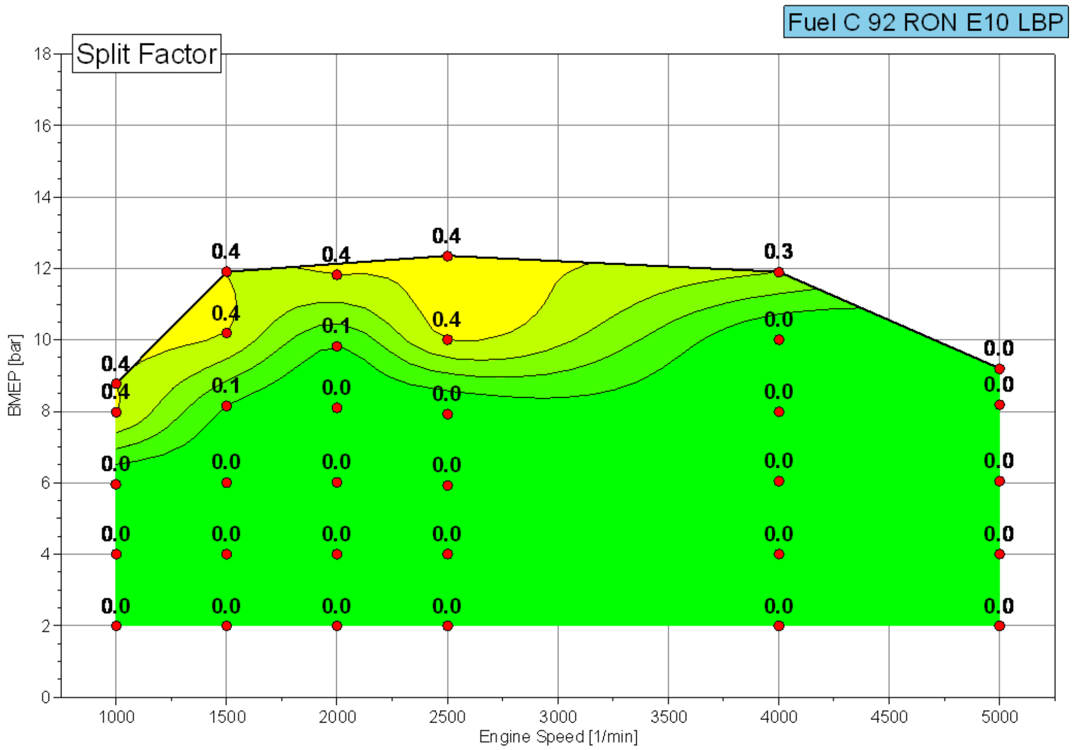

Figure 19: Injection Split Factor

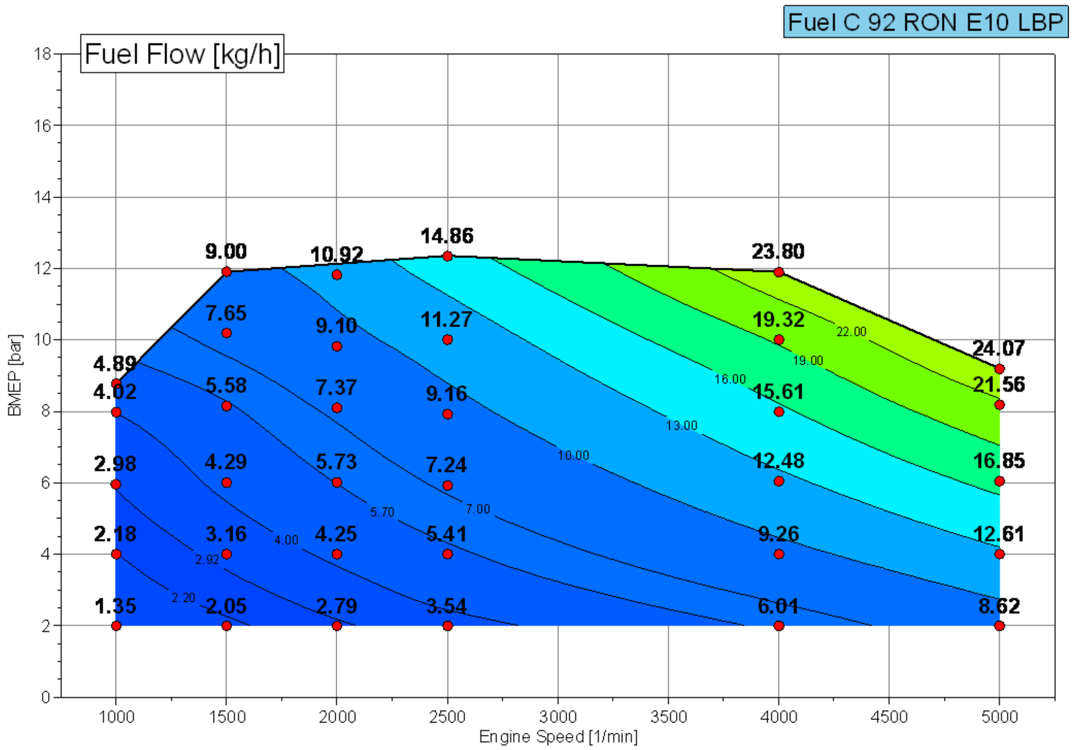

Figure 20: Fuel Flow

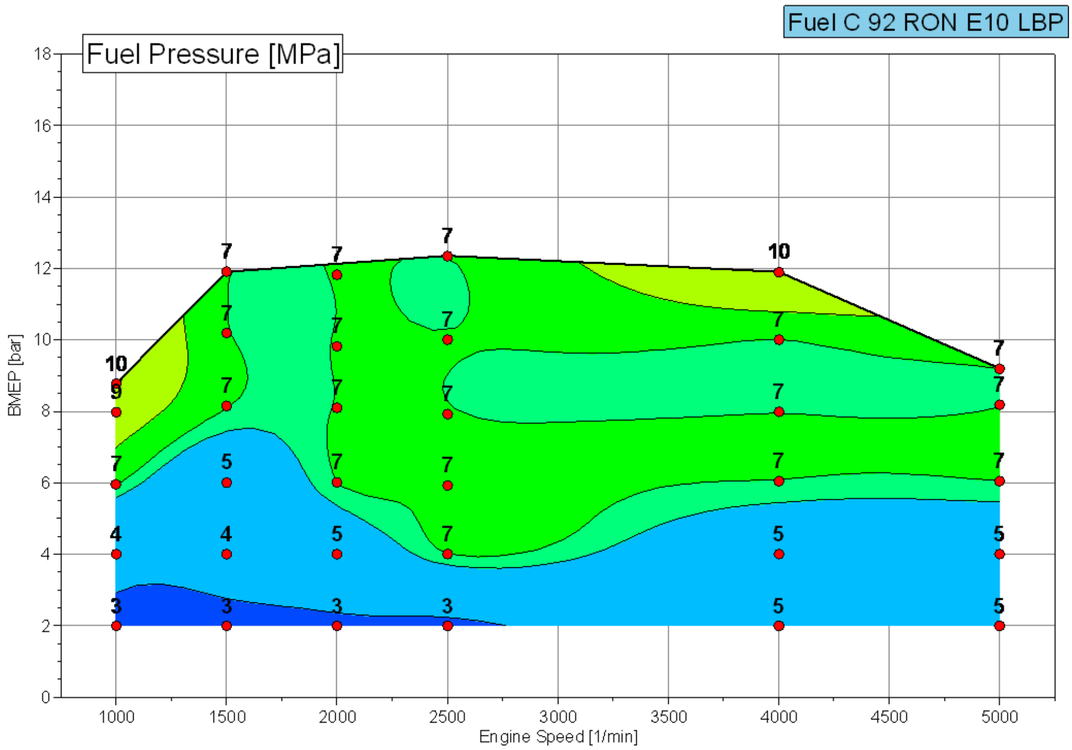

Figure 21: Fuel Rail Pressure

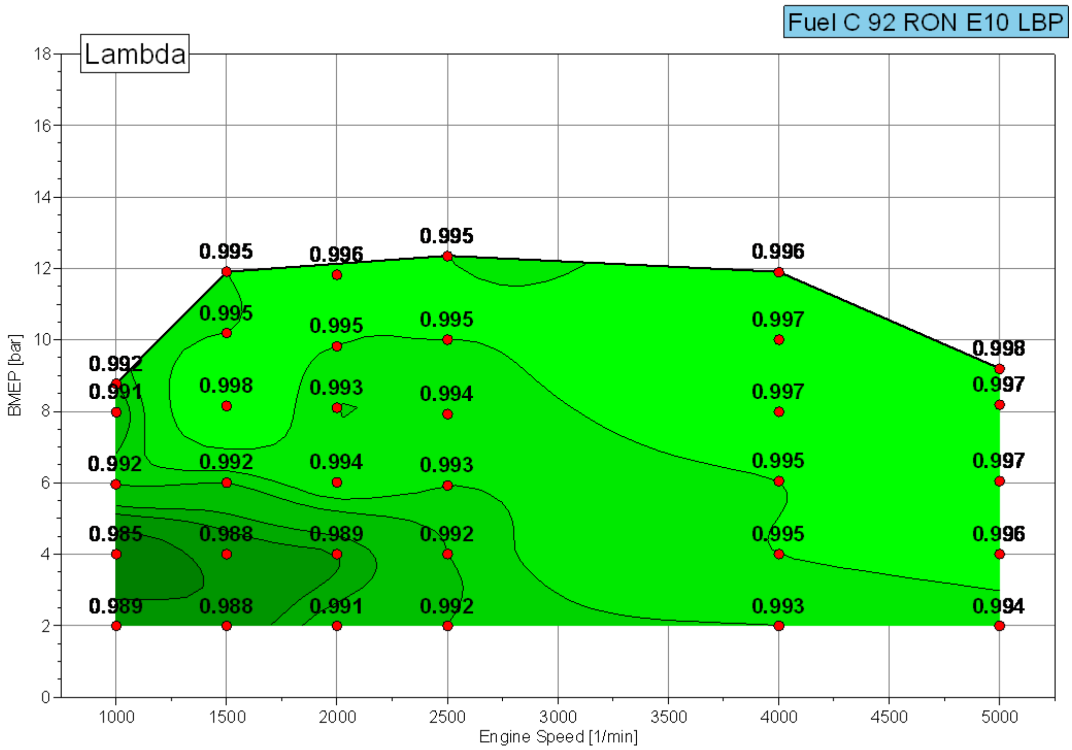

Figure 22: Lambda

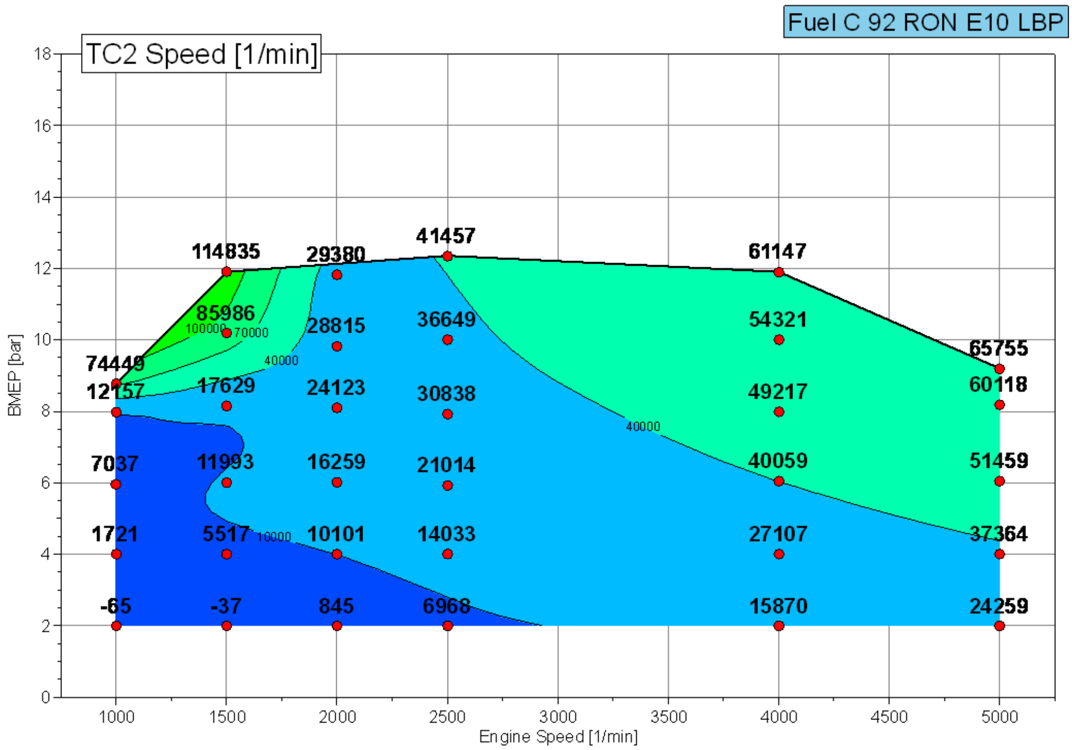

Figure 23: Low Pressure Turbocharger Speed

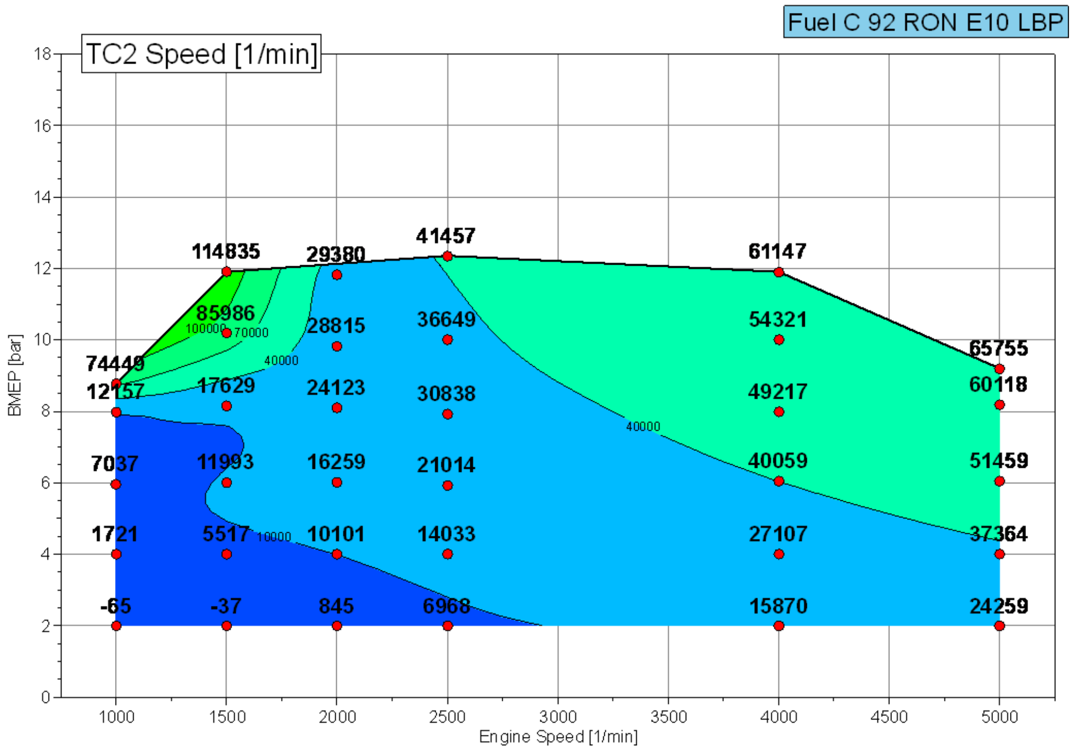

Figure 24: High Pressure Turbocharge Speed

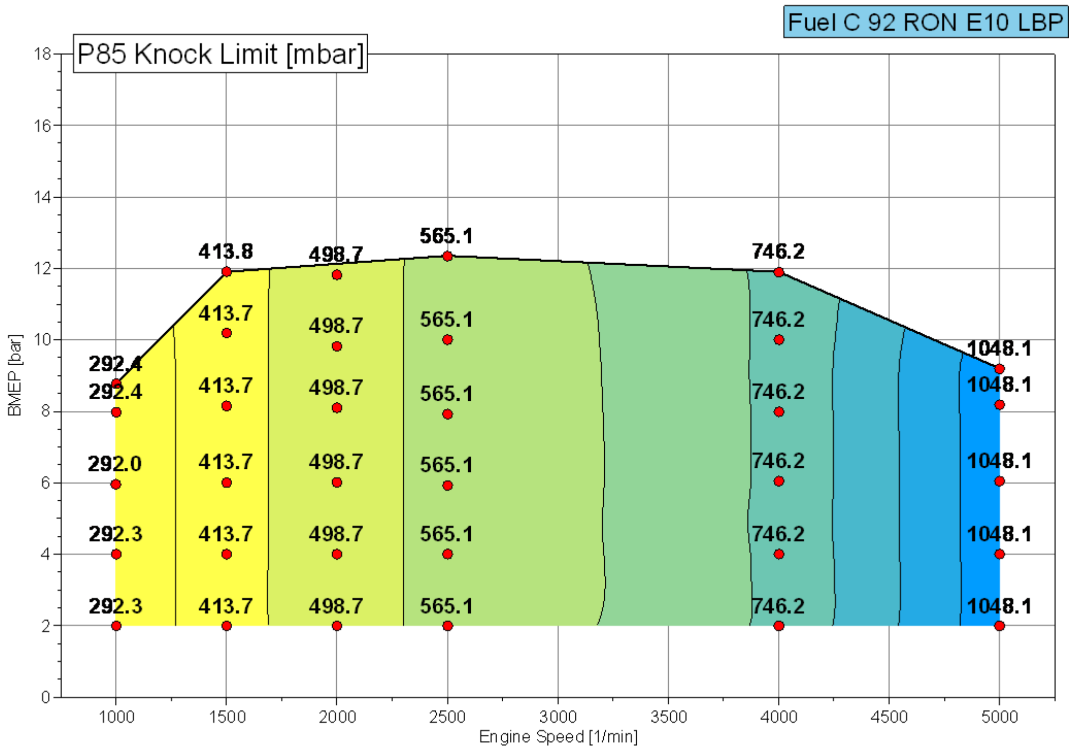

Figure 25: P85 Knock Limit

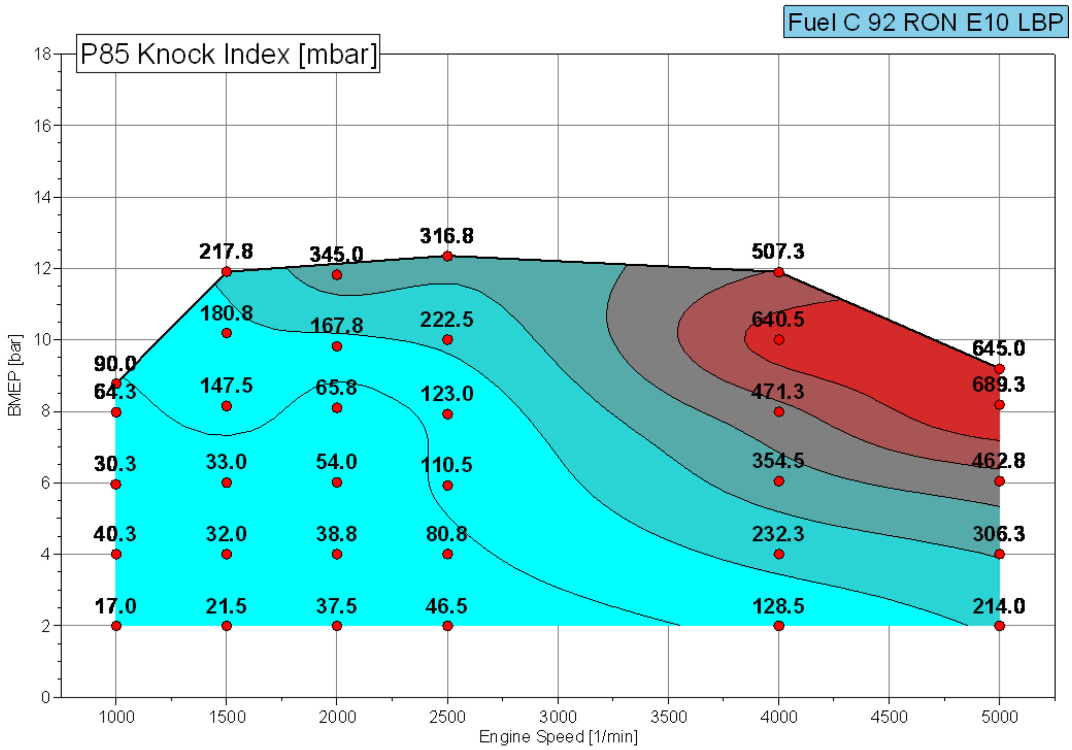

Figure 26: Averaged P85 Knock Index

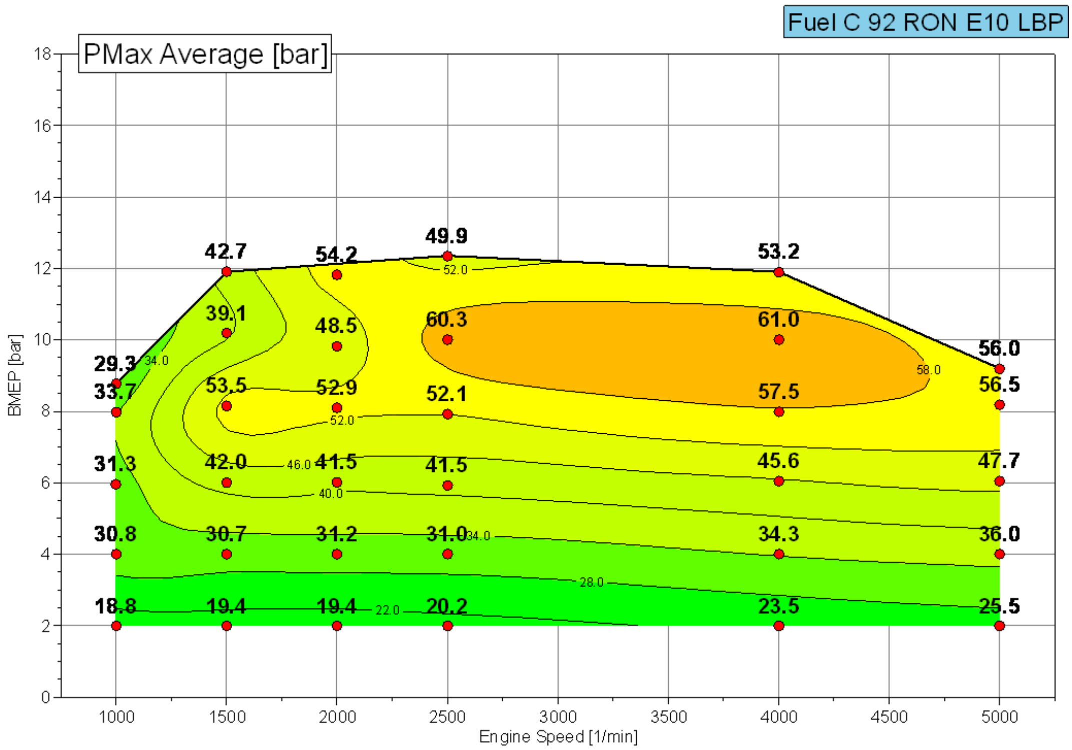

Figure 27: Averaged Max Pressure for Cylinders 1-4

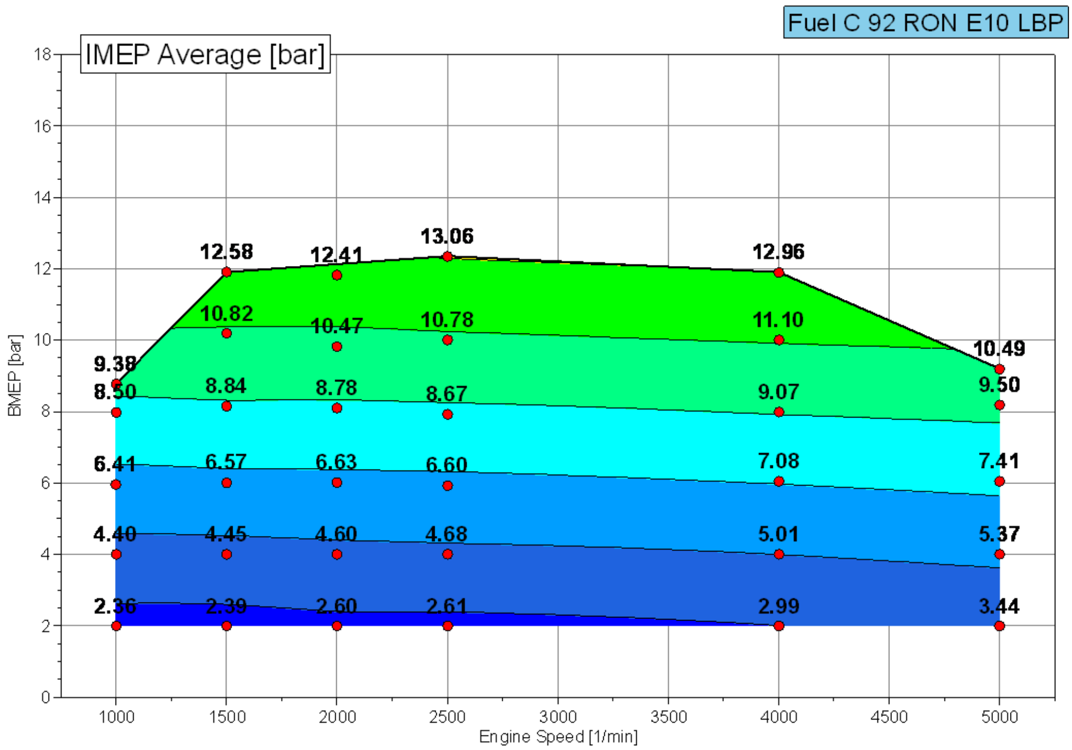

Figure 28: Indicated Mean Effective Pressure

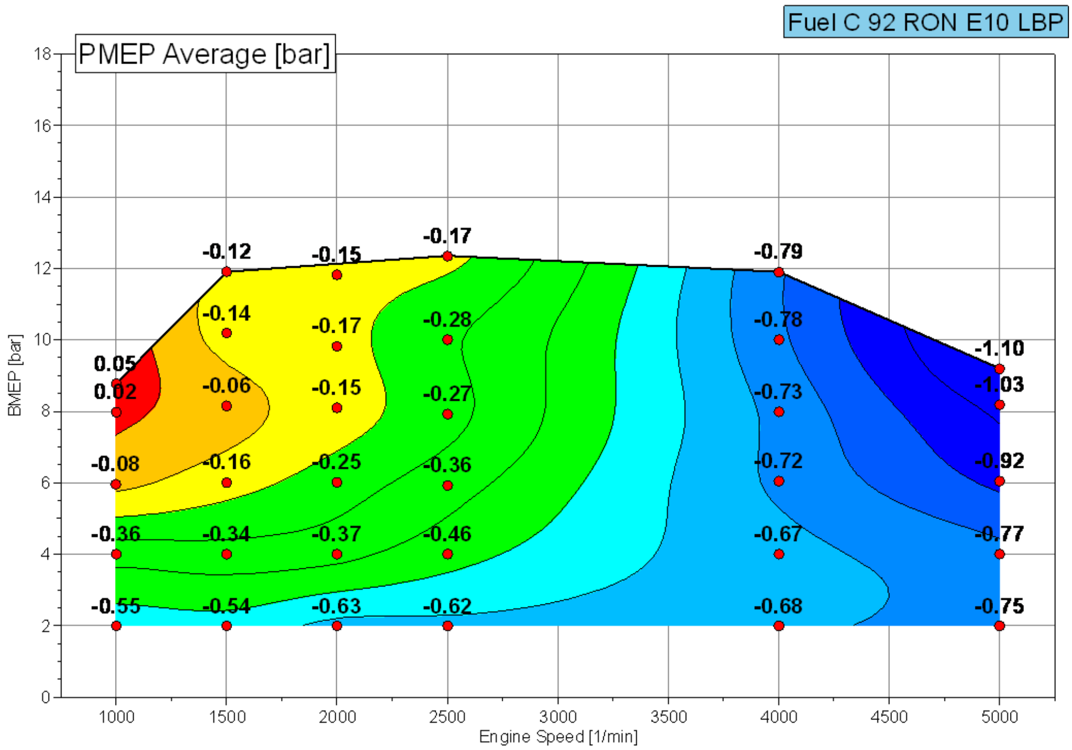

Figure 29: Pumping Mean Effective Pressure

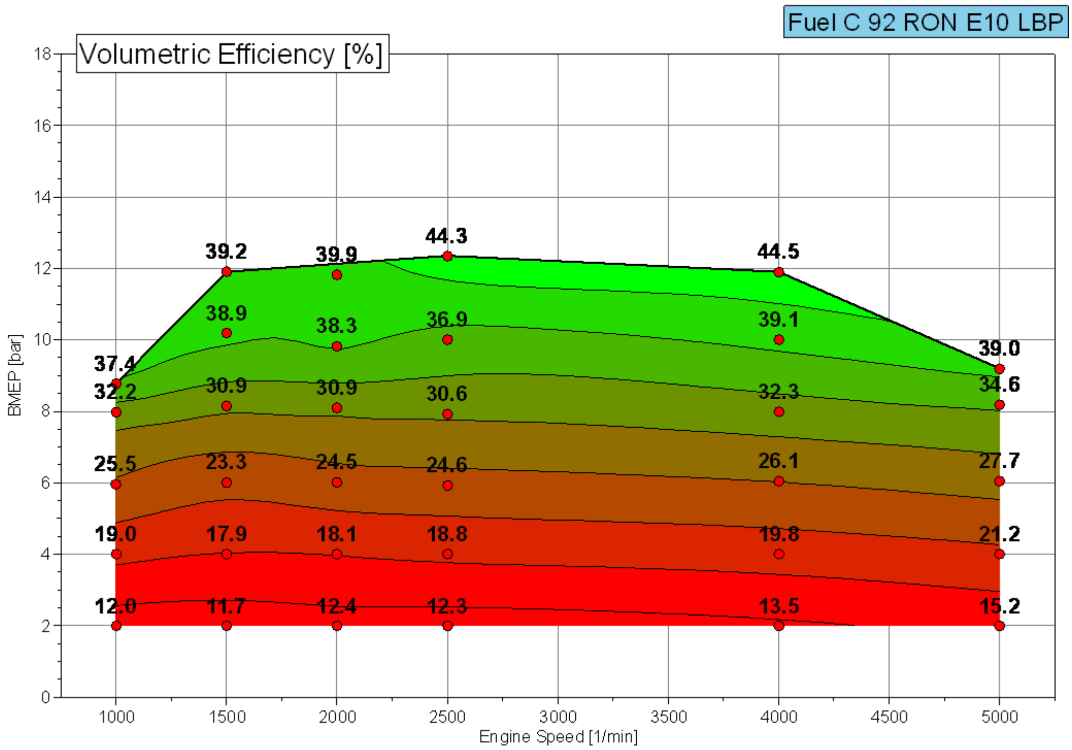

Figure 30: Calculated Volumetric Efficiency

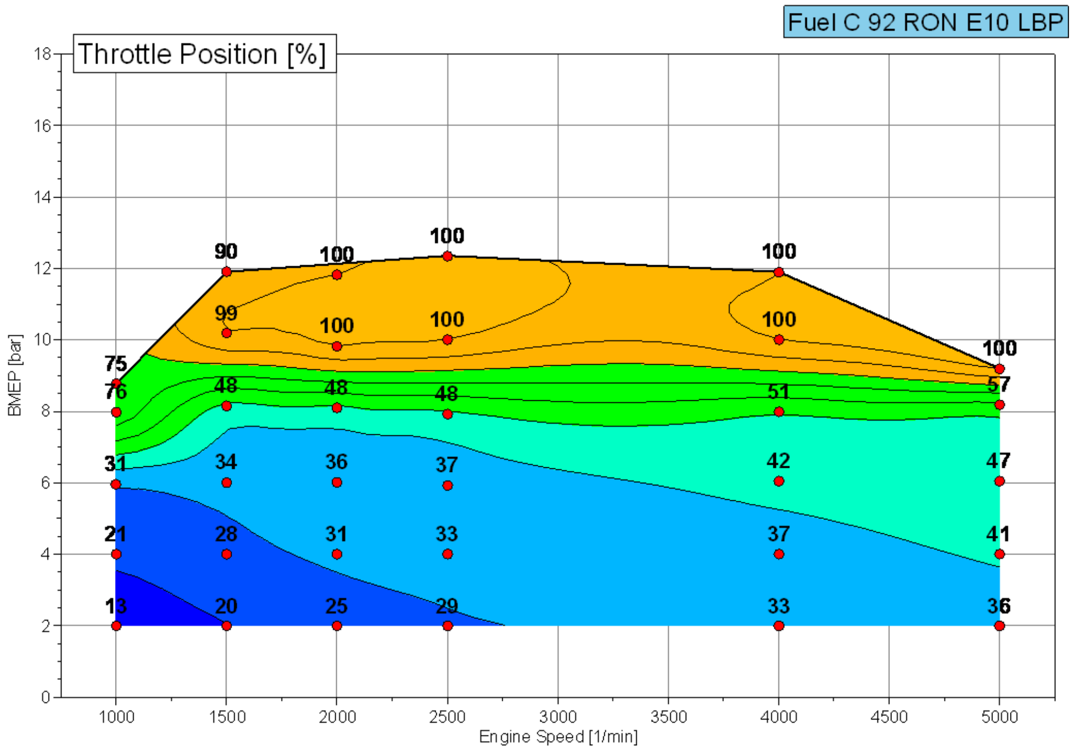

Figure 31: Throttle Position

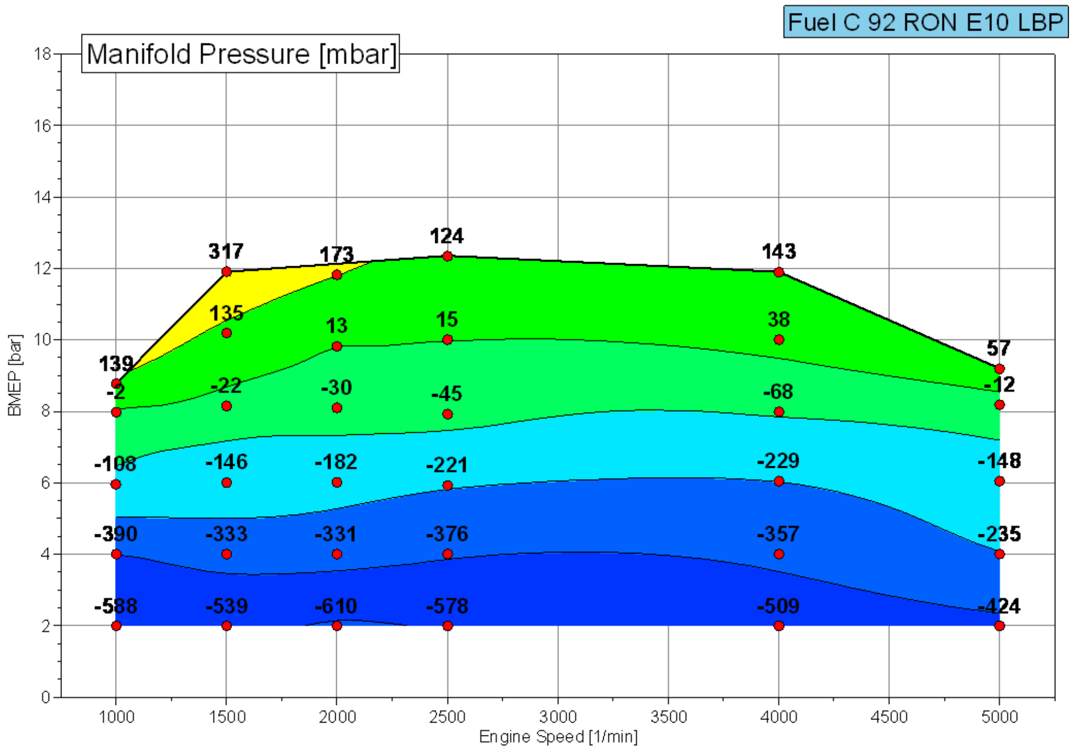

Figure 32: Intake Manifold Pressure

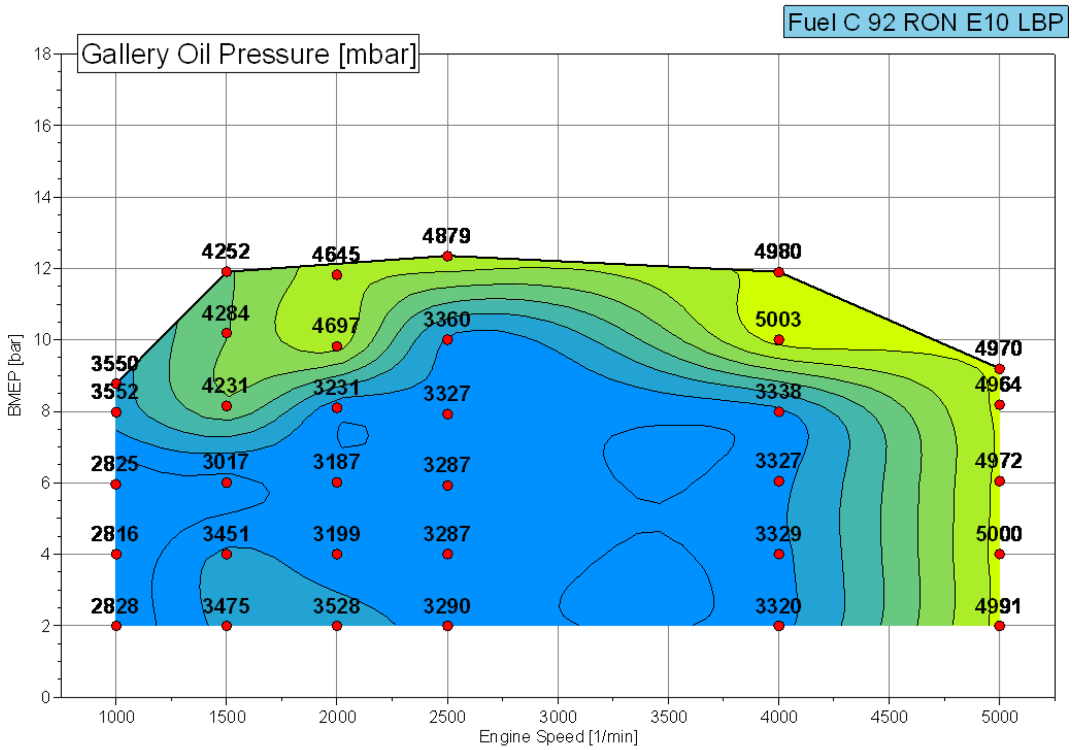

Figure 33: Gallery Oil Pressure

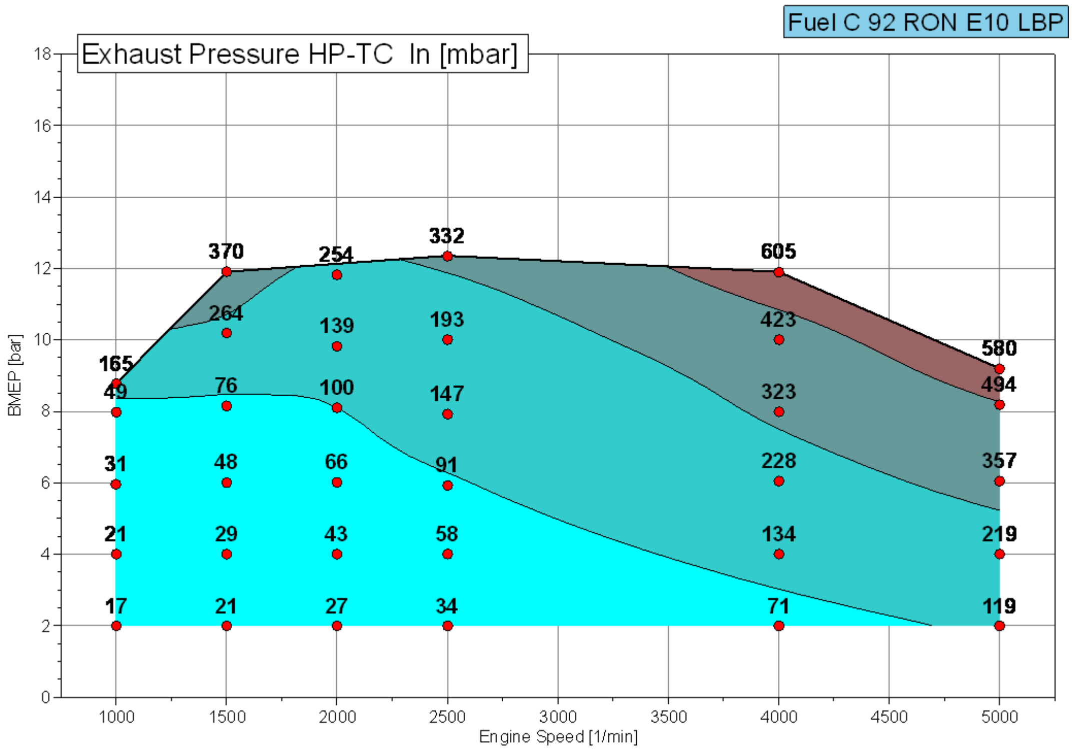

Figure 34: Exhaust Pressure High Pressure Turbocharger In

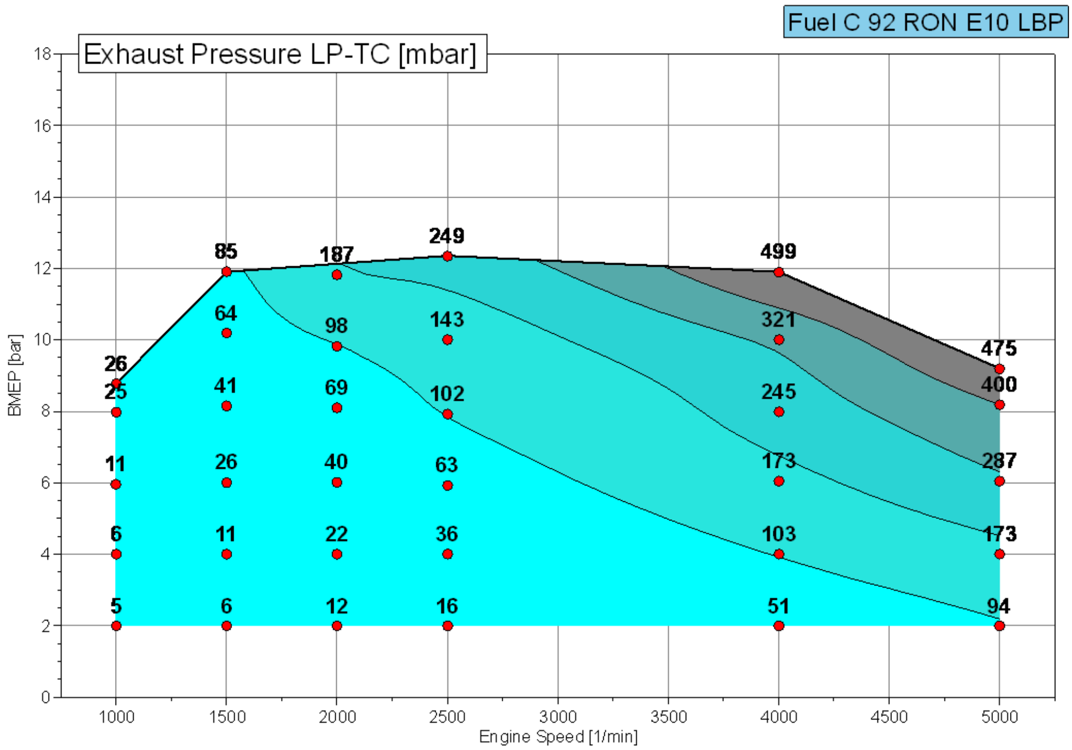

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

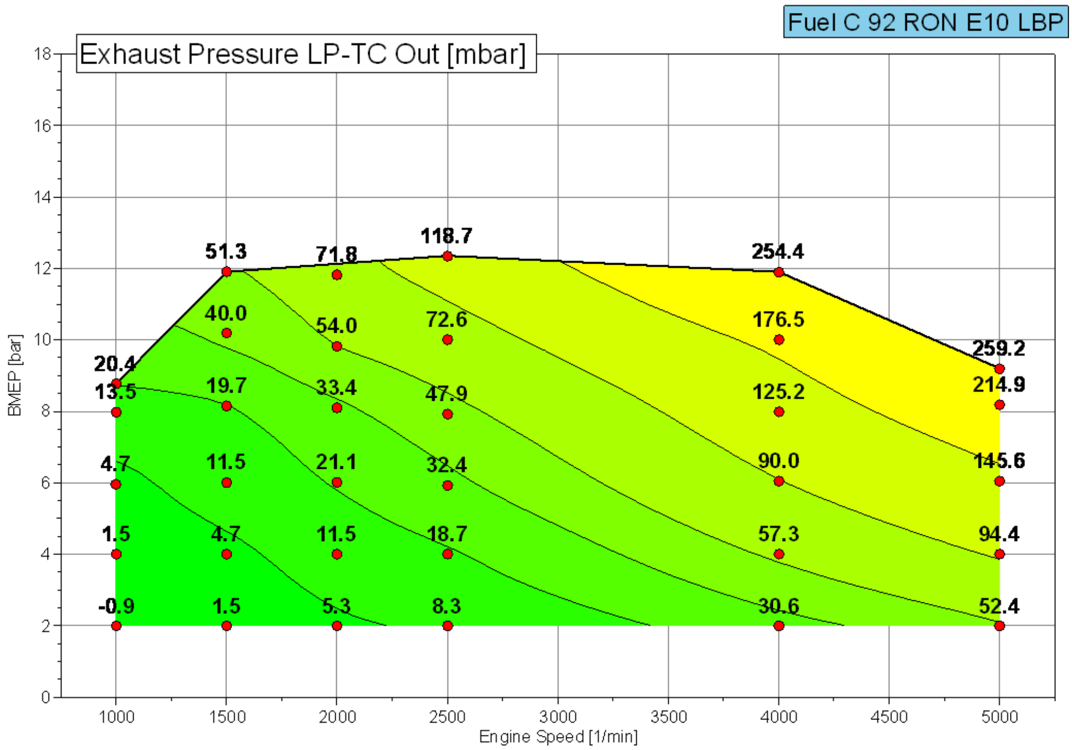

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

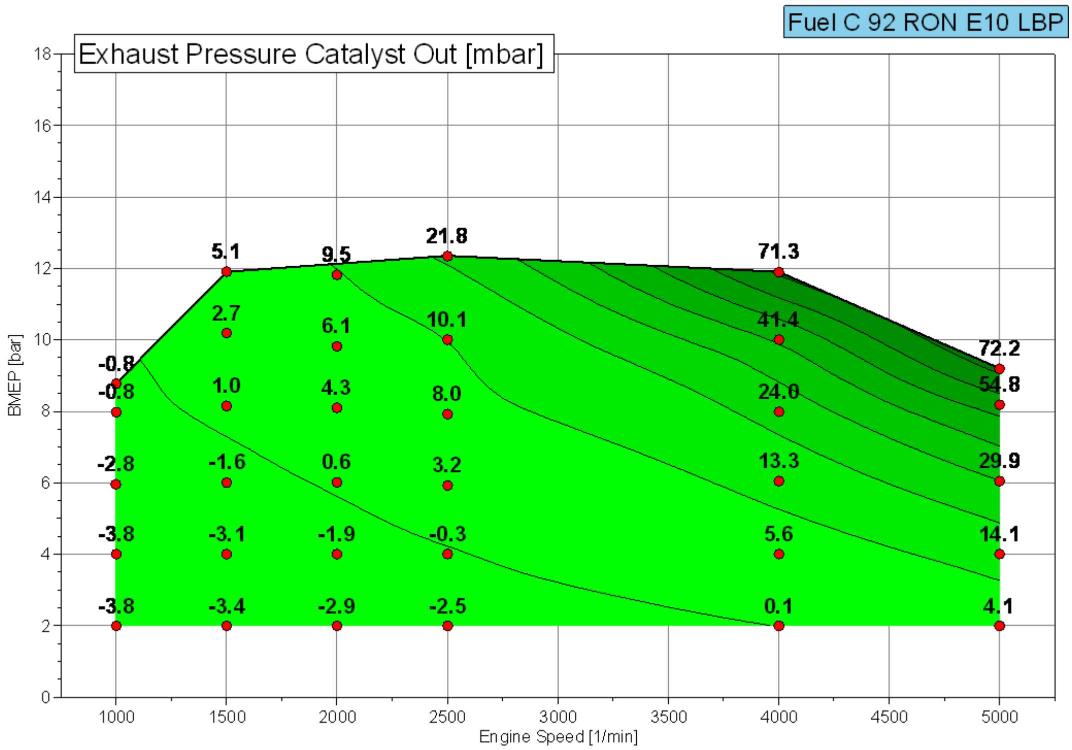

Figure 37: Exhaust Pressure Catalyst Out

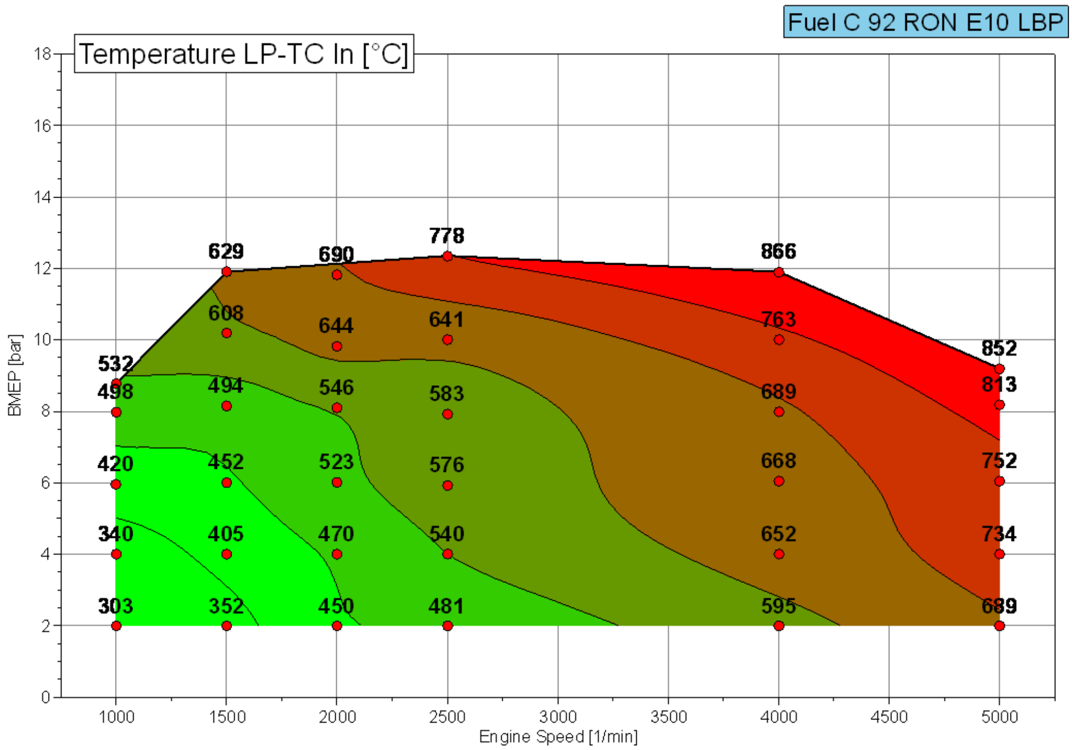

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

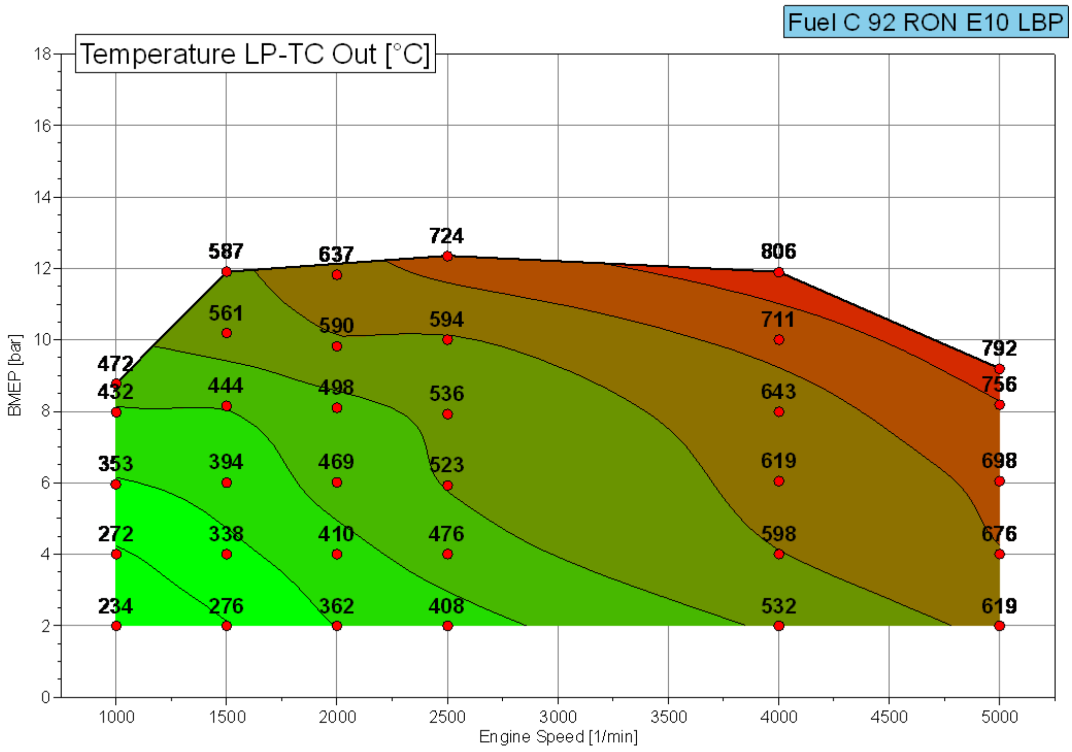

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

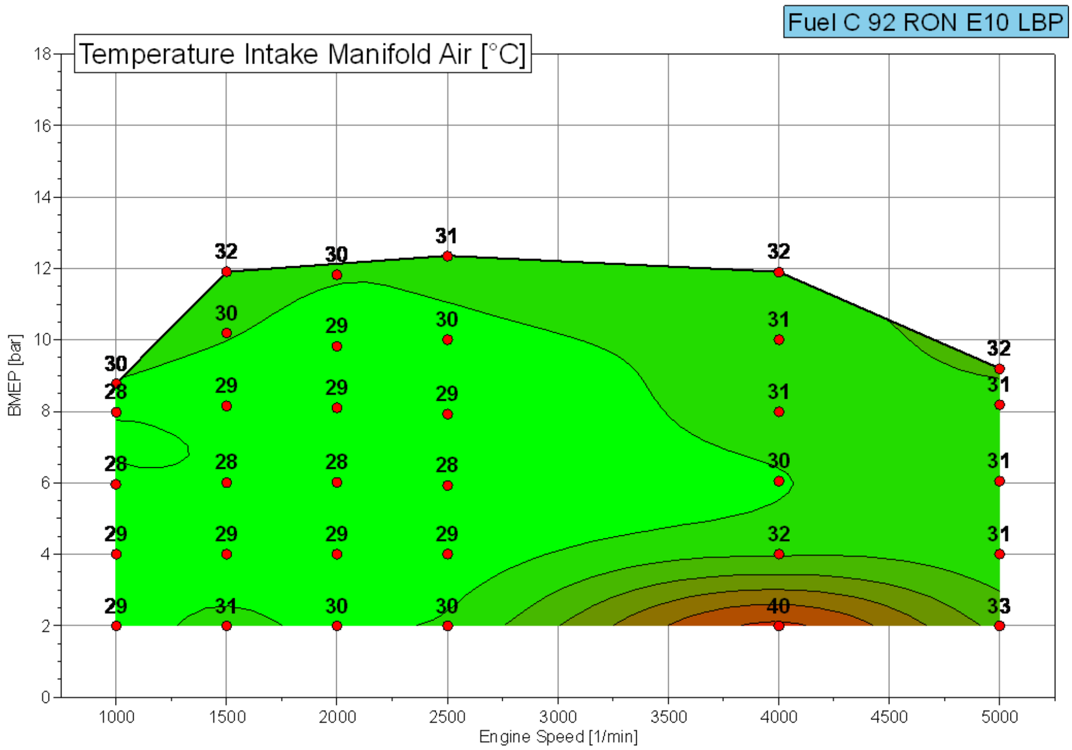

Figure 40: Intake Manifold Air Temperature

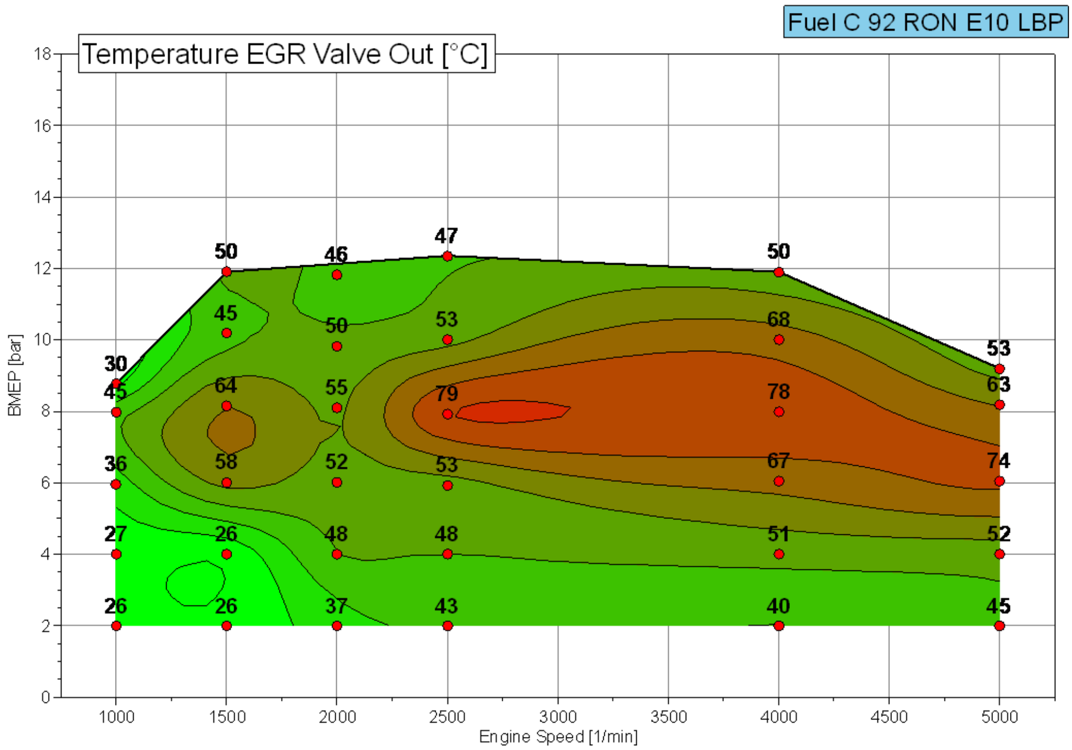

Figure 41: EGR Valve Out Temperature

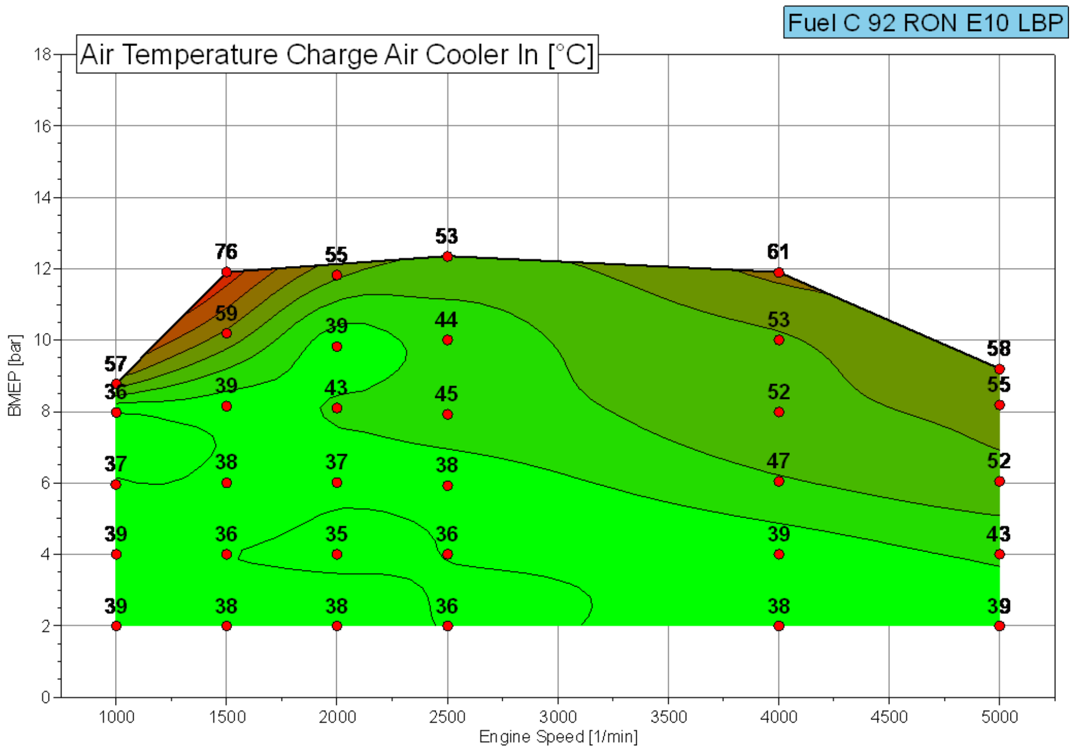

Figure 42: Charge Air Cooler Inlet Air Temperature

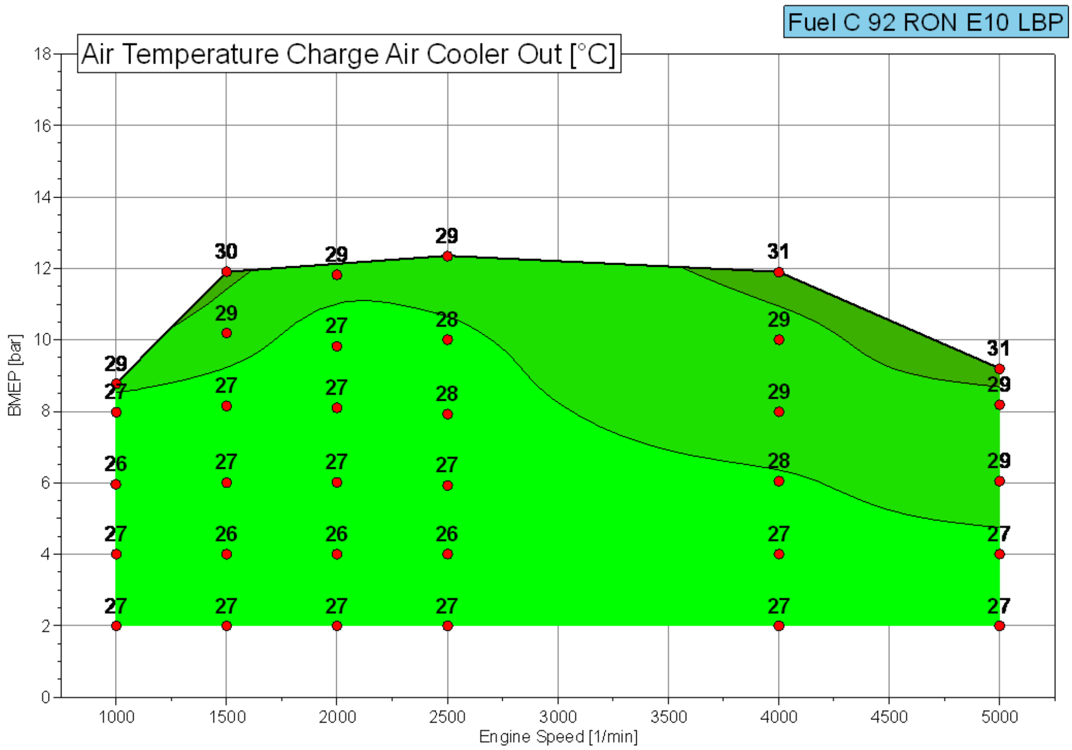

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel E Calibration Results

92 Ron 30% Ethanol Low Boiling Point

automotive engineering

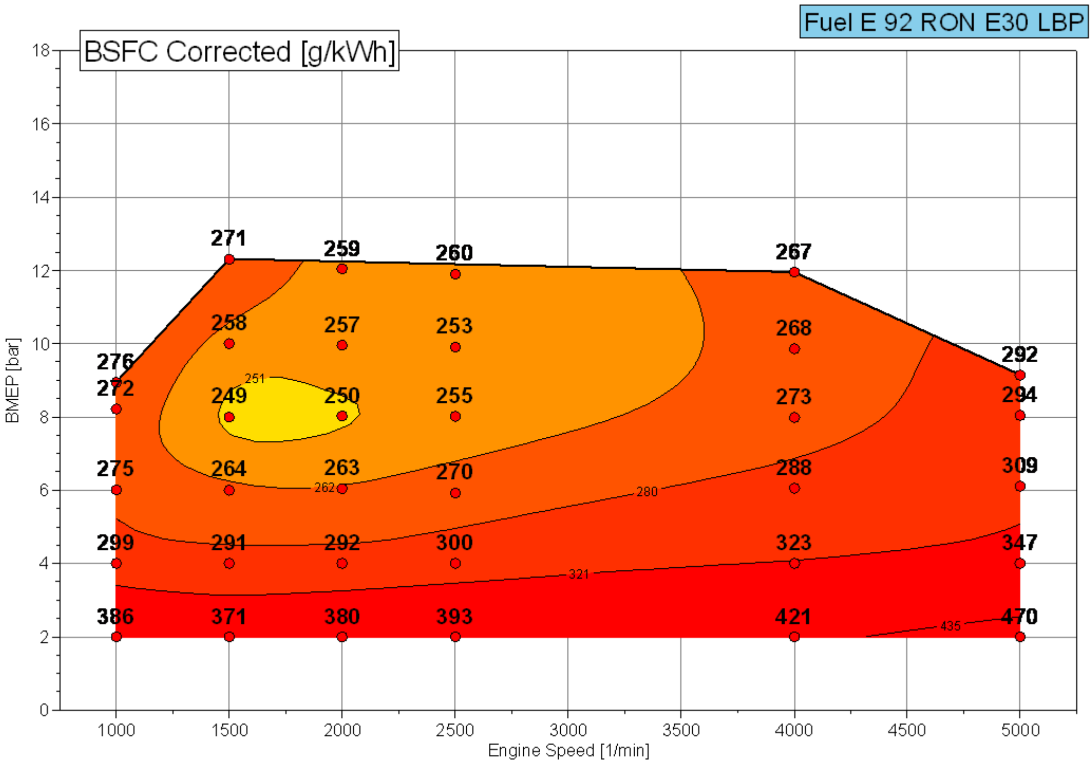

Figure 1: Brake Specific Fuel Consumption

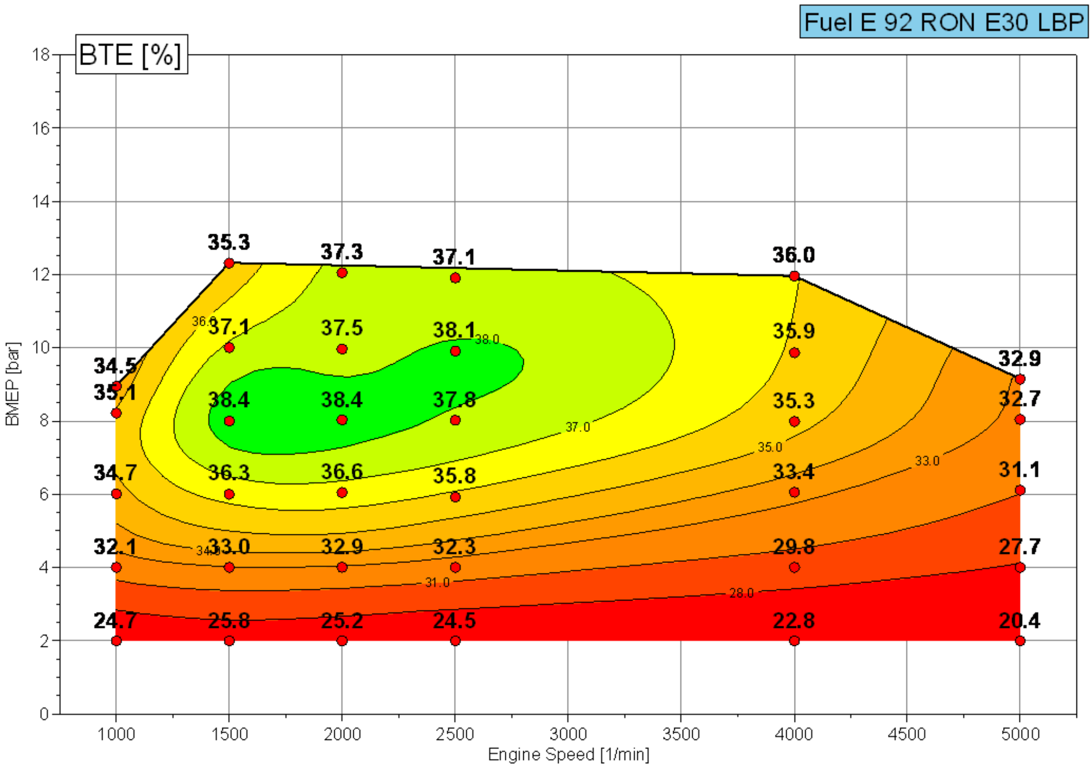

Figure 2: Brake Thermal Efficiency

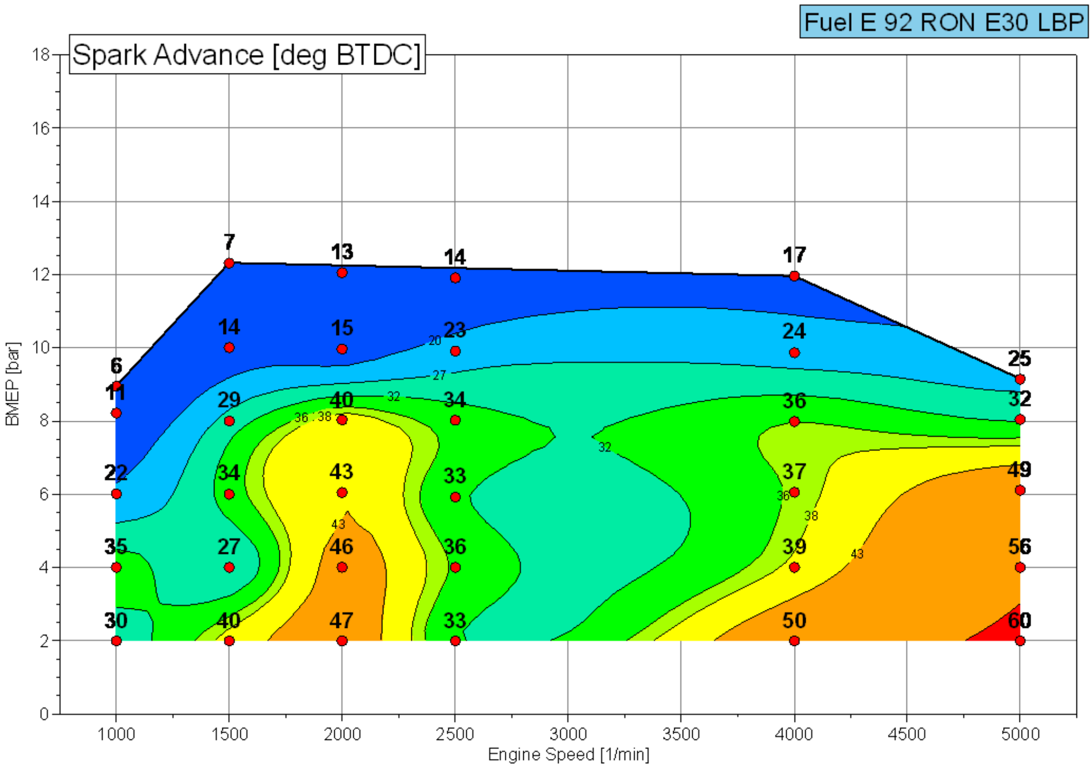

Figure 3: Spark Advance

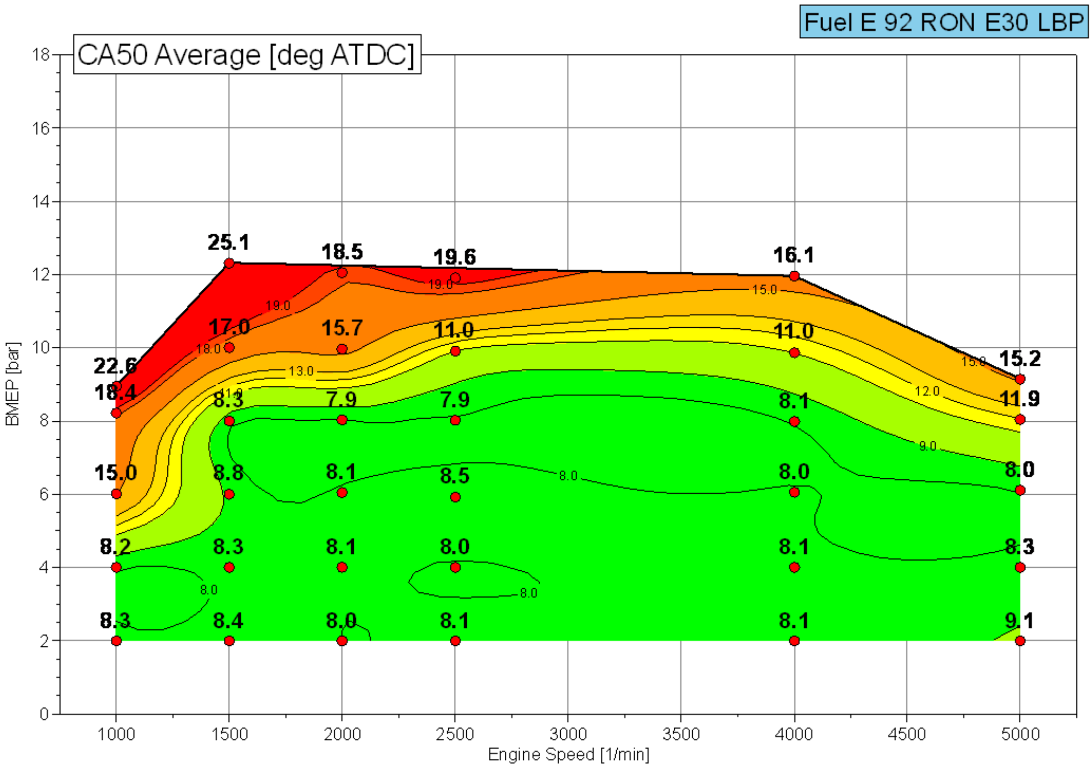

Figure 4: CA50 Average of Cylinders 1-4

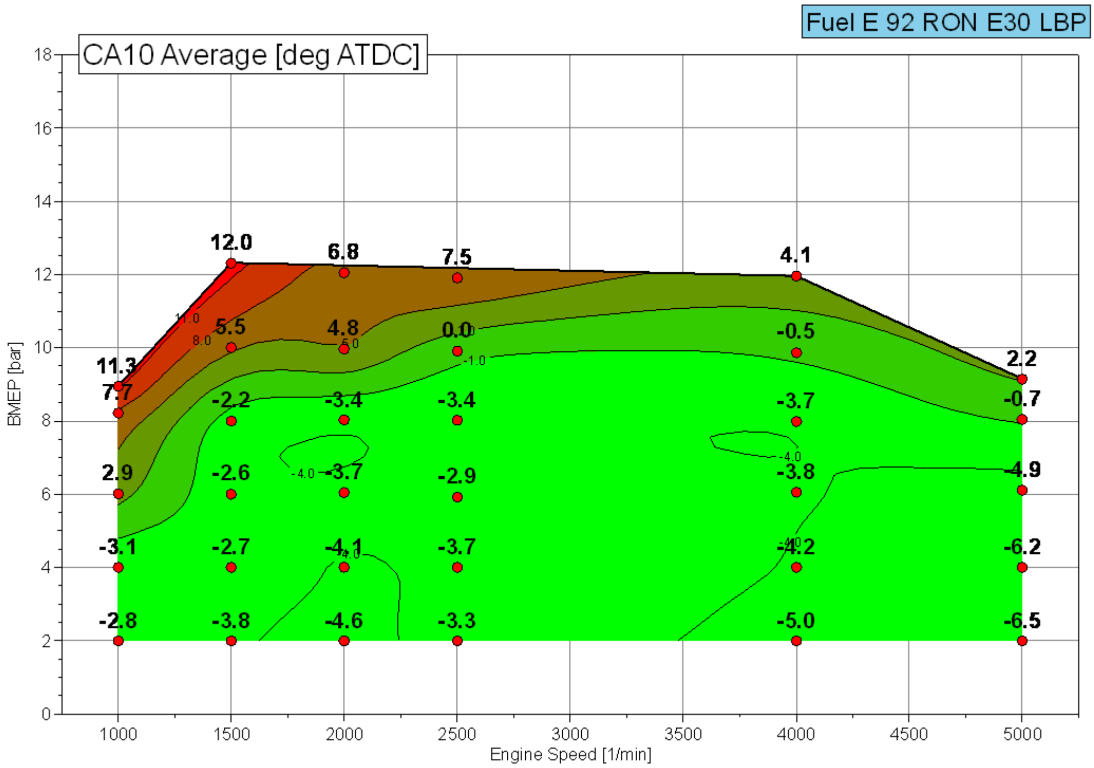

Figure 5: CA10 Average of Cylinders 1-4

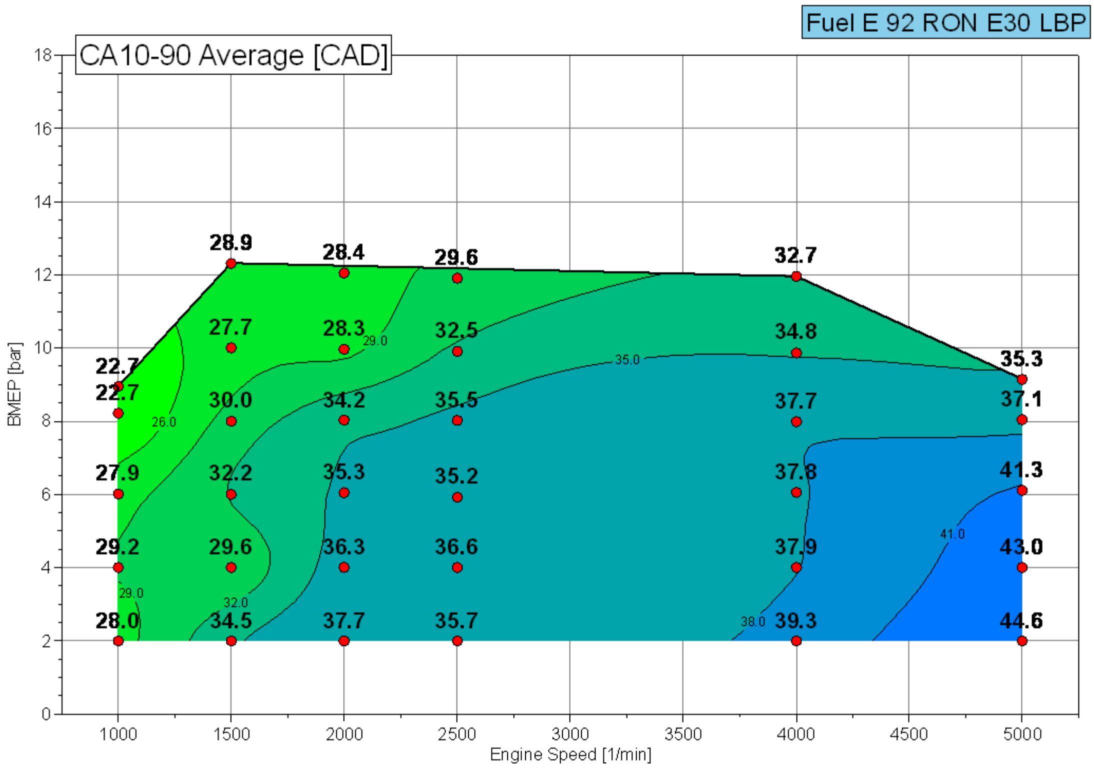

Figure 6: CA10-90 Average of Cylinders 1-4

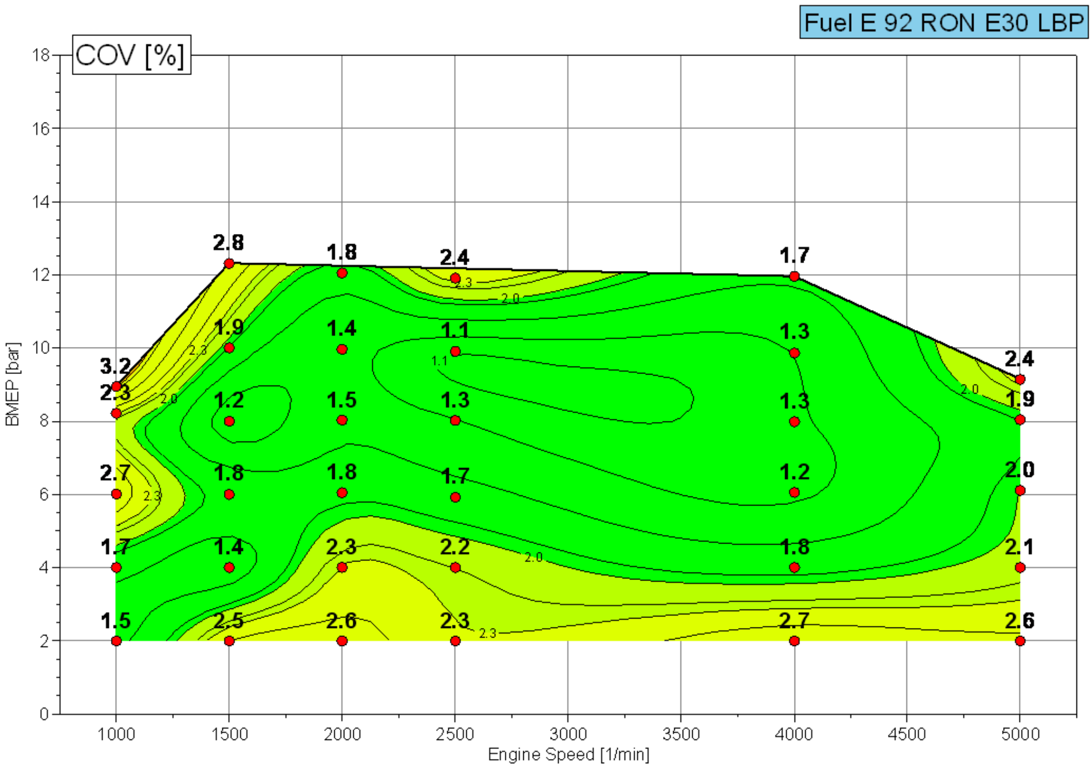

Figure 7: Coefficient of Variation Average of Cylinders 1-4

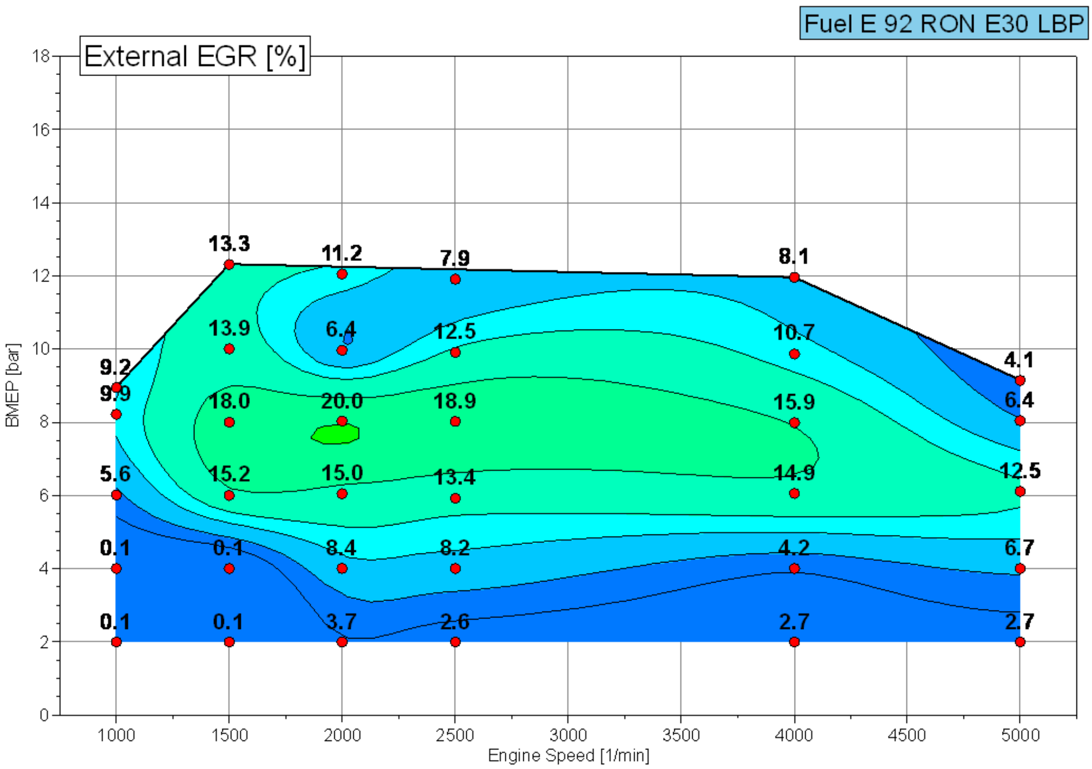

Figure 8: External EGR Percent of Intake Air

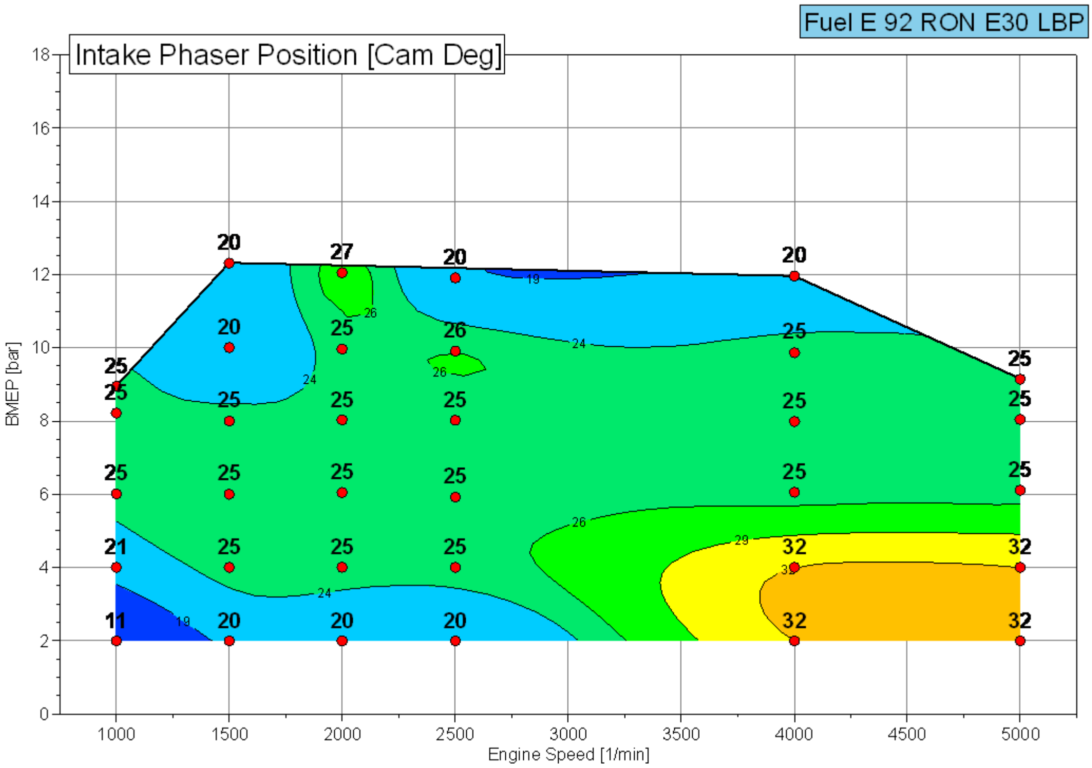

Figure 9: Intake Camshaft Phaser Position

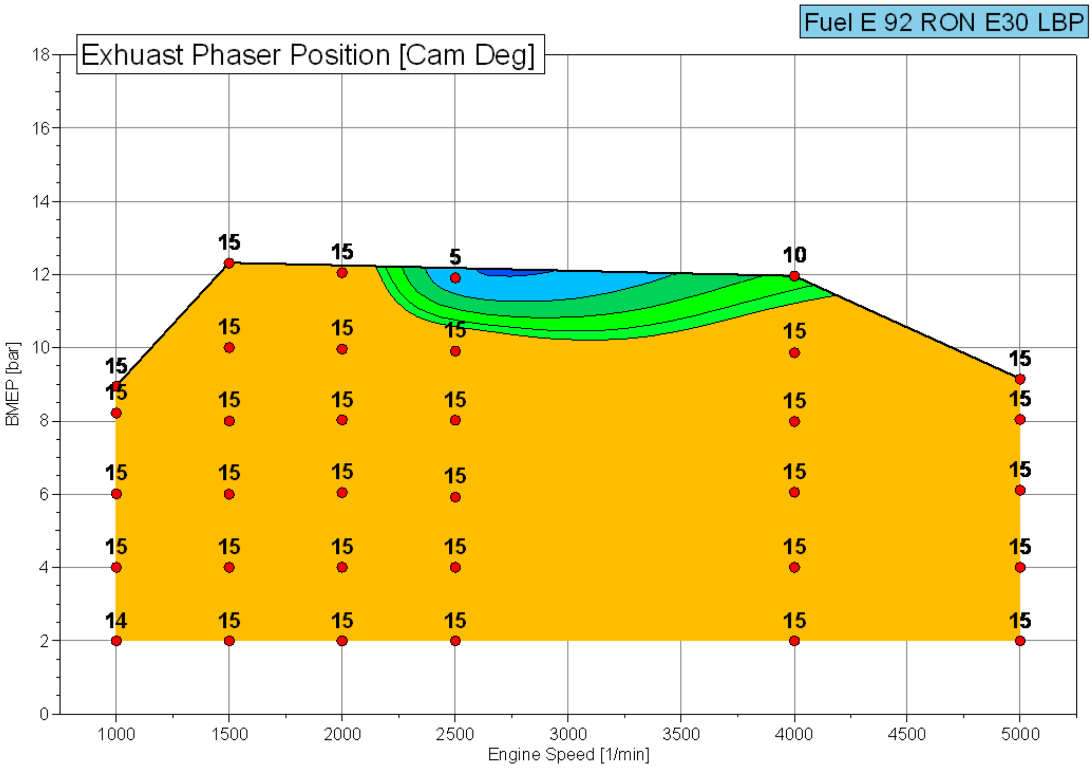

Figure 10: Exhaust Camshaft Phaser Position

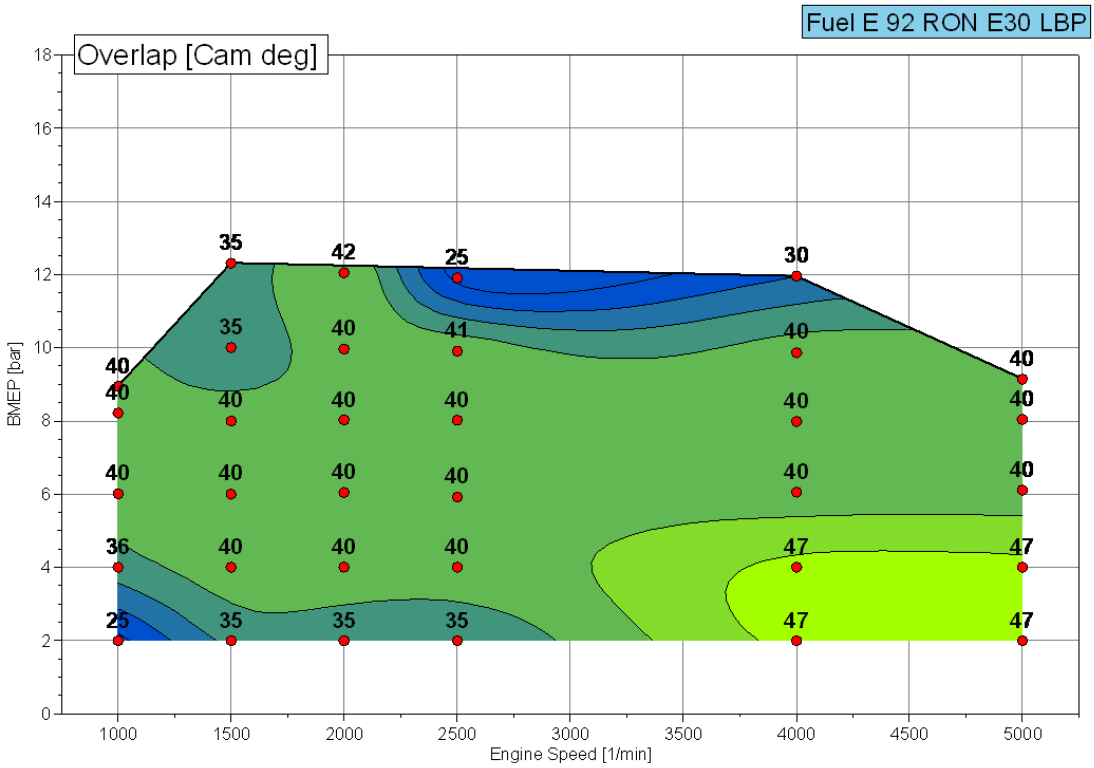

Figure 11: Camshaft Overlap

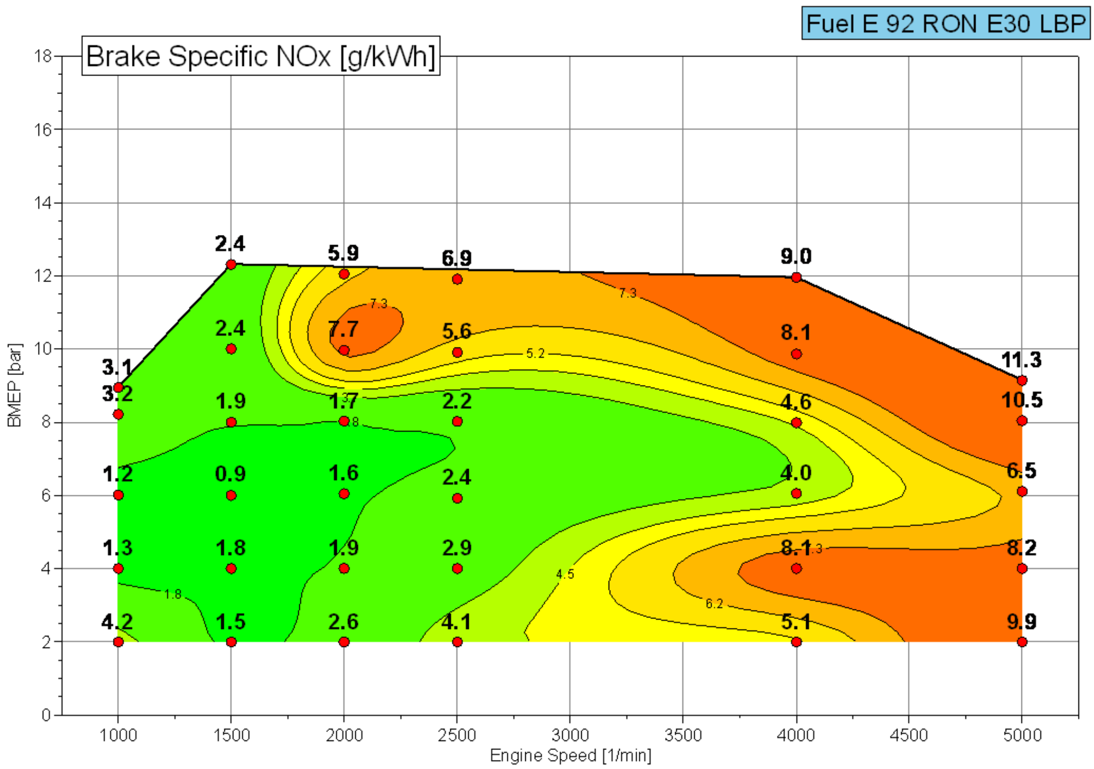

Figure 12: Brake Specific NOx Emissions

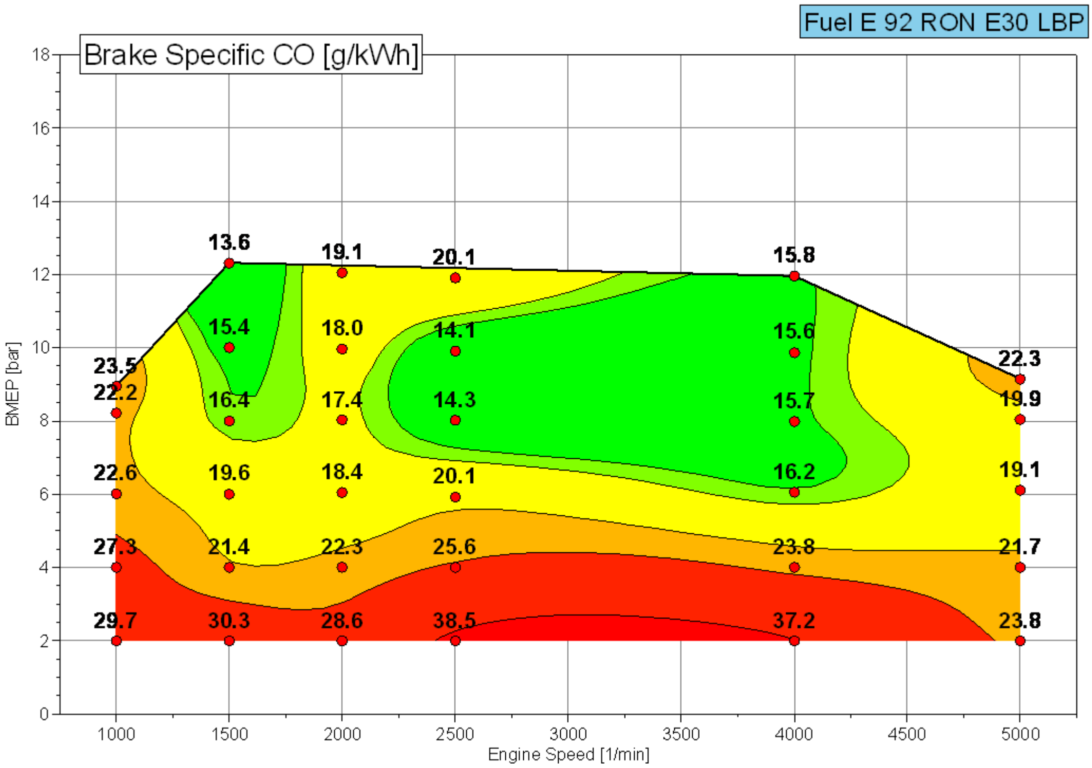

Figure 13: Brake Specific Carbon Monoxide Emissions

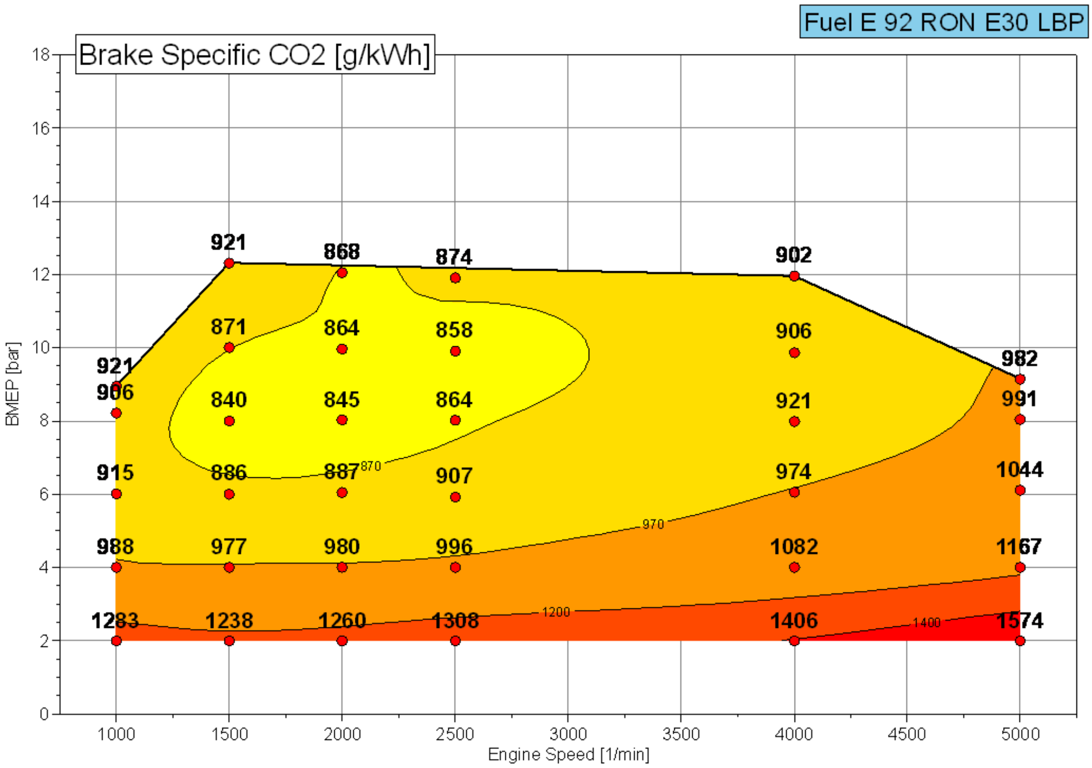

Figure 14: Brake Specific Carbon Dioxide Emissions

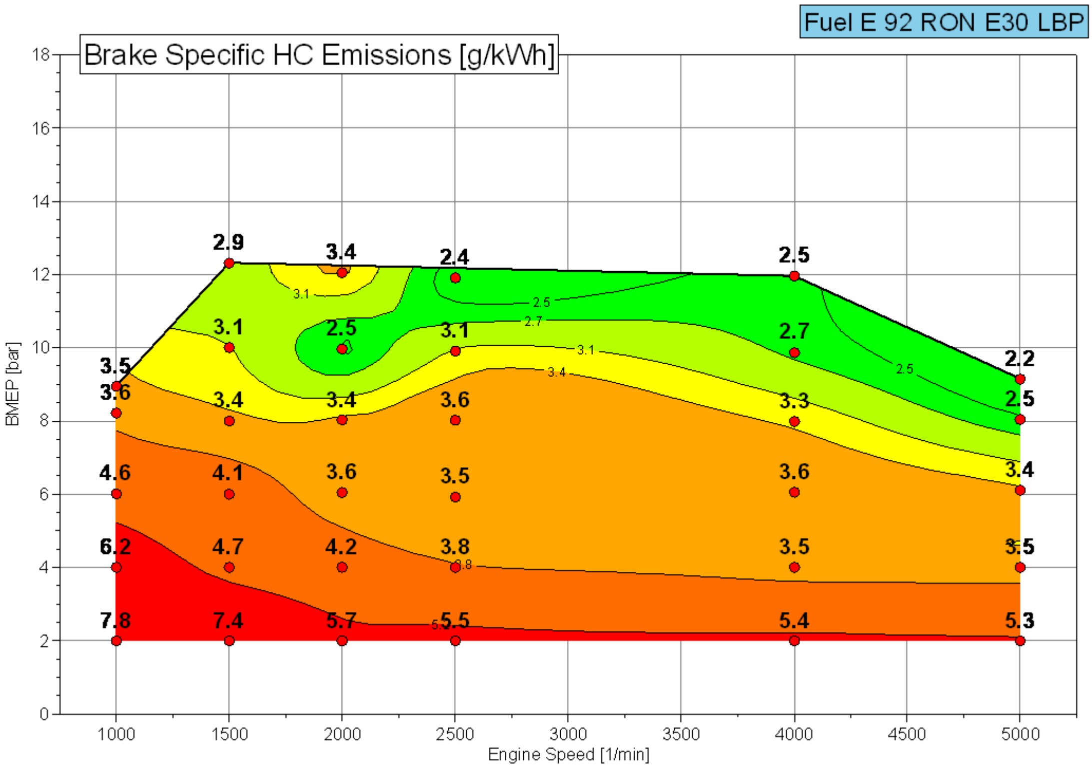

Figure 15: Brake Specific Hydrocarbon Emissions

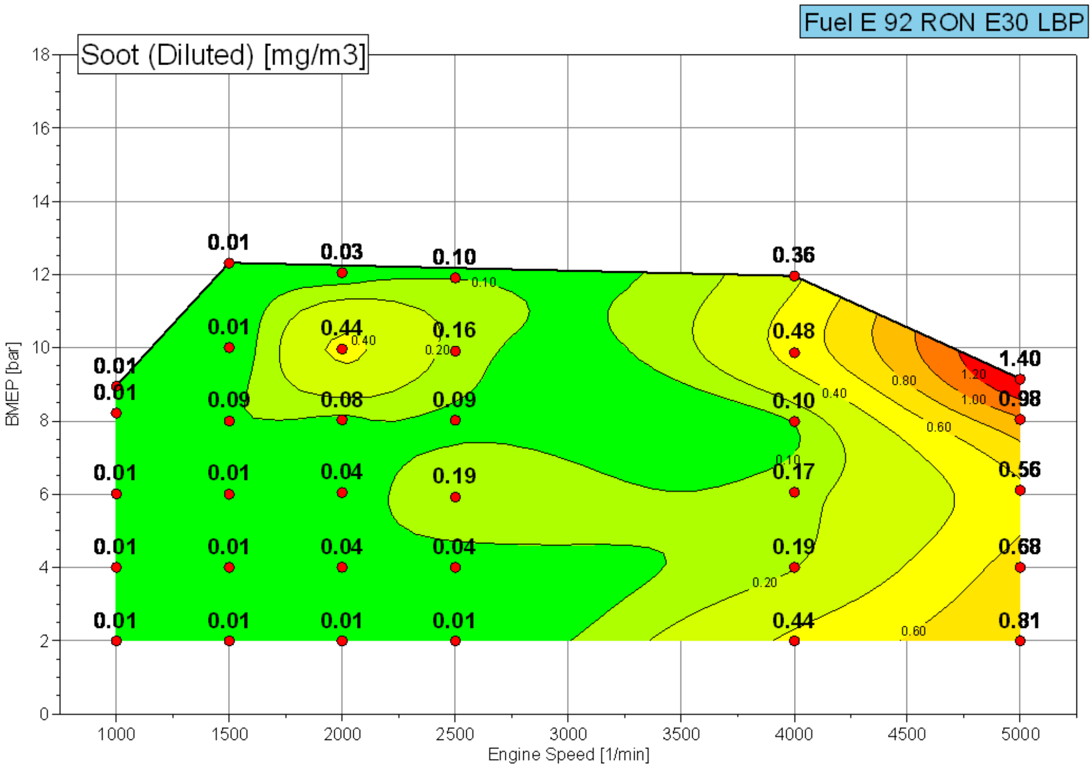

Figure 16: Particulate Soot Emissions

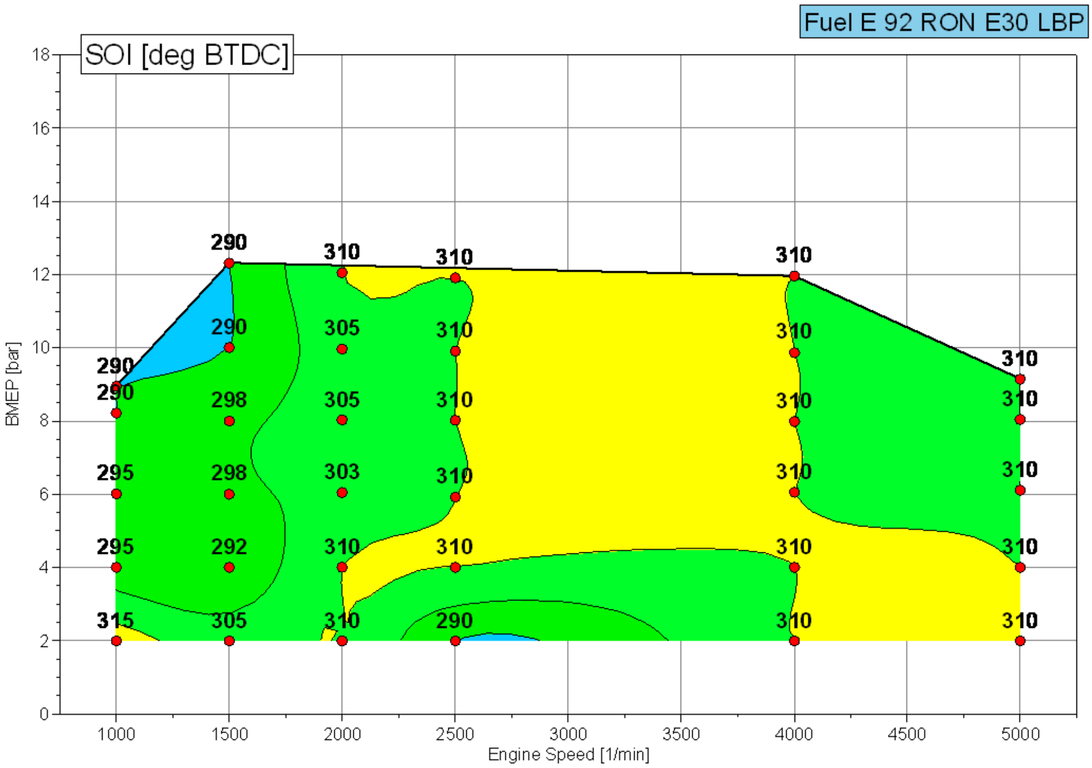

Figure 17: Start of Injection

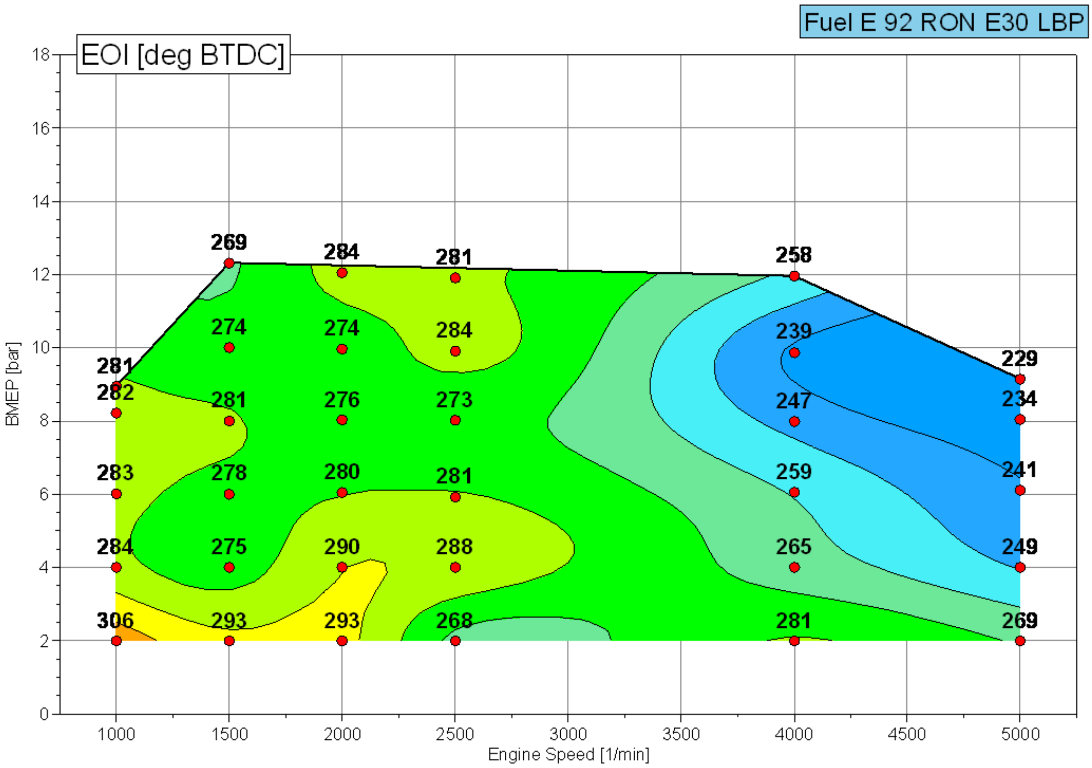

Figure 18: End of Injection

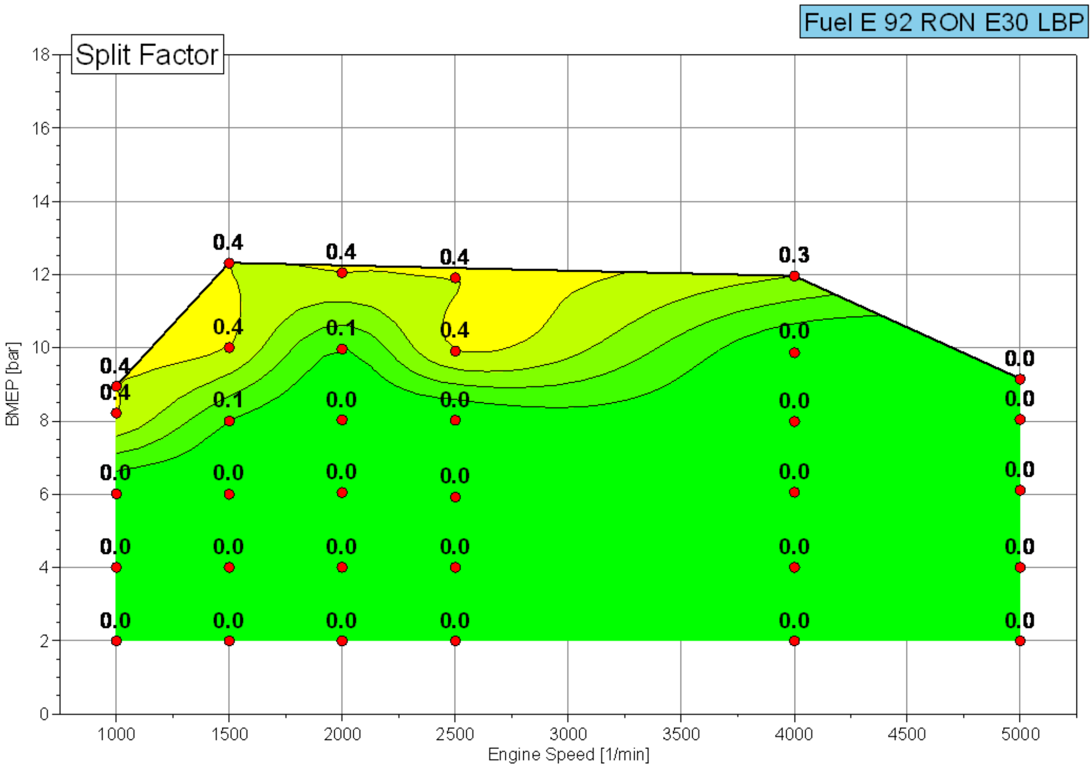

Figure 19: Injection Split Factor

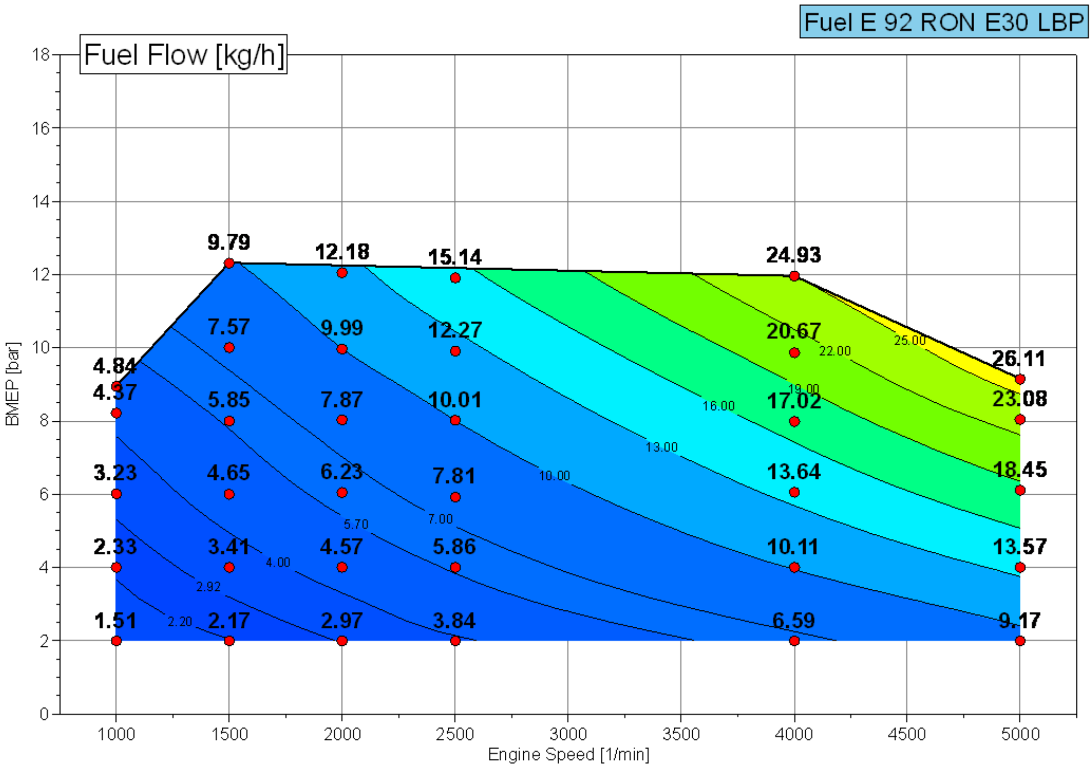

Figure 20: Fuel Flow

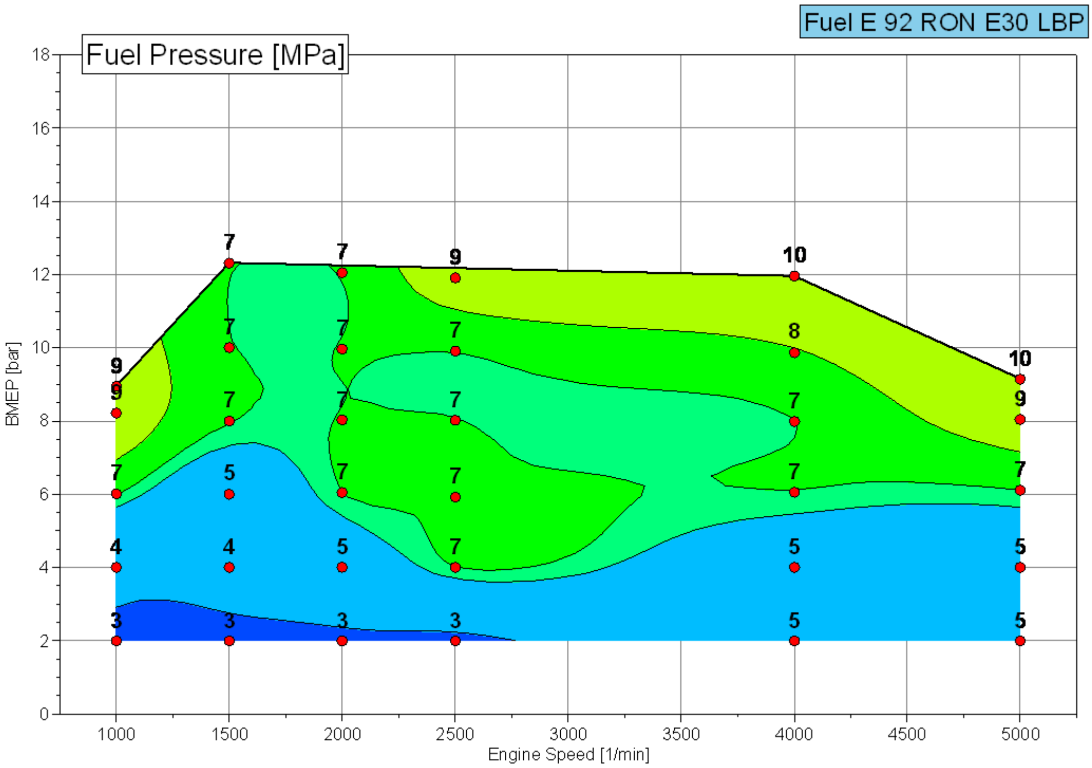

Figure 21: Fuel Rail Pressure

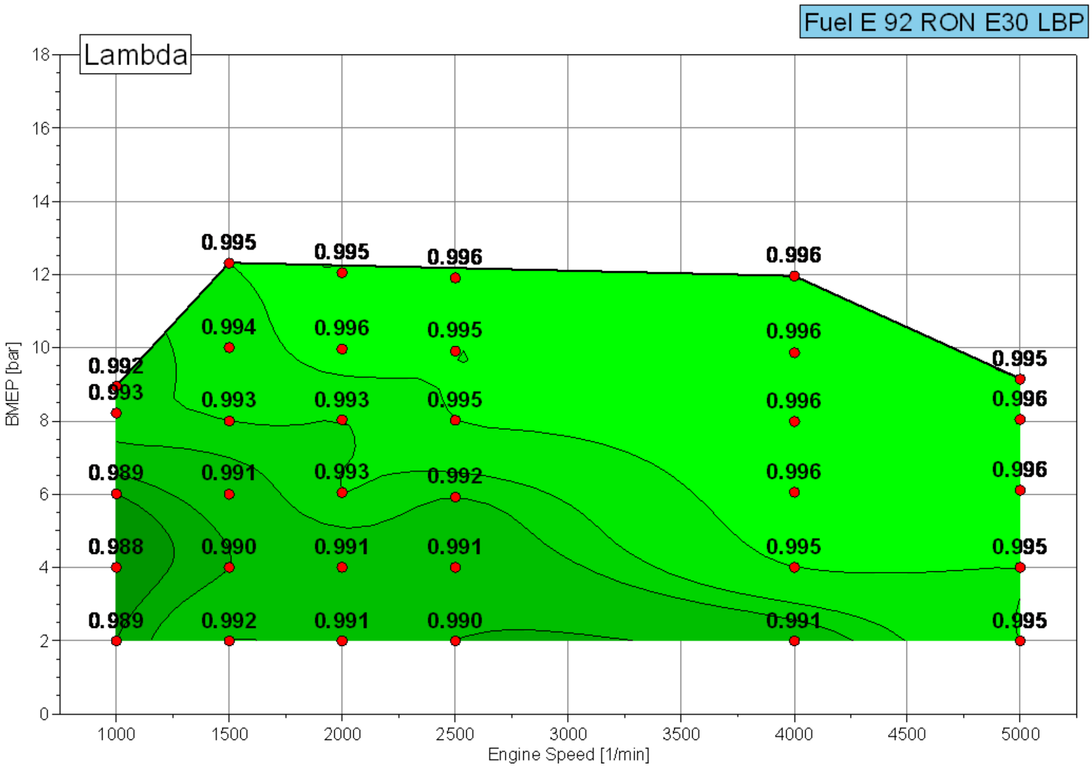

Figure 22: Lambda

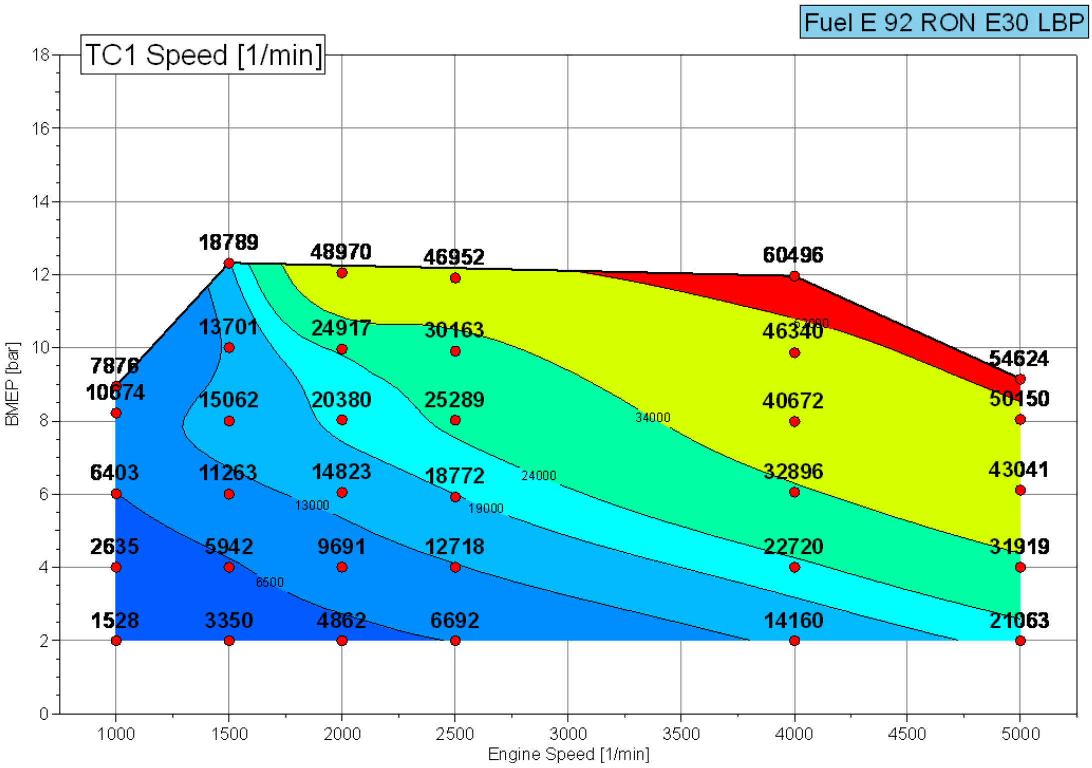

Figure 23: Low Pressure Turbocharger Speed

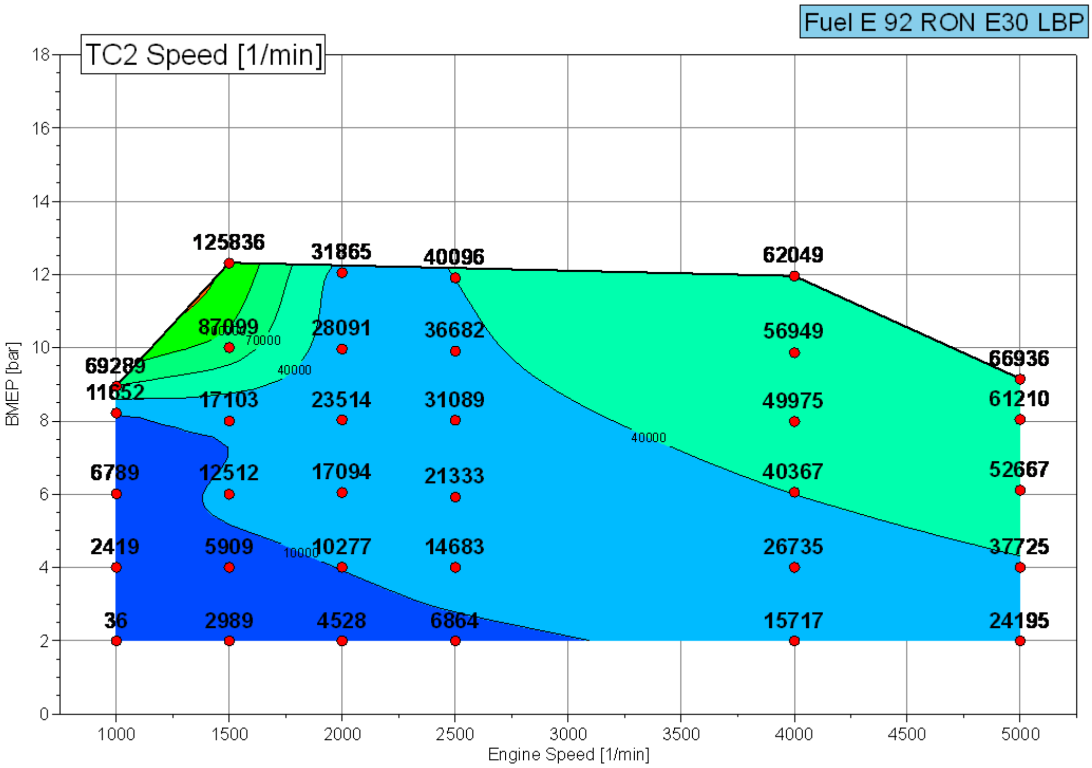

Figure 24: High Pressure Turbocharge Speed

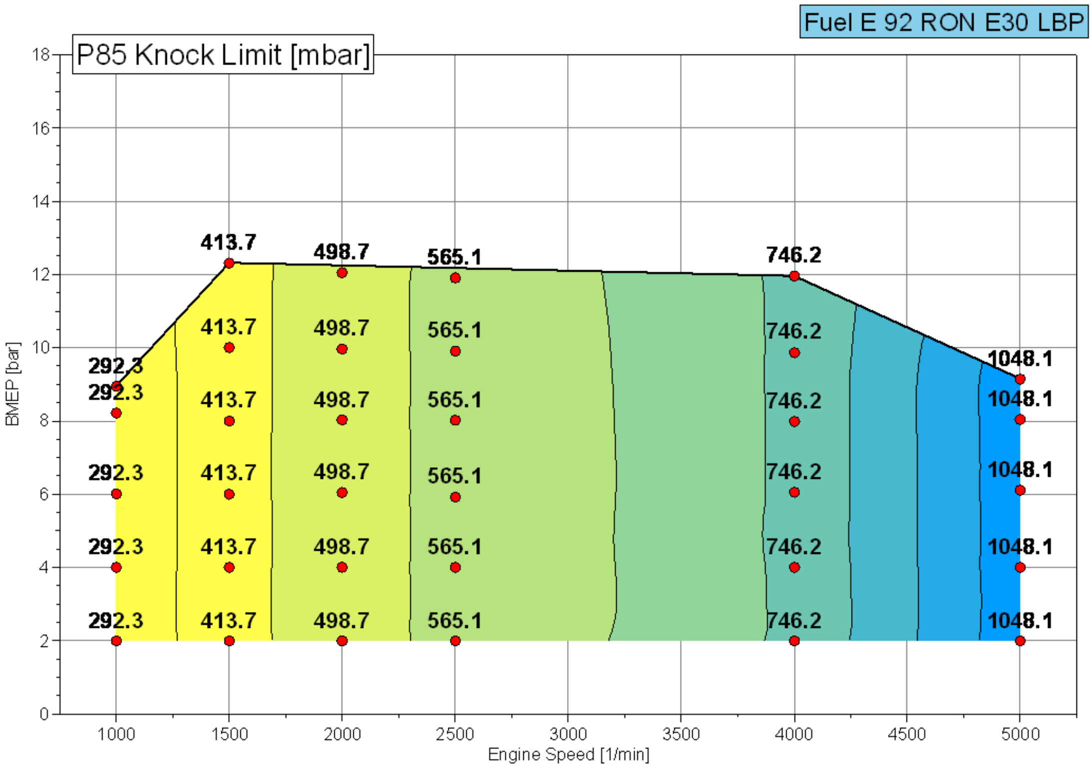

Figure 25: P85 Knock Limit

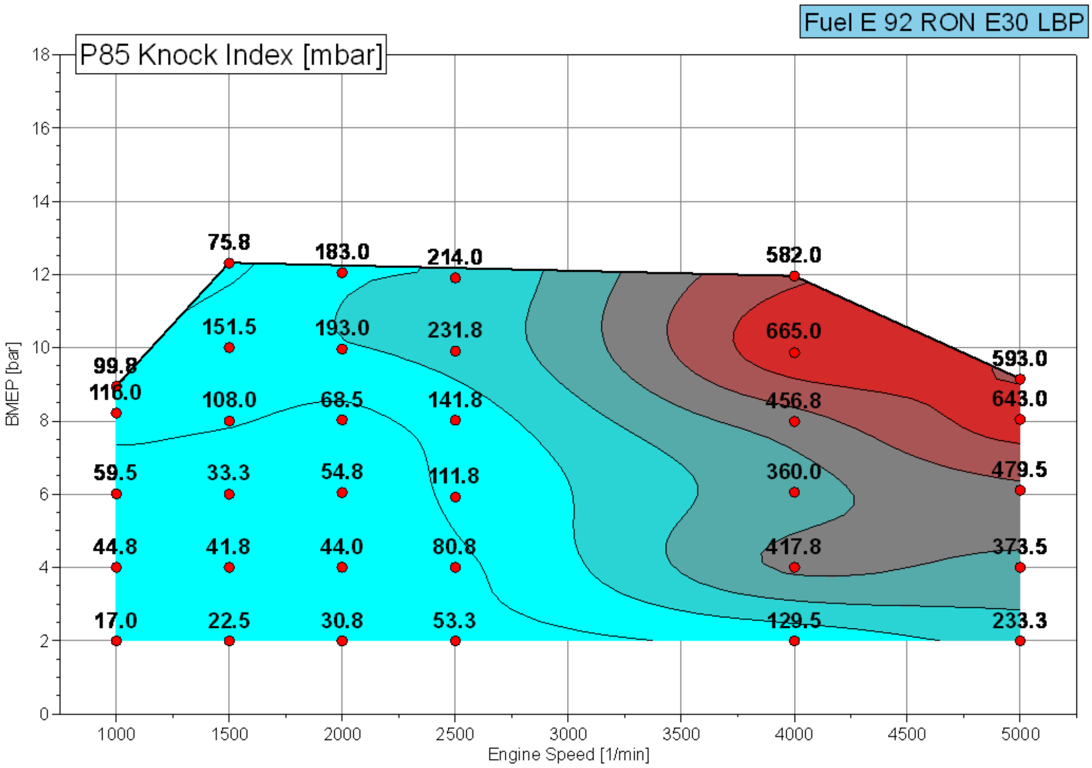

Figure 26: Averaged P85 Knock Index

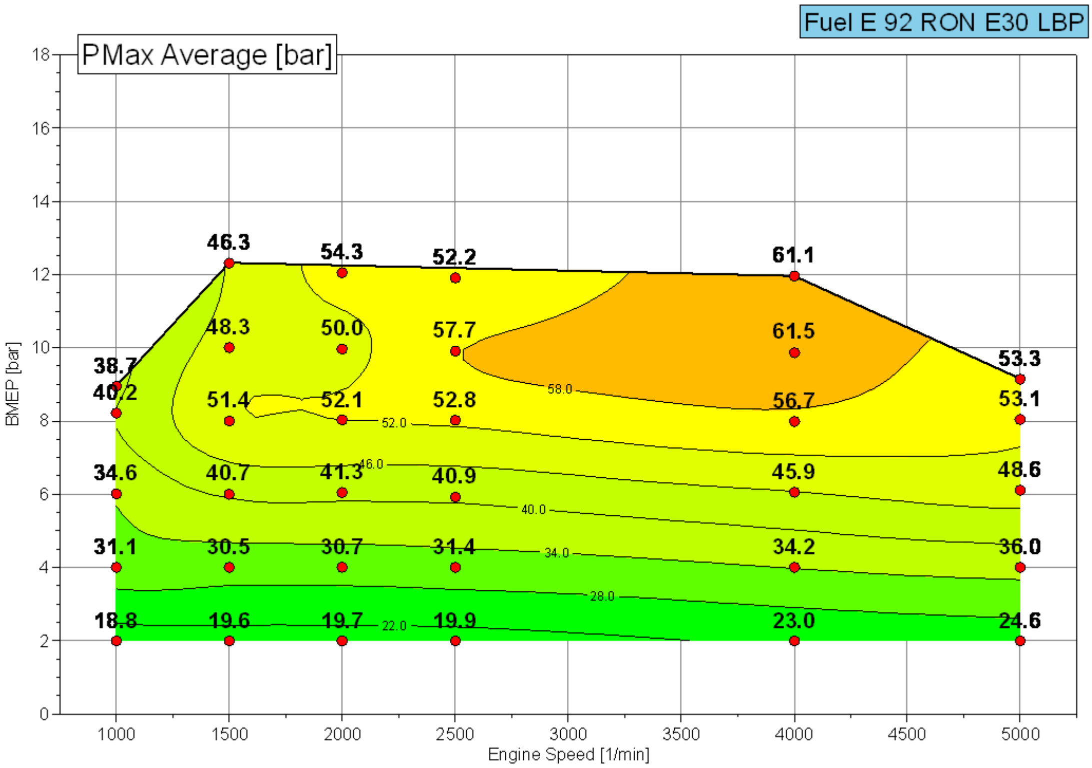

Figure 27: Averaged Max Pressure for Cylinders 1-4

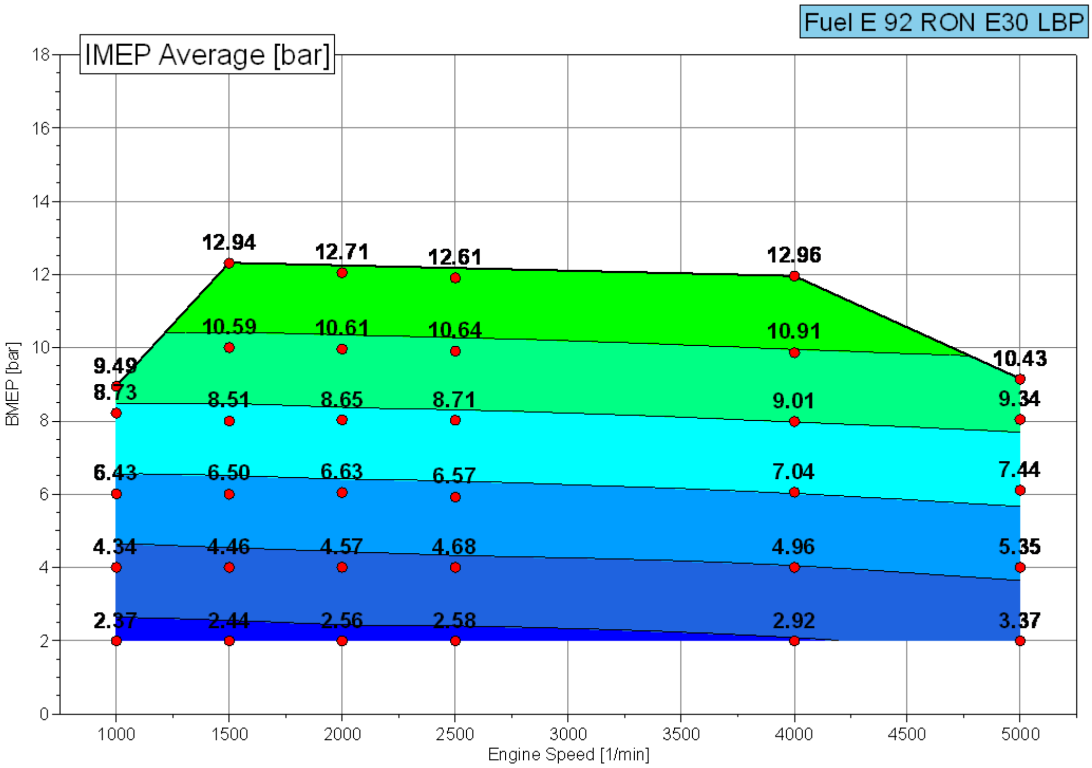

Figure 28: Indicated Mean Effective Pressure

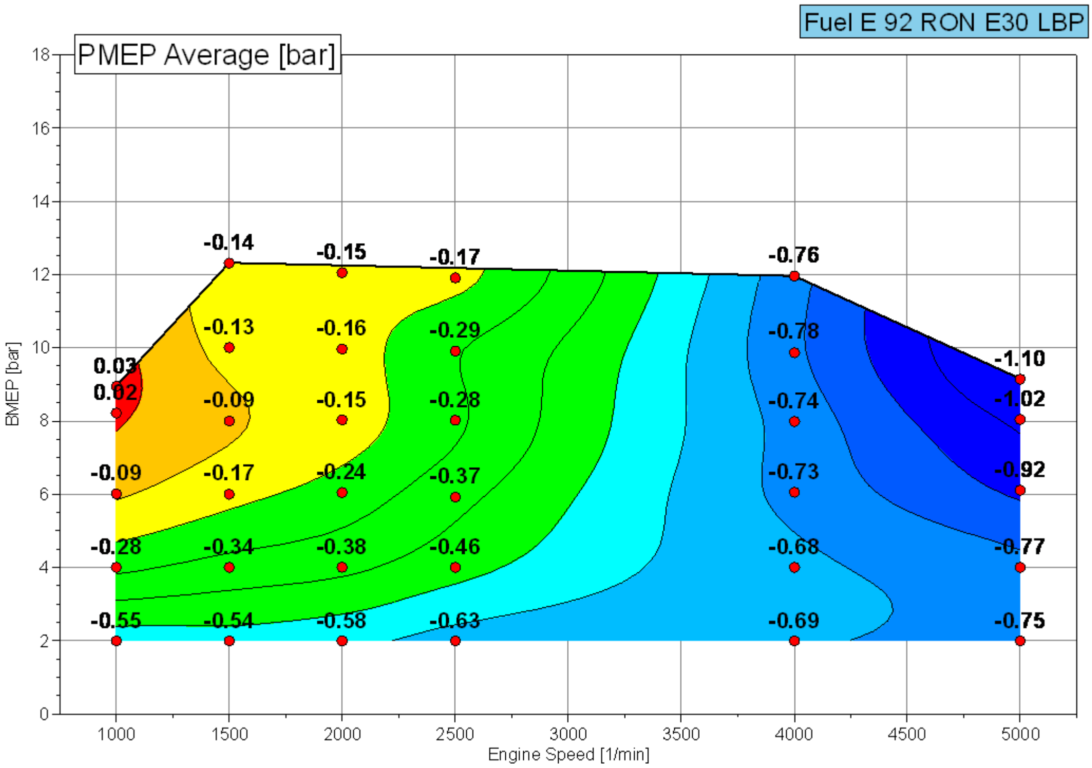

Figure 29: Pumping Mean Effective Pressure

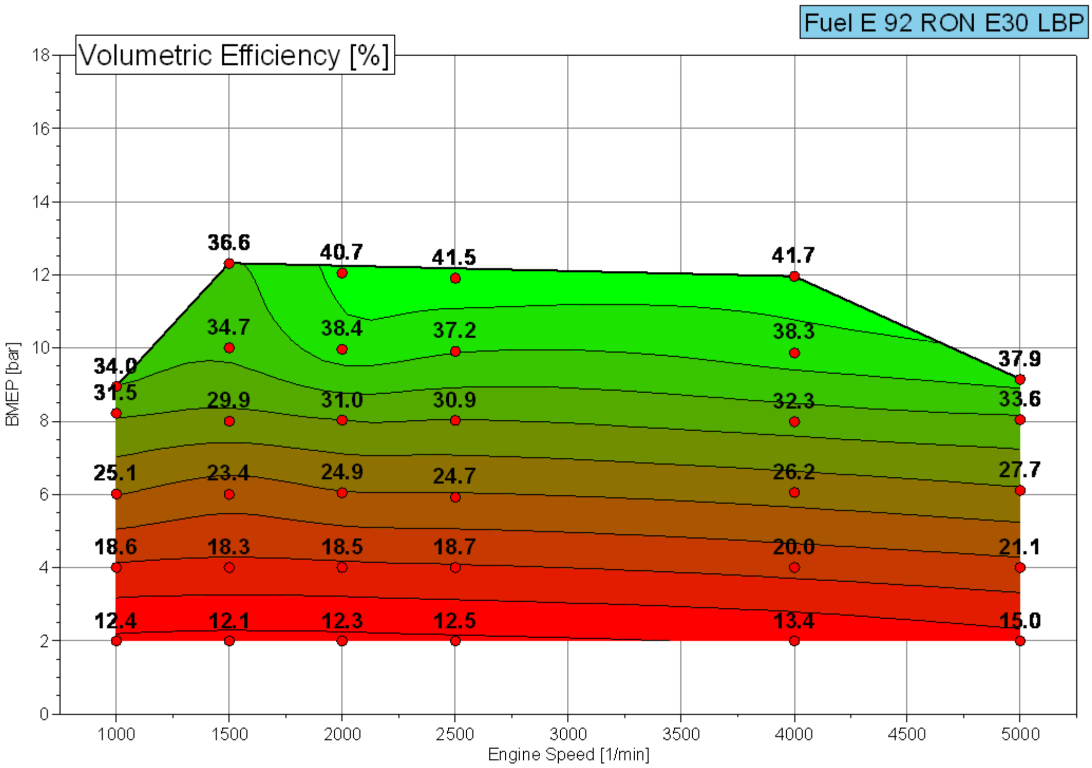

Figure 30: Calculated Volumetric Efficiency

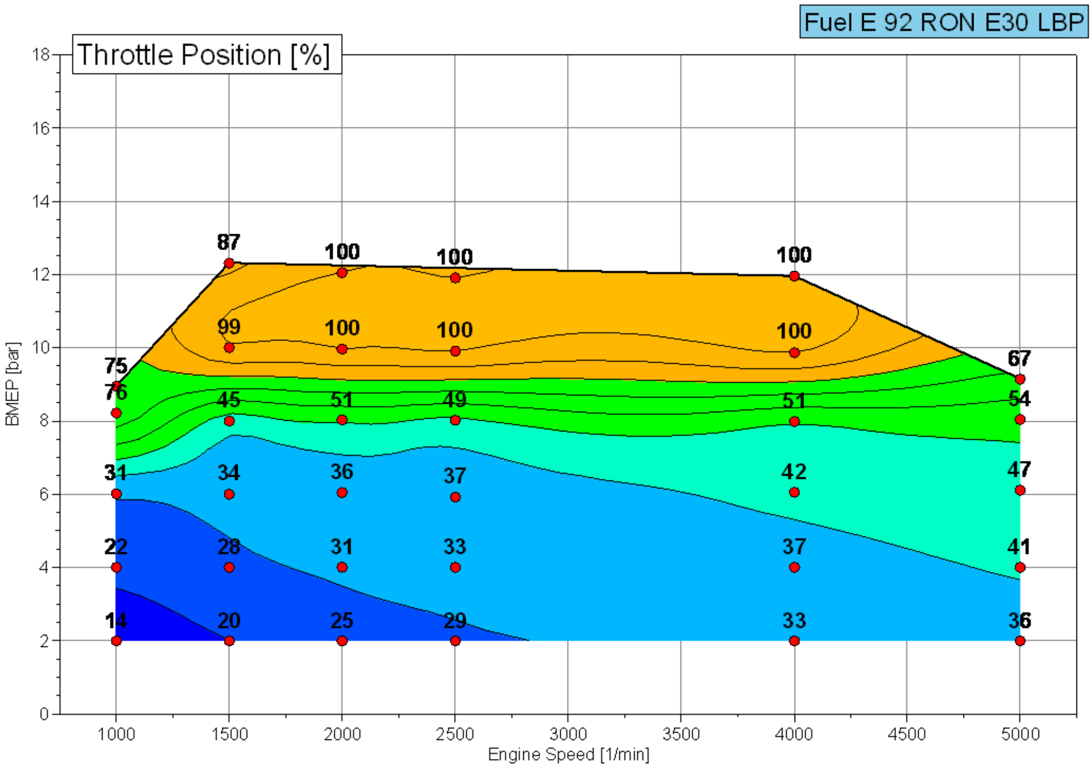

Figure 31: Throttle Position

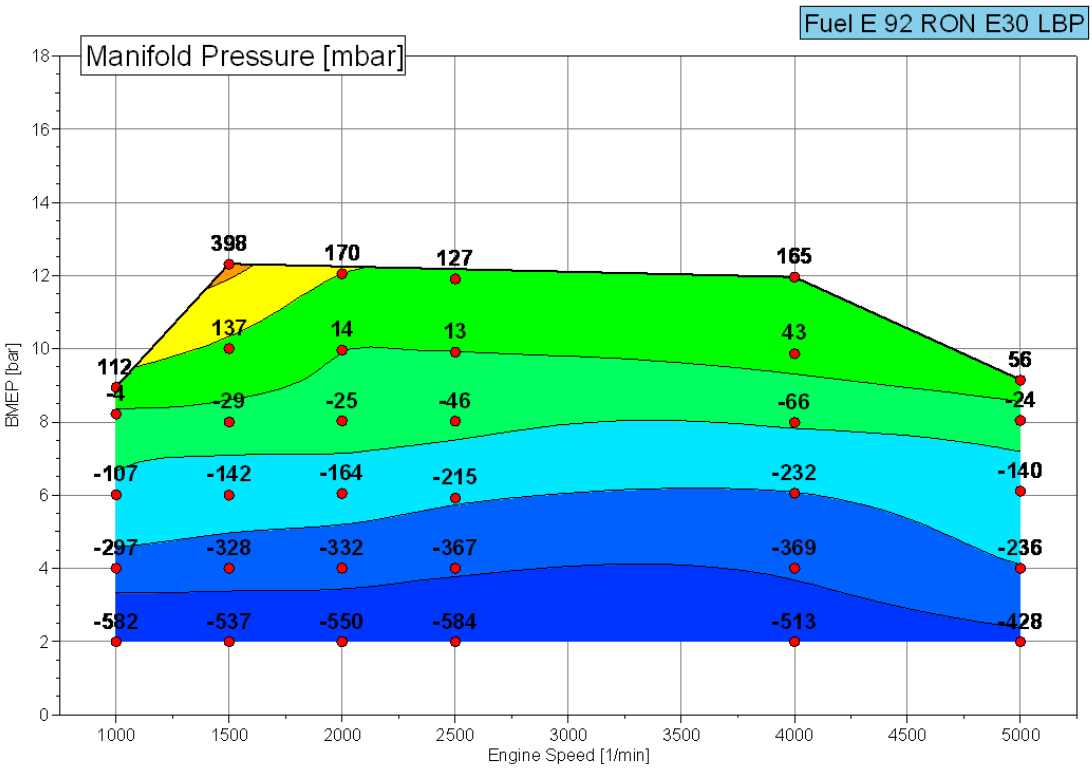

Figure 32: Intake Manifold Pressure

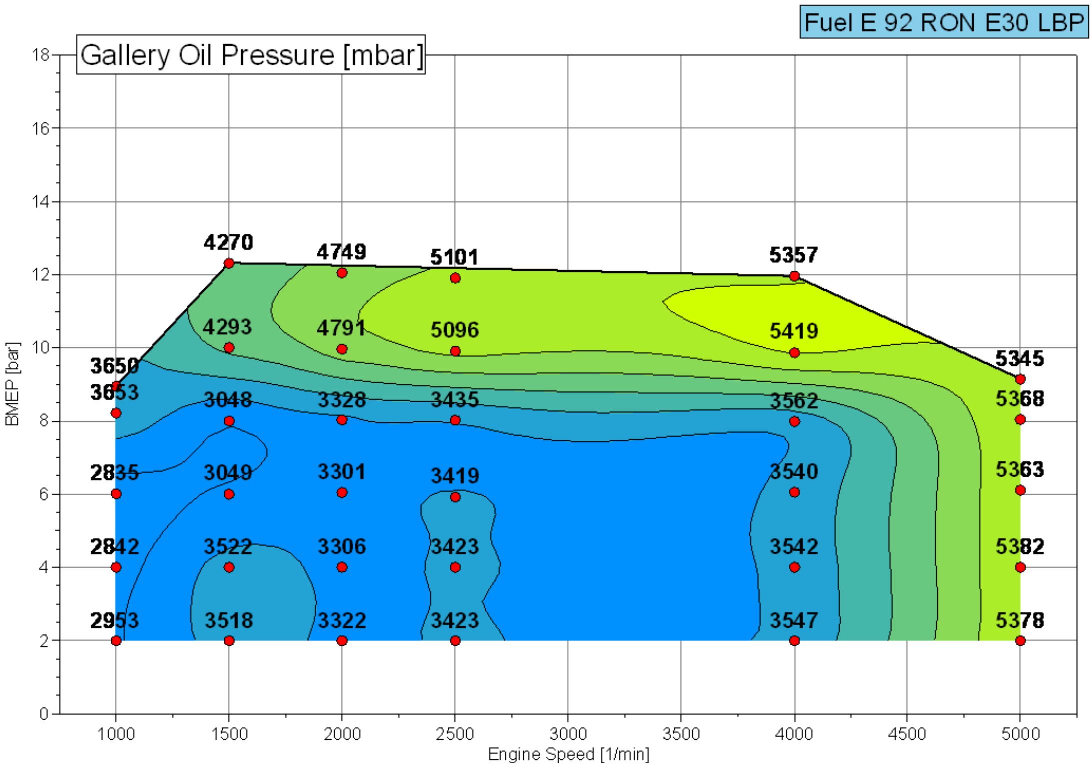

Figure 33: Gallery Oil Pressure

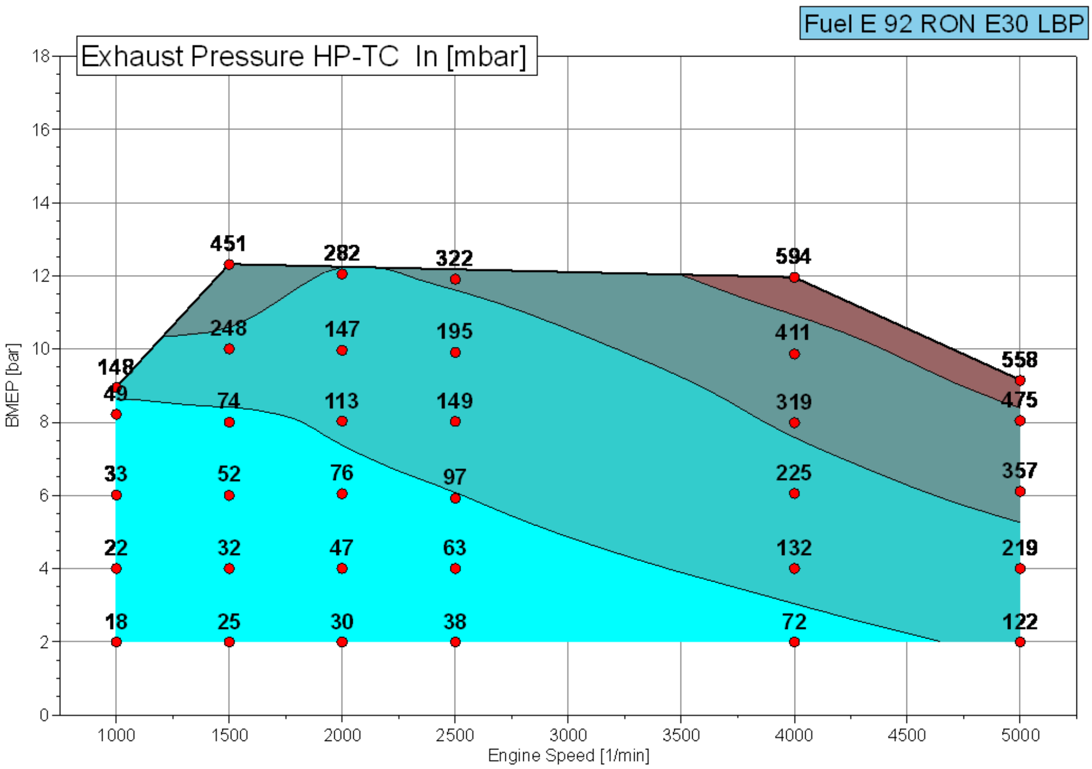

Figure 34: Exhaust Pressure High Pressure Turbocharger In

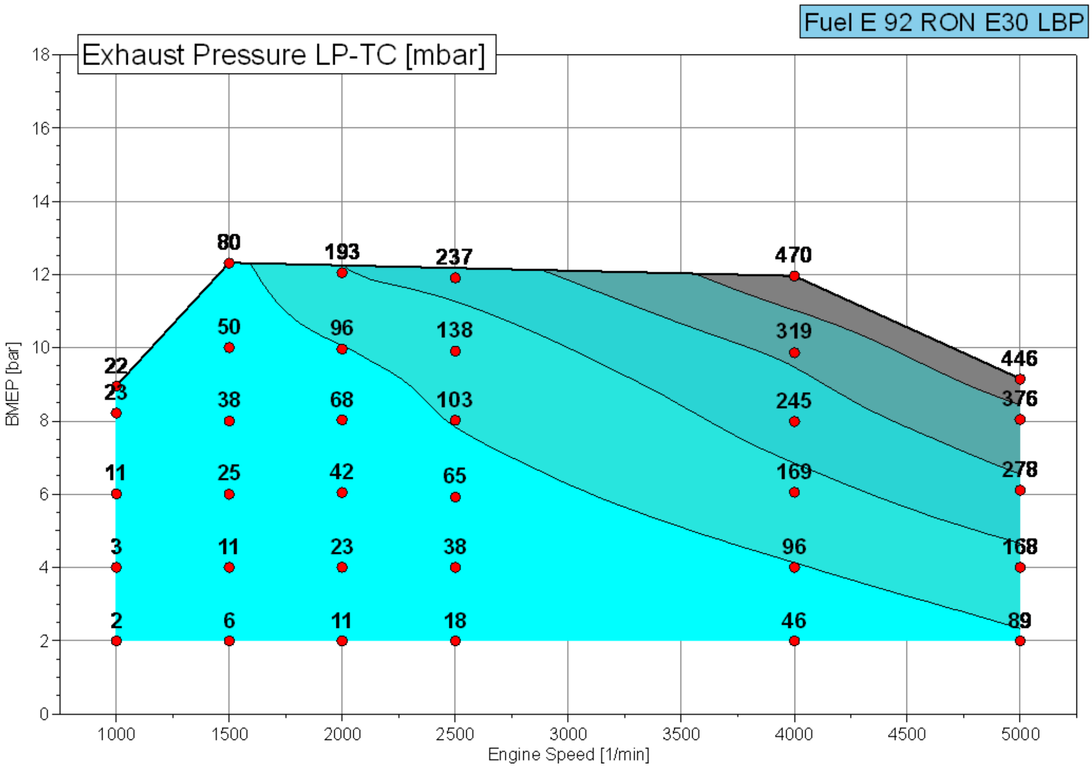

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

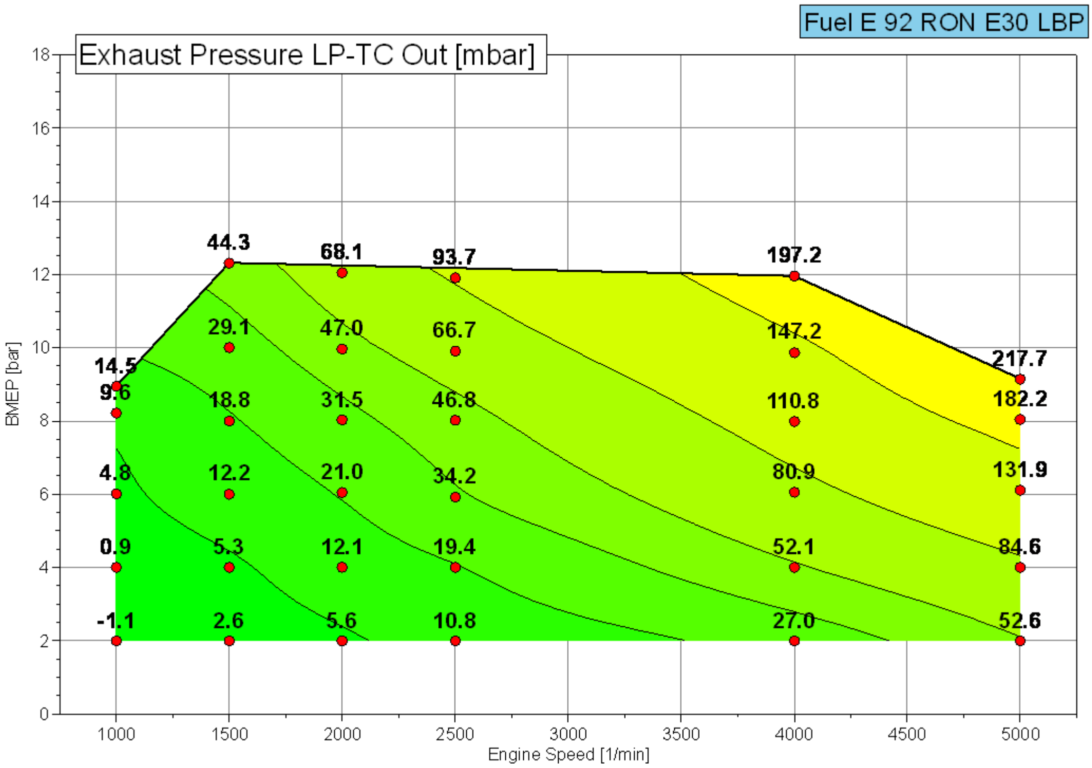

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

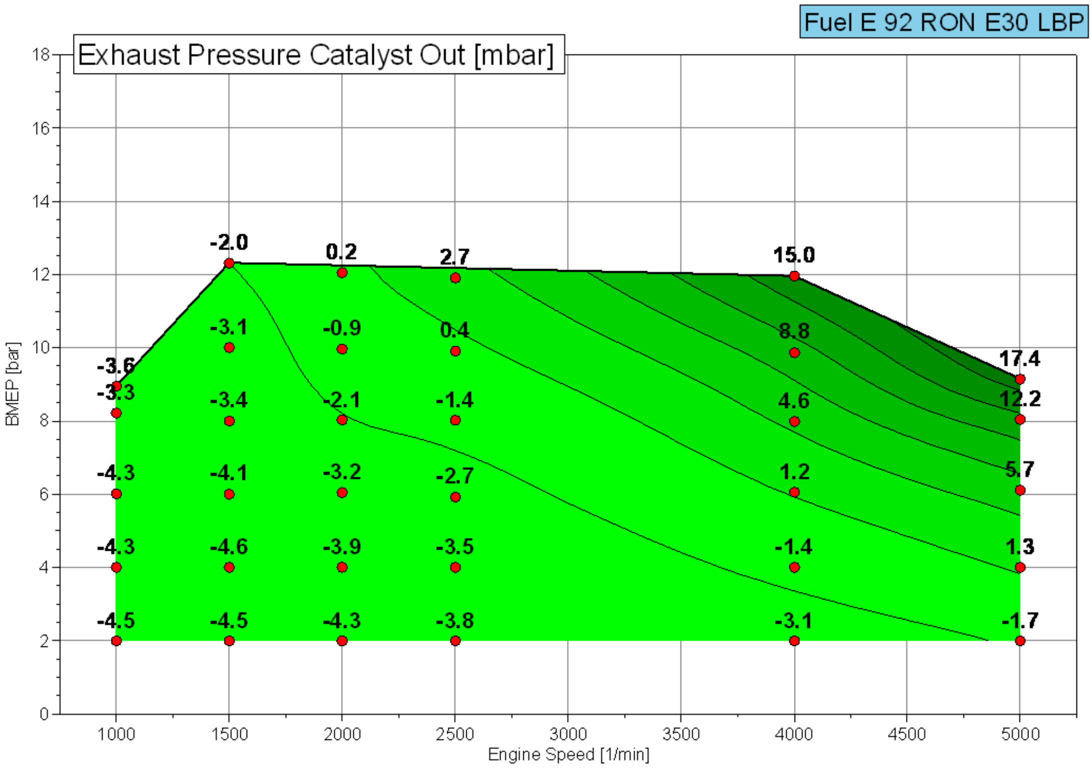

Figure 37: Exhaust Pressure Catalyst Out

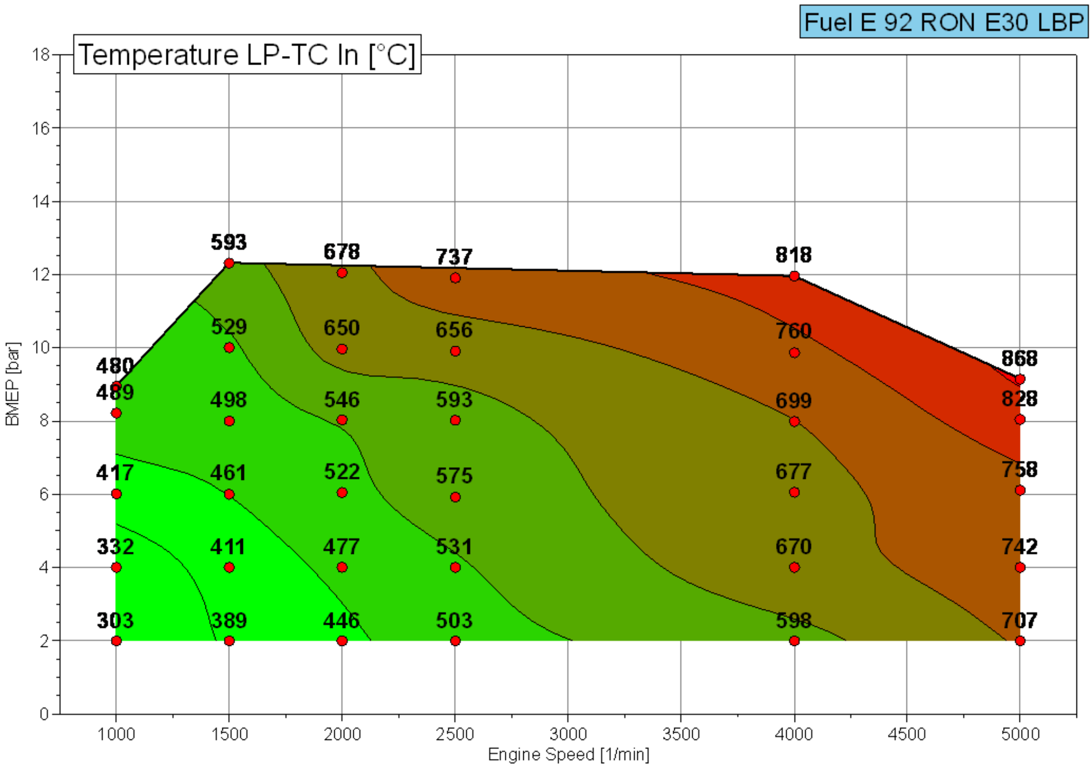

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

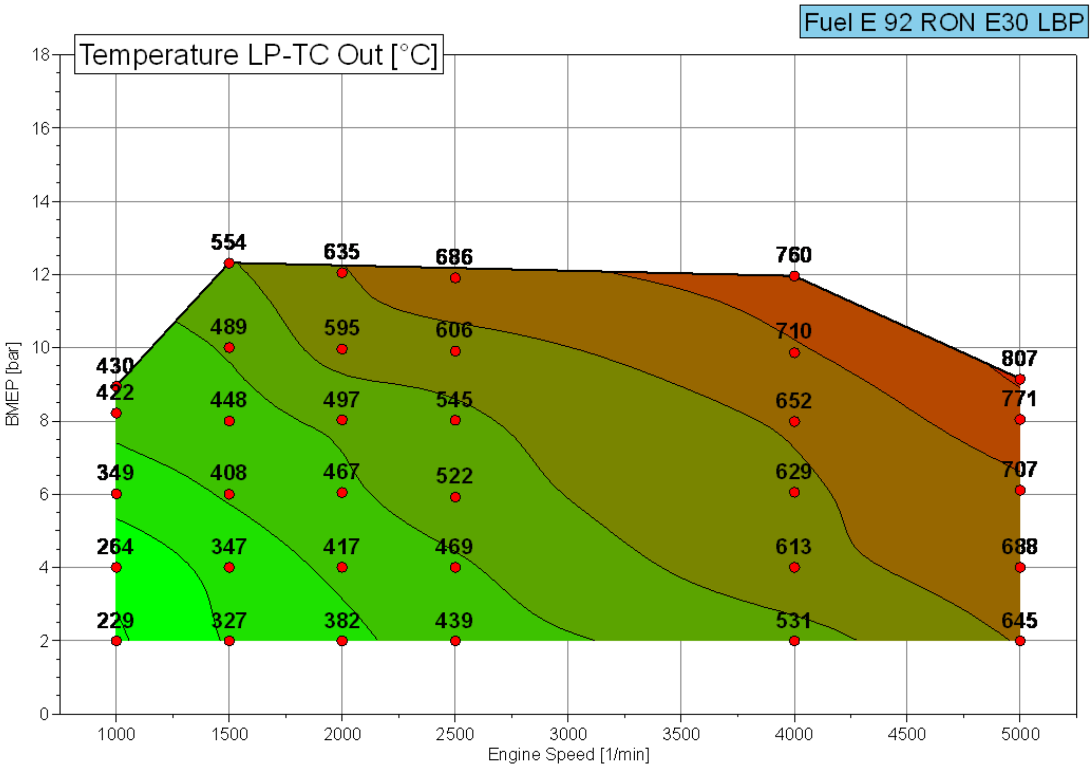

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

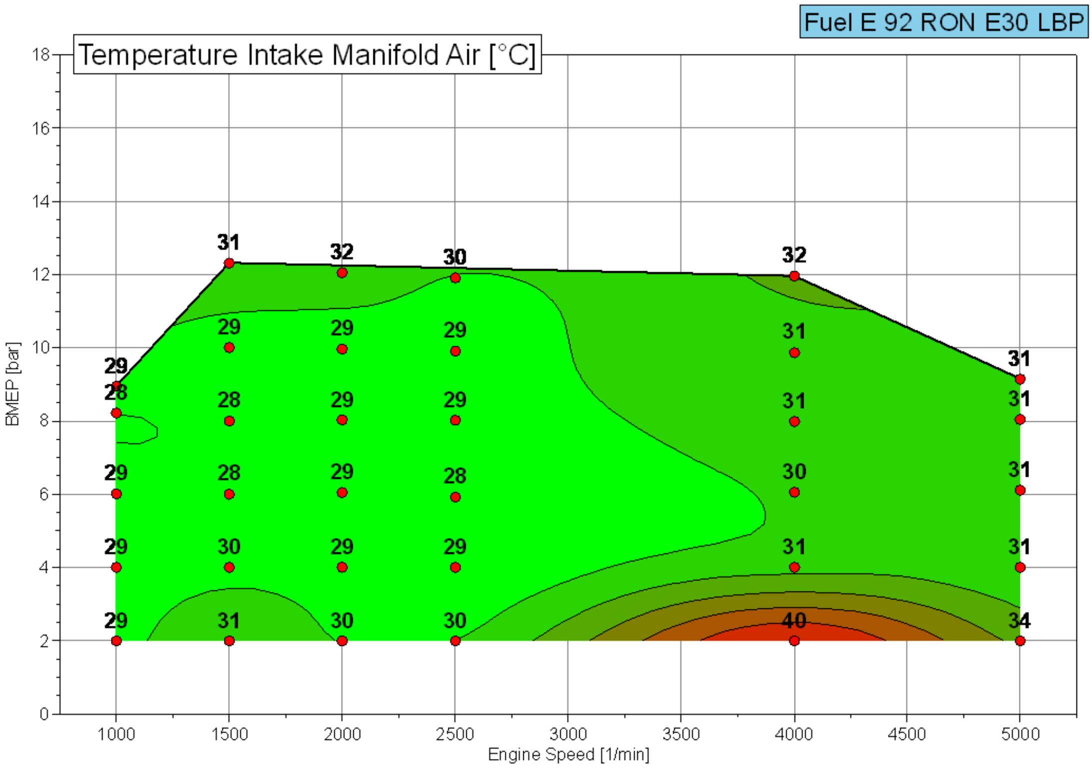

Figure 40: Intake Manifold Air Temperature

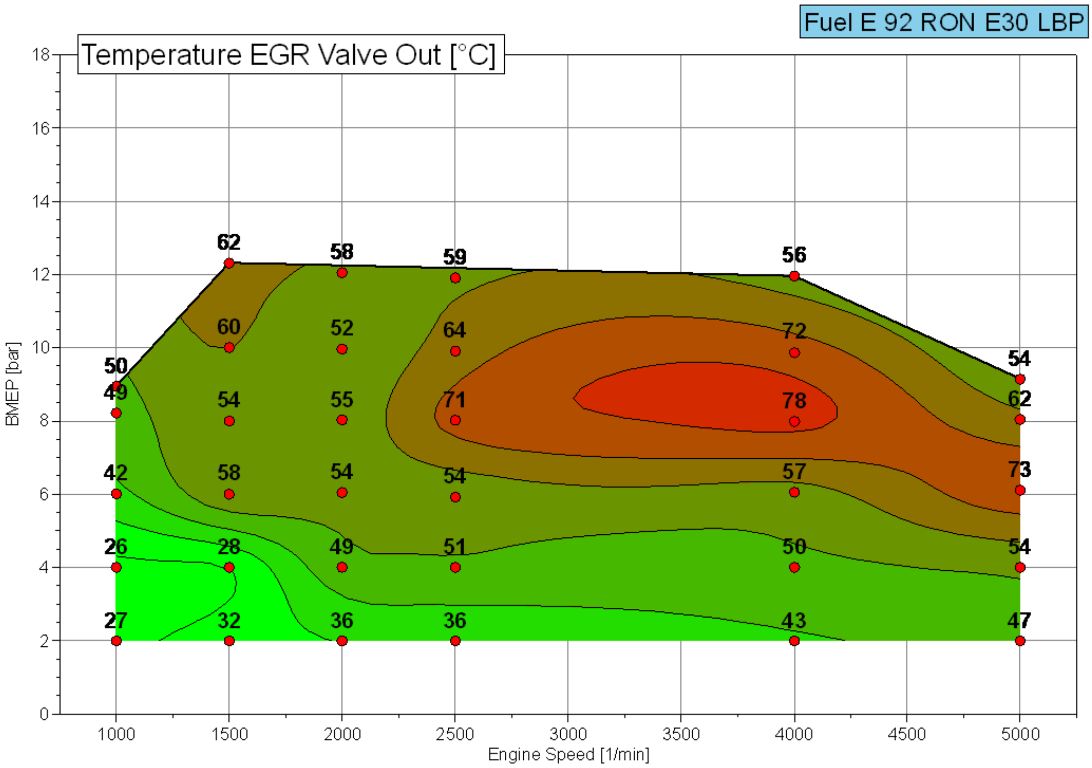

Figure 41: EGR Valve Out Temperature

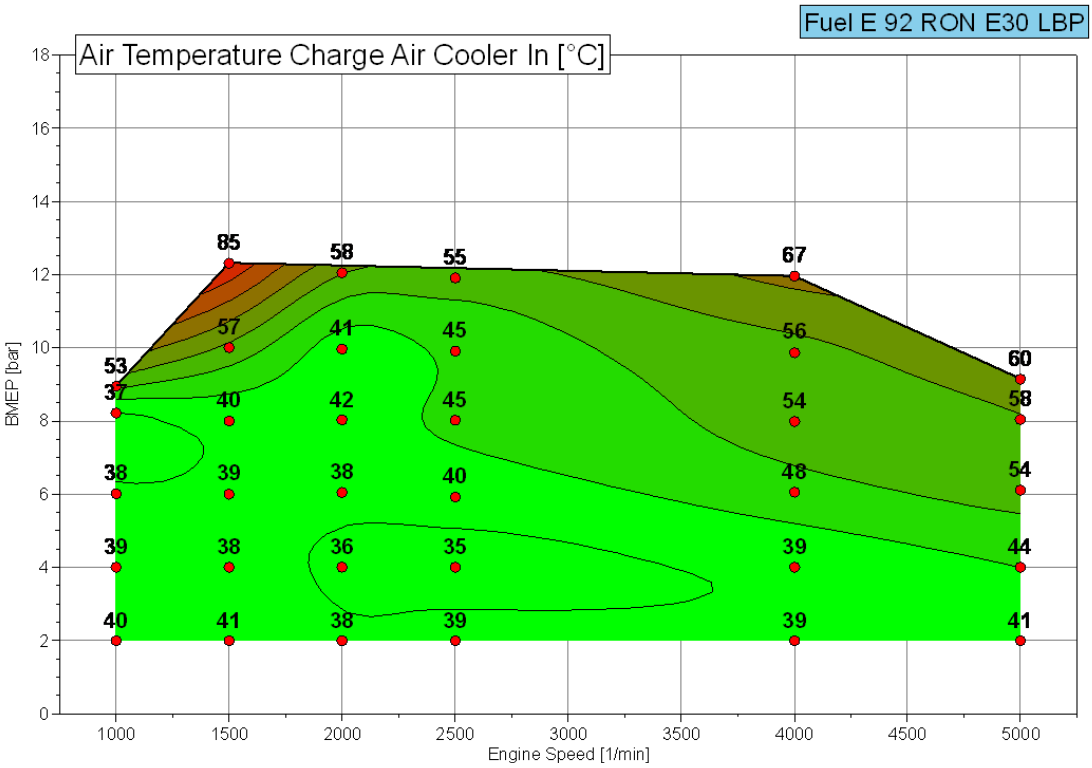

Figure 42: Charge Air Cooler Inlet Air Temperature

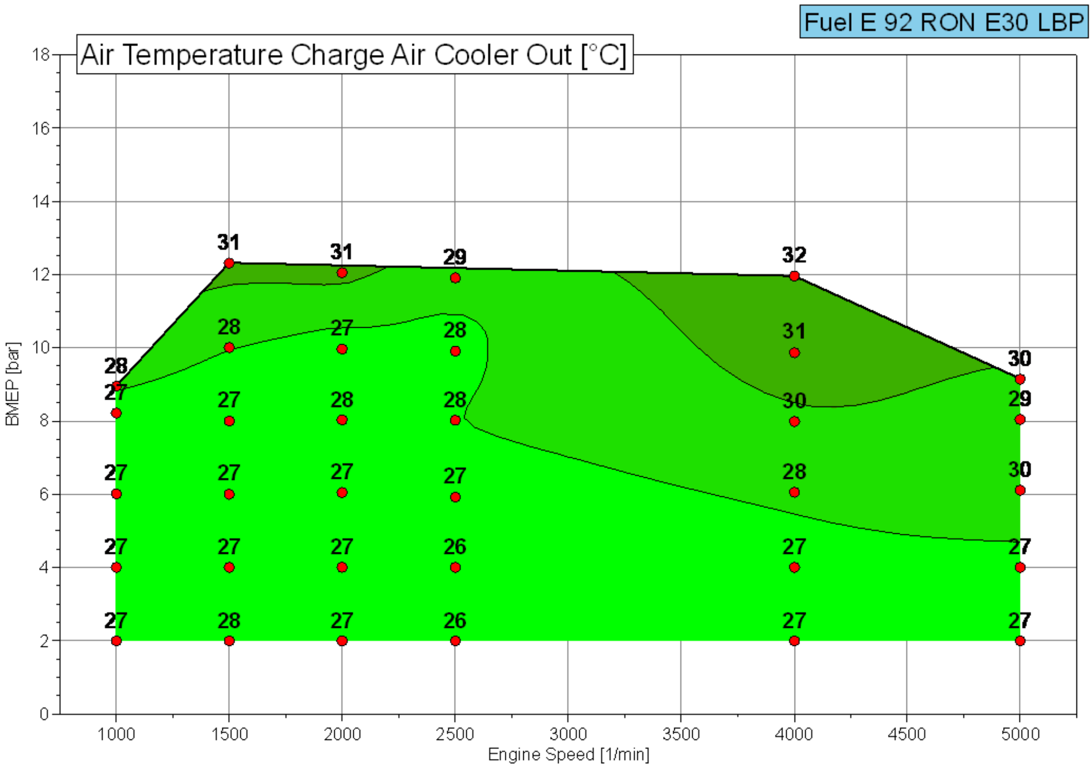

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel D Calibration Results

92 Ron 10% Ethanol High Boiling Point

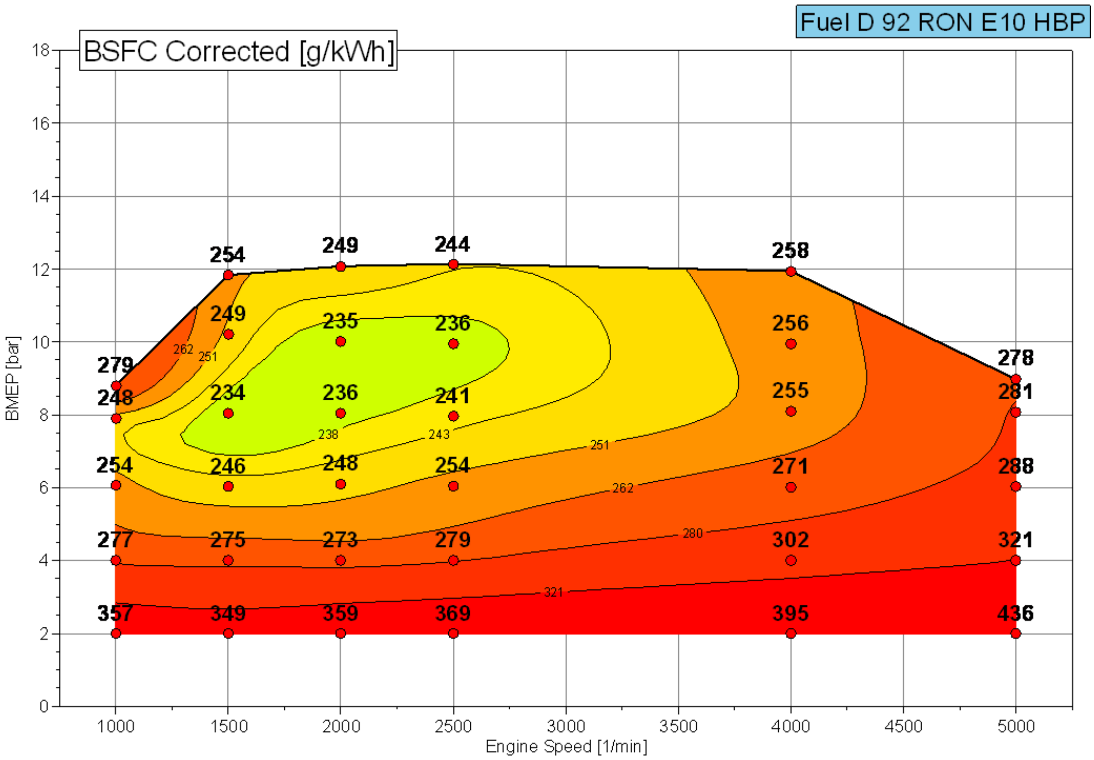

Figure 1: Brake Specific Fuel Consumption

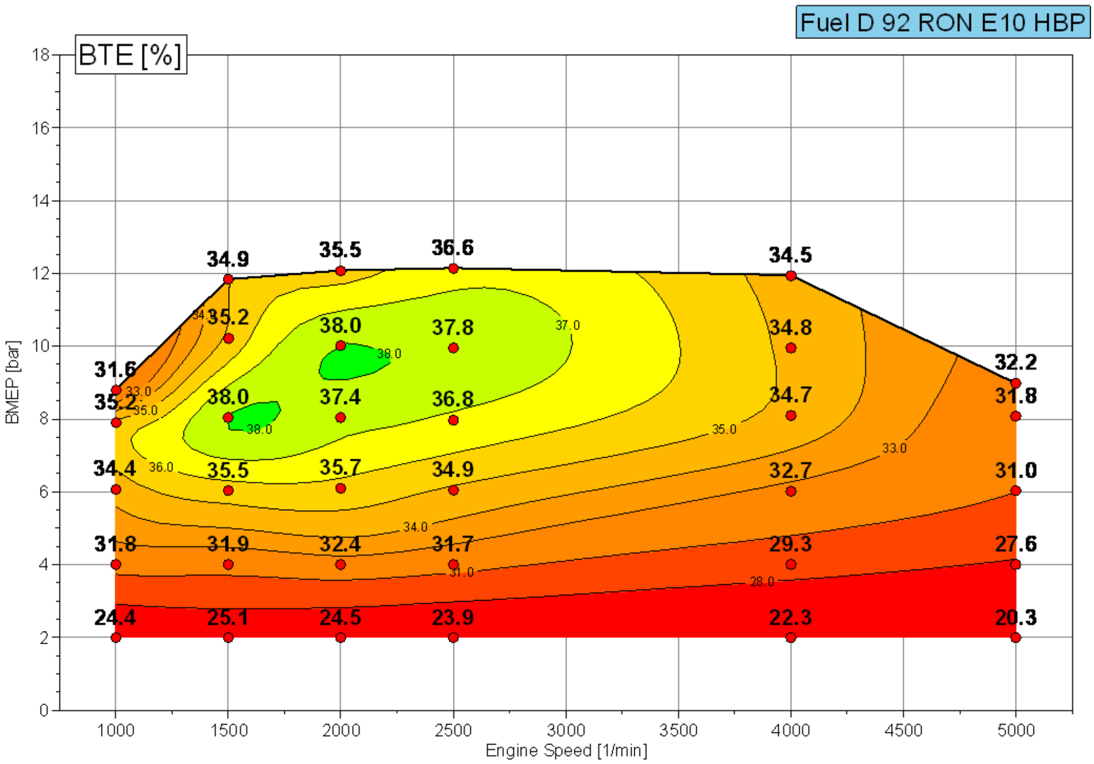

Figure 2: Brake Thermal Efficiency

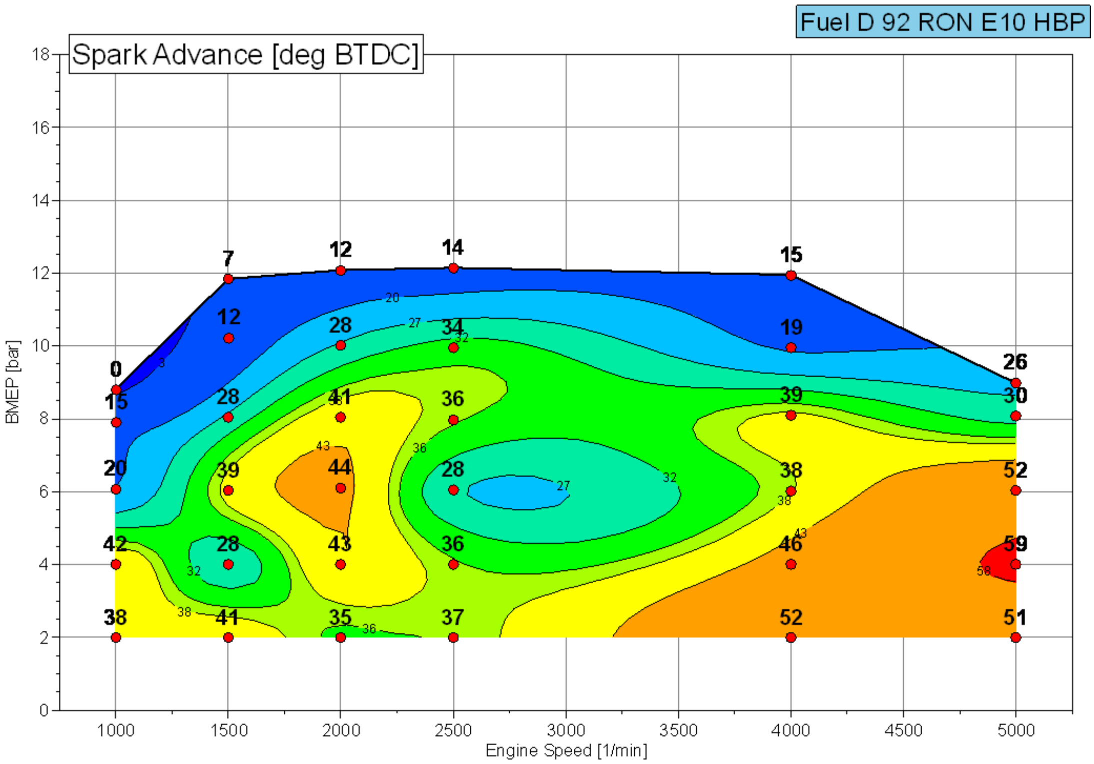

Figure 3: Spark Advance

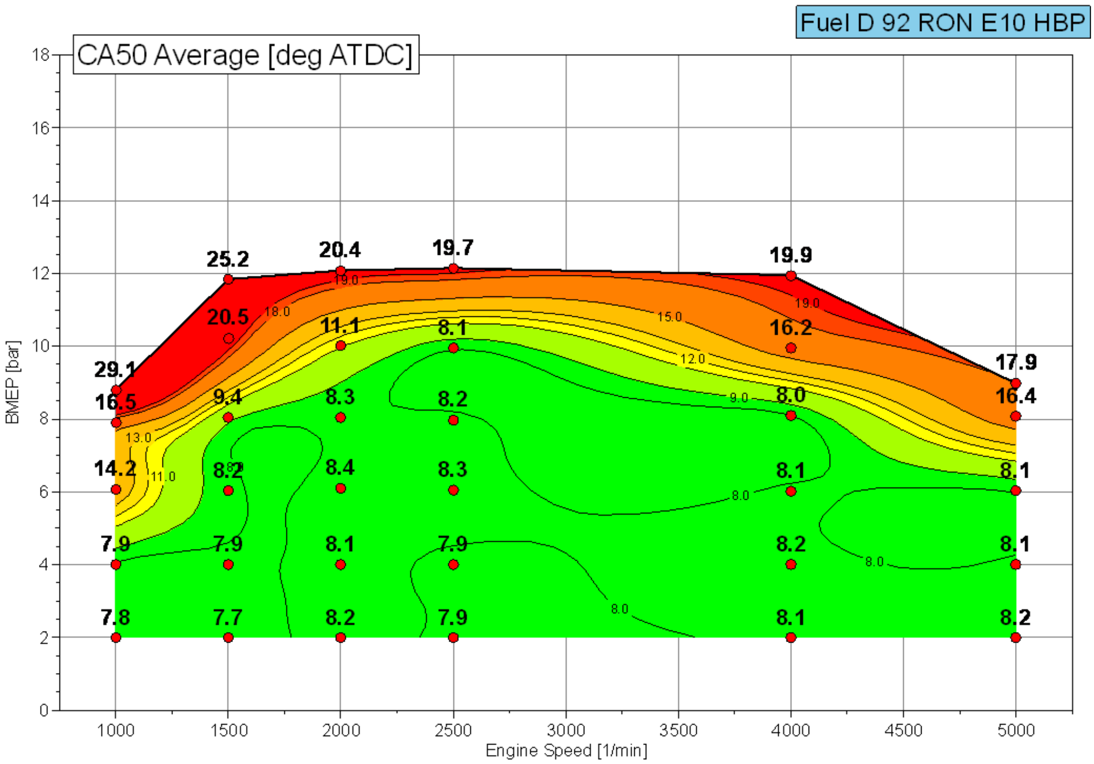

Figure 4: CA50 Average of Cylinders 1-4

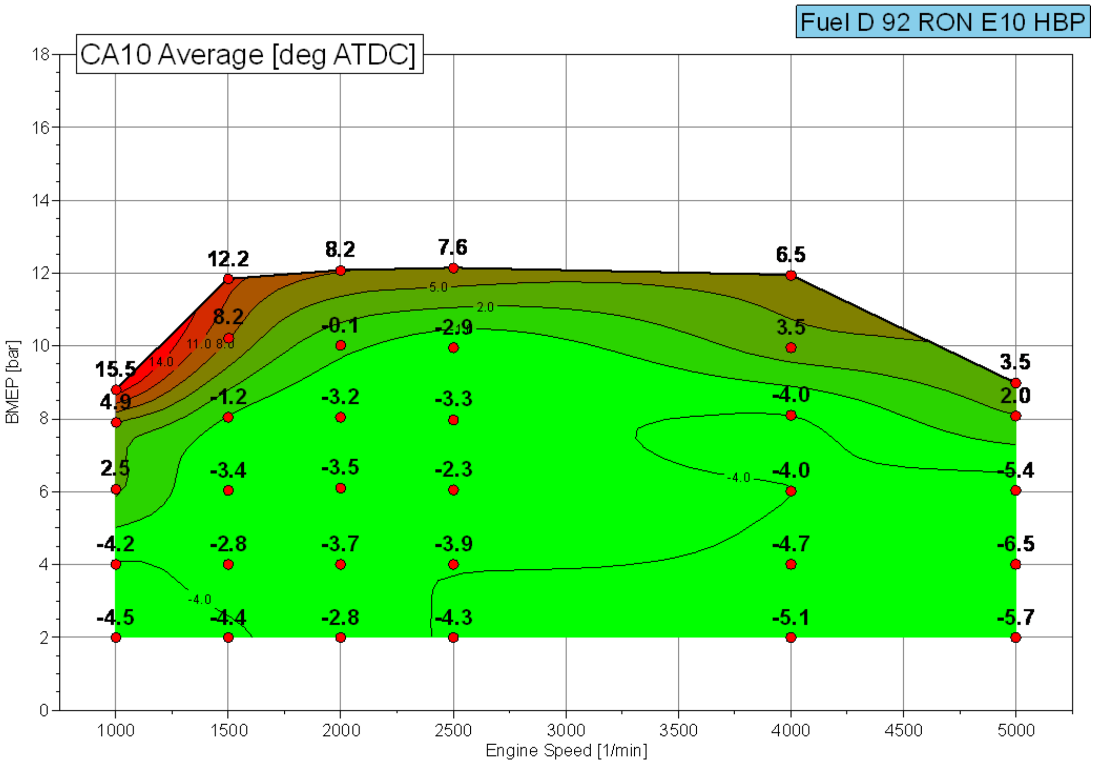

Figure 5: CA10 Average of Cylinders 1-4

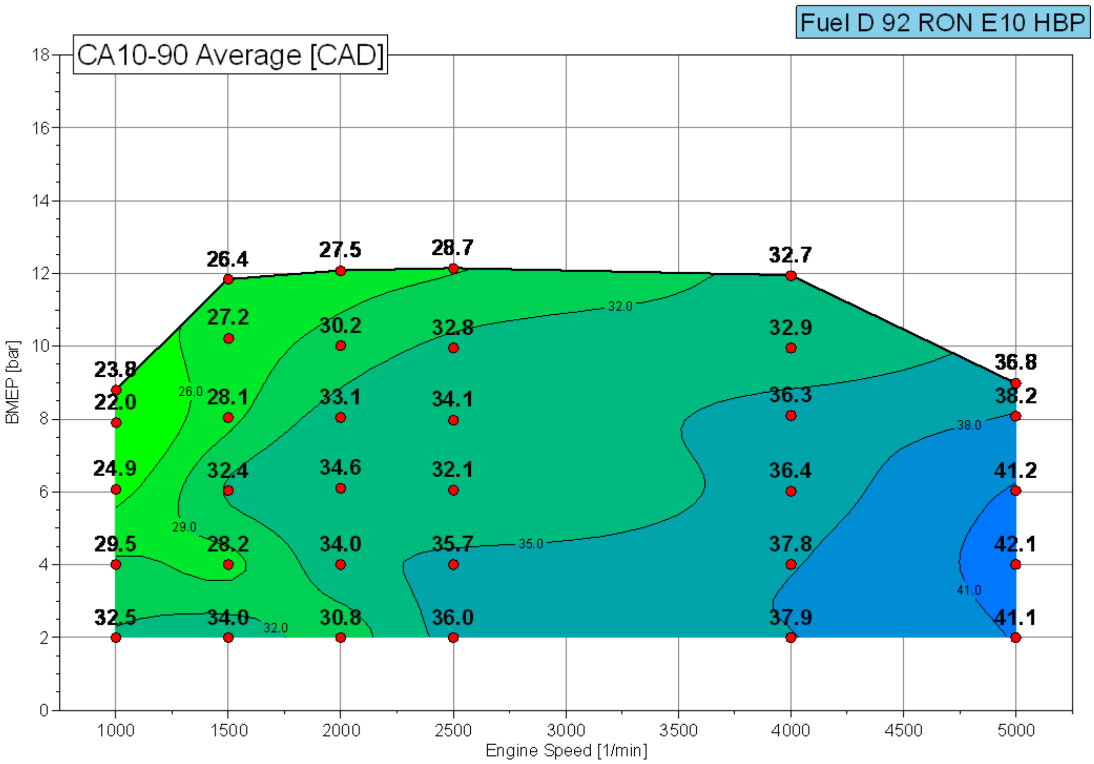

Figure **6:** CA10-90 Average of Cylinders 1-4

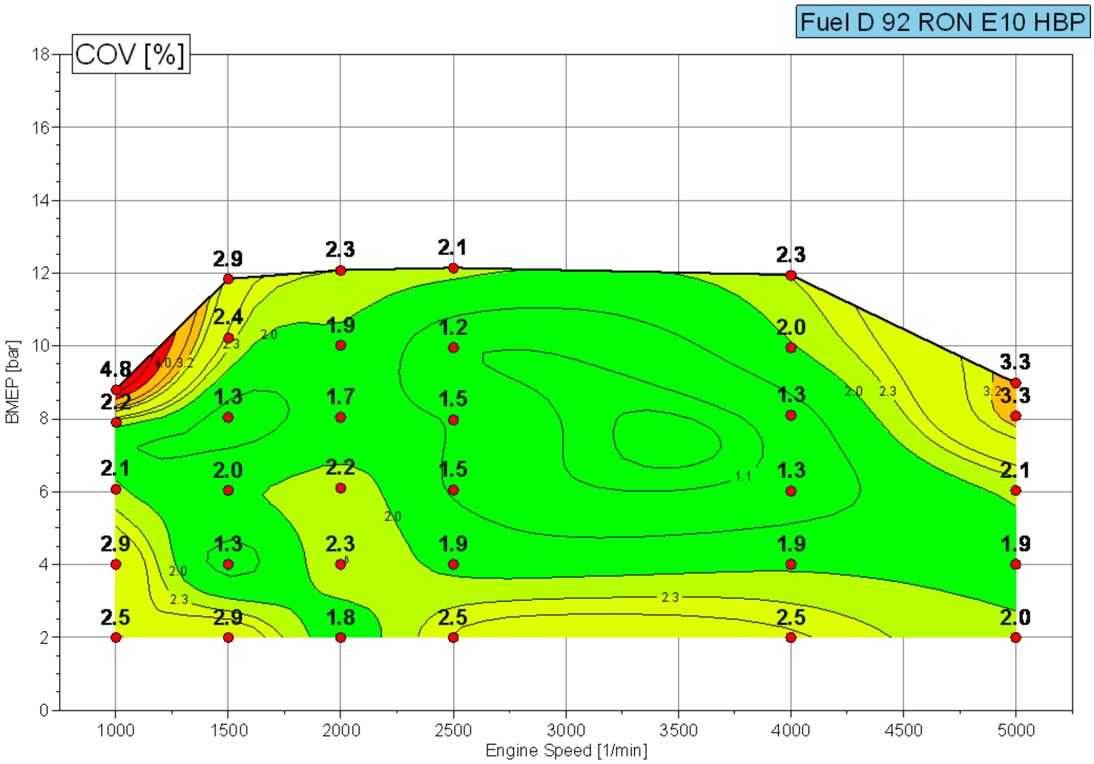

Figure 7: Coefficient of Variation Average of Cylinders 1-4

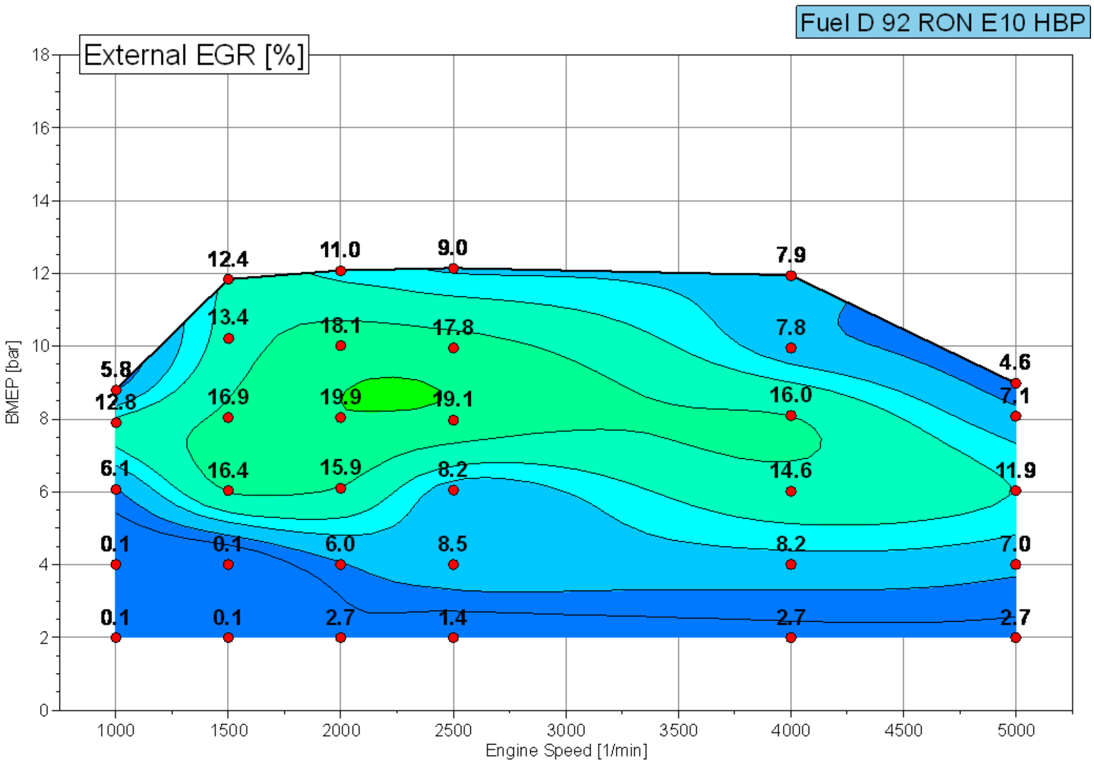

Figure 8: External EGR Percent of Intake Air

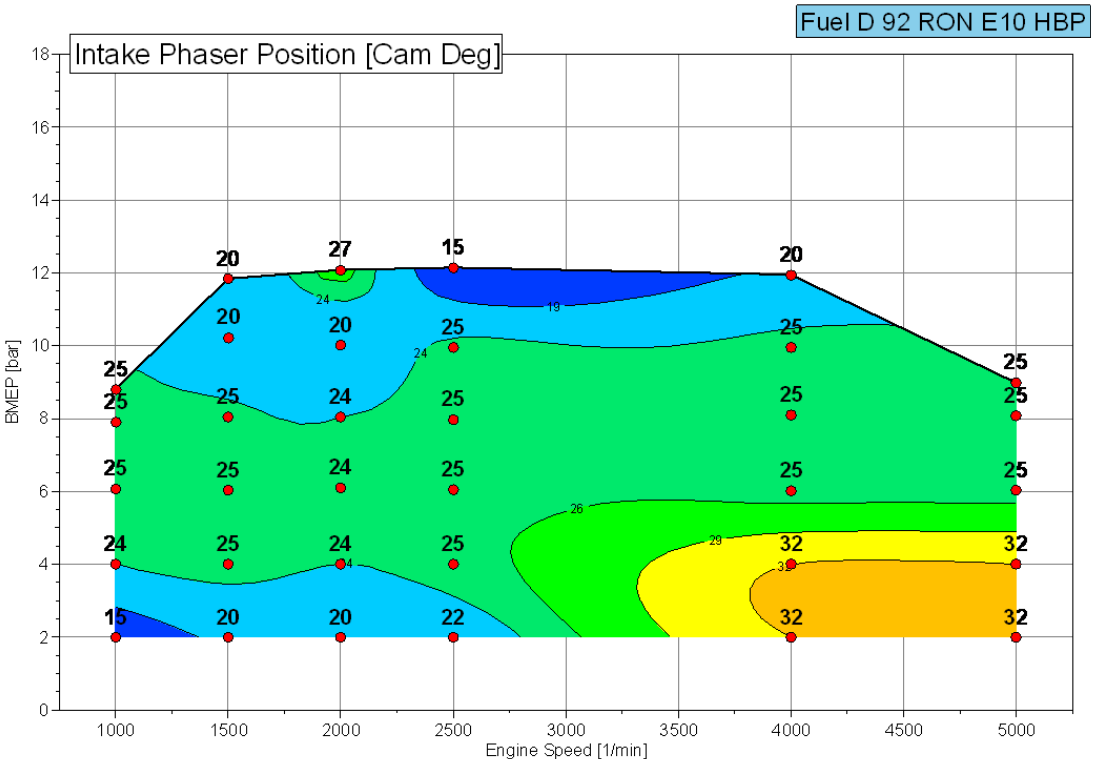

Figure 9: Intake Camshaft Phaser Position

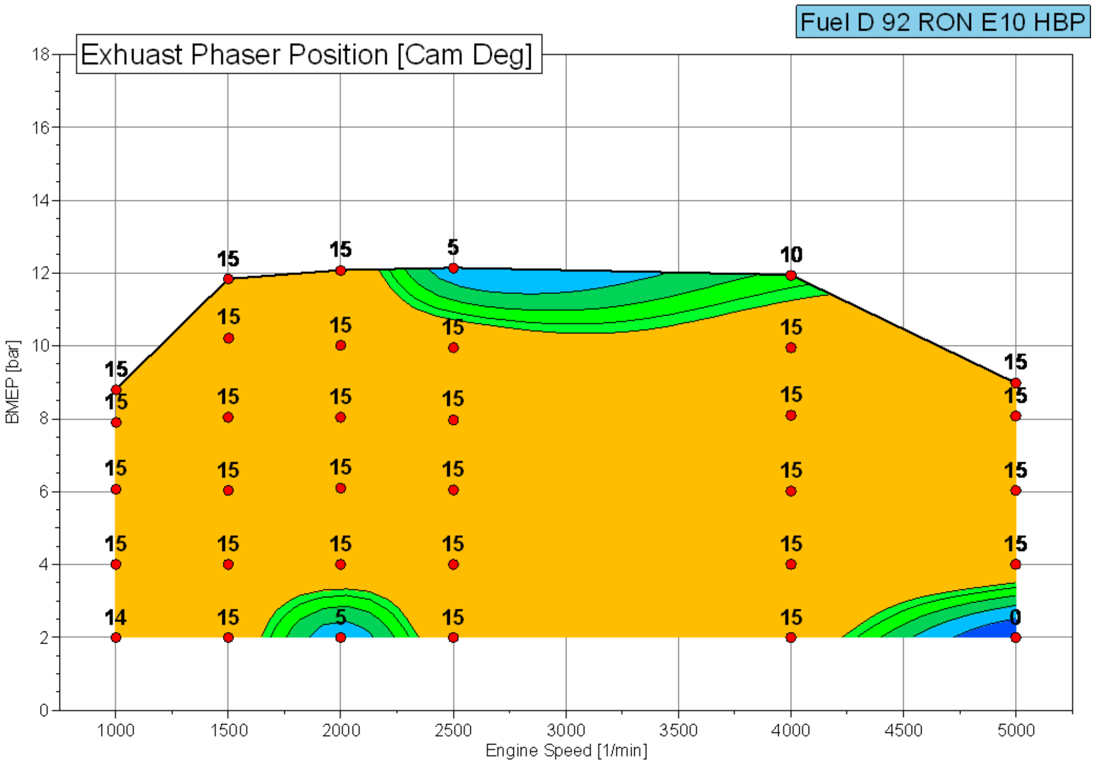

Figure 10: Exhaust Camshaft Phaser Position

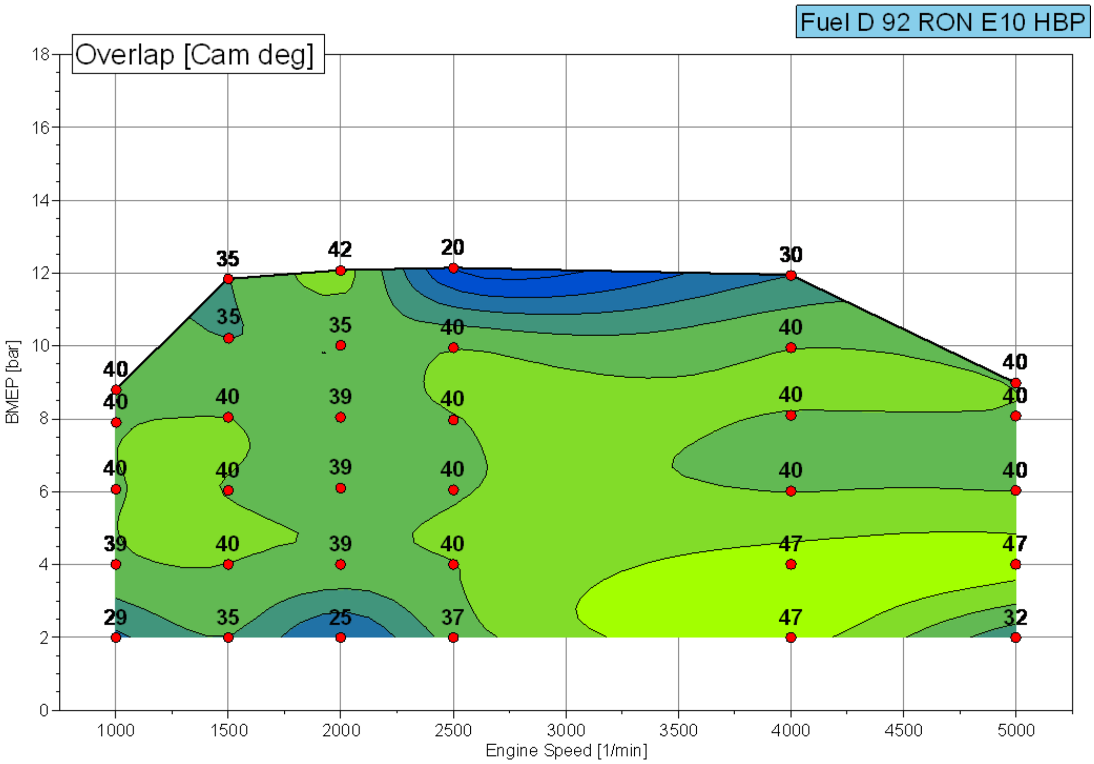

Figure 11: Camshaft Overlap

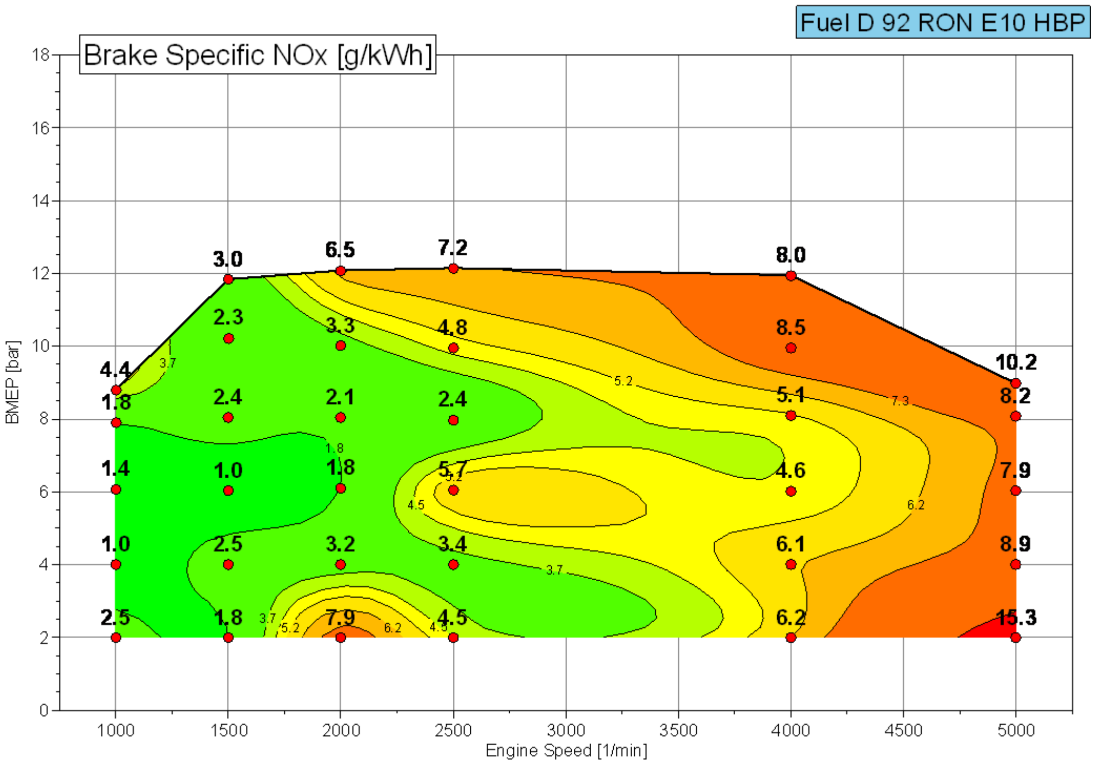

Figure 12: Brake Specific NOx Emissions

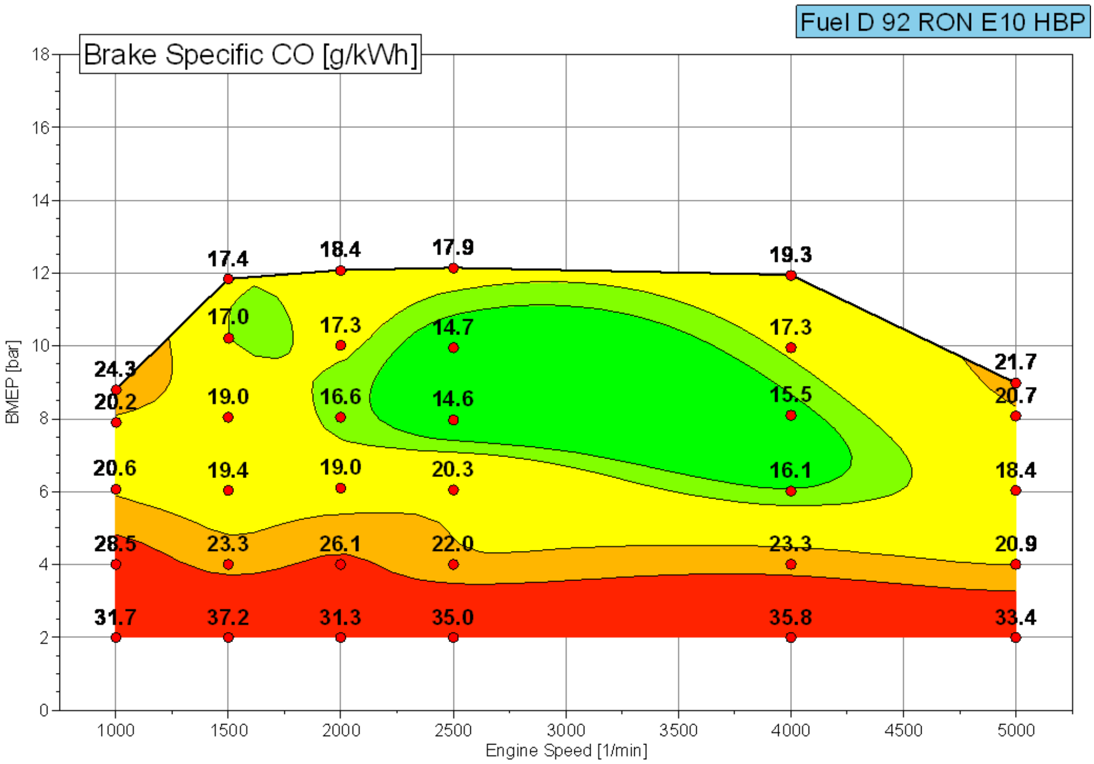

Figure 13: Brake Specific Carbon Monoxide Emissions

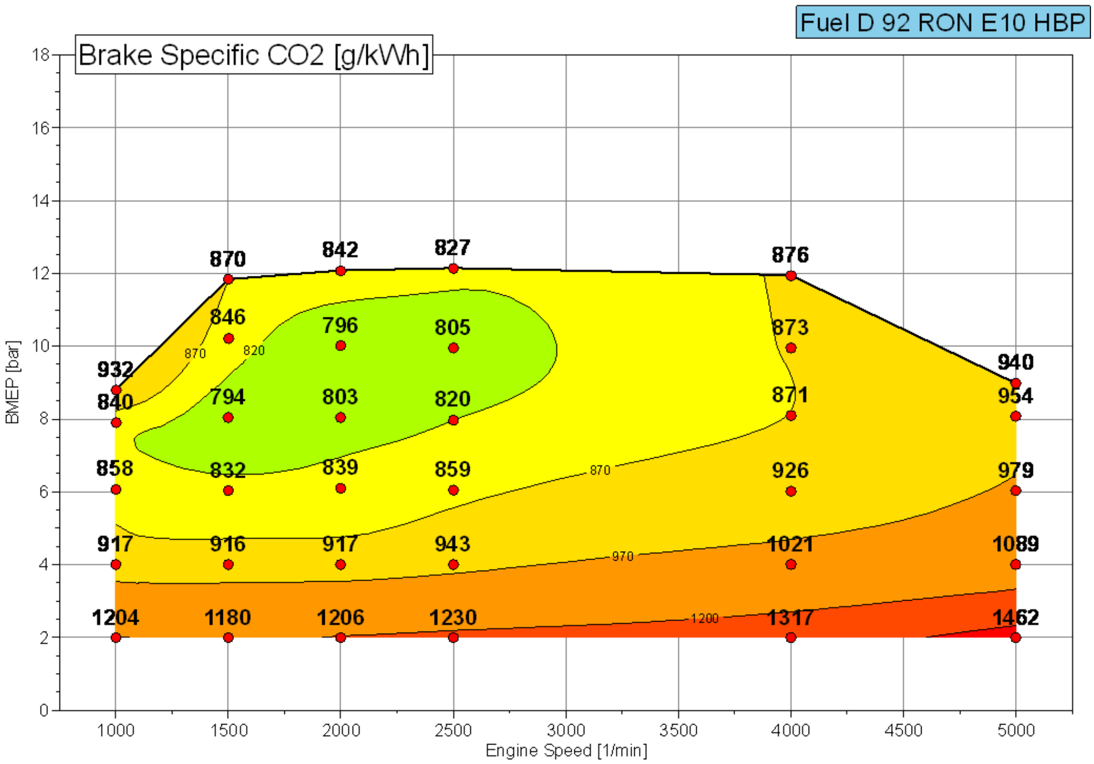

Figure 14: Brake Specific Carbon Dioxide Emissions

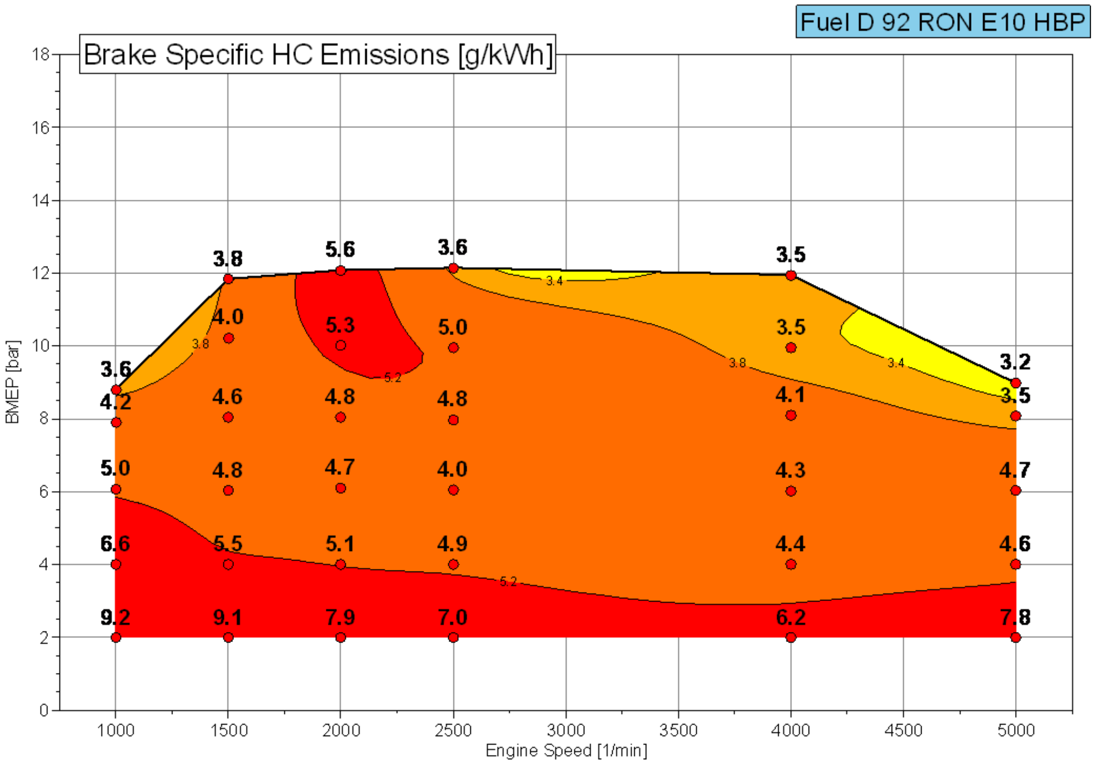

Figure 15: Brake Specific Hydrocarbon Emissions

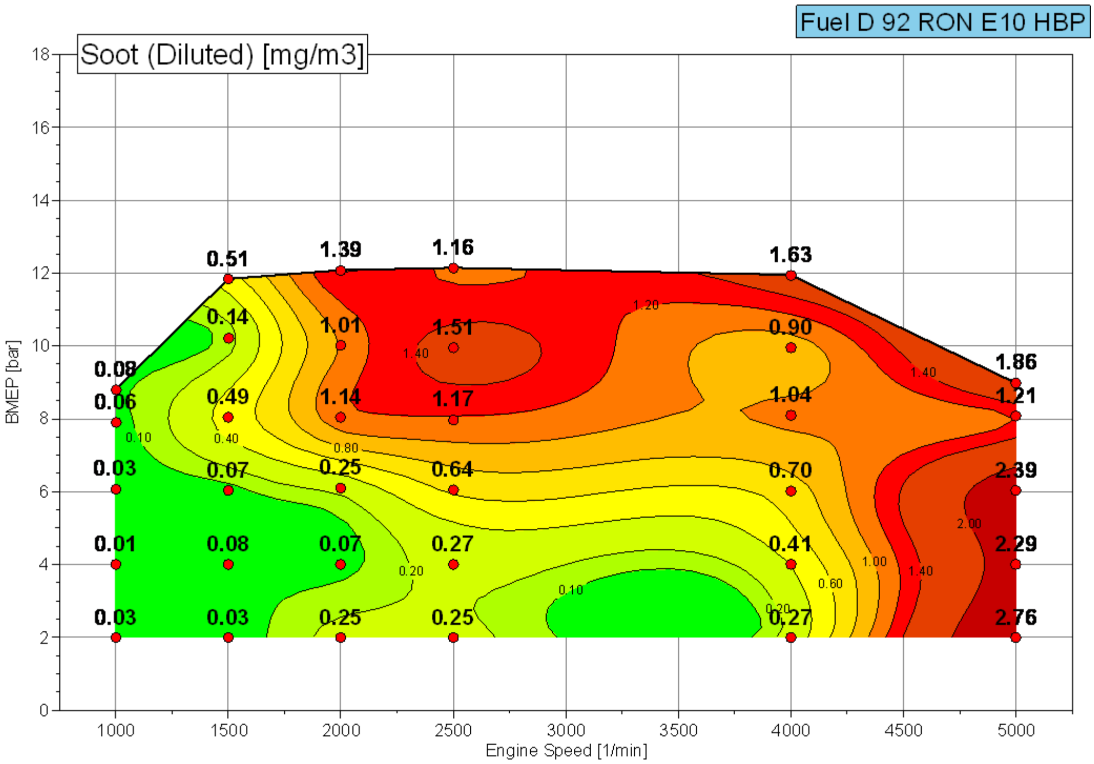

Figure 16: Particulate Soot Emissions

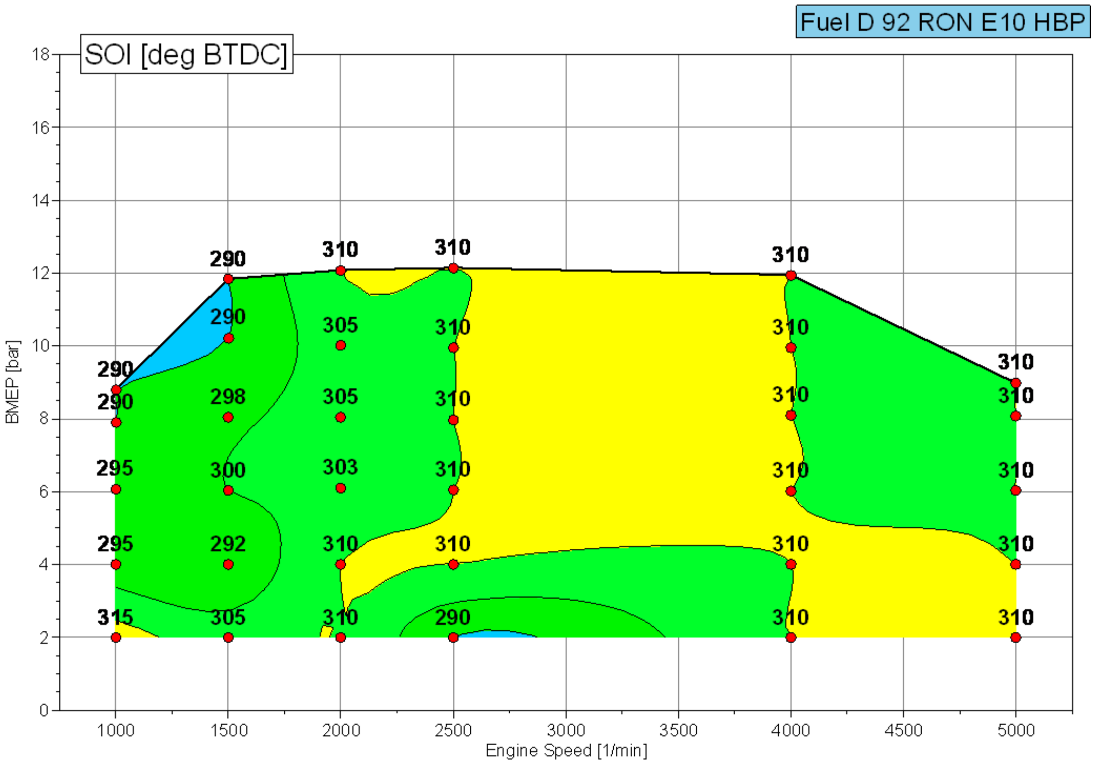

Figure 17: Start of Injection

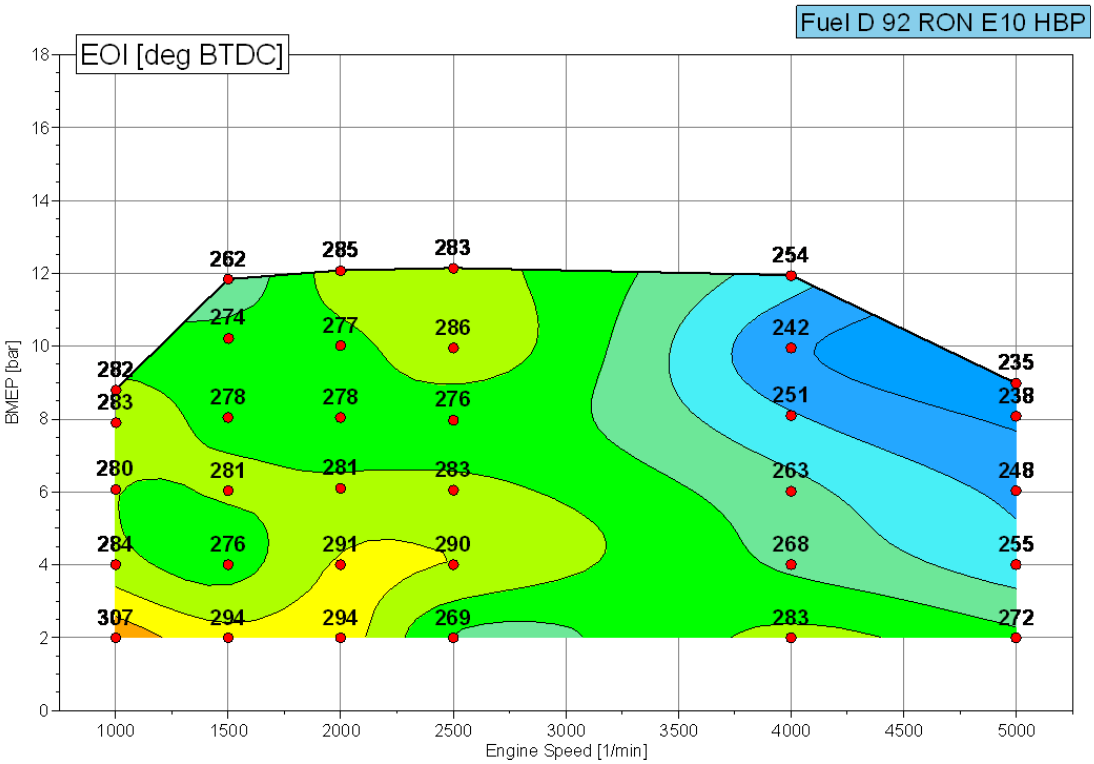

Figure 18: End of Injection

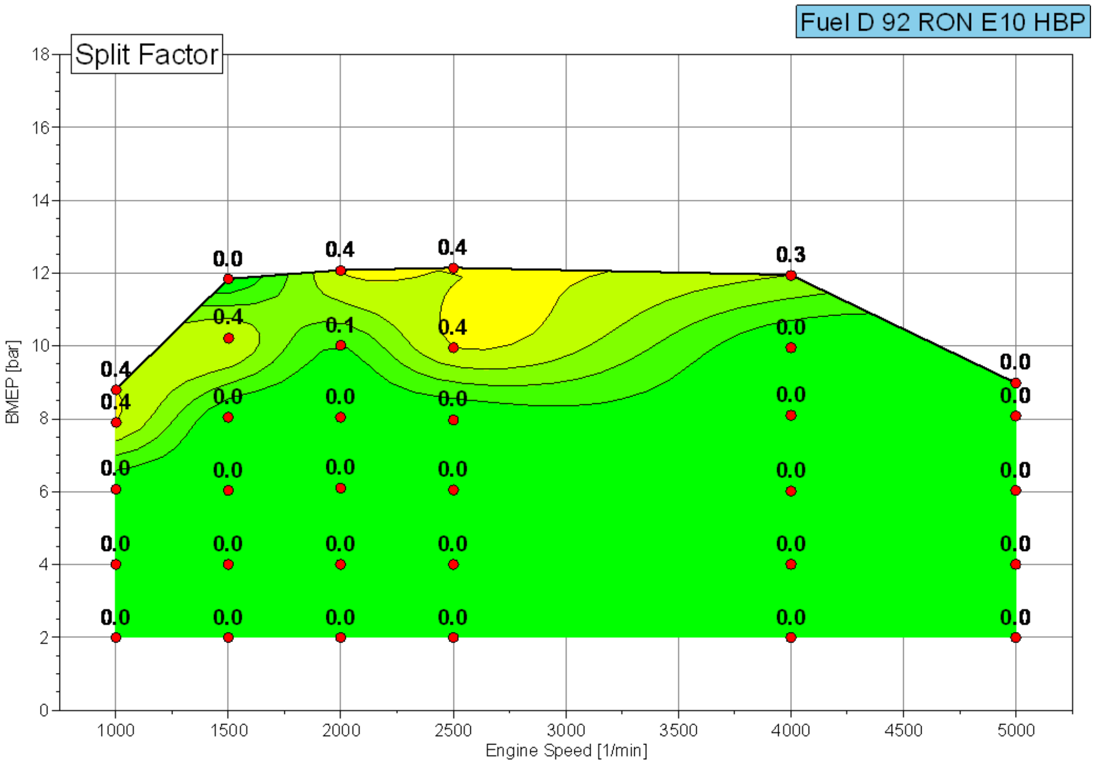

Figure 19: Injection Split Factor

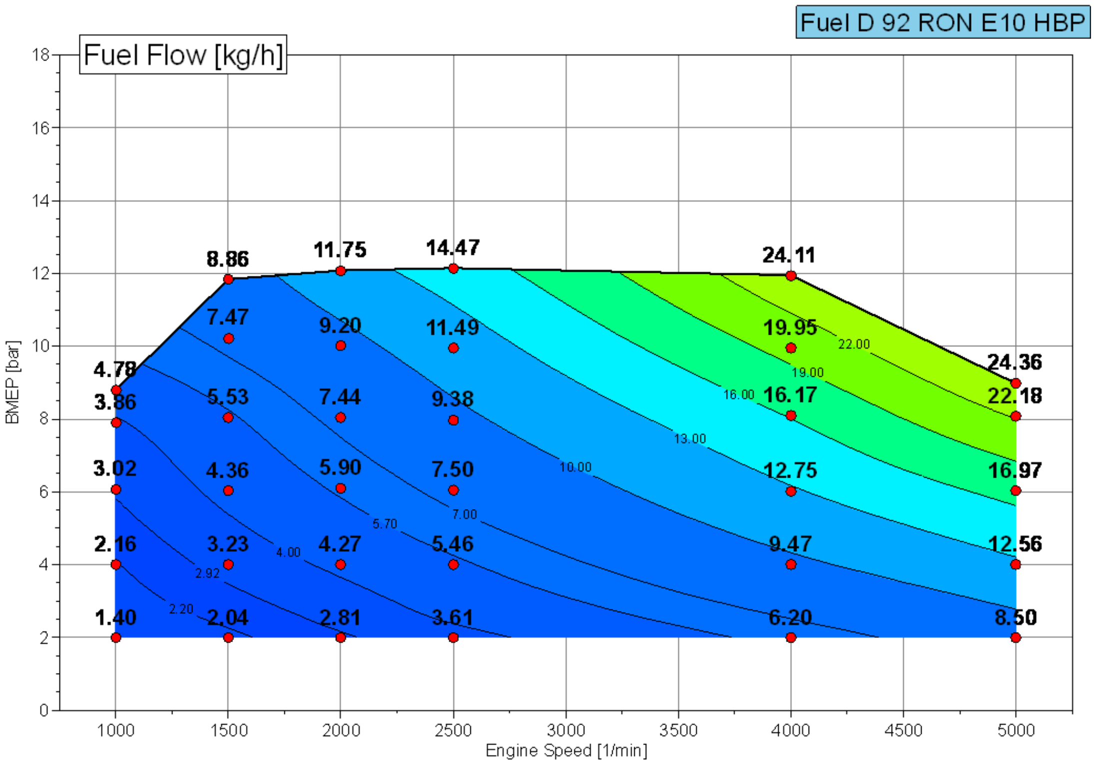

Figure 20: Fuel Flow

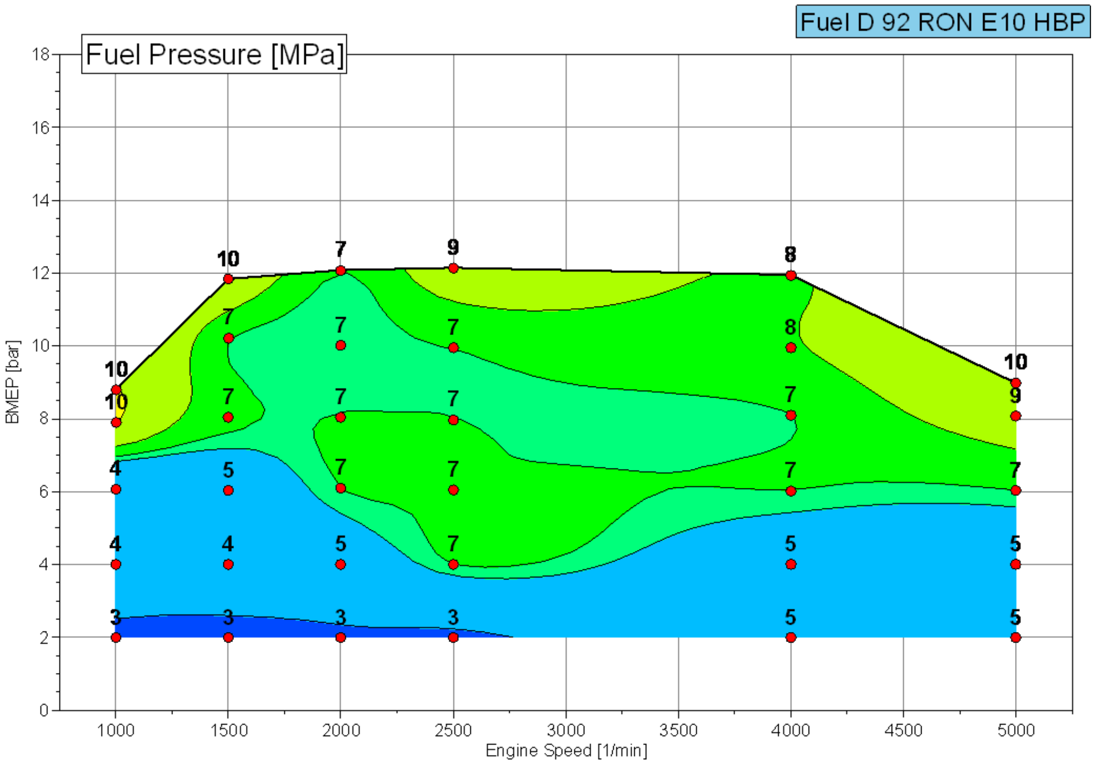

Figure 21: Fuel Rail Pressure

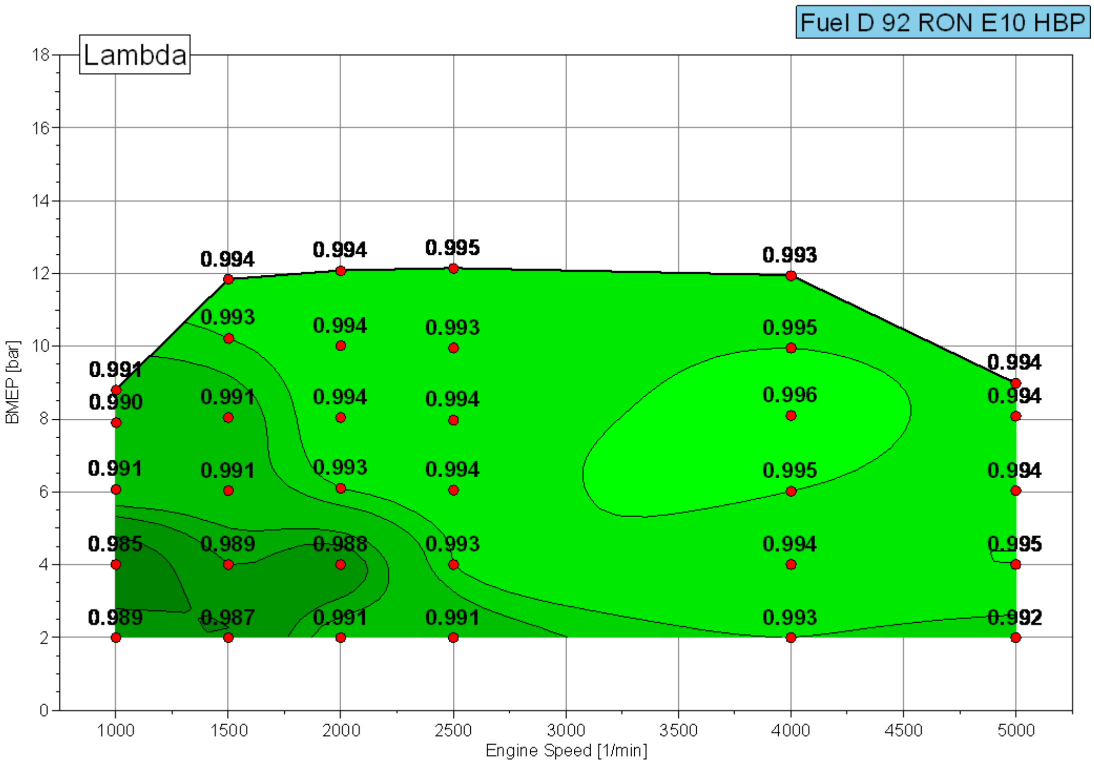

Figure 22: Lambda

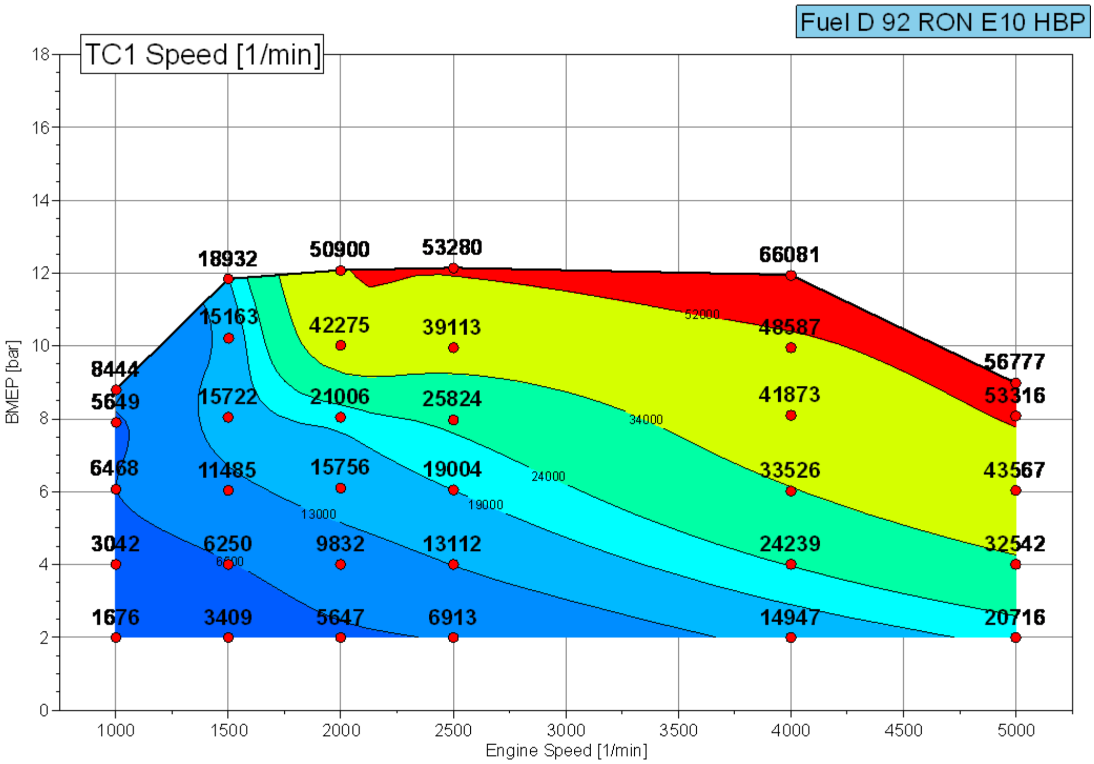

Figure 23: Low Pressure Turbocharger Speed

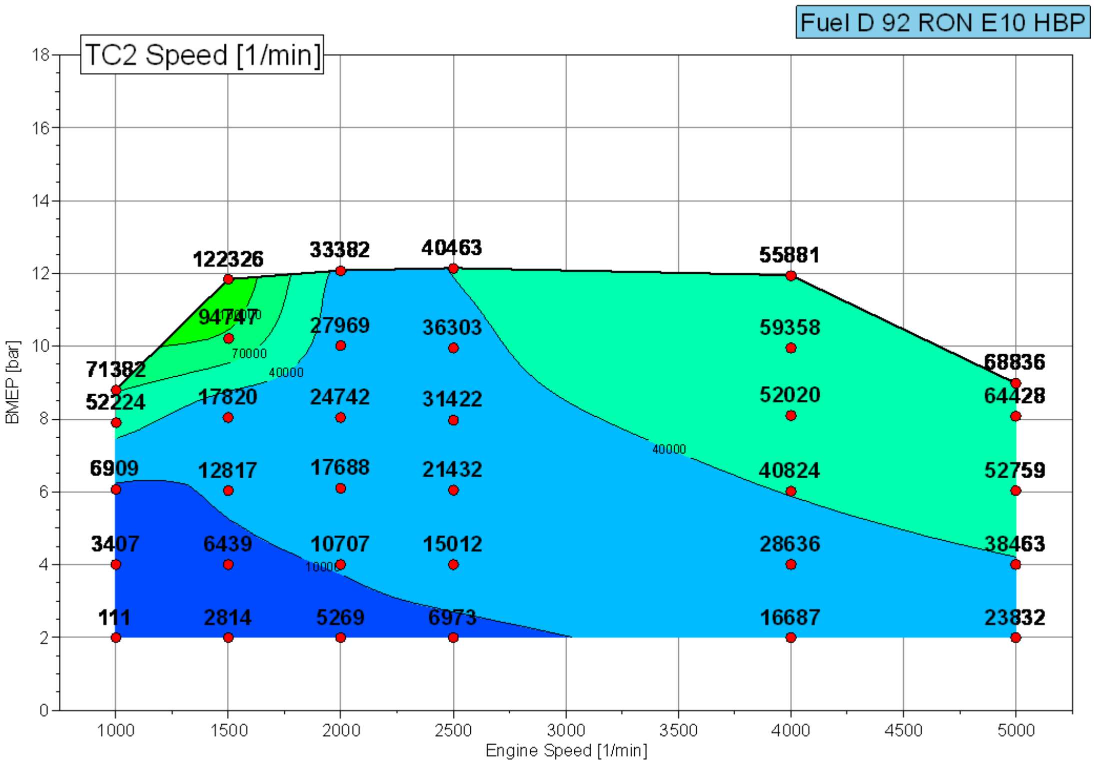

Figure 24: High Pressure Turbocharge Speed

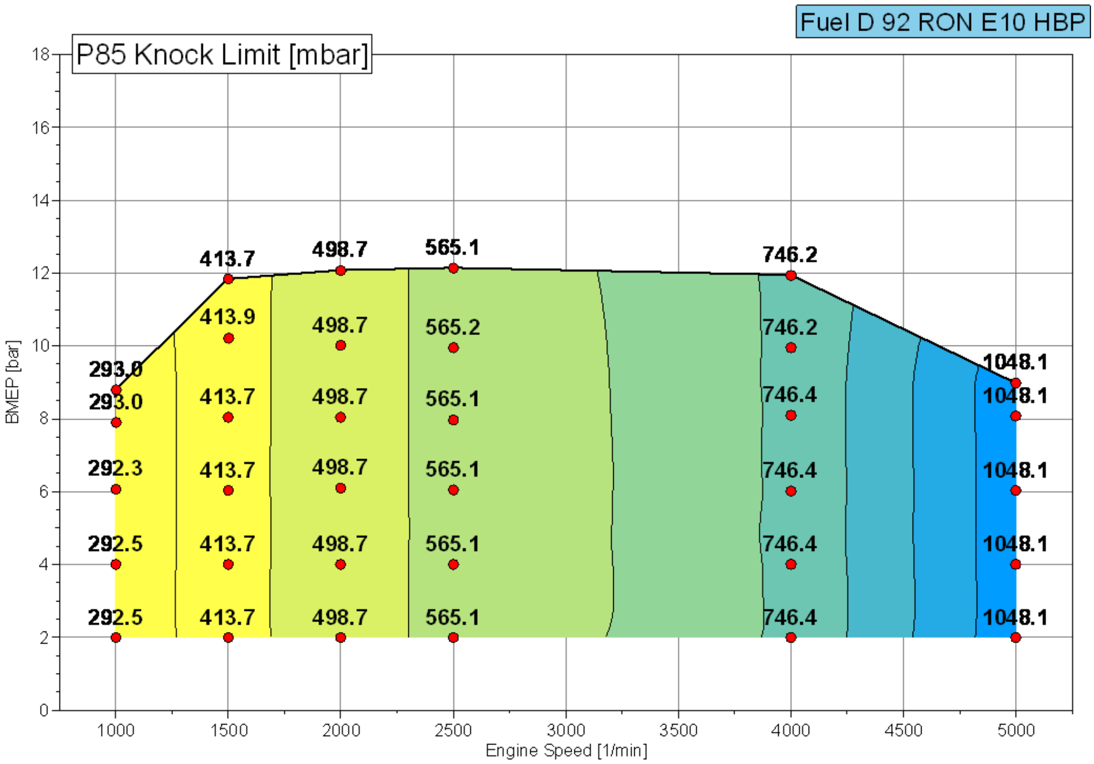

Figure 25: P85 Knock Limit

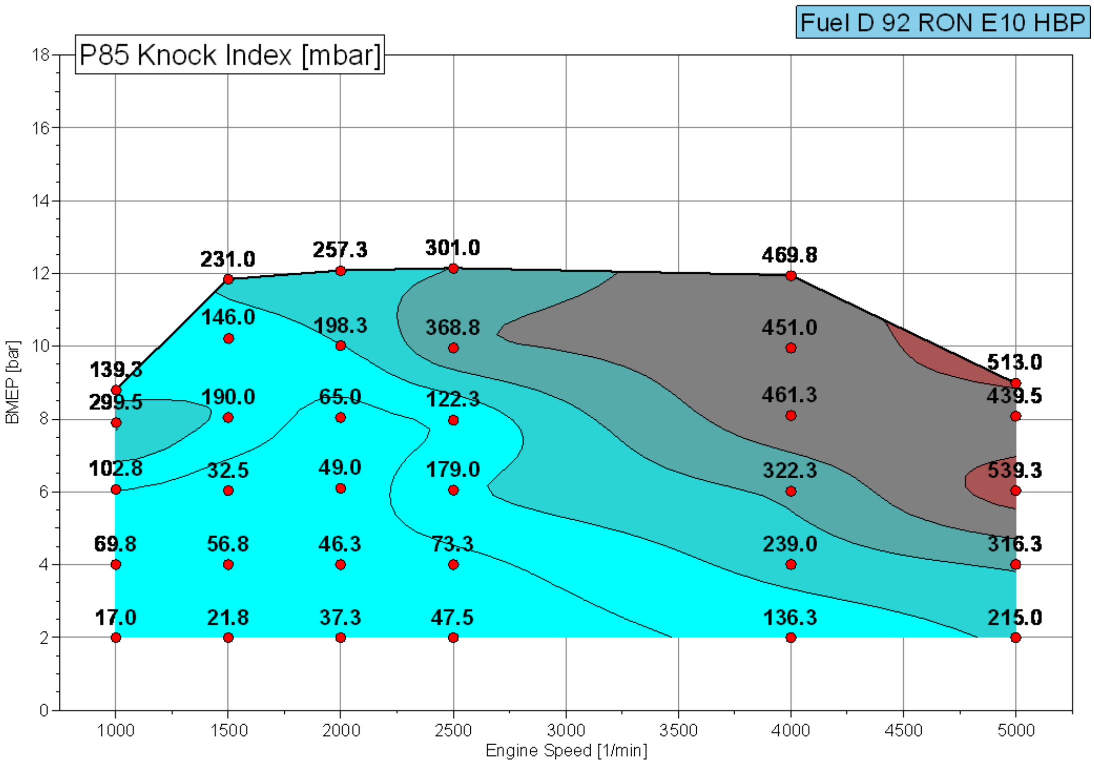

Figure 26: Averaged P85 Knock Index

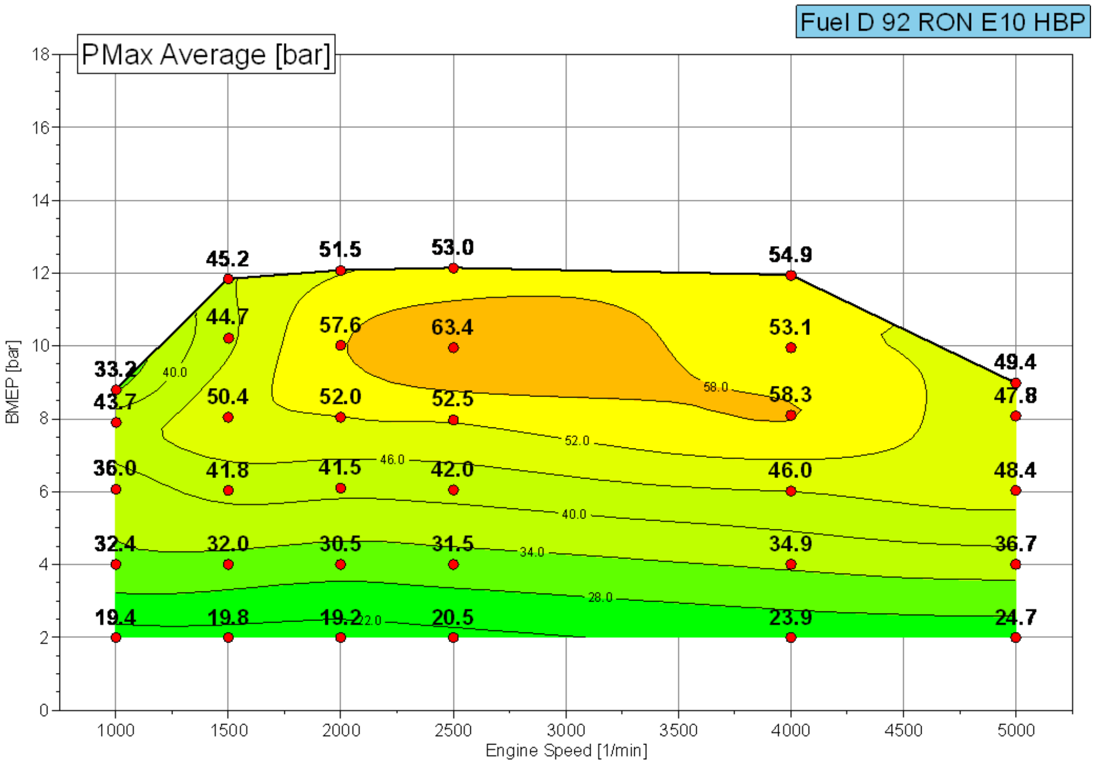

Figure 27: Averaged Max Pressure for Cylinders 1-4

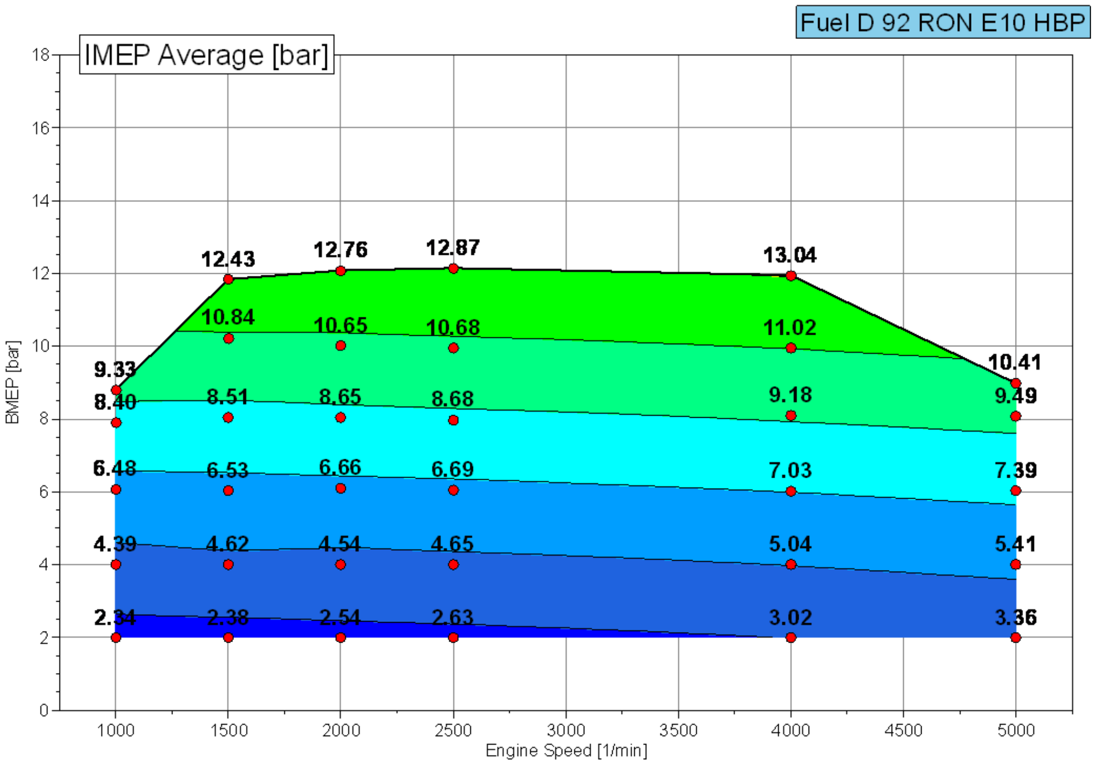

Figure 28: Indicated Mean Effective Pressure

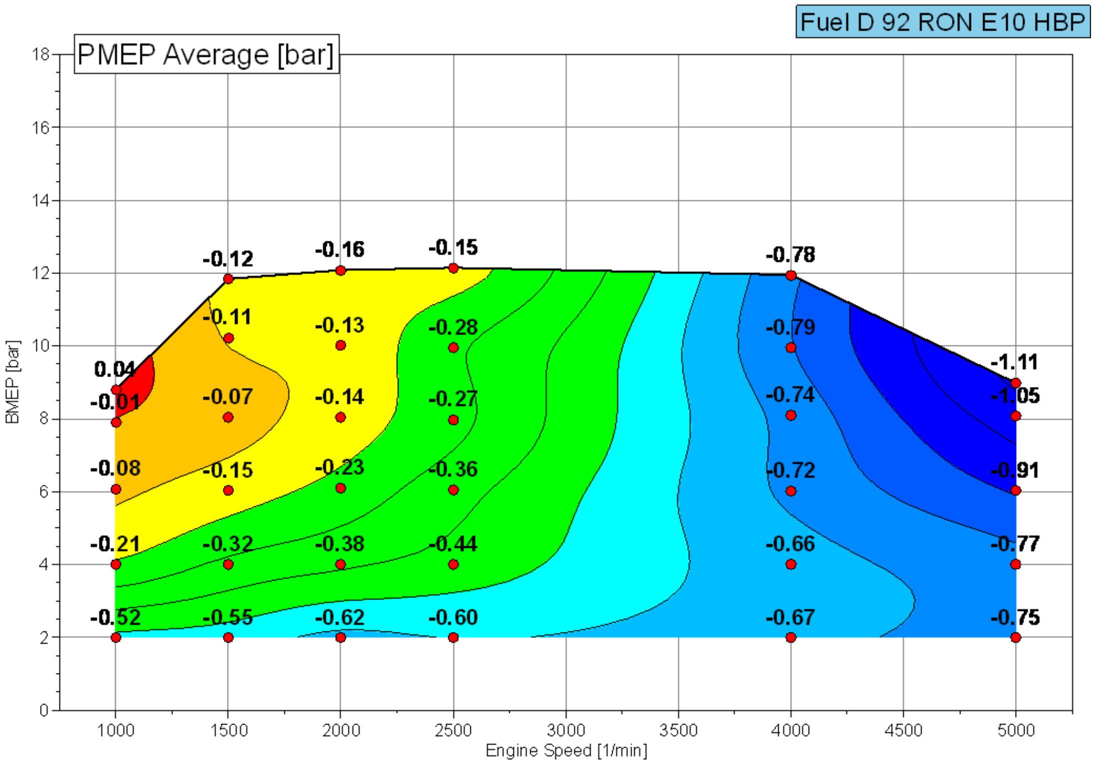

Figure 29: Pumping Mean Effective Pressure

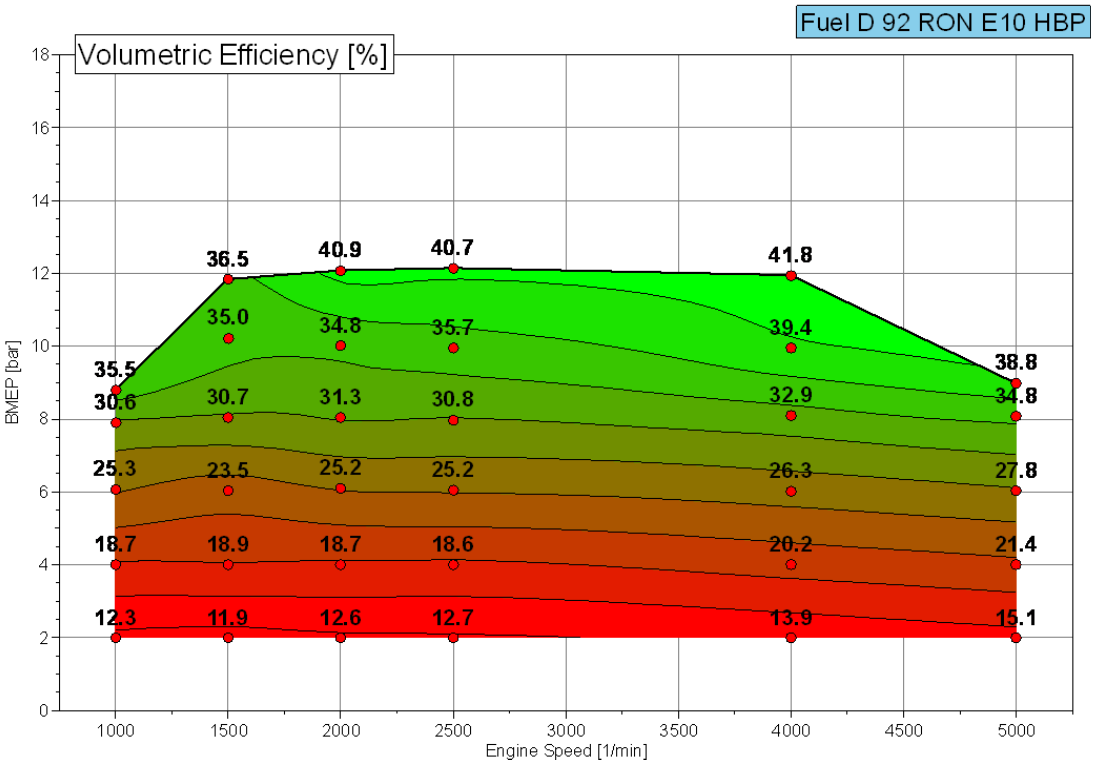

Figure 30: Calculated Volumetric Efficiency

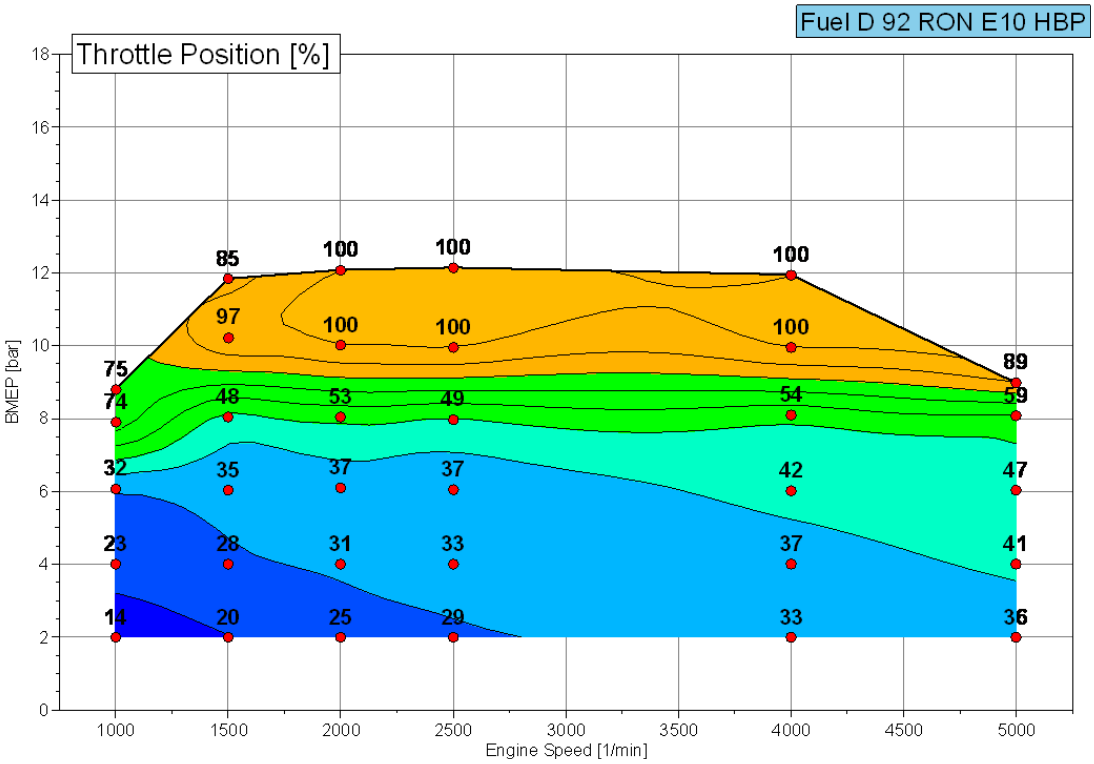

Figure 31: Throttle Position

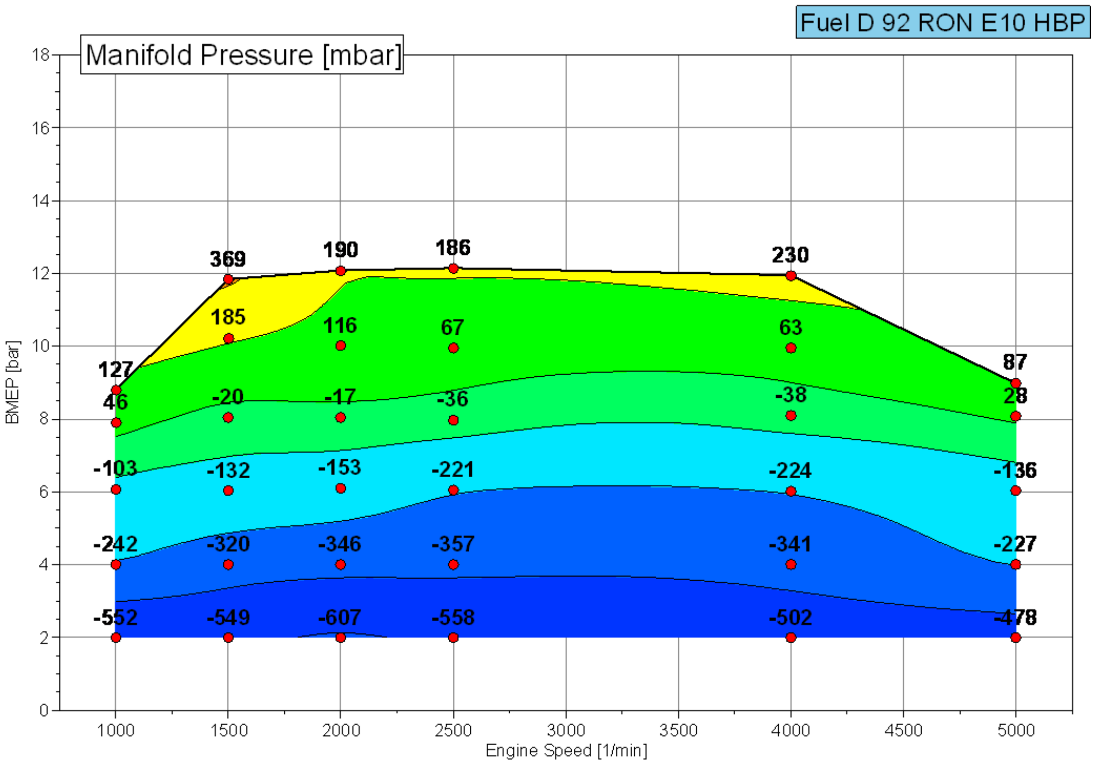

Figure 32: Intake Manifold Pressure

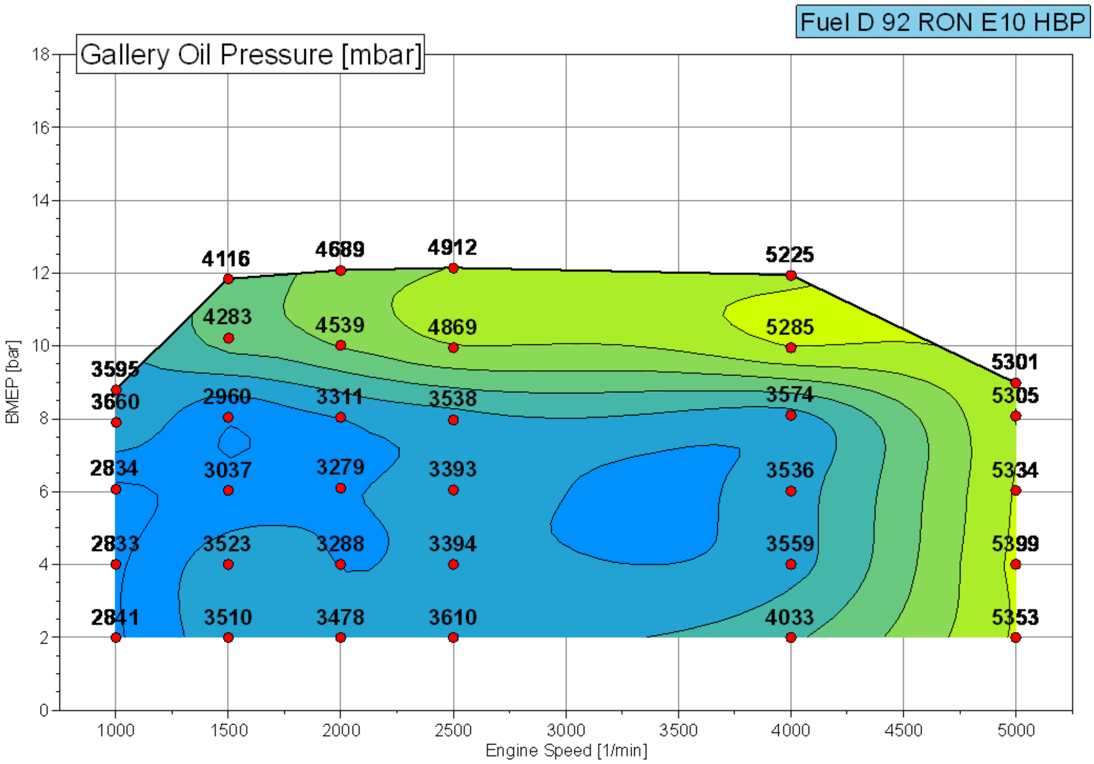

Figure 33: Gallery Oil Pressure

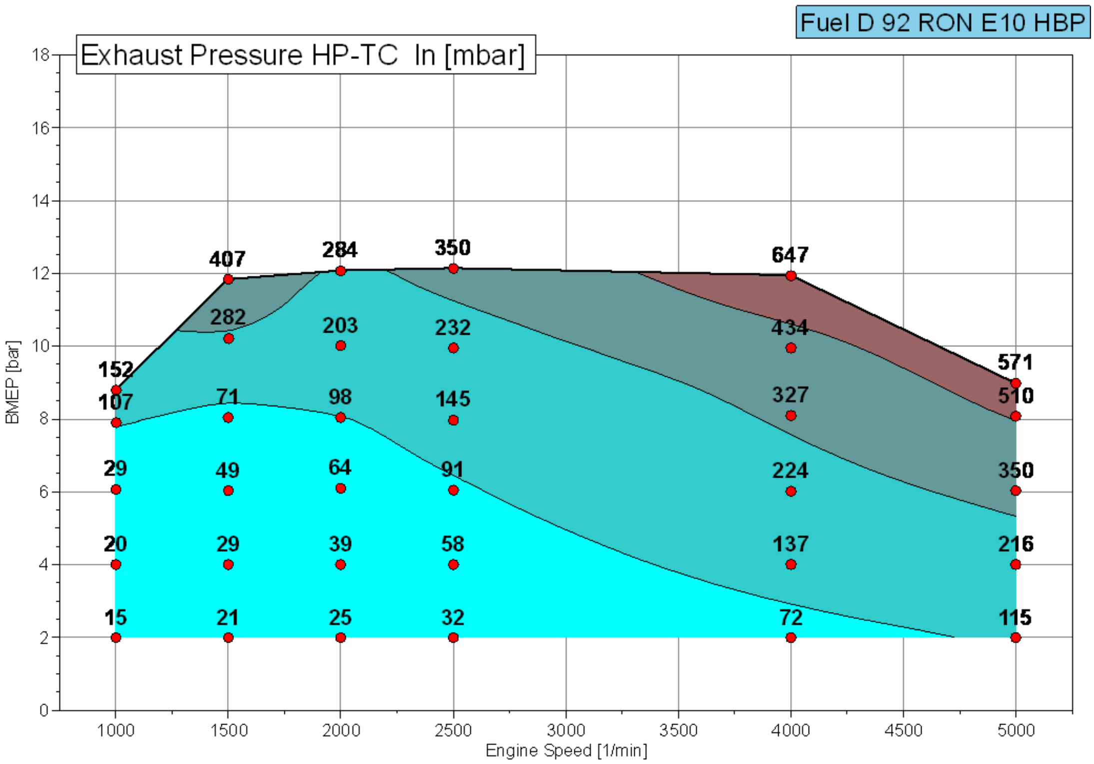

Figure 34: Exhaust Pressure High Pressure Turbocharger In

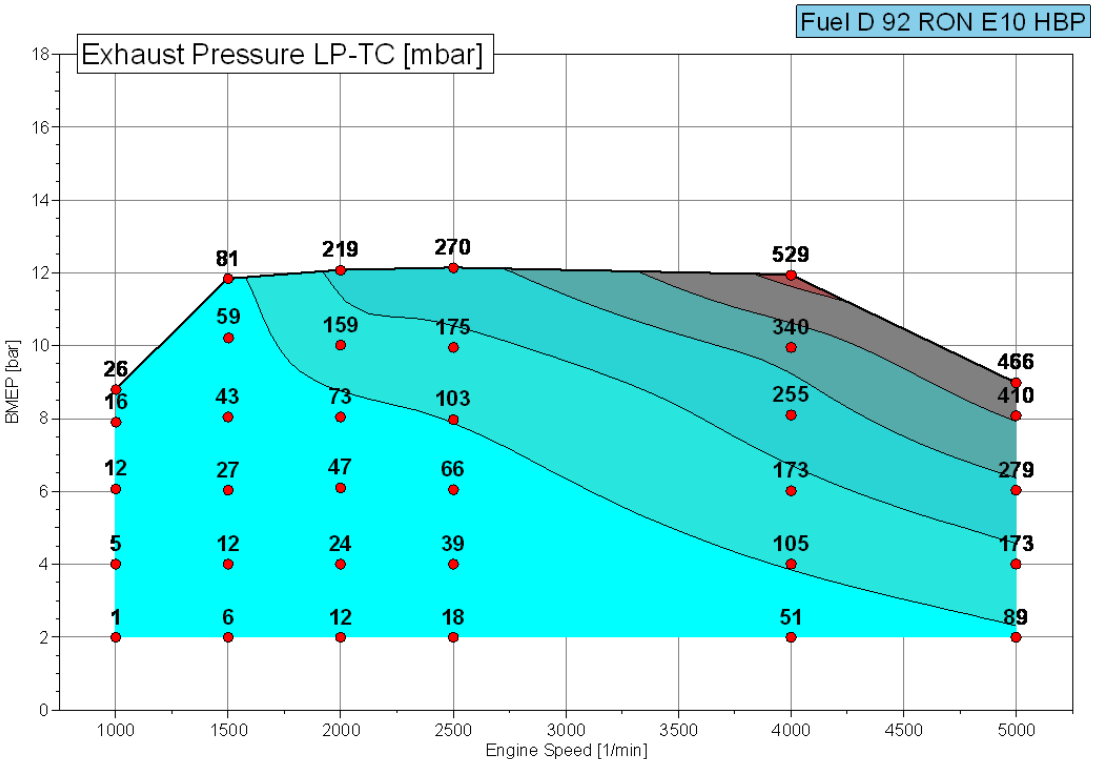

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

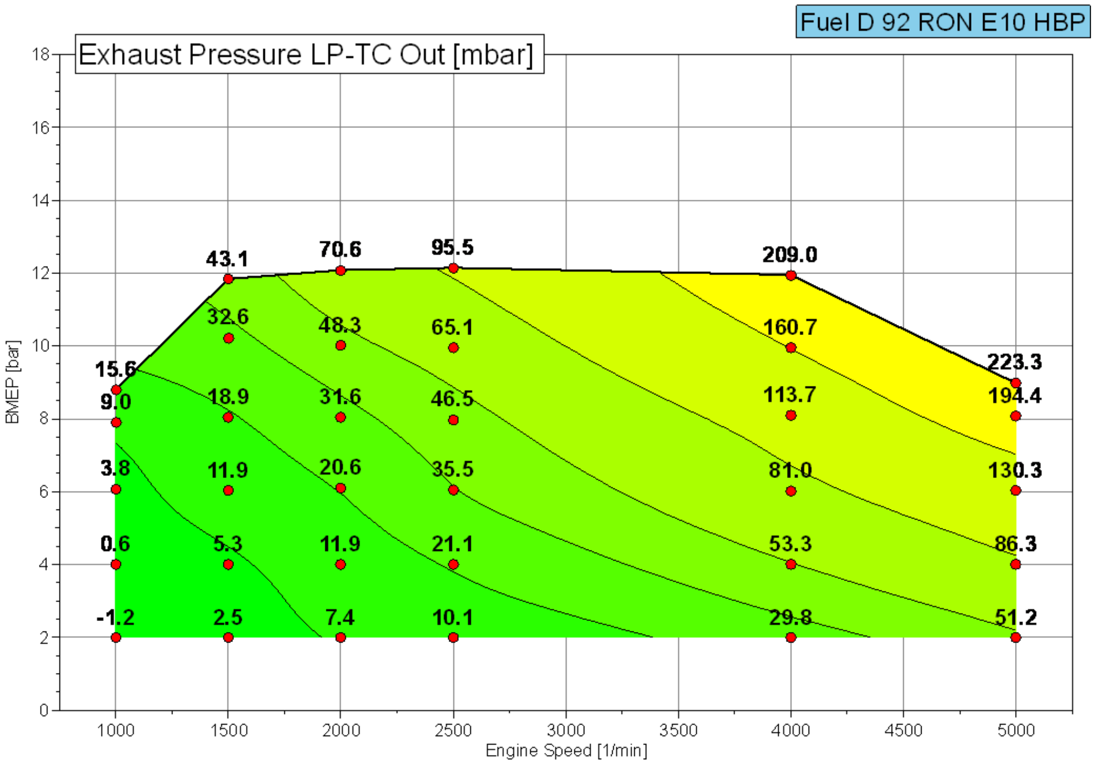

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

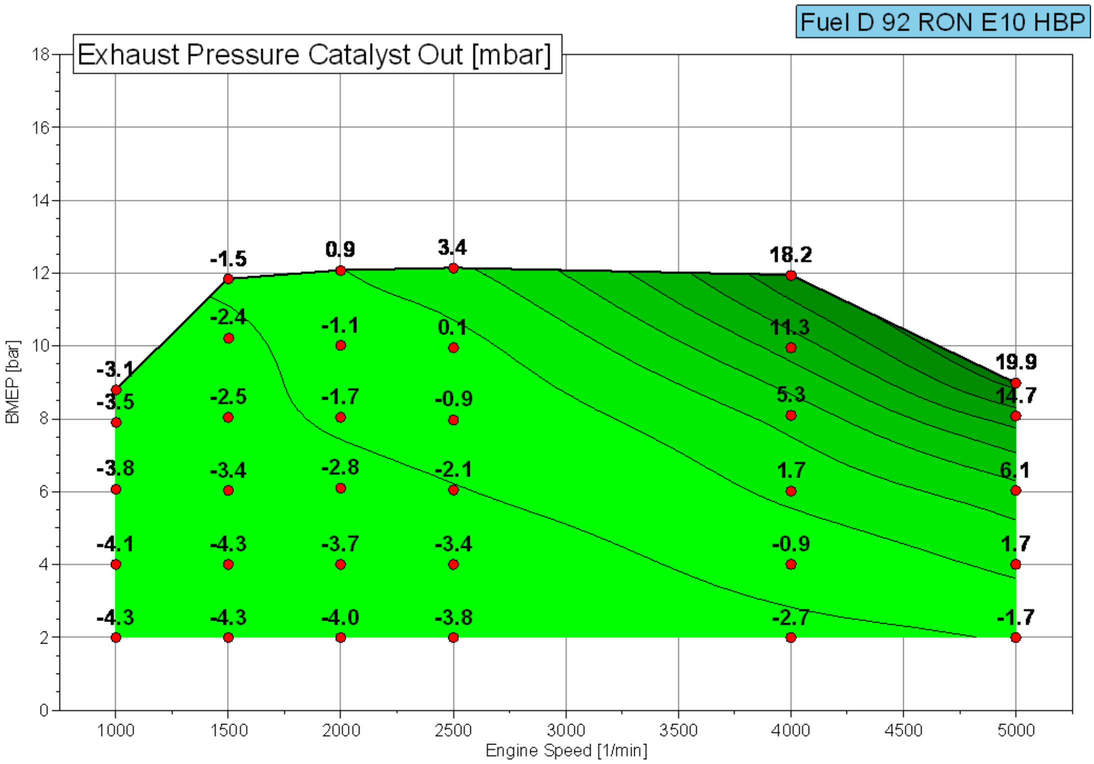

Figure 37: Exhaust Pressure Catalyst Out

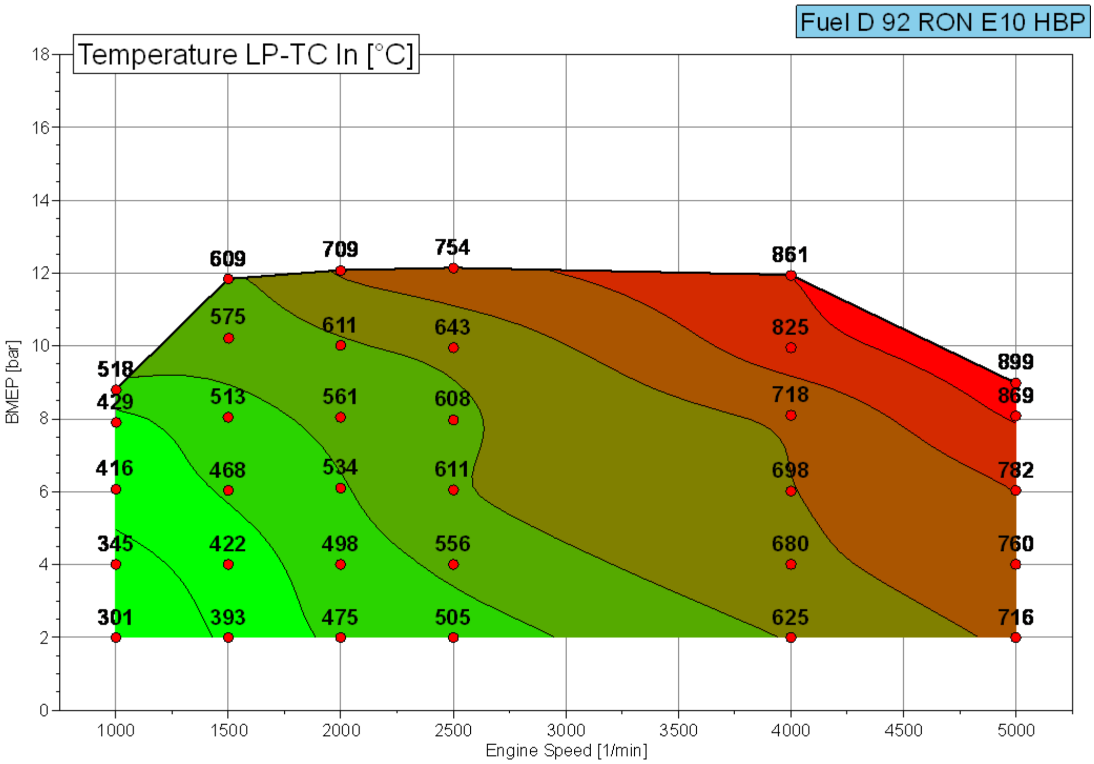

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

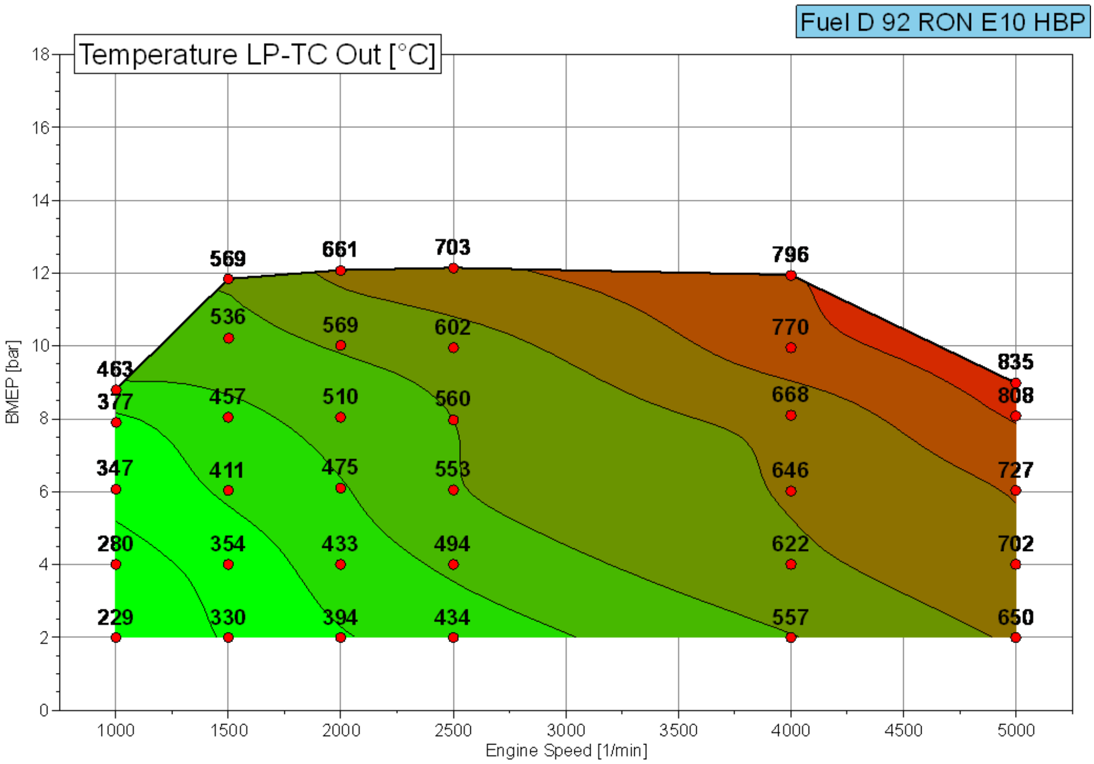

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

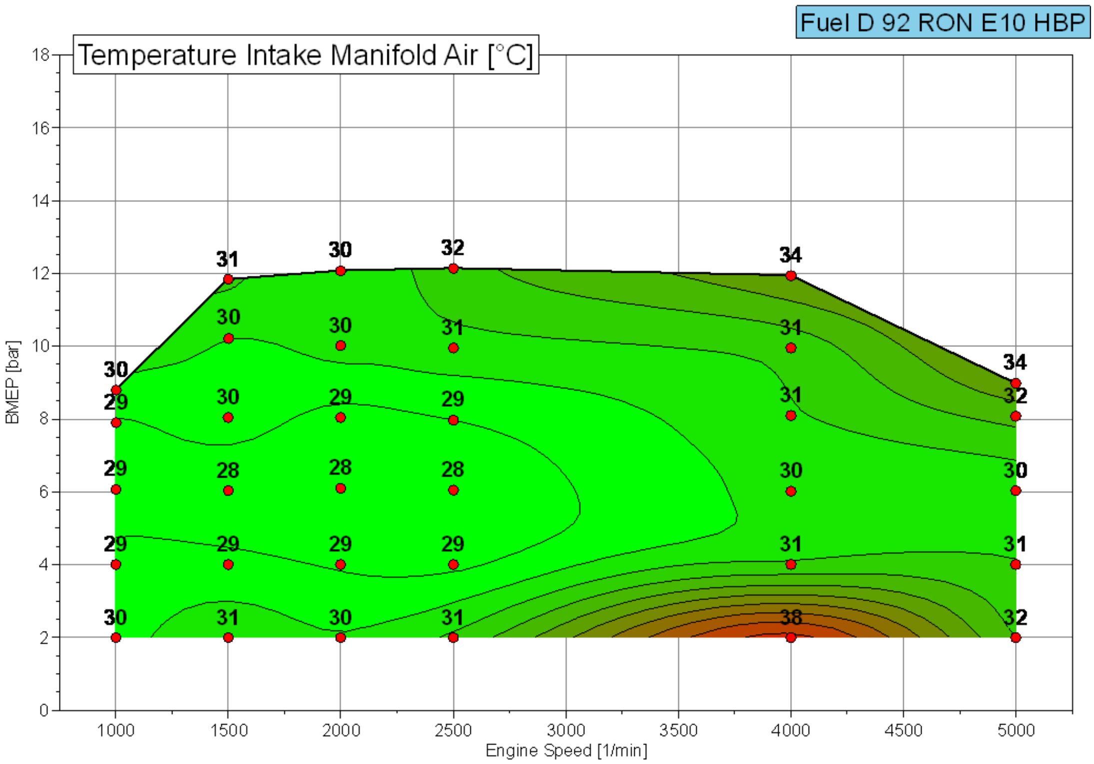

Figure 40: Intake Manifold Air Temperature

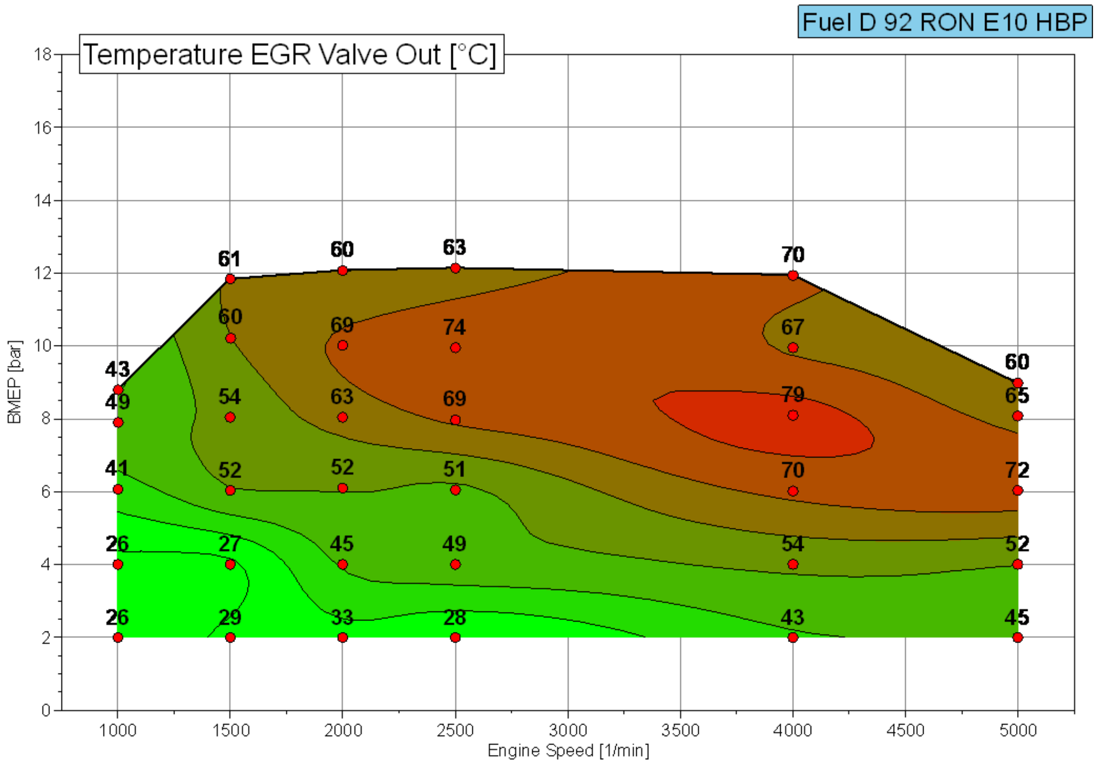

Figure 41: EGR Valve Out Temperature

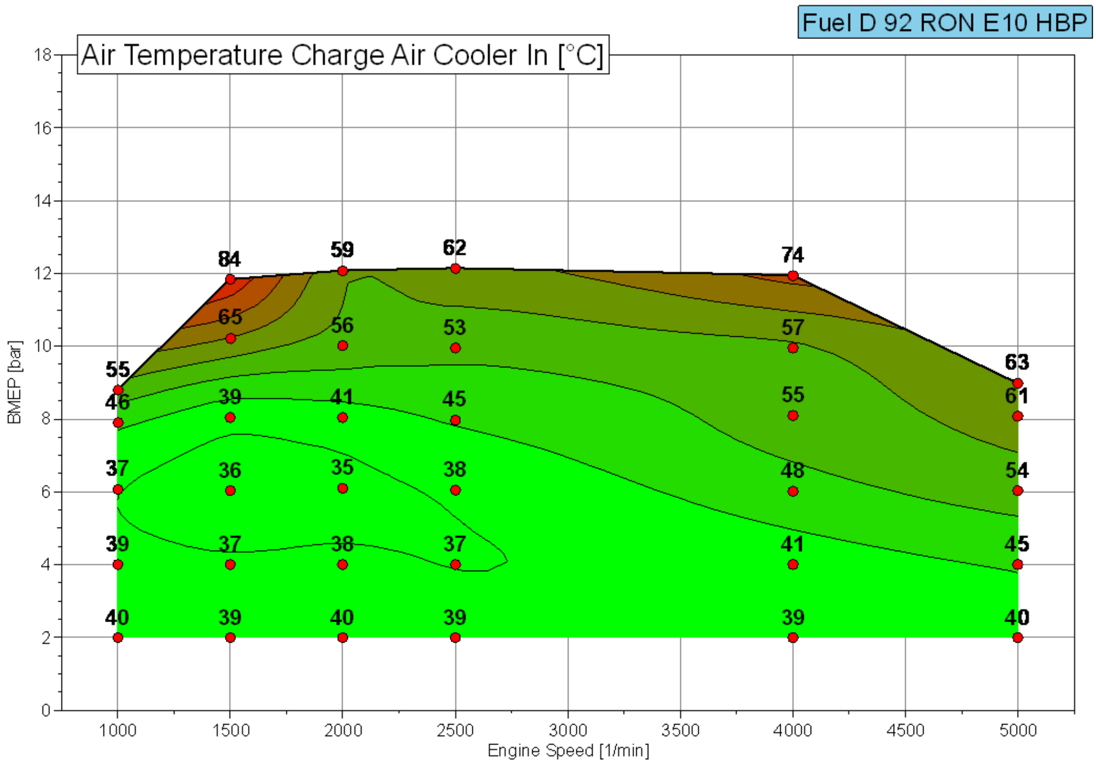

Figure 42: Charge Air Cooler Inlet Air Temperature

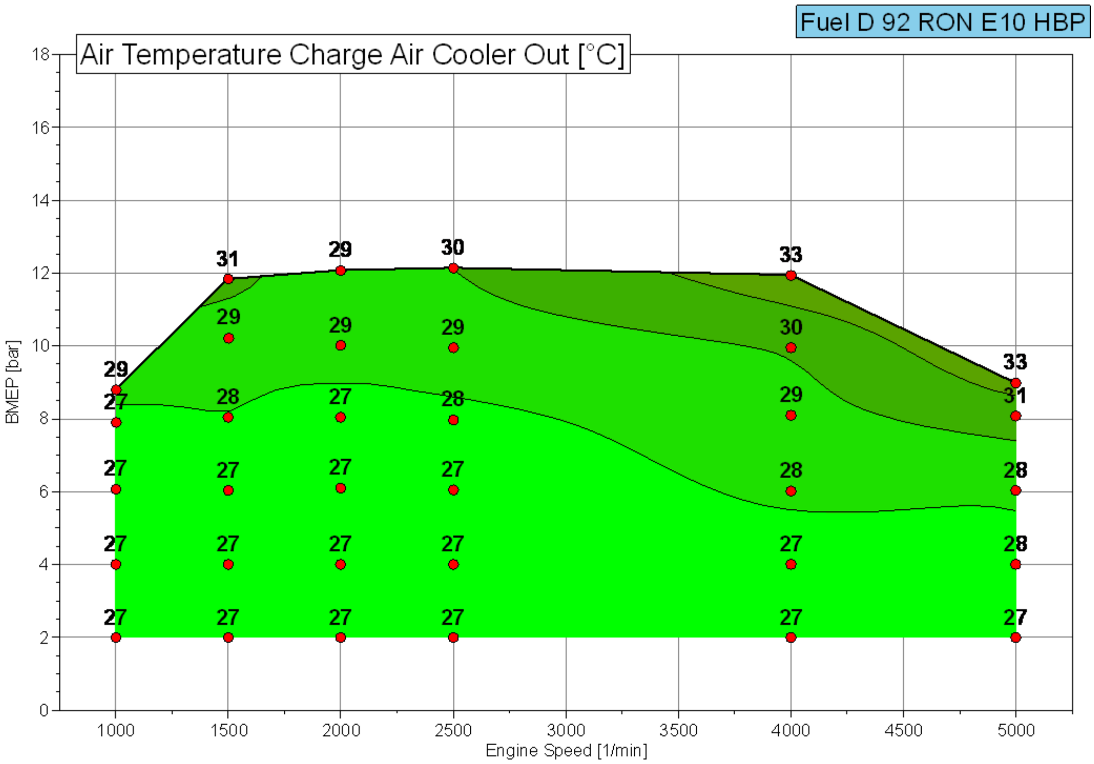

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel F Calibration Results

92 Ron 30% Ethanol High Boiling Point

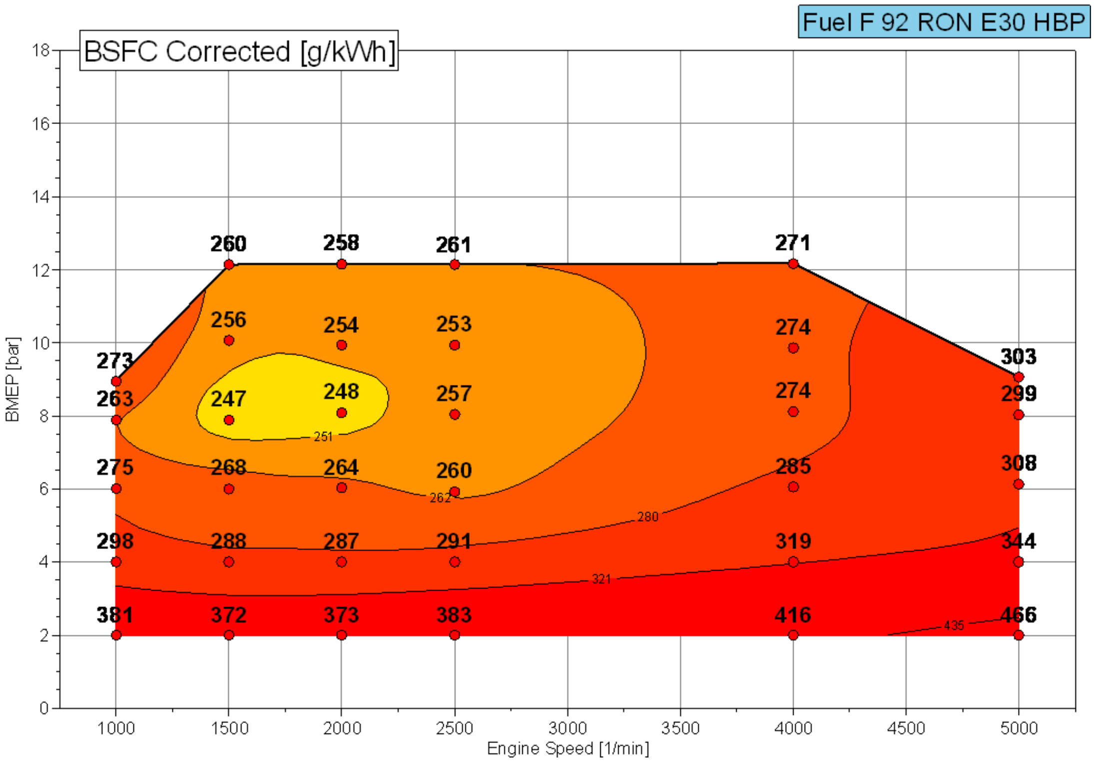

Figure 1: Brake Specific Fuel Consumption

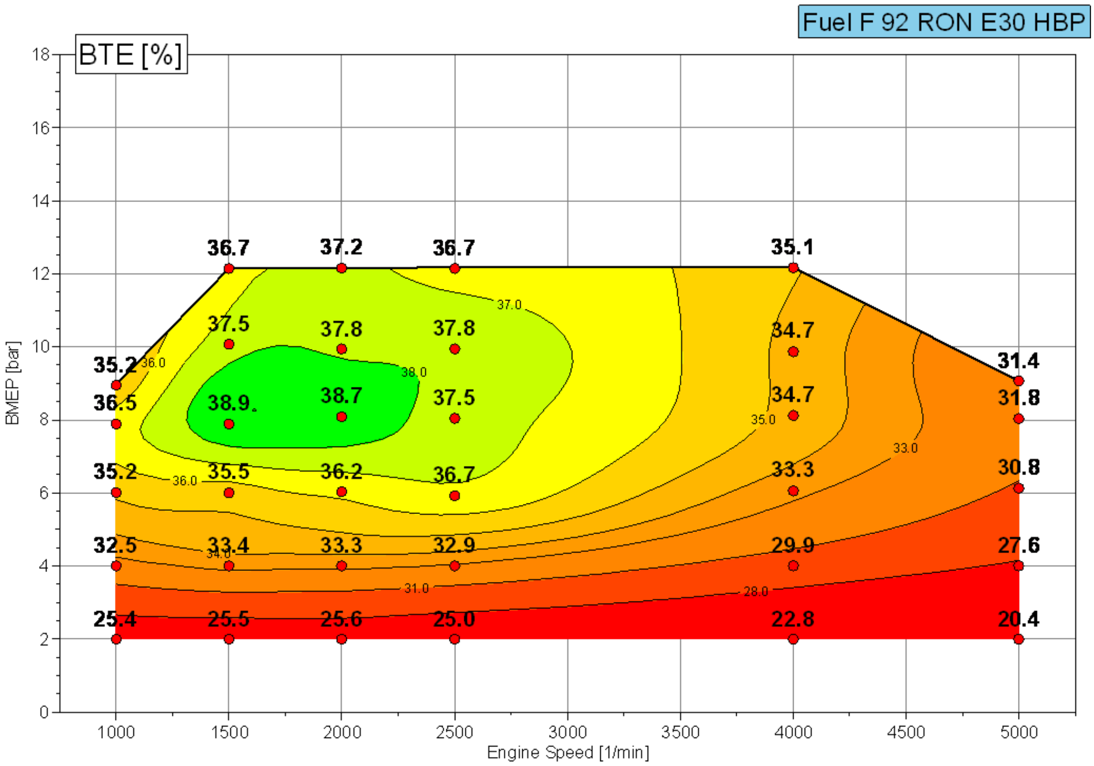

Figure 2: Brake Thermal Efficiency

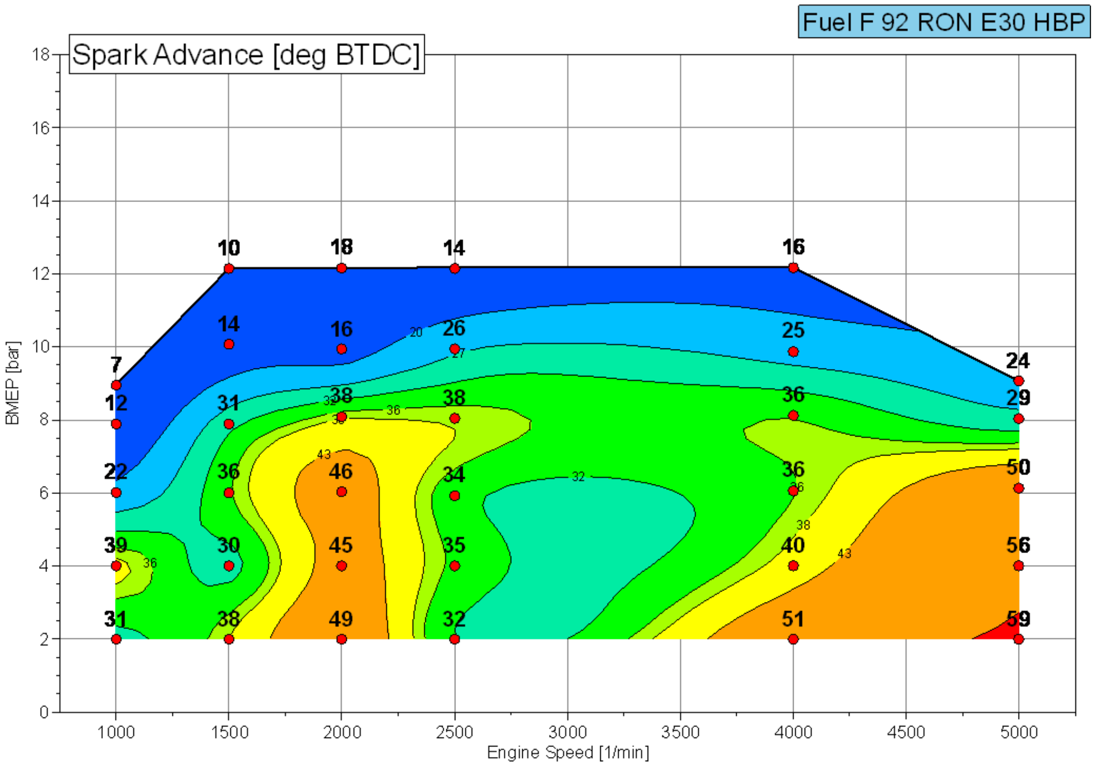

Figure 3: Spark Advance

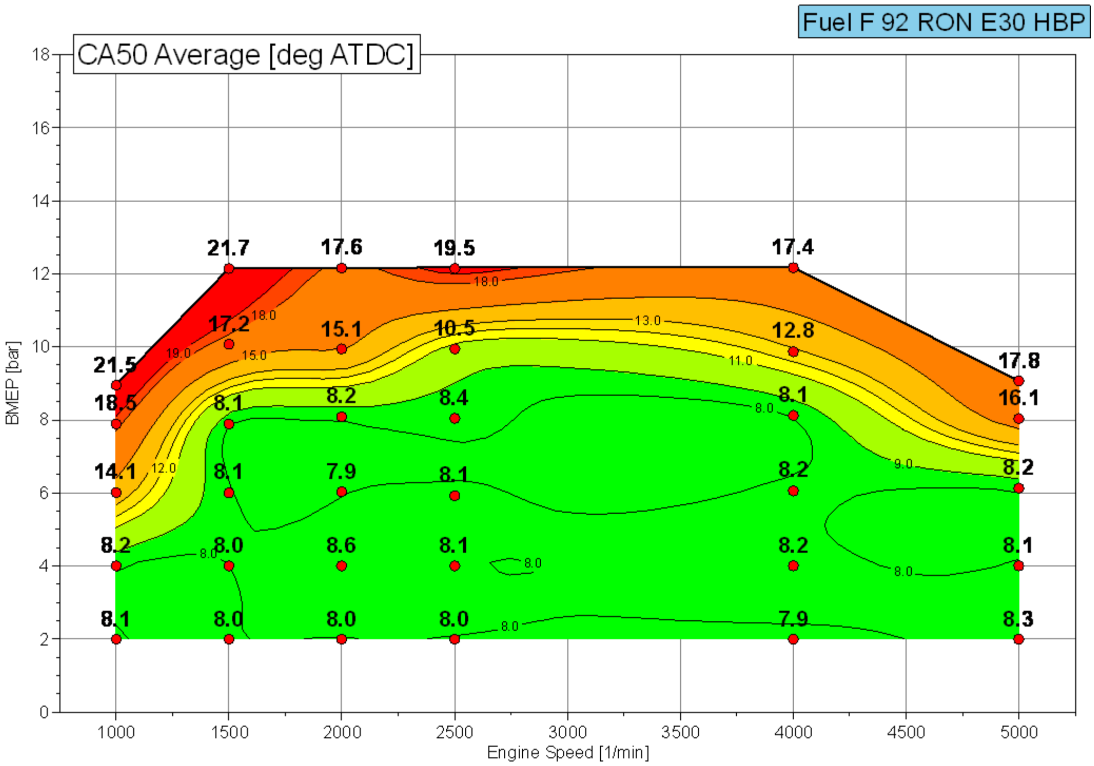

Figure 4: CA50 Average of Cylinders 1-4

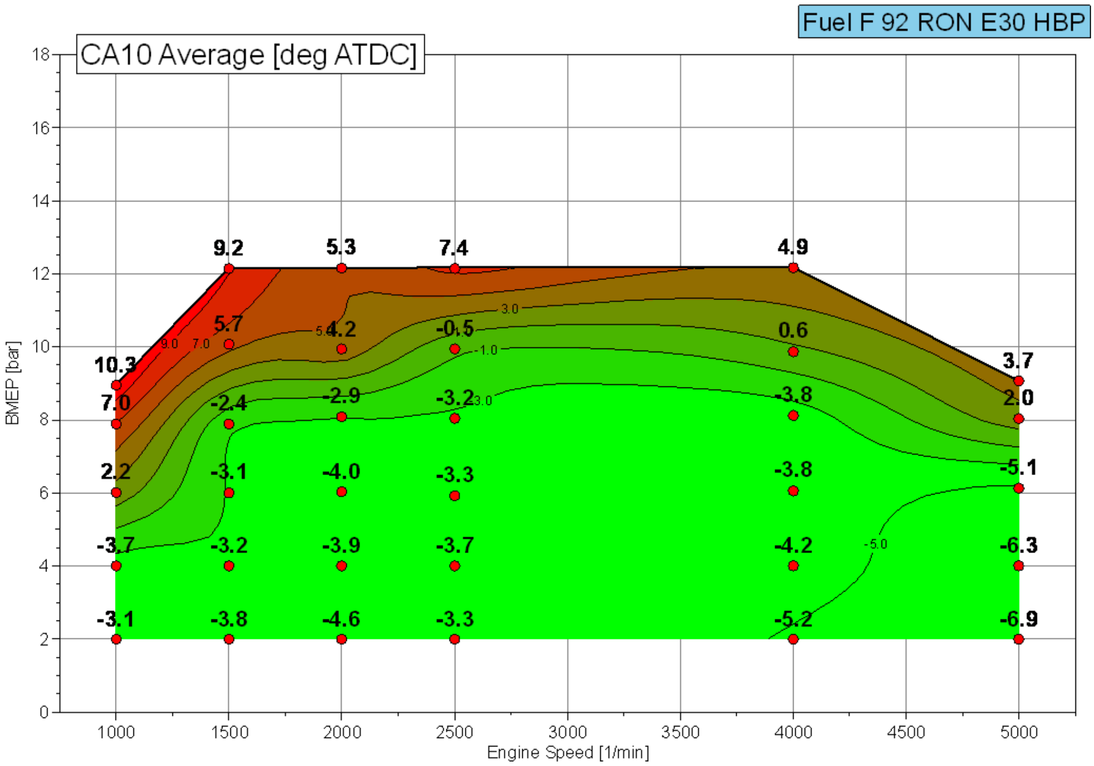

Figure 5: CA10 Average of Cylinders 1-4

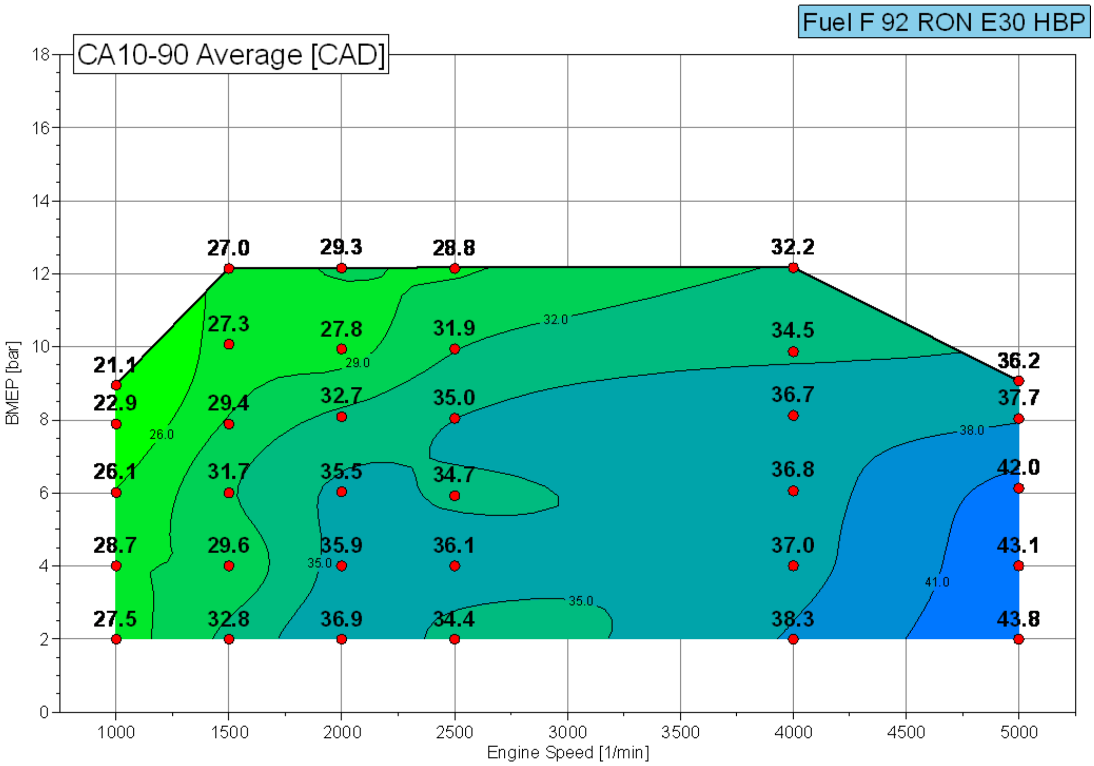

Figure 6: CA10-90 Average of Cylinders 1-4

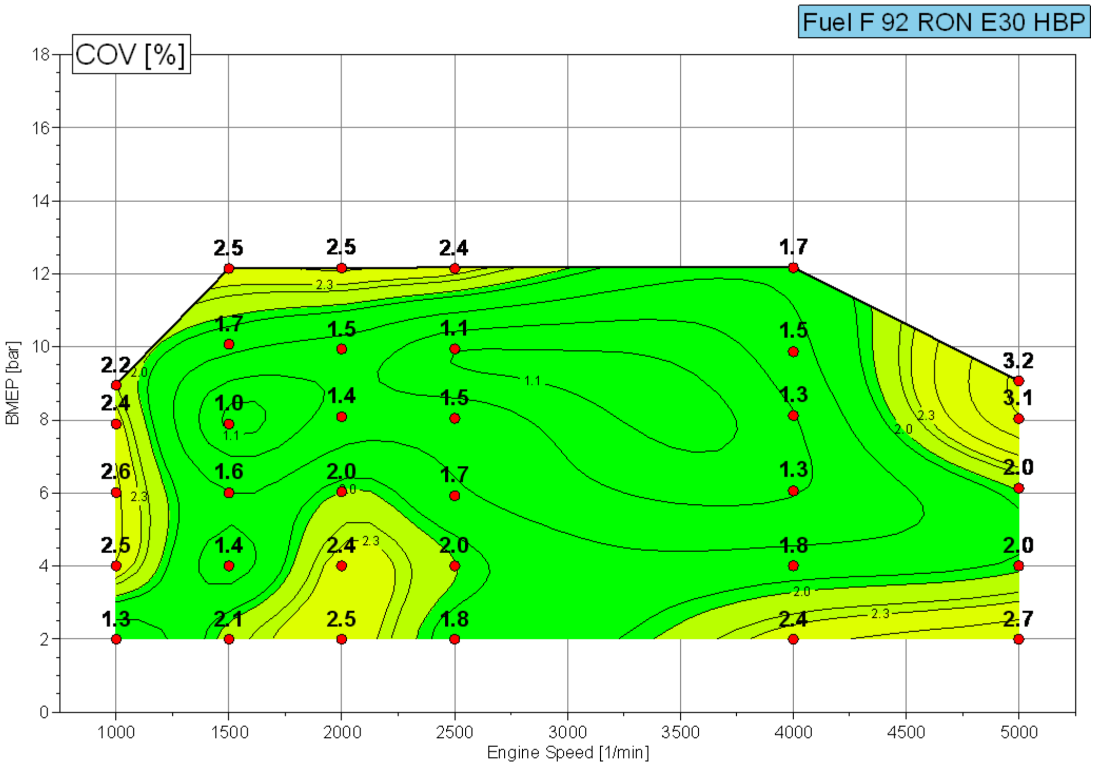

Figure 7: Coefficient of Variation Average of Cylinders 1-4

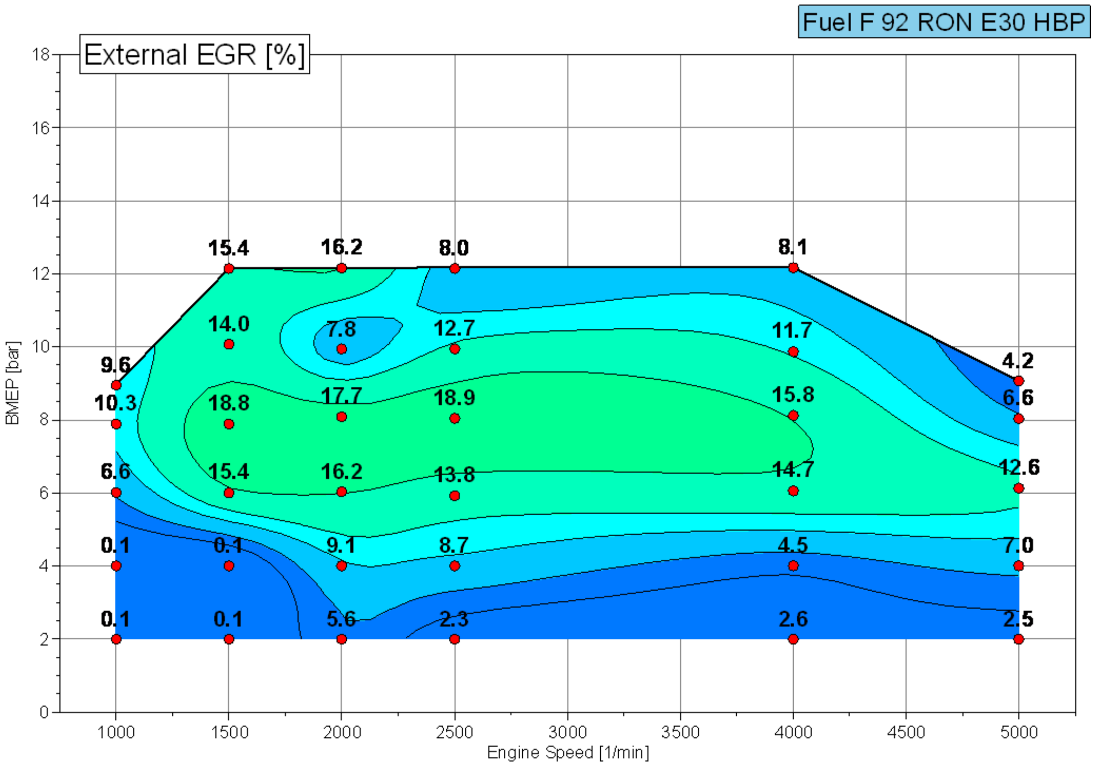

Figure 8: External EGR Percent of Intake Air

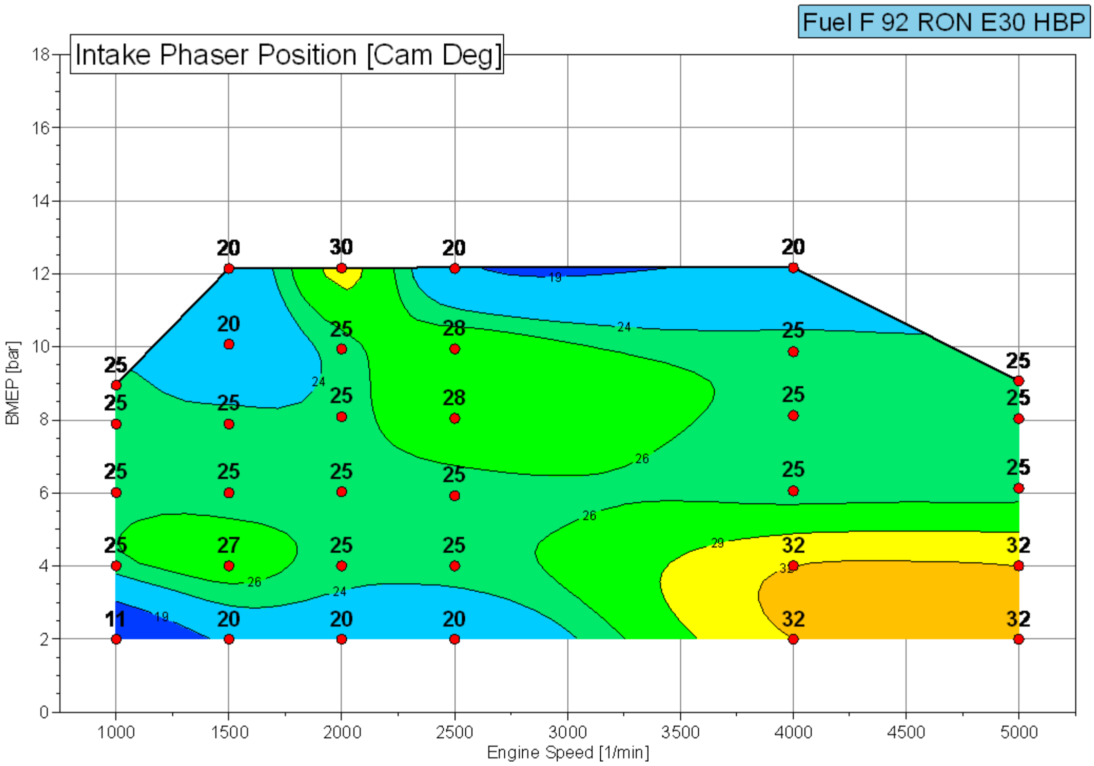

Figure 9: Intake Camshaft Phaser Position

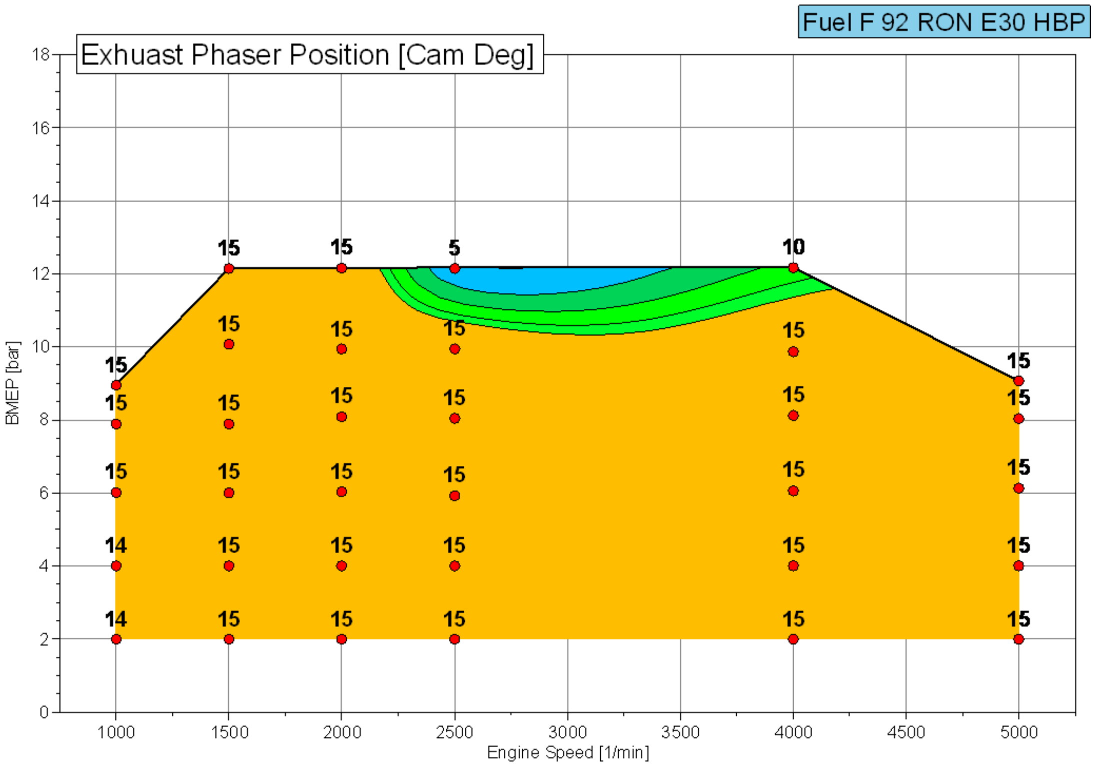

Figure 10: Exhaust Camshaft Phaser Position

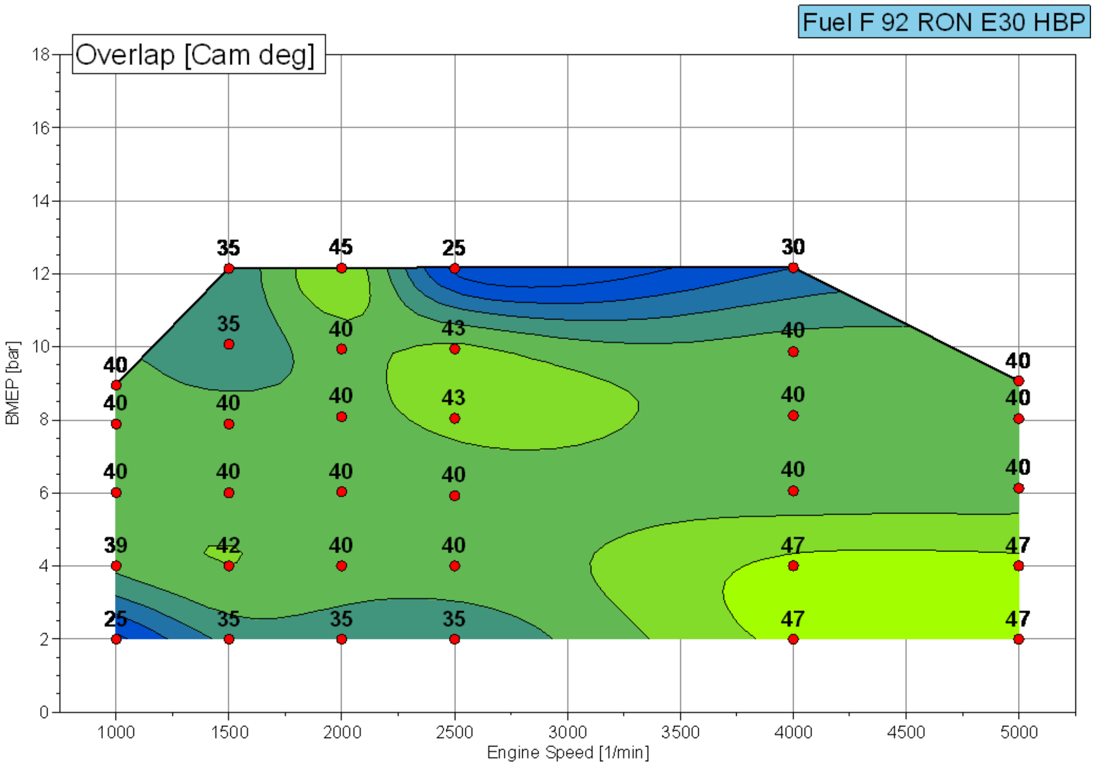

Figure 11: Camshaft Overlap

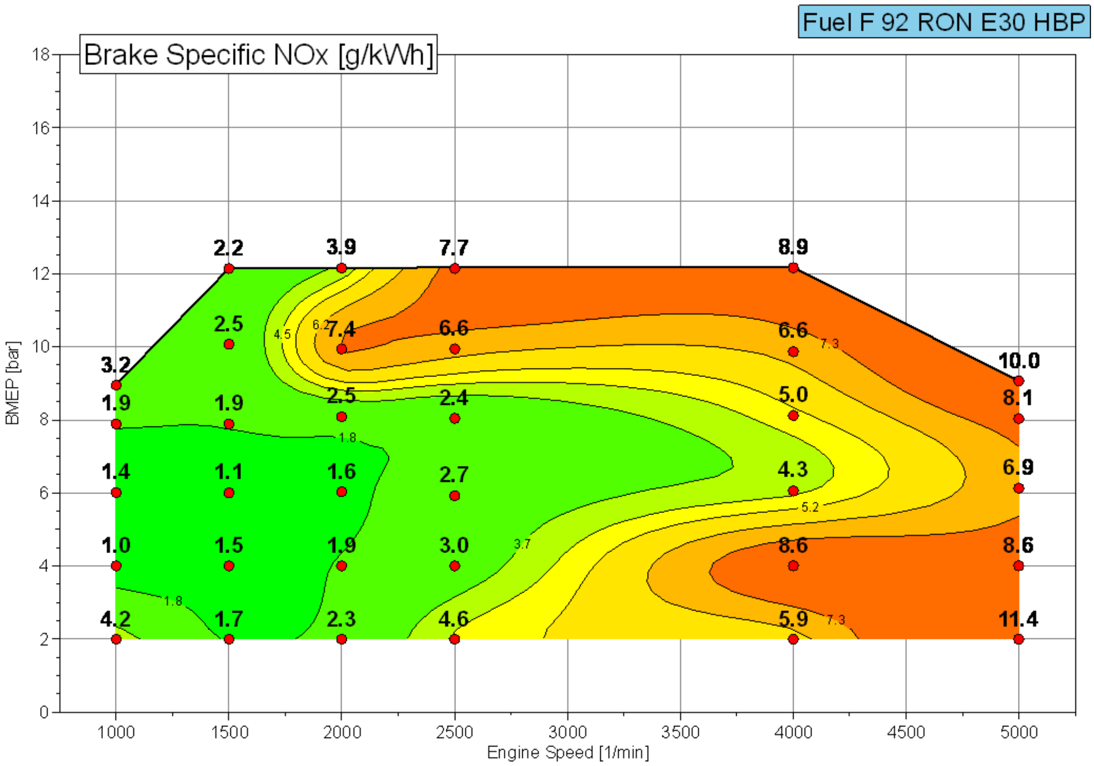

Figure 12: Brake Specific NOx Emissions

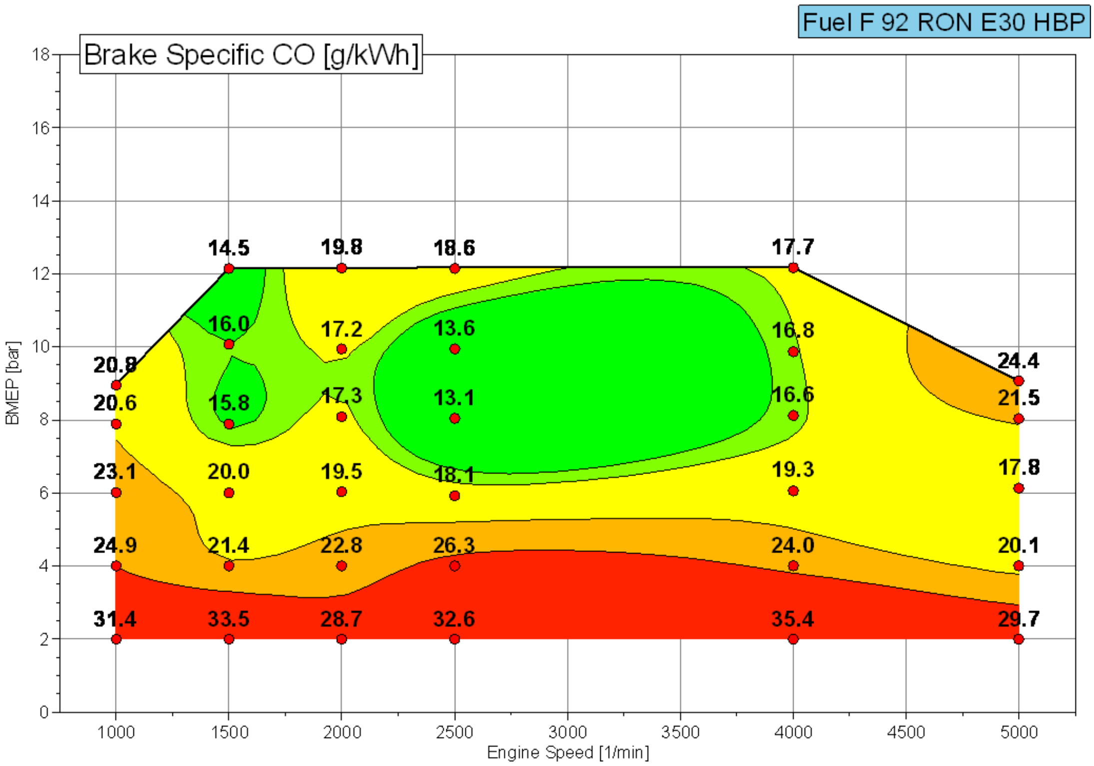

Figure 13: Brake Specific Carbon Monoxide Emissions

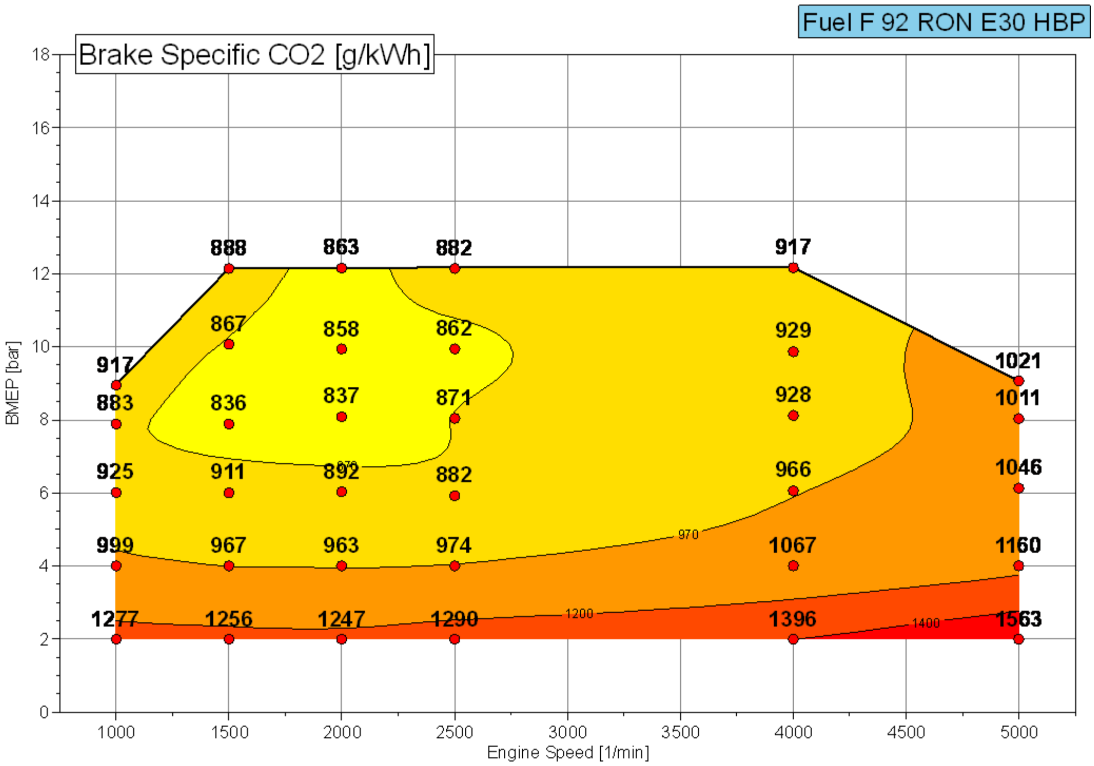

Figure 14: Brake Specific Carbon Dioxide Emissions

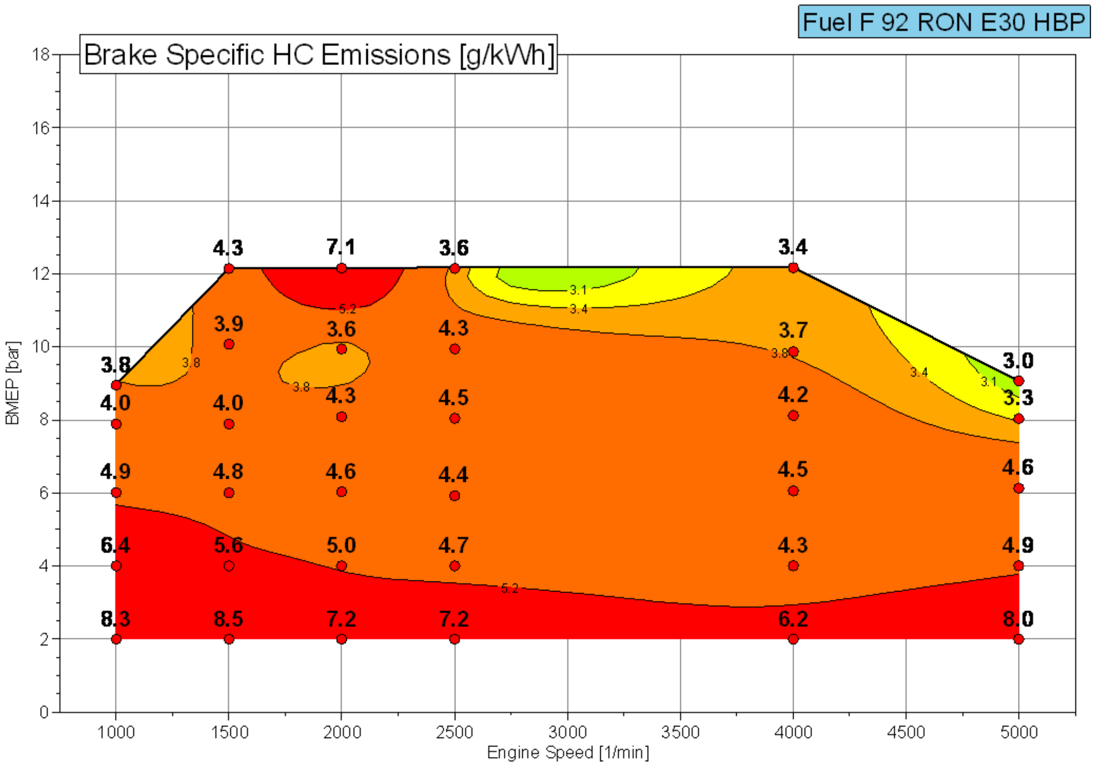

Figure 15: Brake Specific Hydrocarbon Emissions

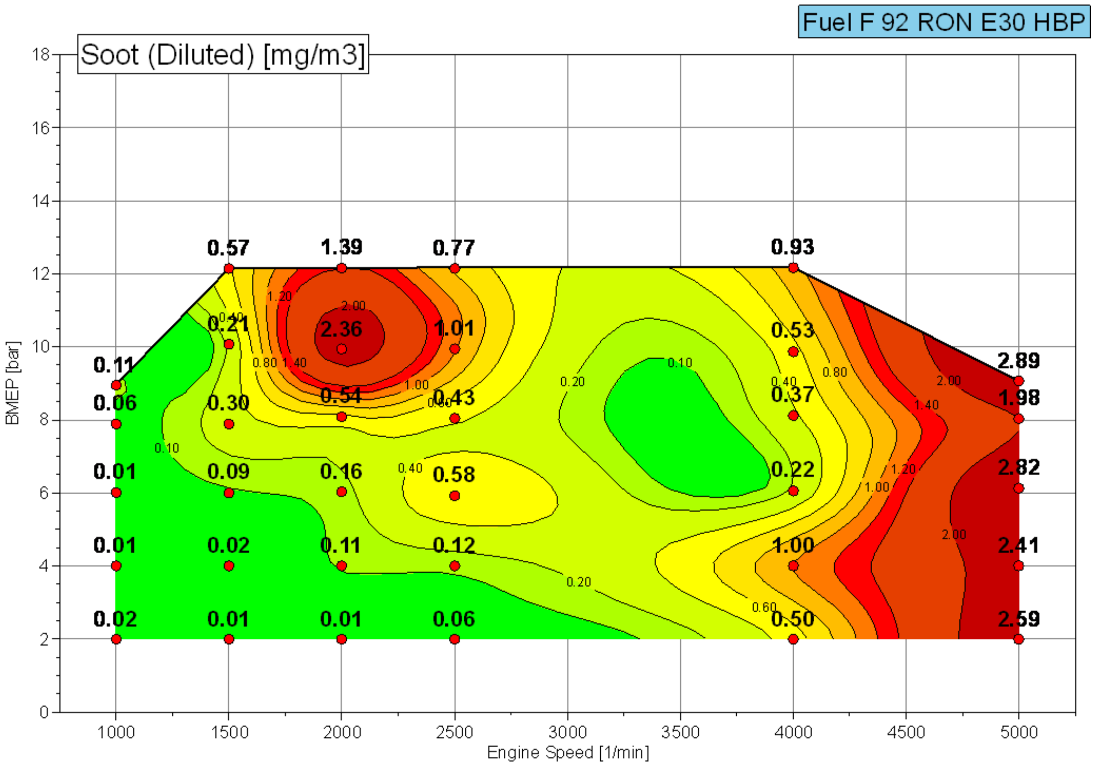

Figure 16: Particulate Soot Emissions

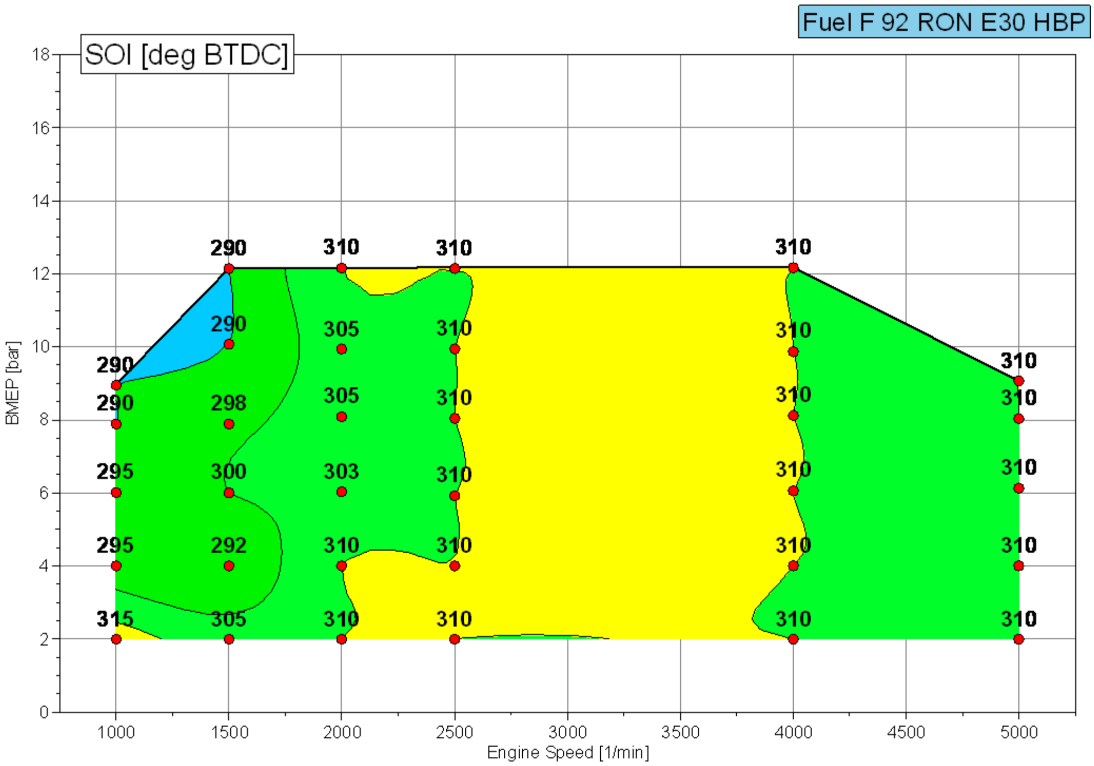

Figure 17: Start of Injection

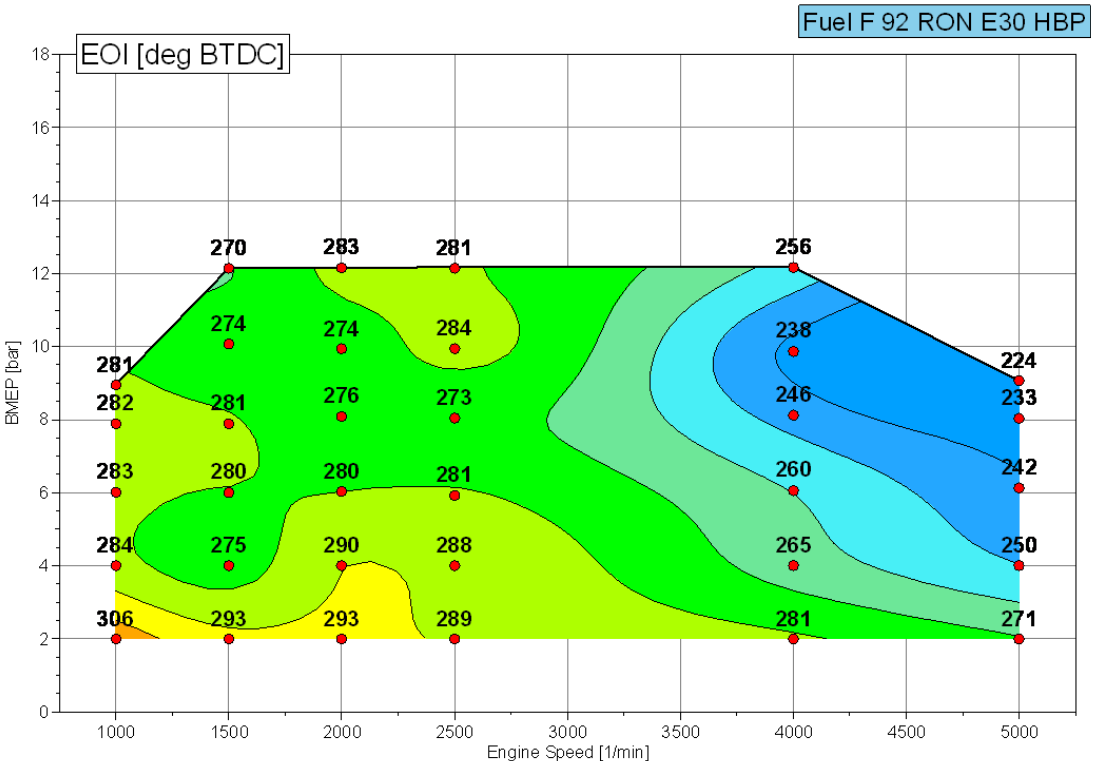

Figure 18: End of Injection

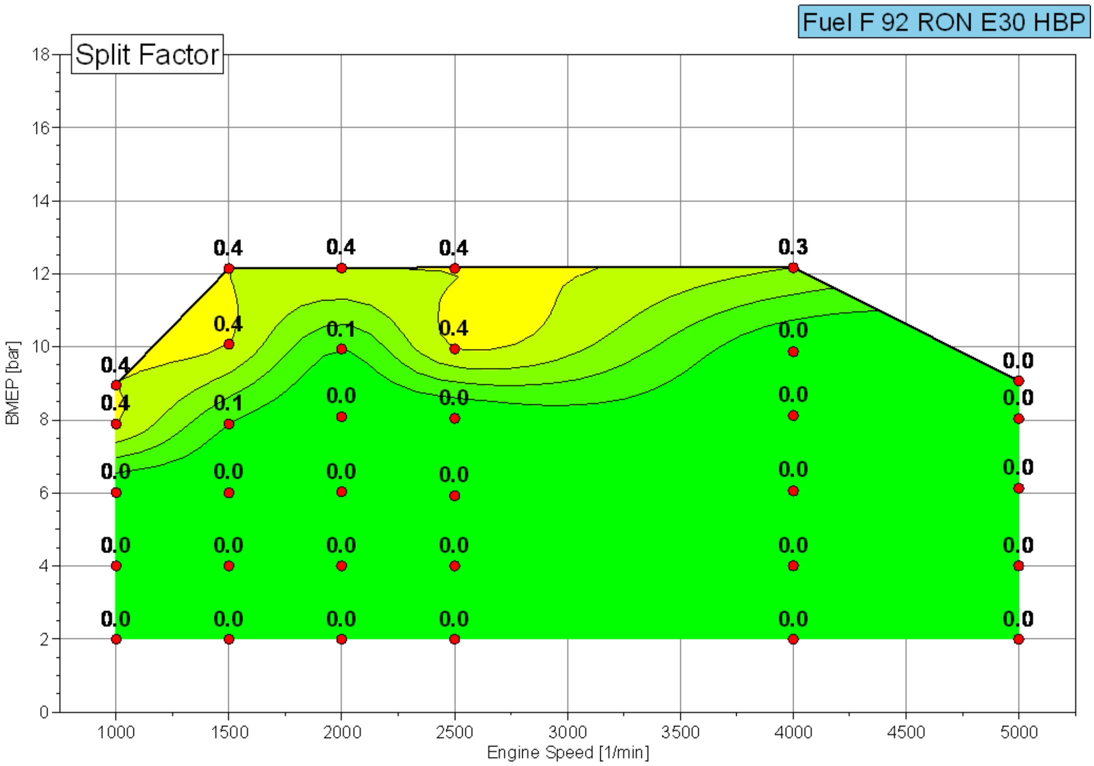

Figure 19: Injection Split Factor

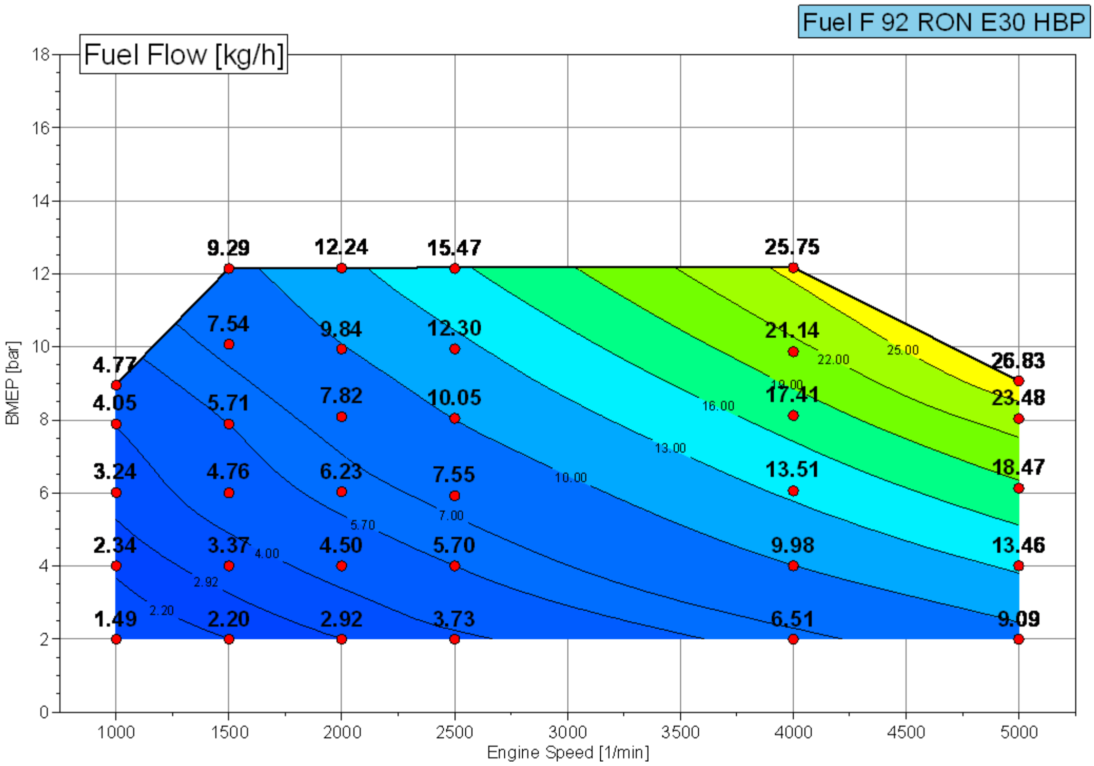

Figure 20: Fuel Flow

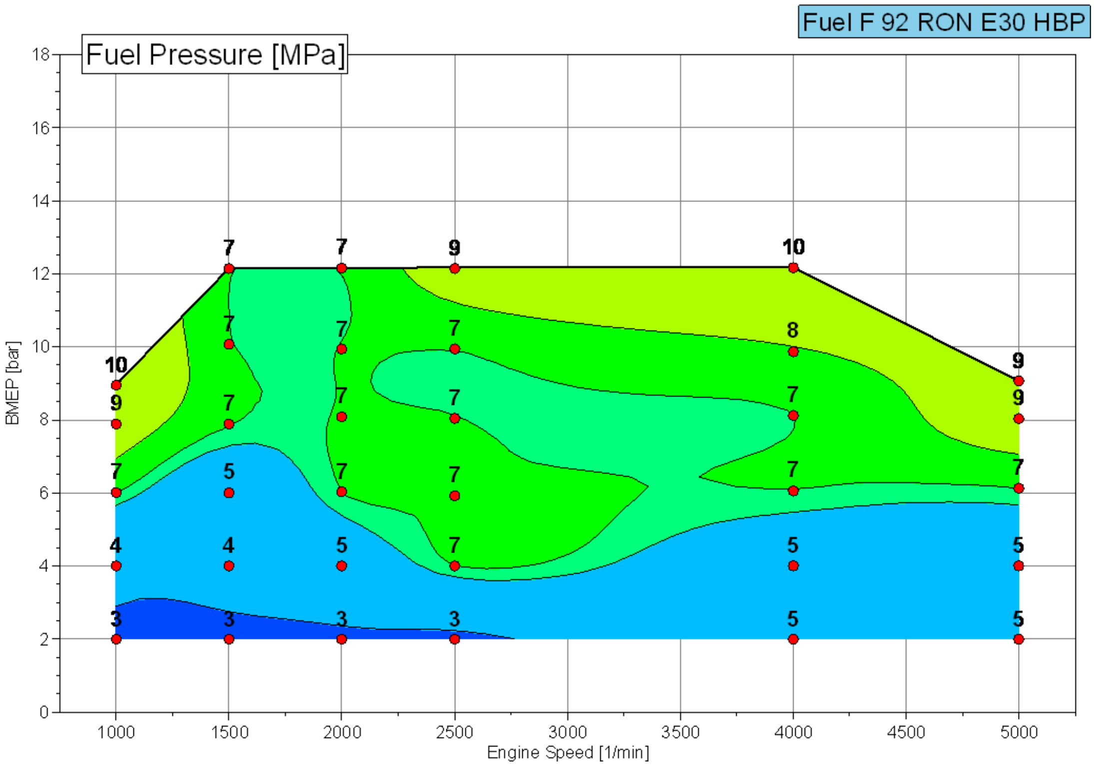

Figure 21: Fuel Rail Pressure

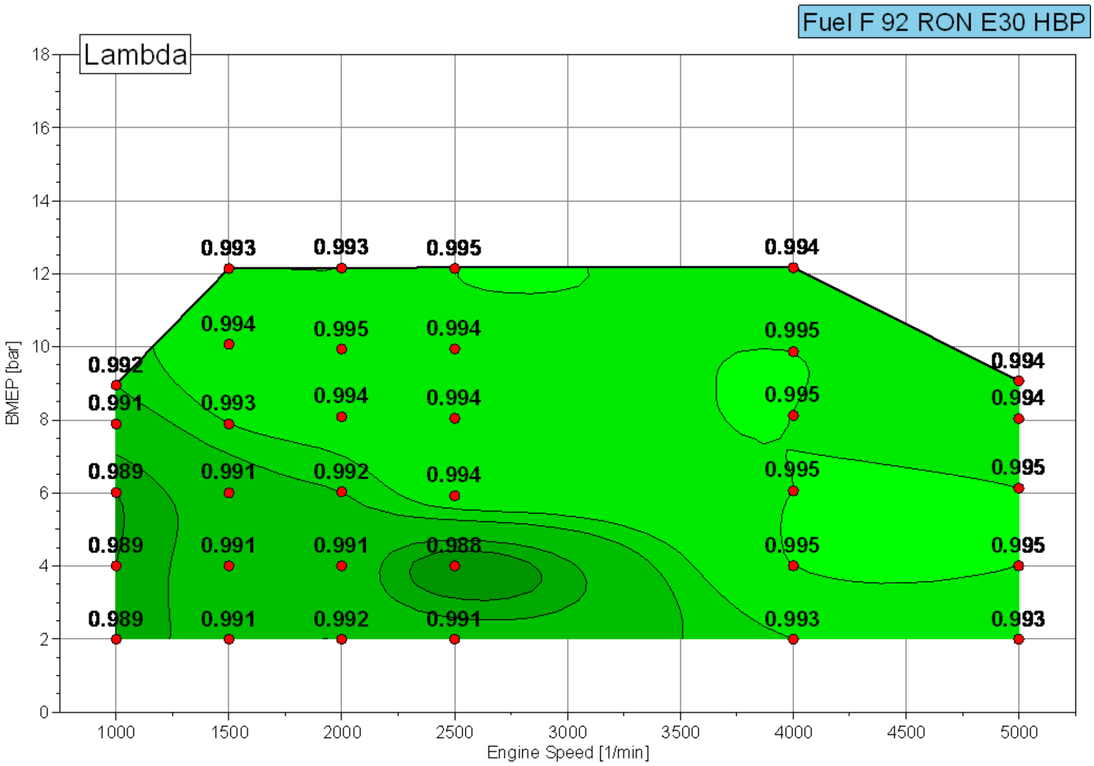

Figure 22: Lambda

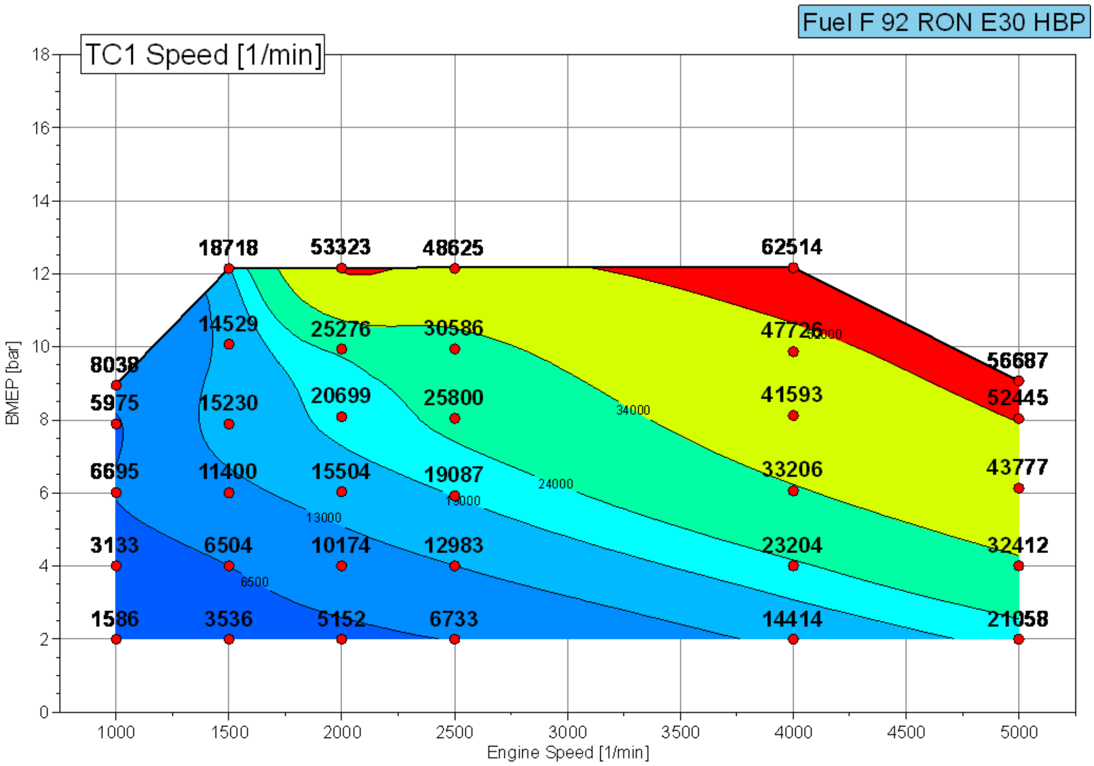

Figure 23: Low Pressure Turbocharger Speed

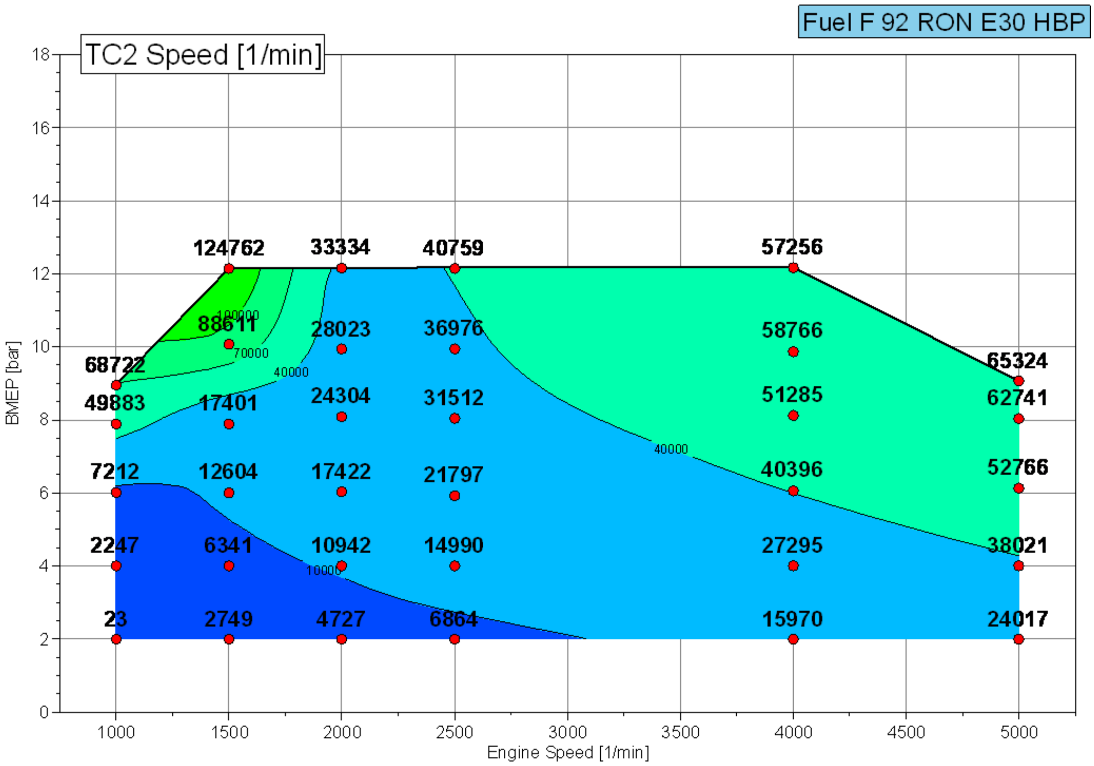

Figure 24: High Pressure Turbocharge Speed

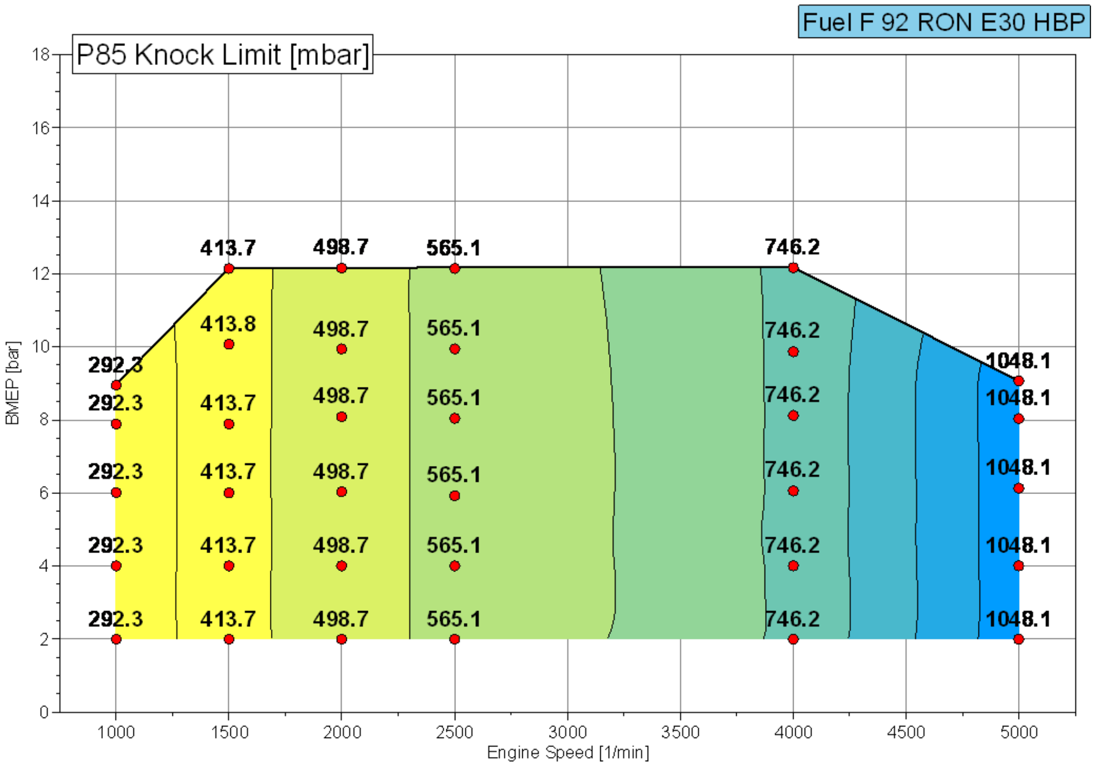

Figure 25: P85 Knock Limit

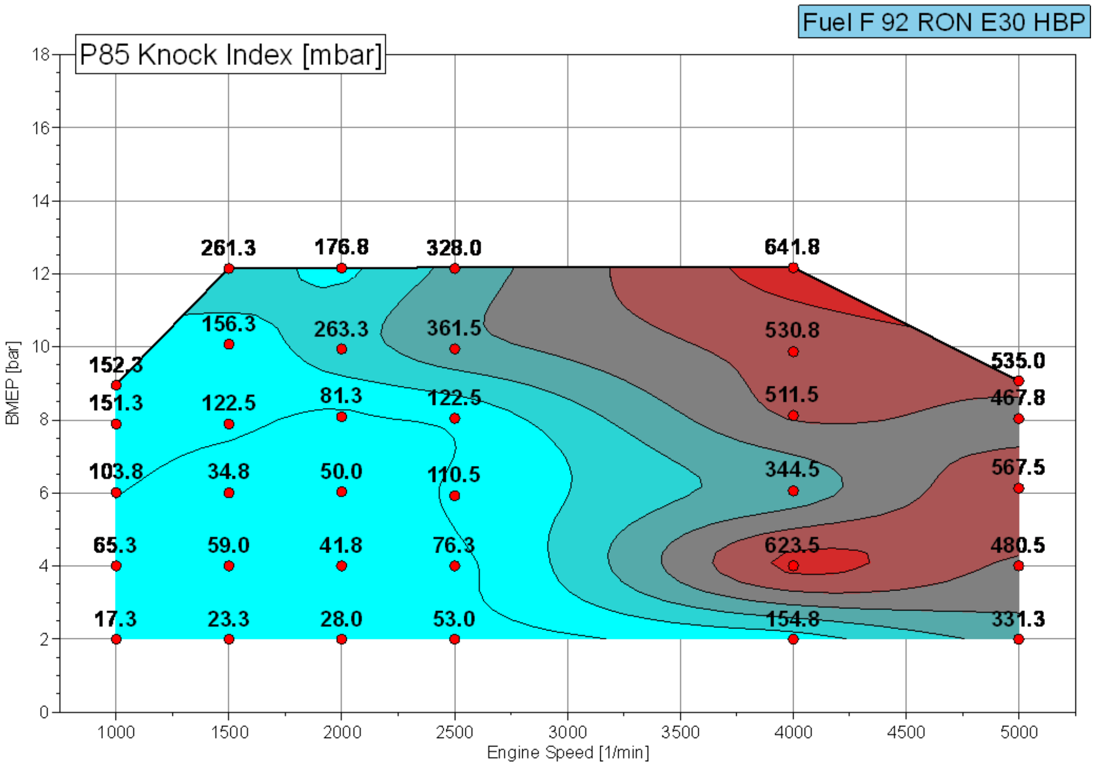

Figure 26: Averaged P85 Knock Index

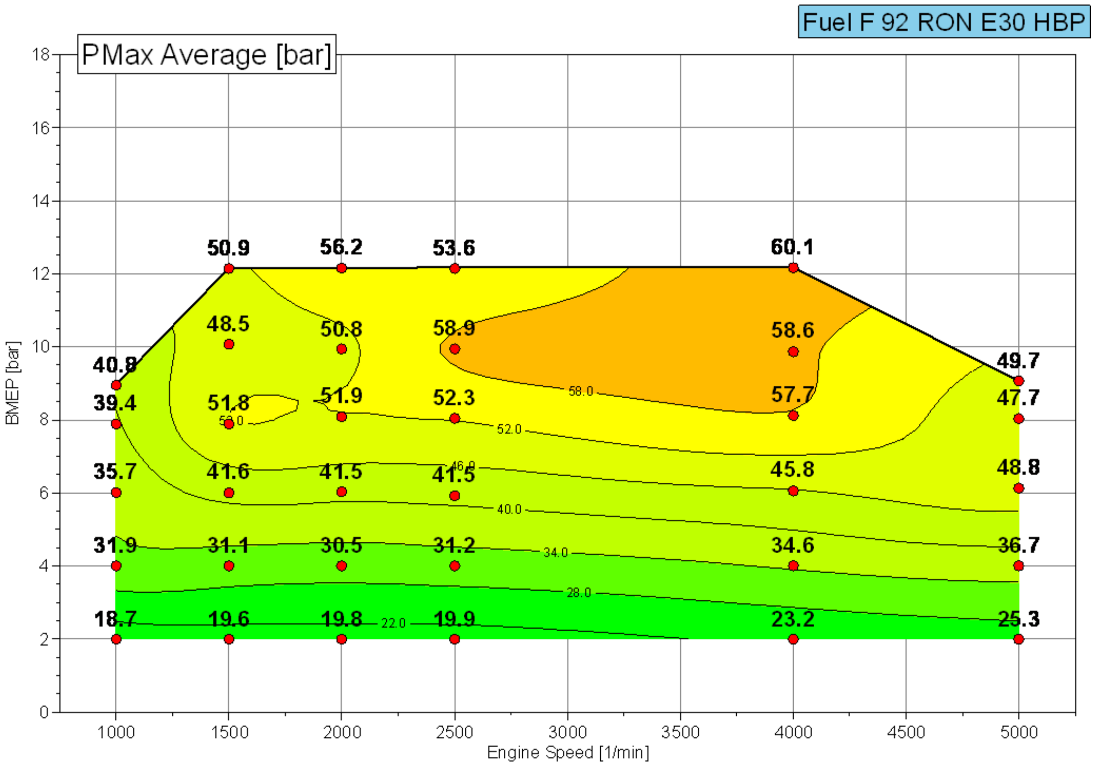

Figure 27: Averaged Max Pressure for Cylinders 1-4

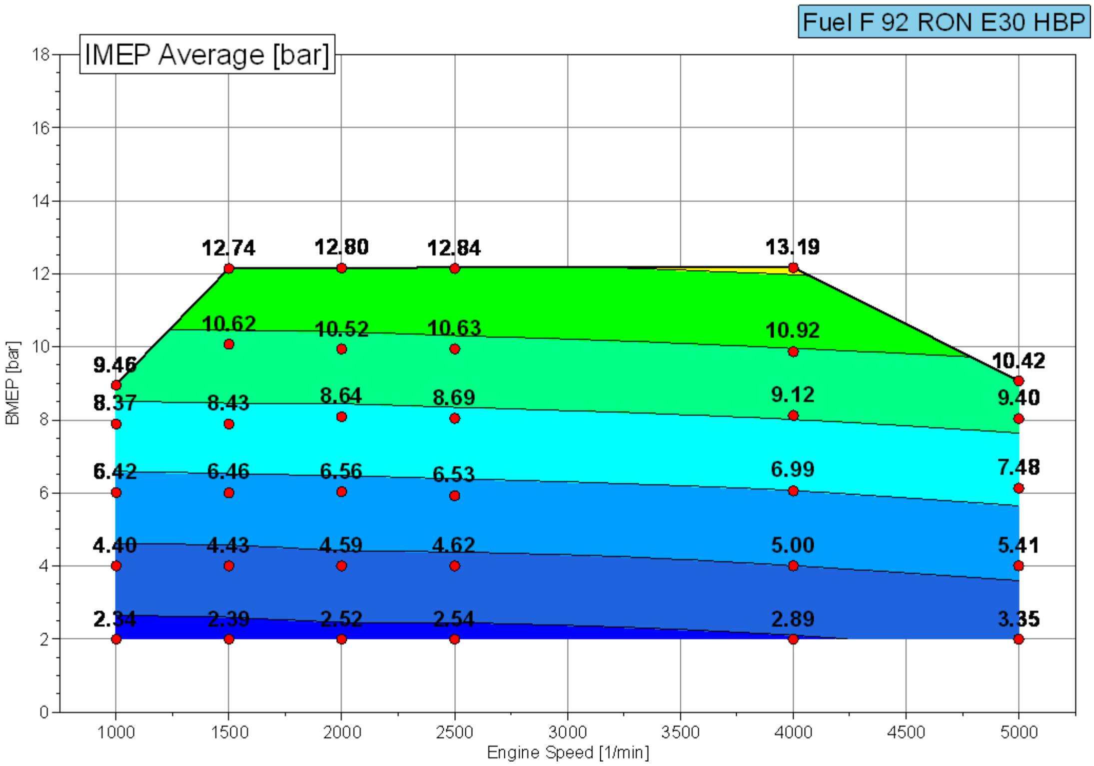

Figure 28: Indicated Mean Effective Pressure

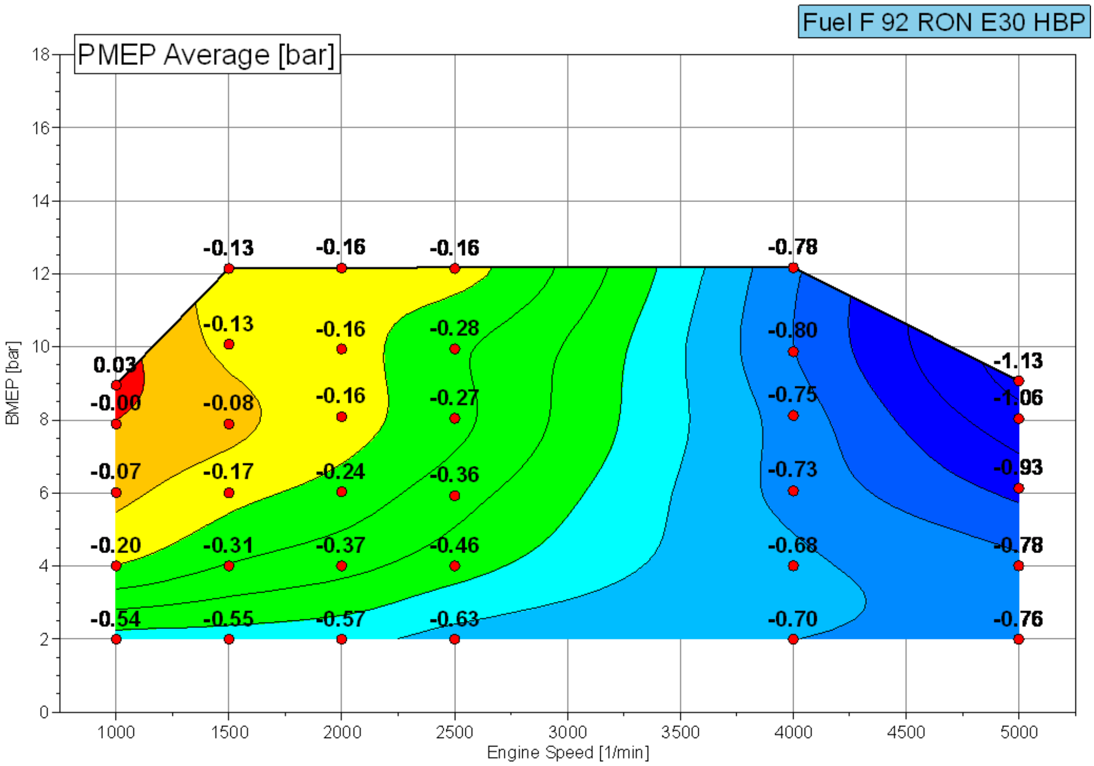

Figure 29: Pumping Mean Effective Pressure

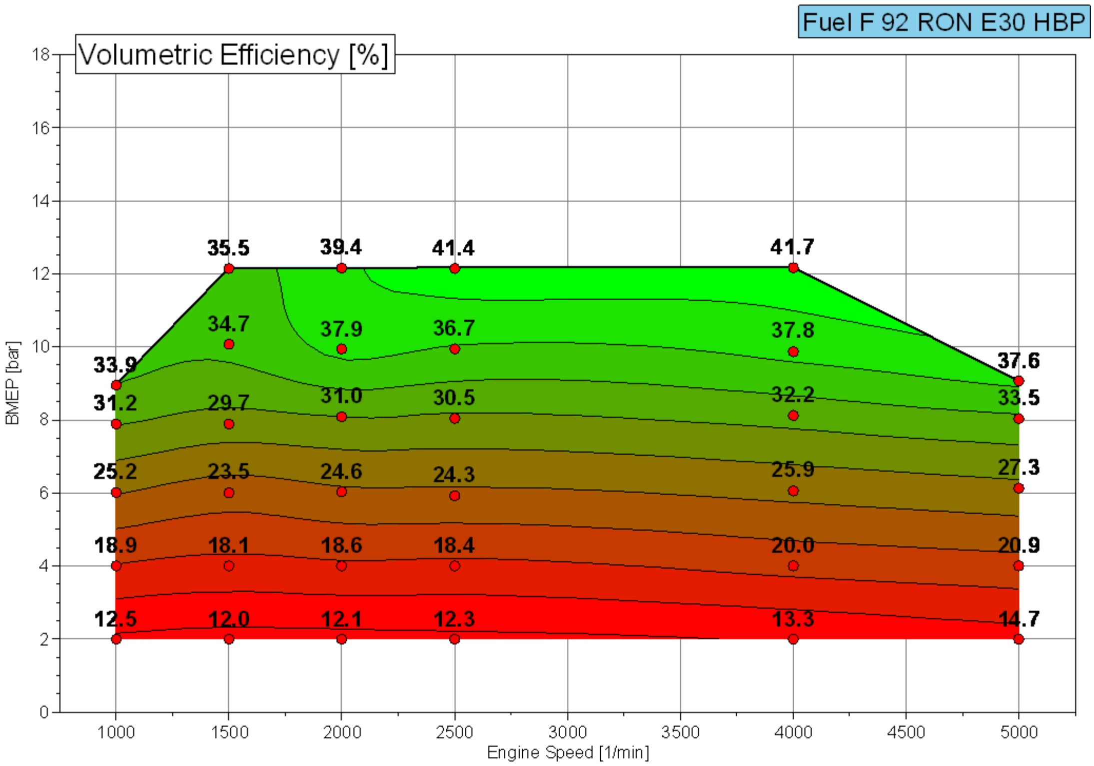

Figure 30: Calculated Volumetric Efficiency

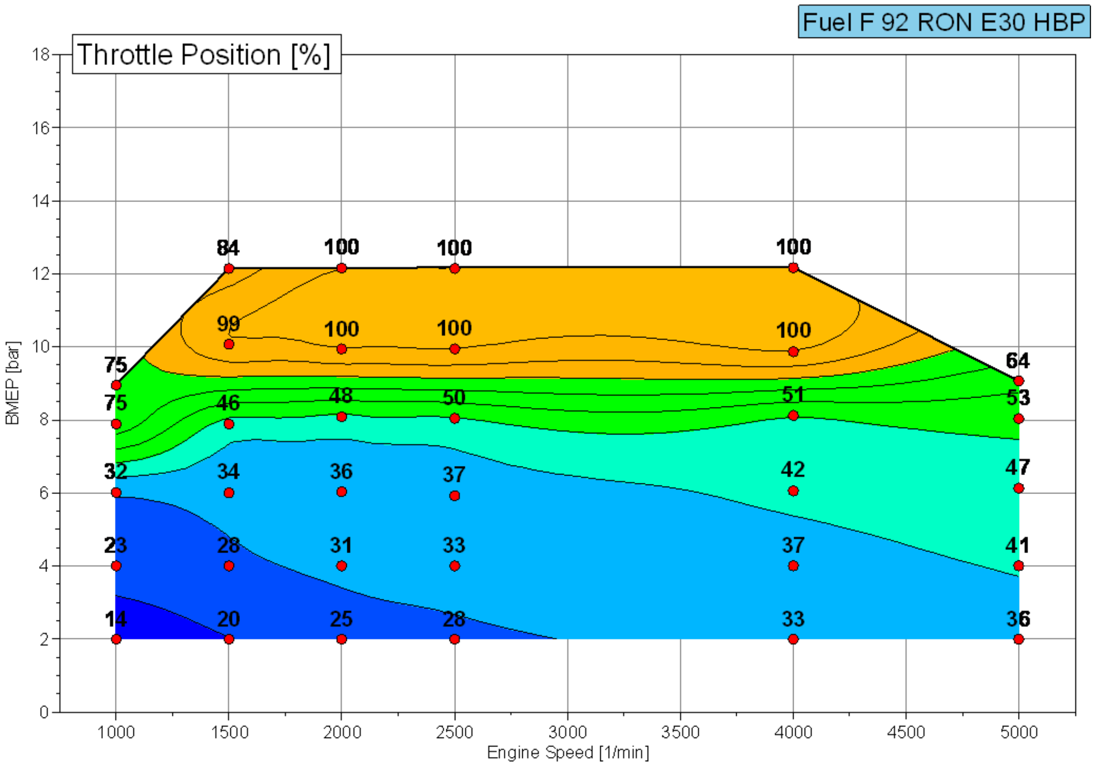

Figure 31: Throttle Position

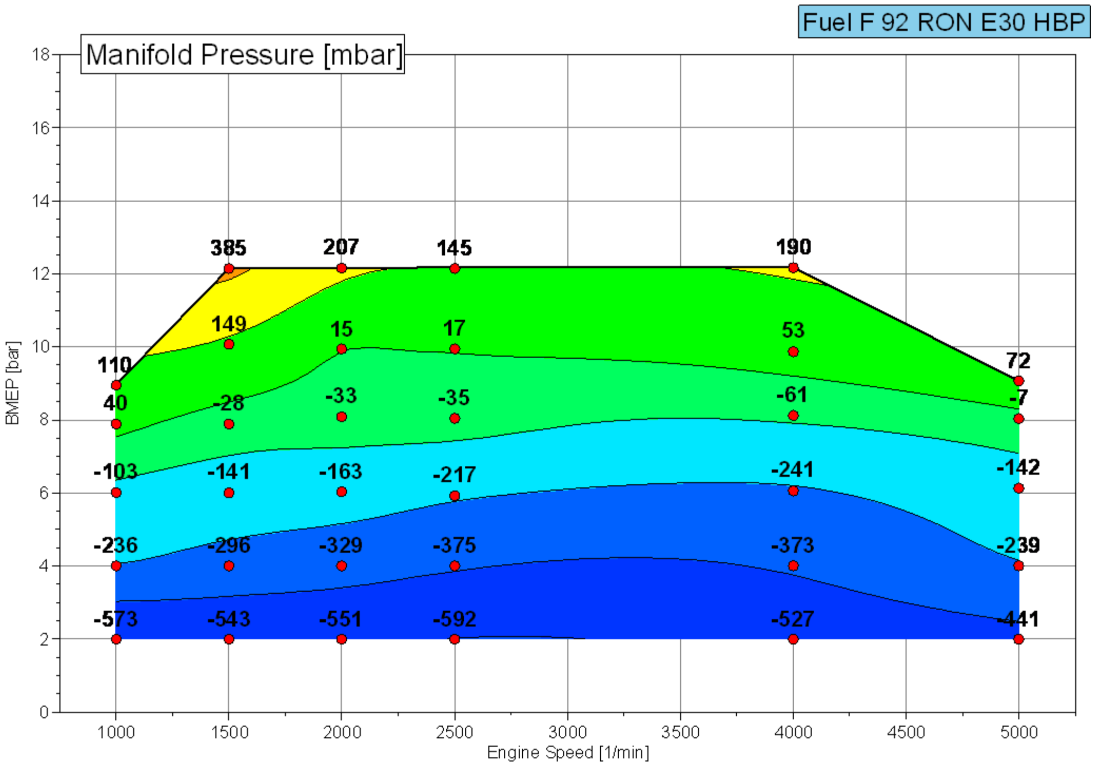

Figure 32: Intake Manifold Pressure

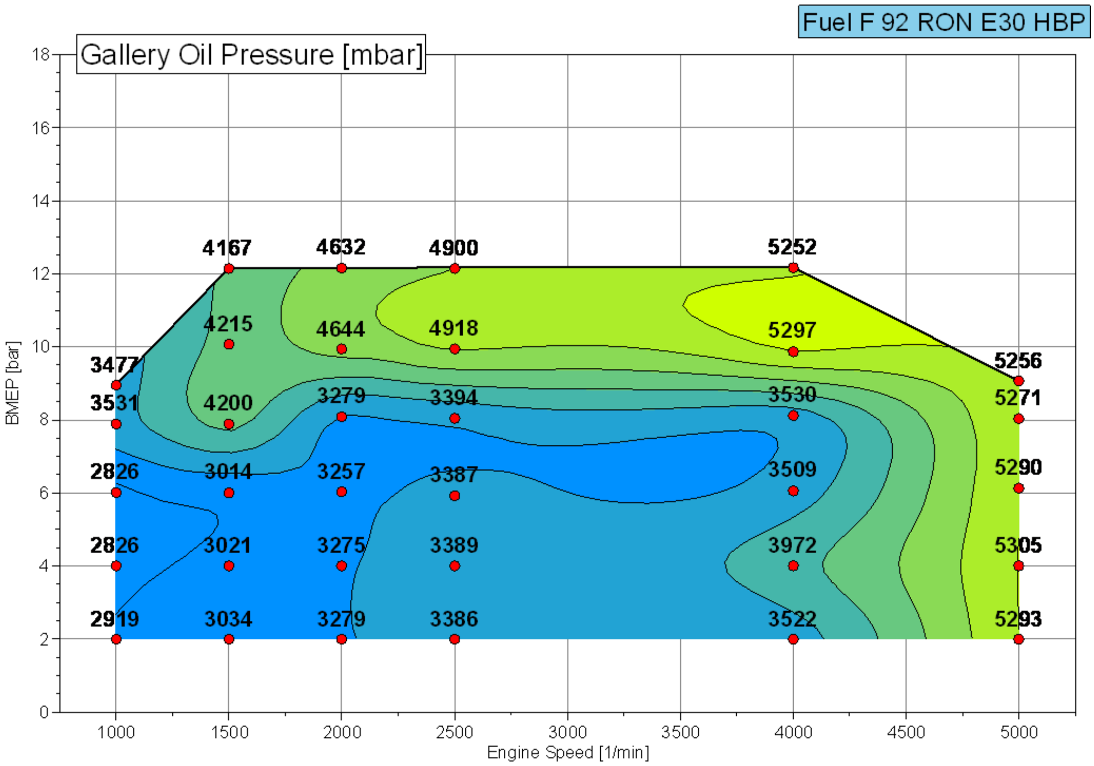

Figure 33: Gallery Oil Pressure

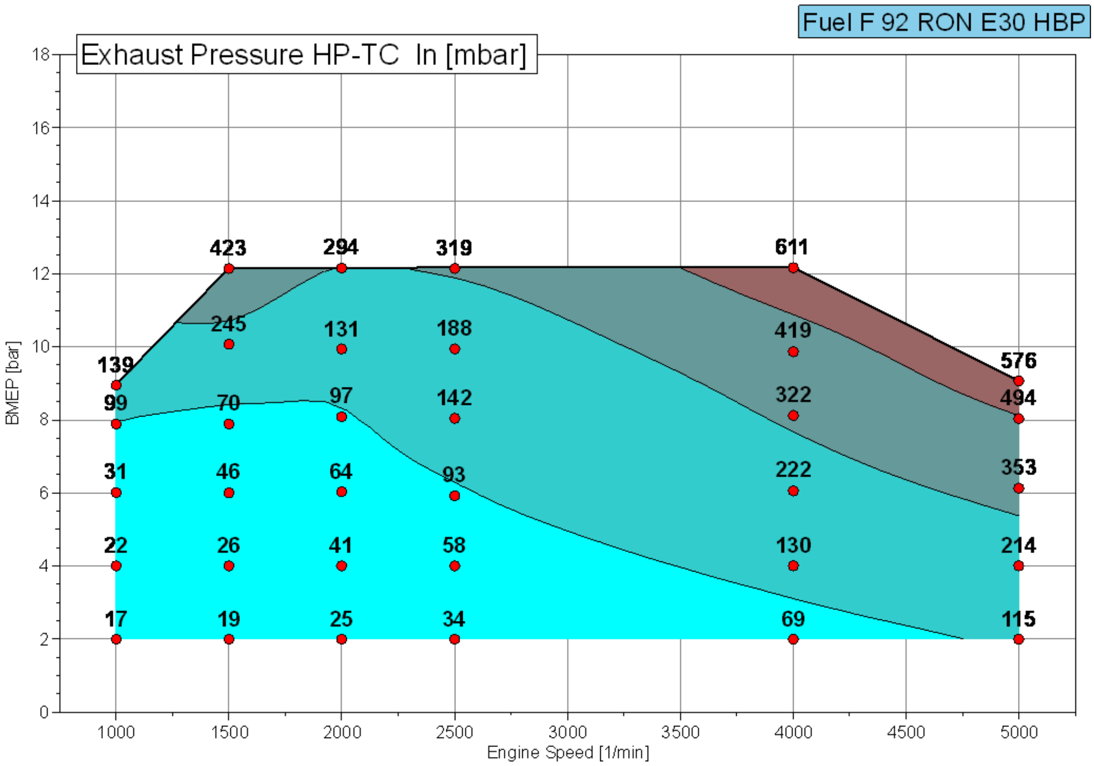

Figure 34: Exhaust Pressure High Pressure Turbocharger In

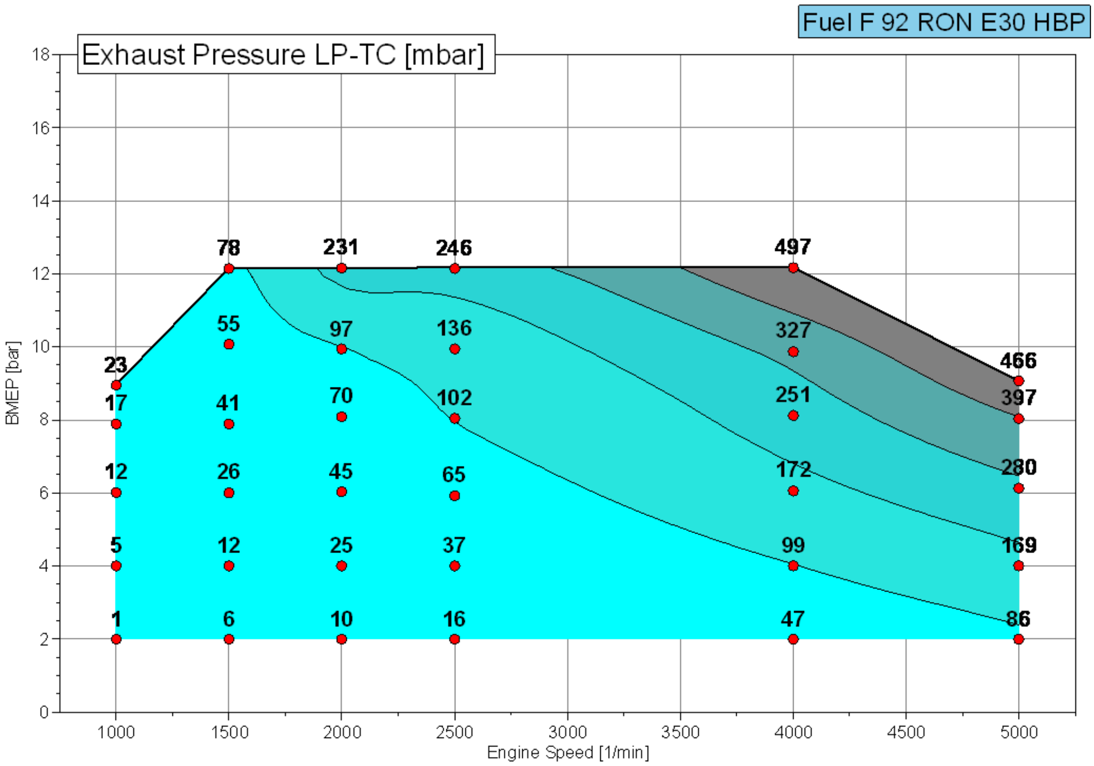

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

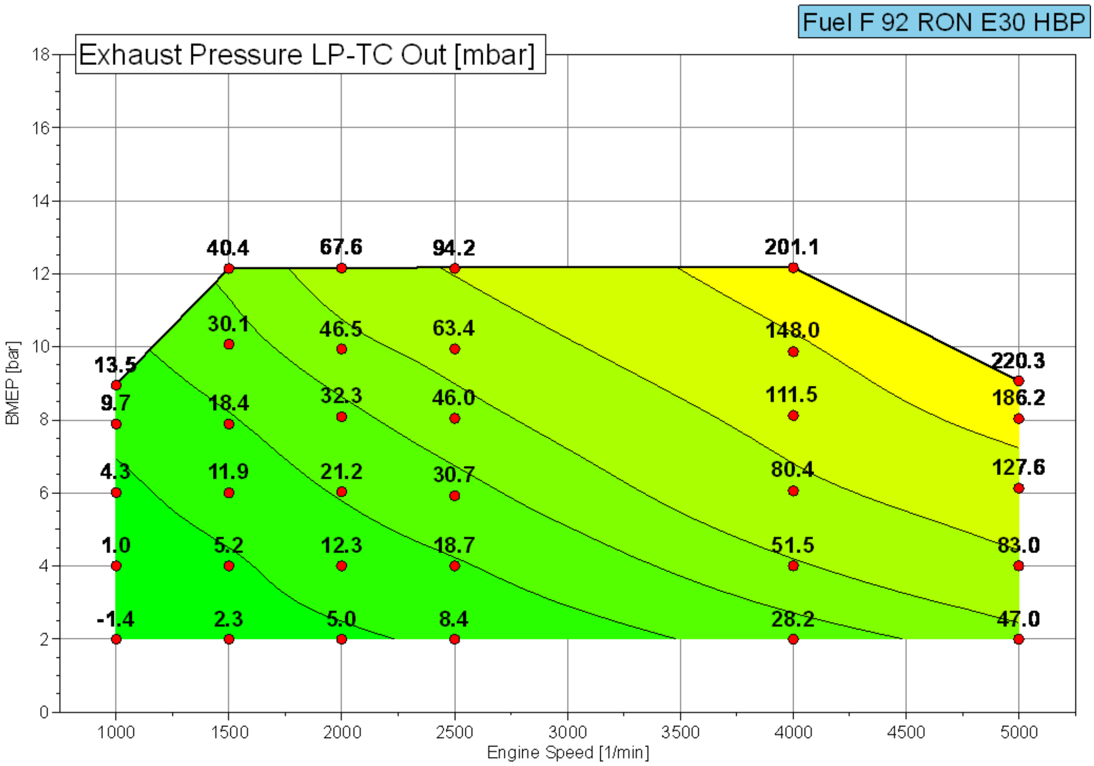

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

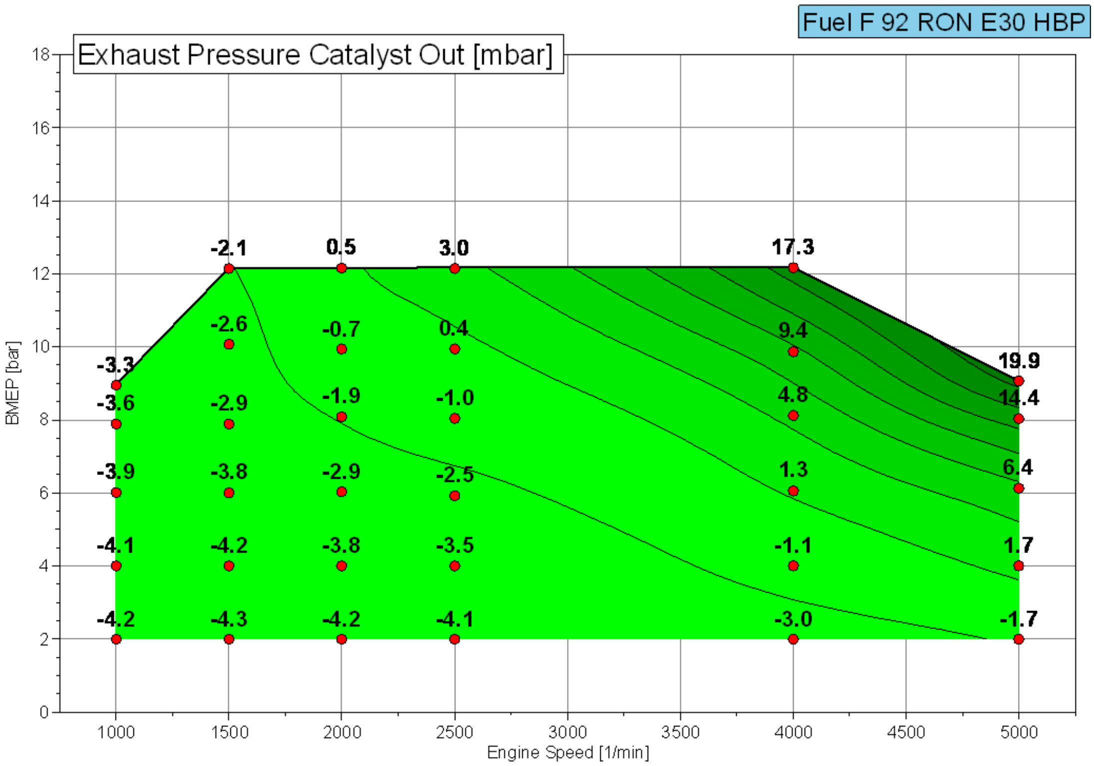

Figure 37: Exhaust Pressure Catalyst Out

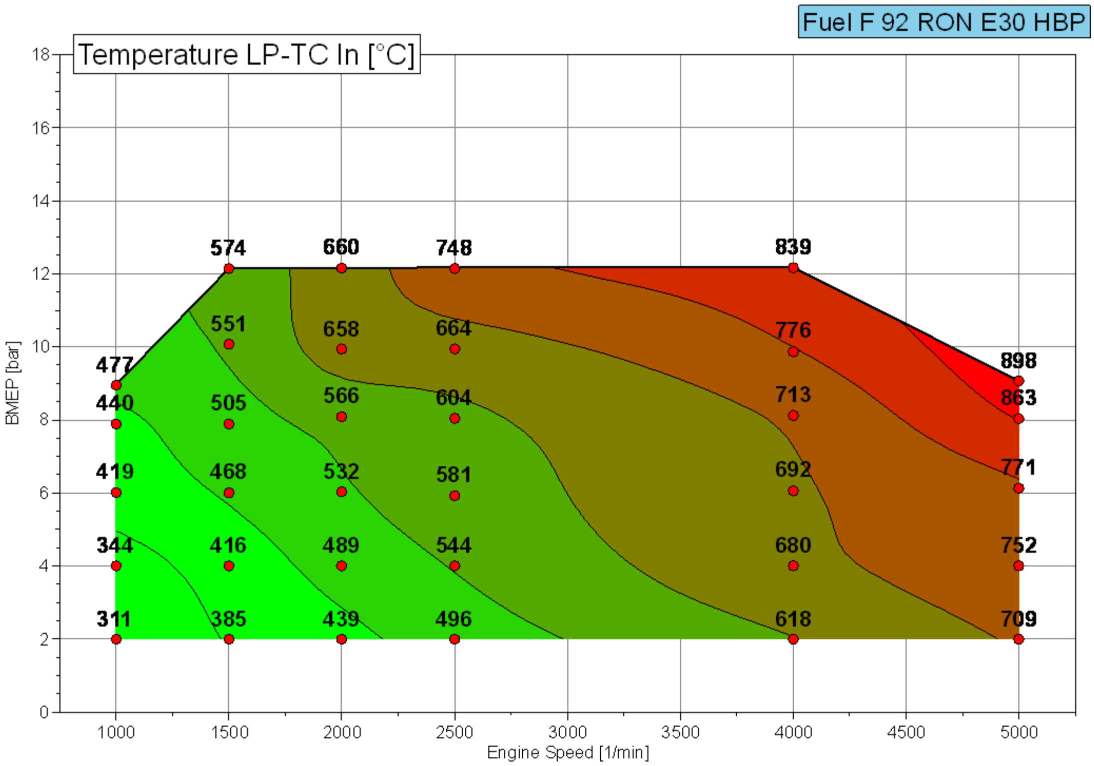

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

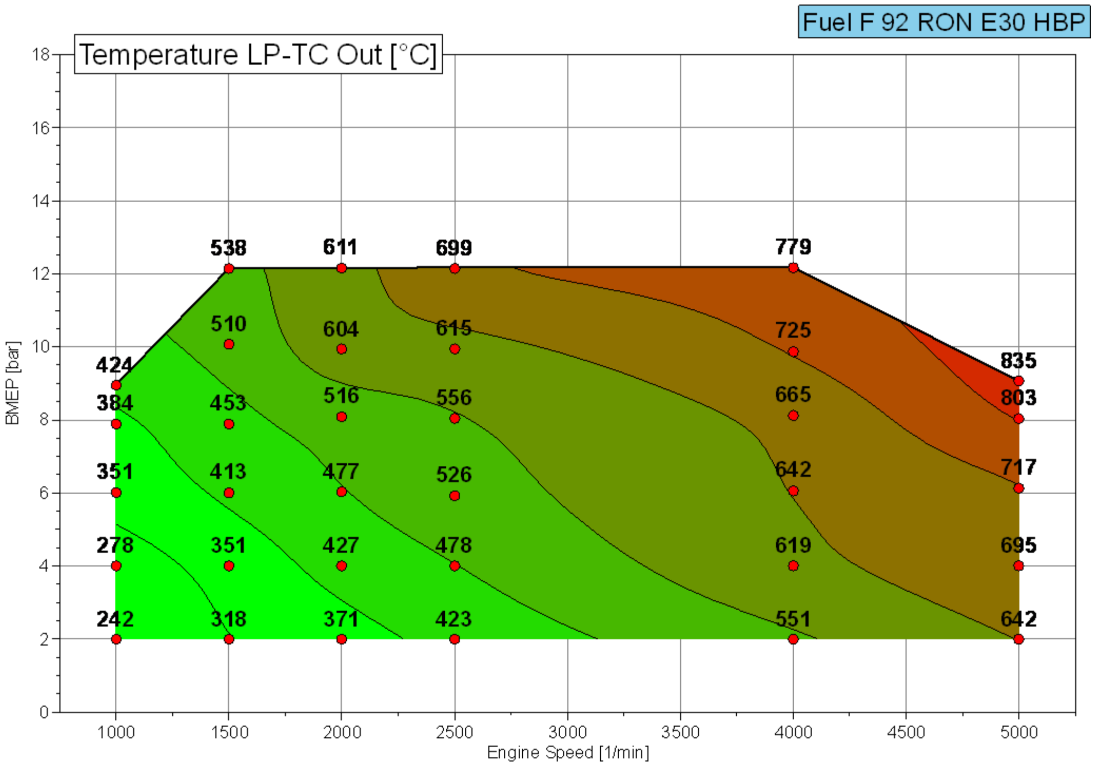

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

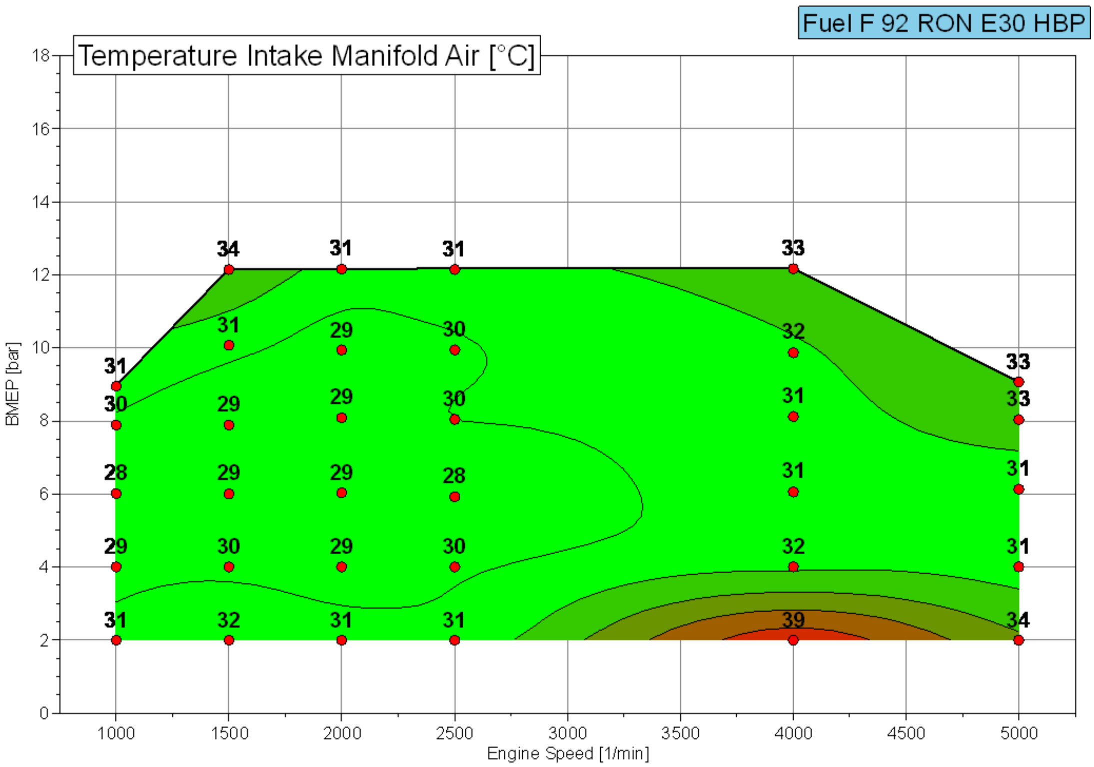

Figure 40: Intake Manifold Air Temperature

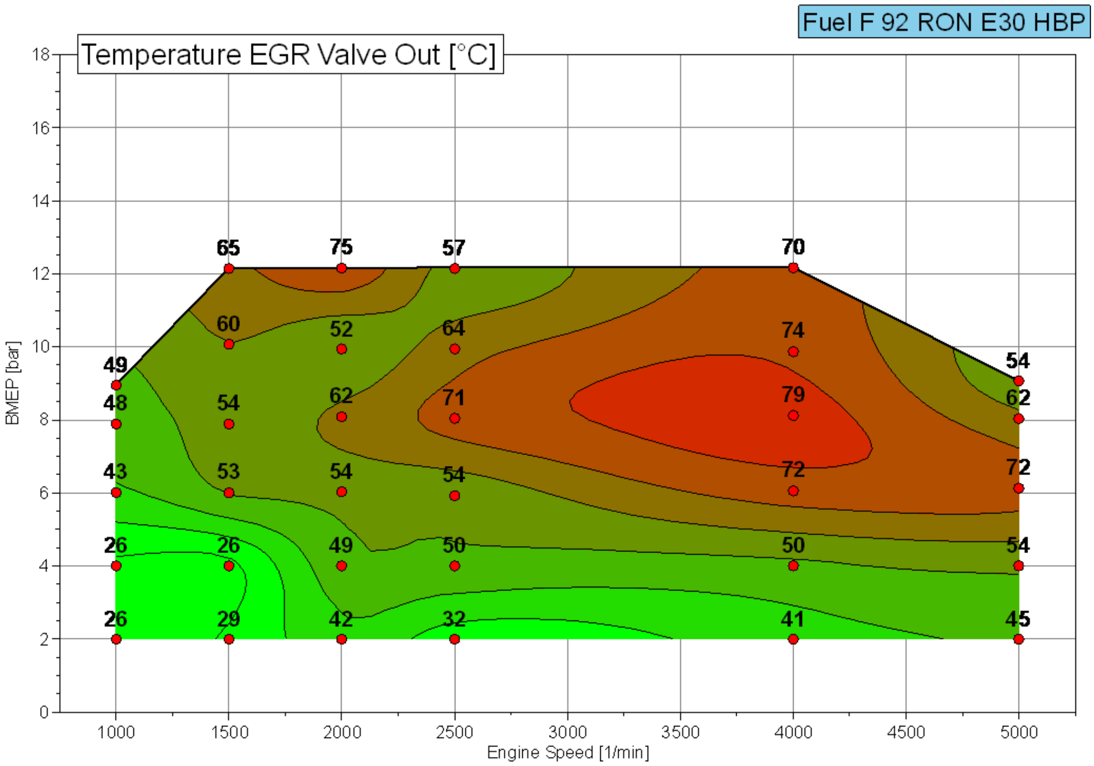

Figure 41: EGR Valve Out Temperature

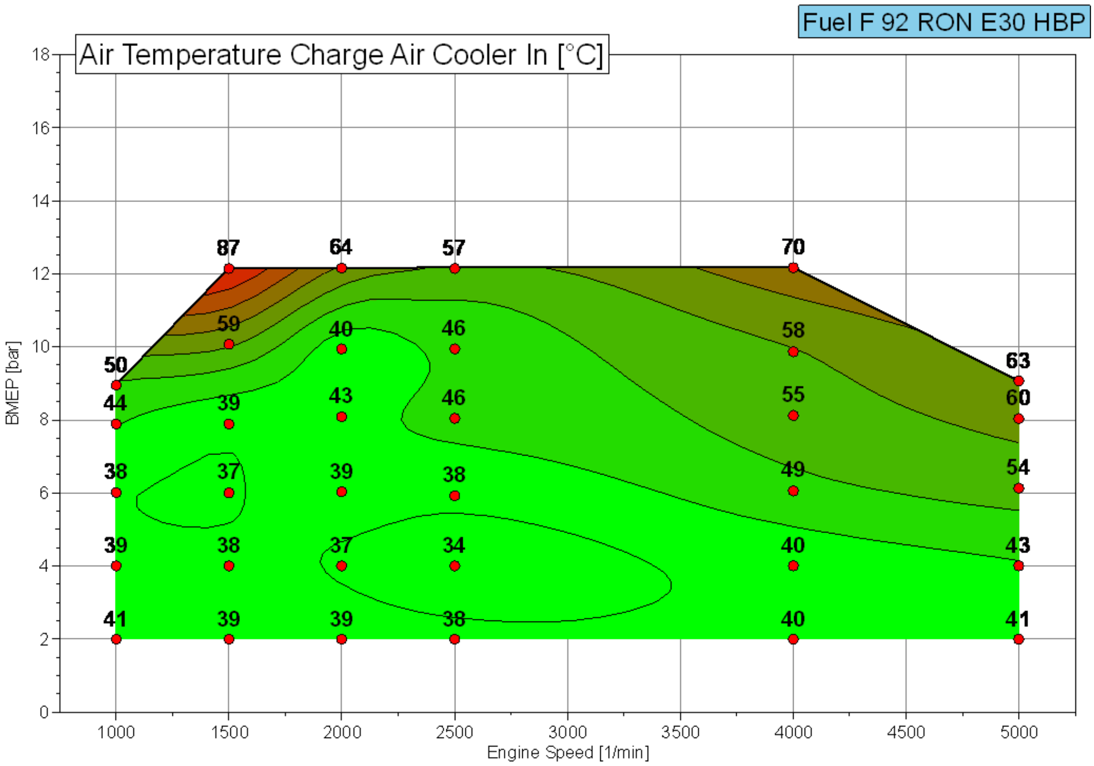

Figure 42: Charge Air Cooler Inlet Air Temperature

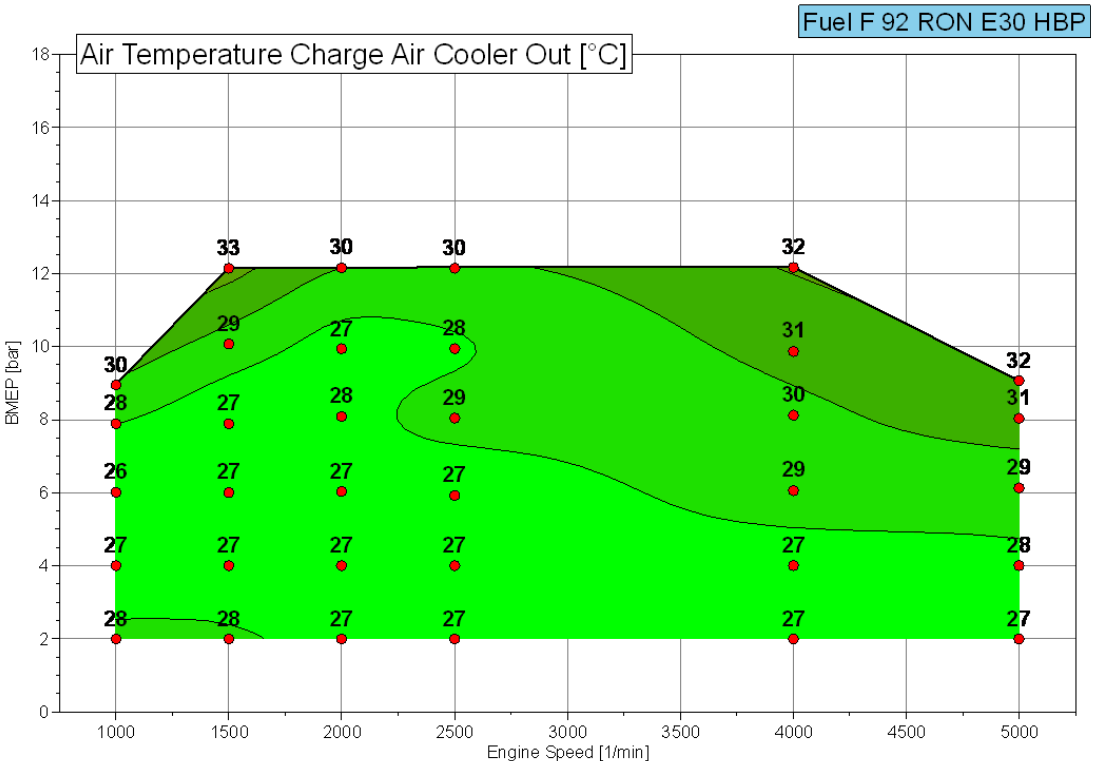

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel G Calibration Results

102 Ron 0% Ethanol Low Boiling Point

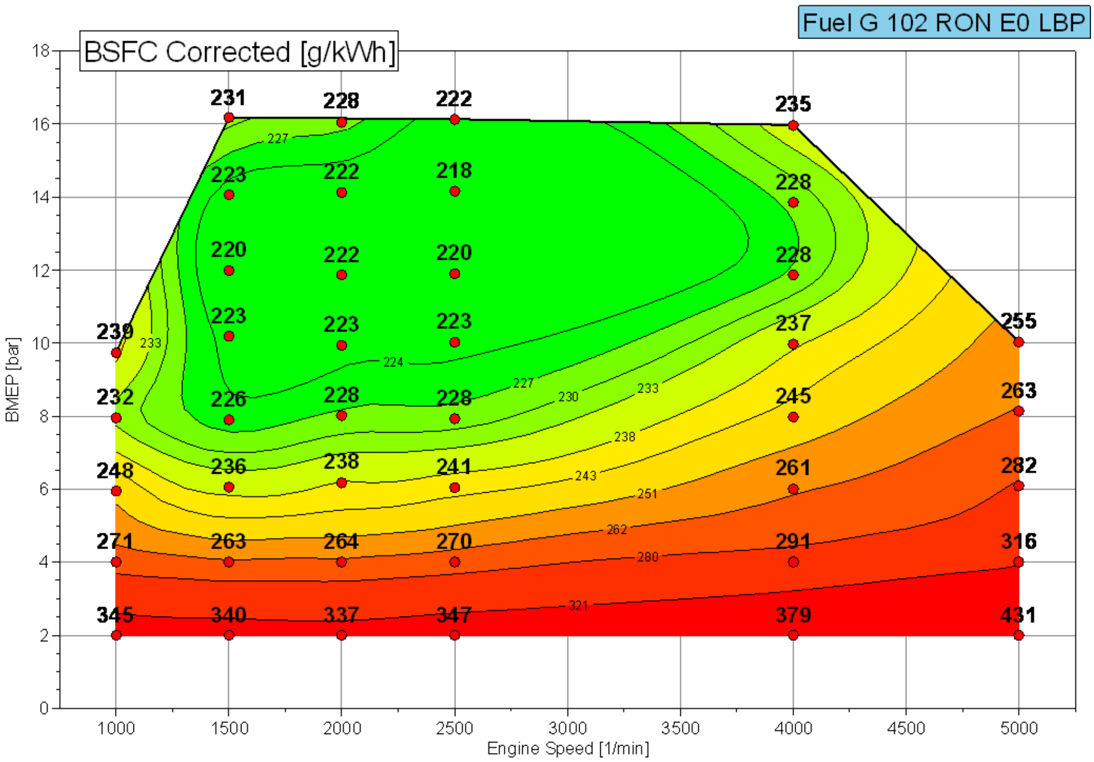

Figure 1: Brake Specific Fuel Consumption

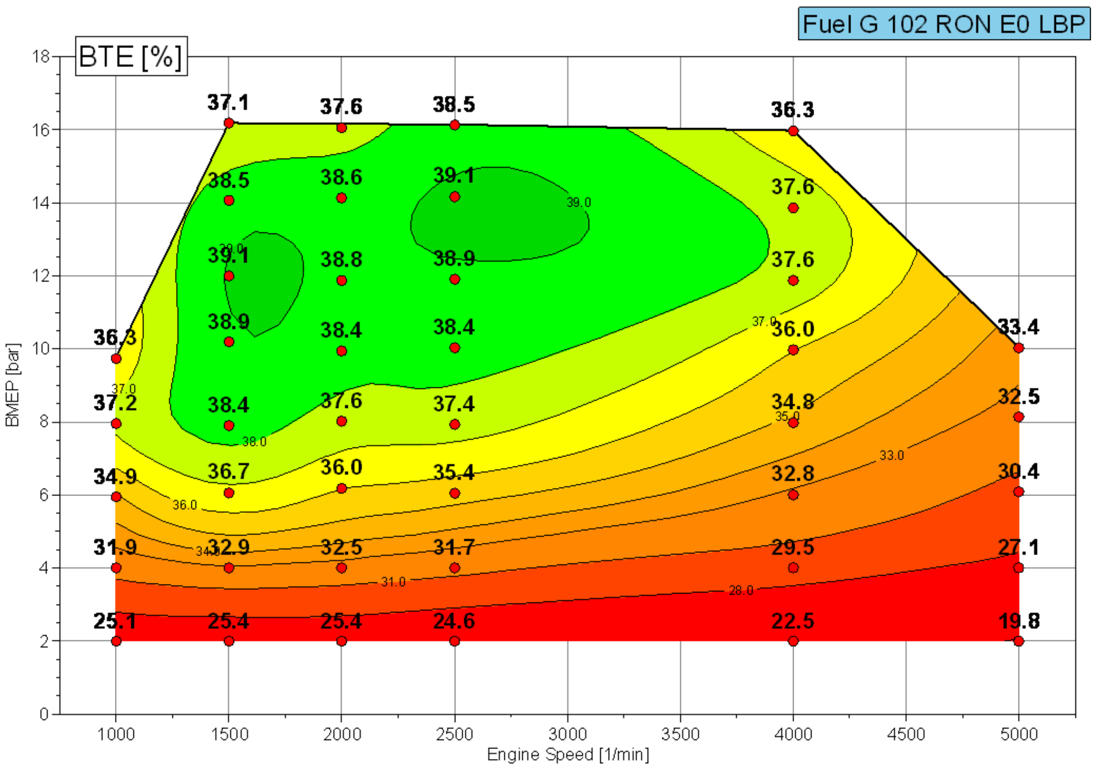

Figure 2: Brake Thermal Efficiency

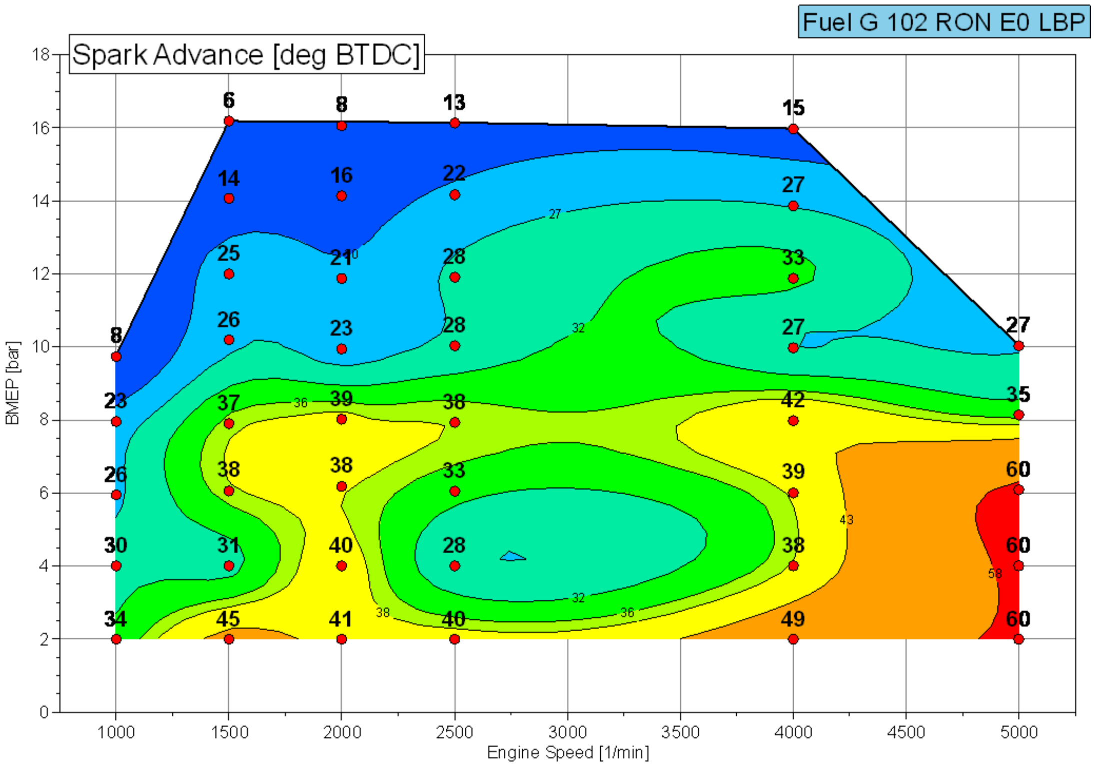

Figure 3: Spark Advance

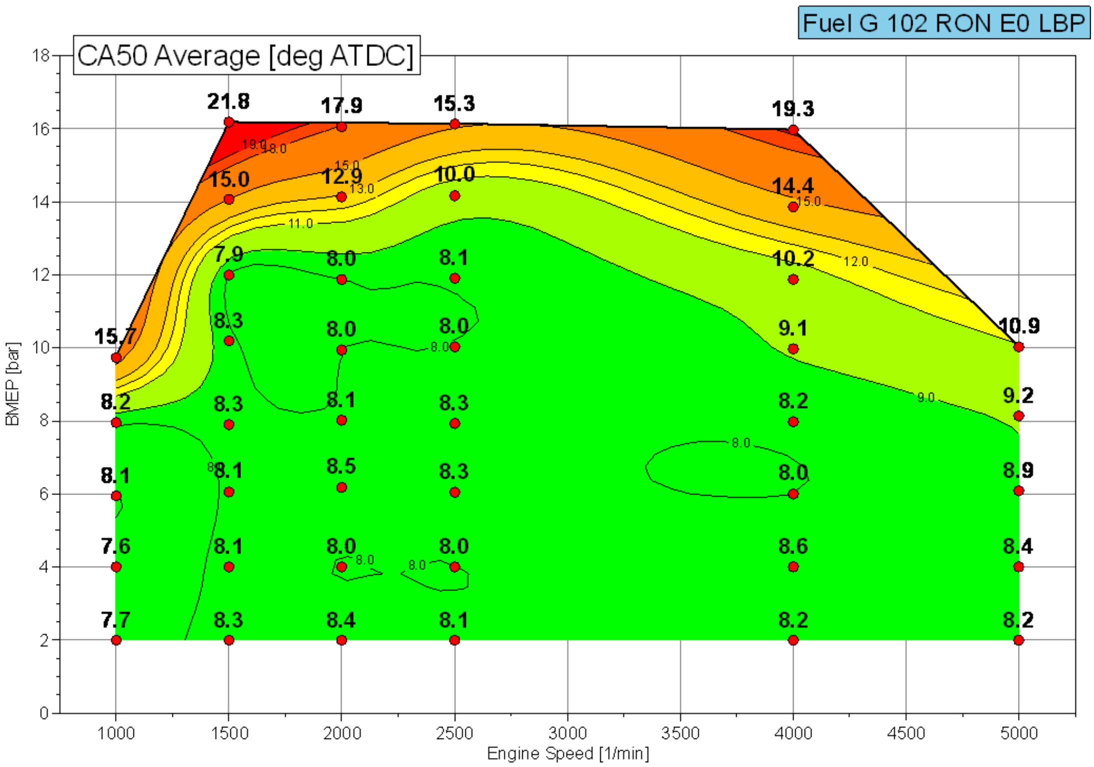

Figure 4: CA50 Average of Cylinders 1-4

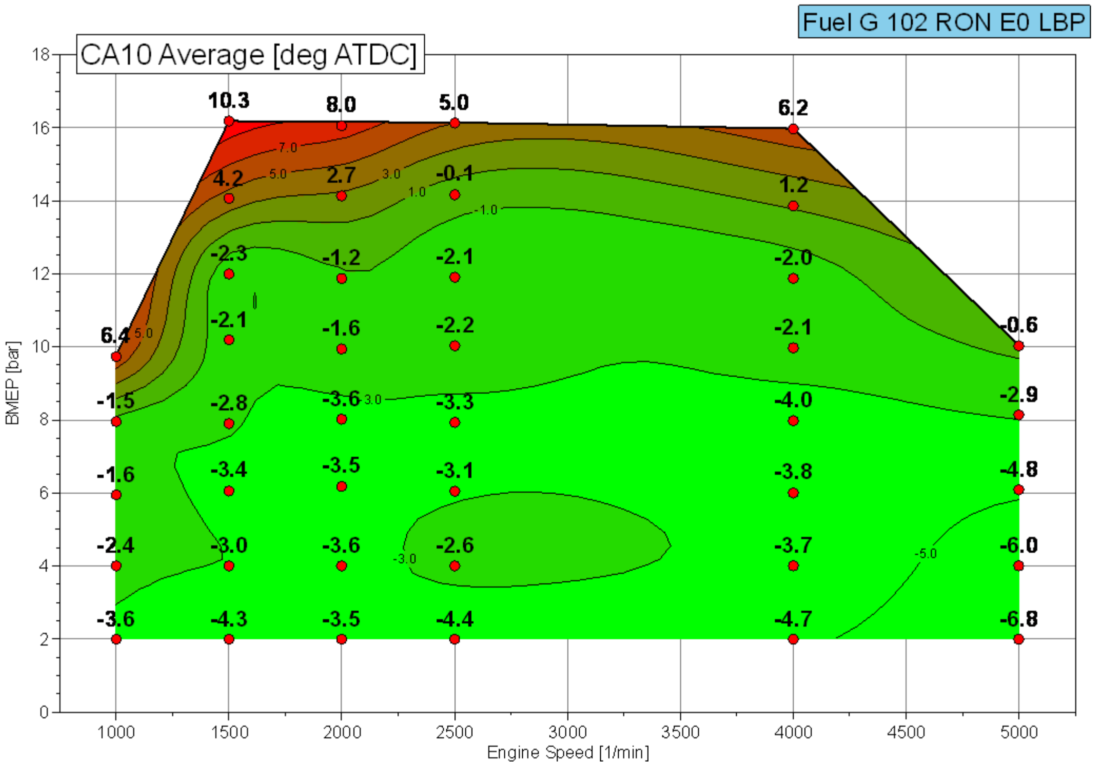

Figure 5: CA10 Average of Cylinders 1-4

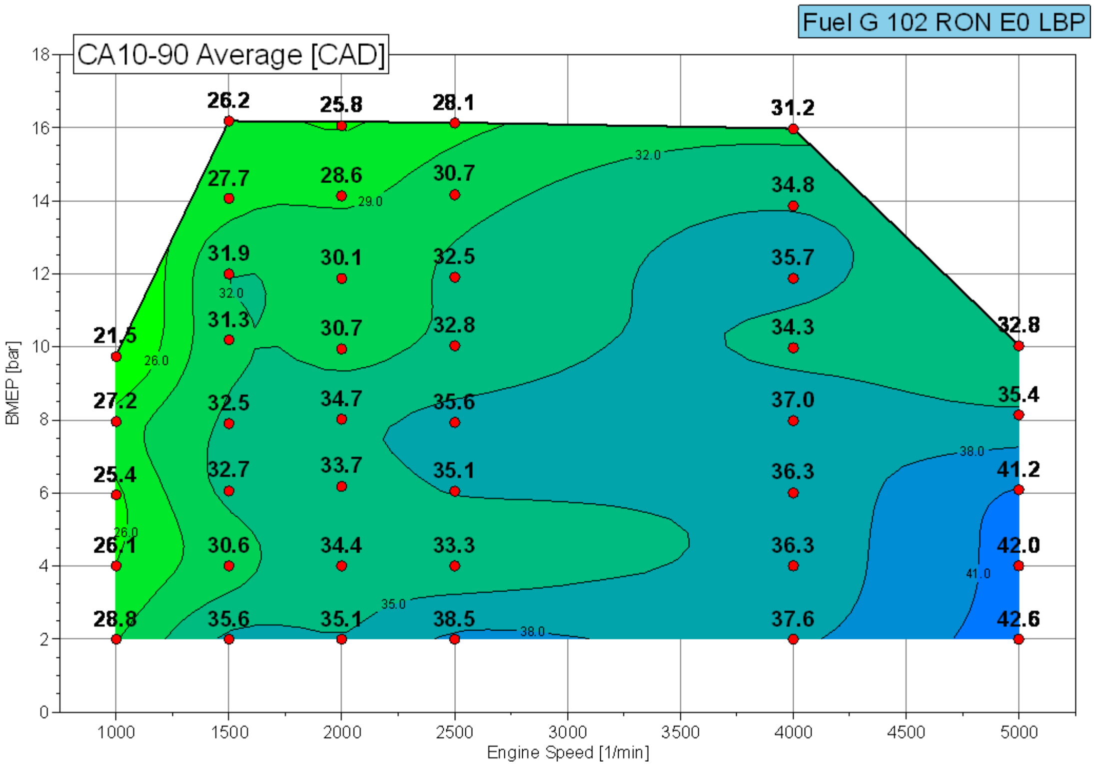

Figure 6: CA10-90 Average of Cylinders 1-4

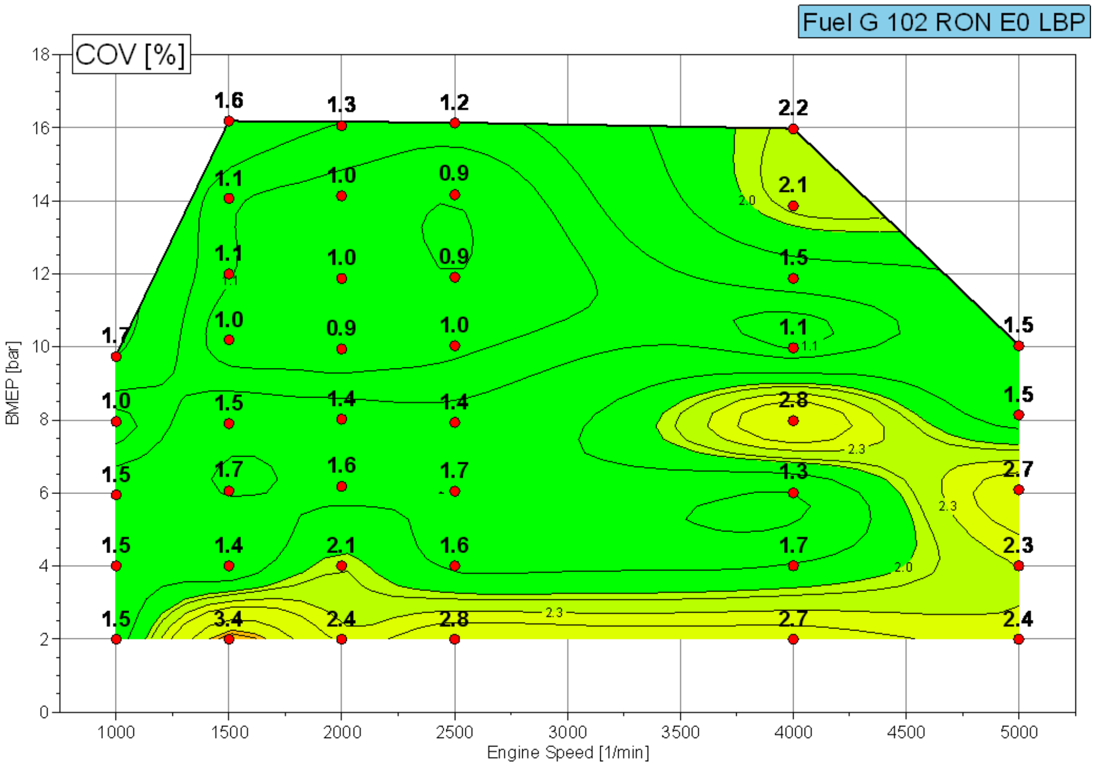

Figure 7: Coefficient of Variation Average of Cylinders 1-4

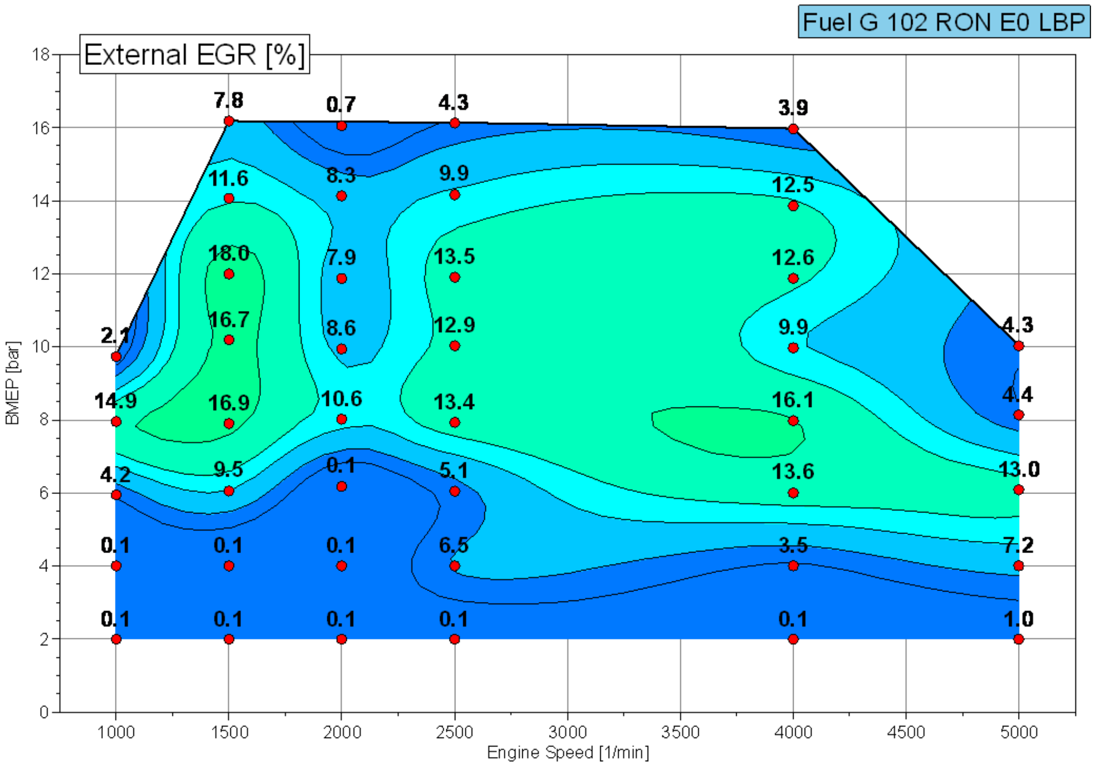

Figure 8: External EGR Percent of Intake Air

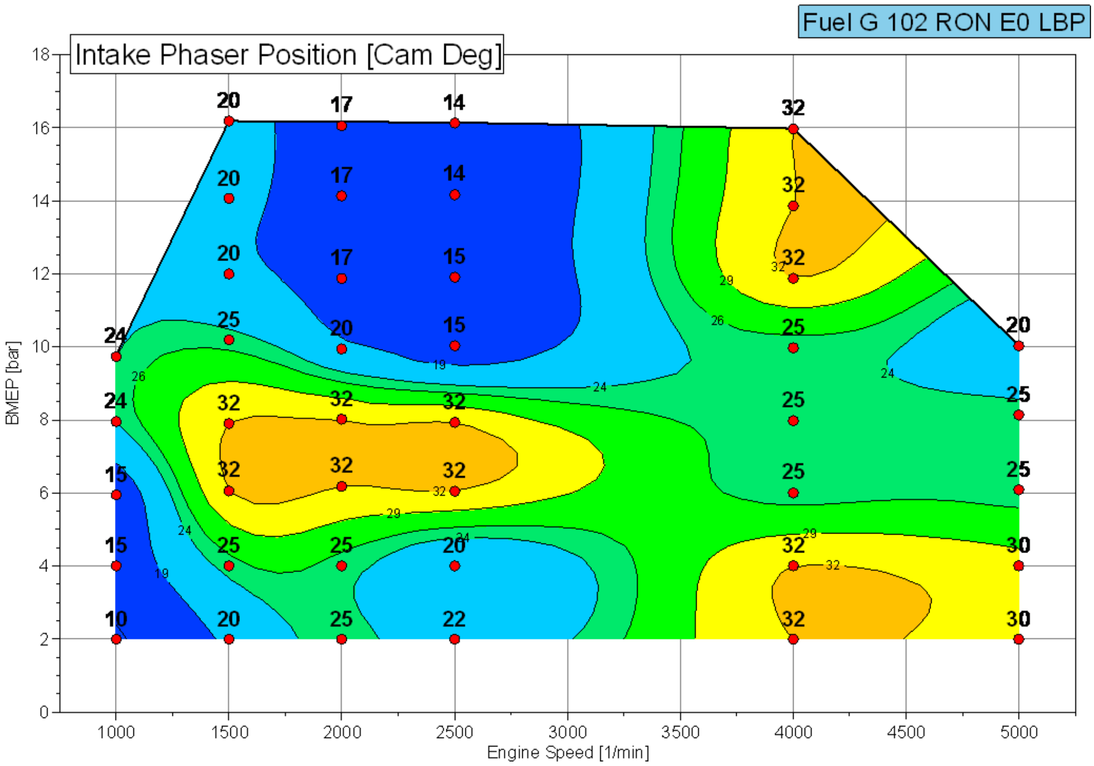

Figure 9: Intake Camshaft Phaser Position

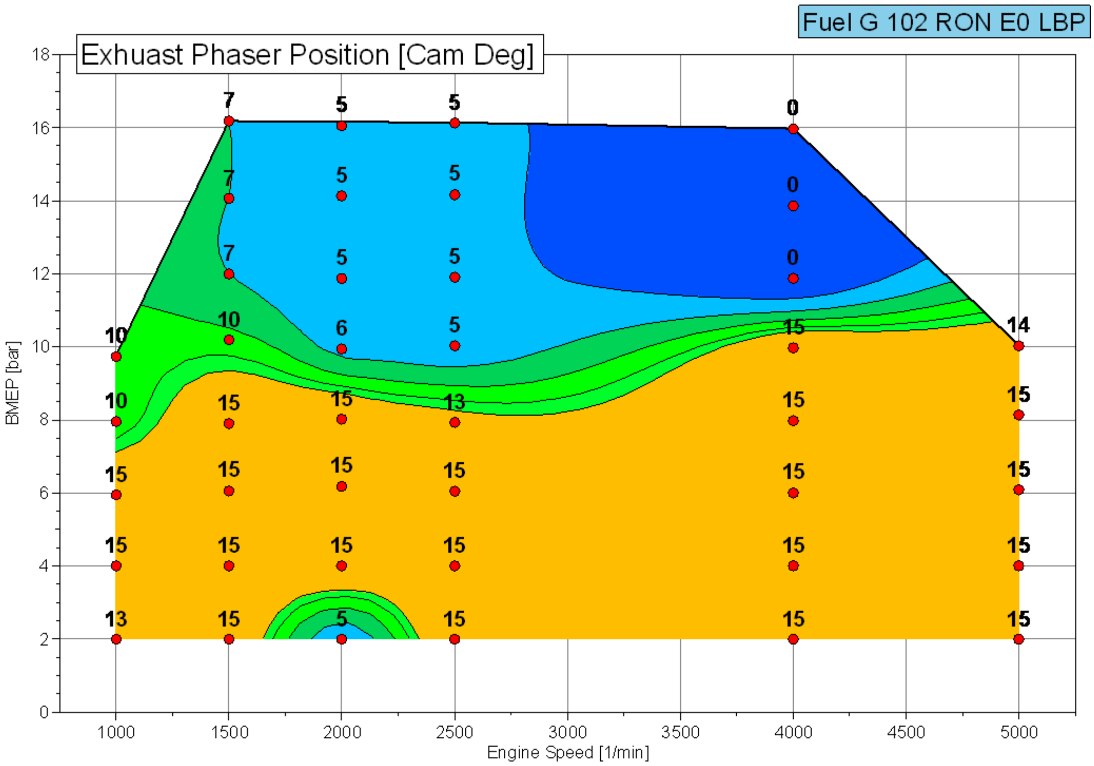

Figure 10: Exhaust Camshaft Phaser Position

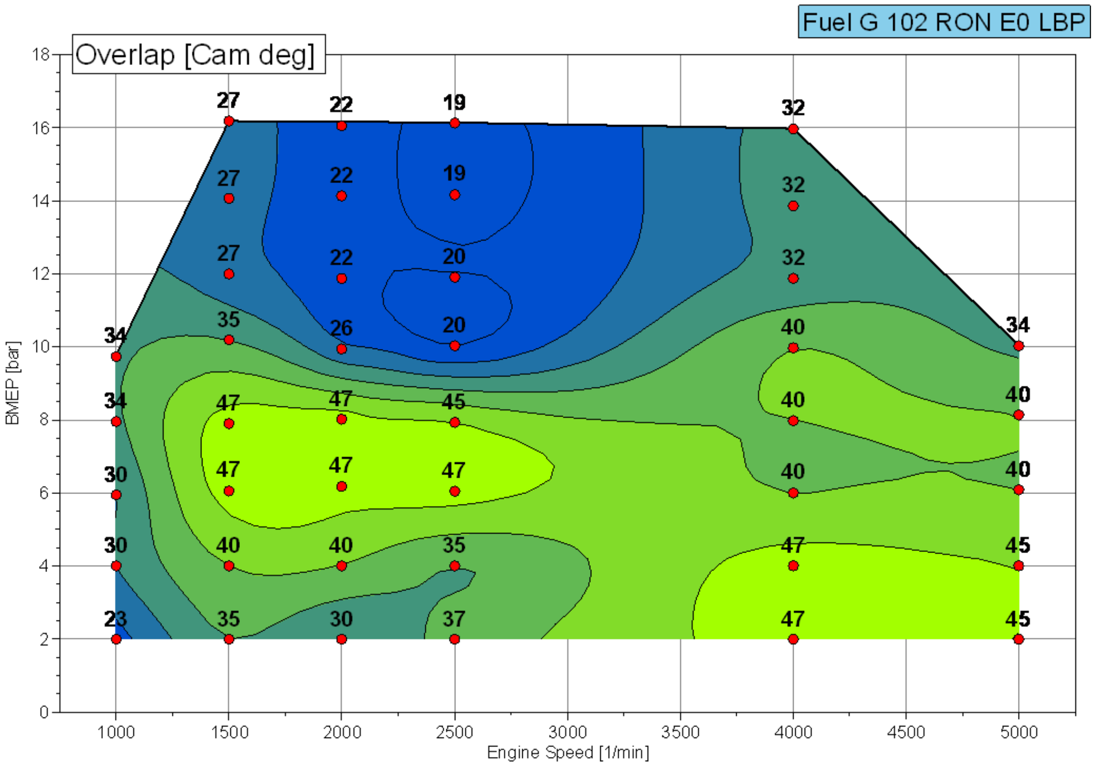

Figure 11: Camshaft Overlap

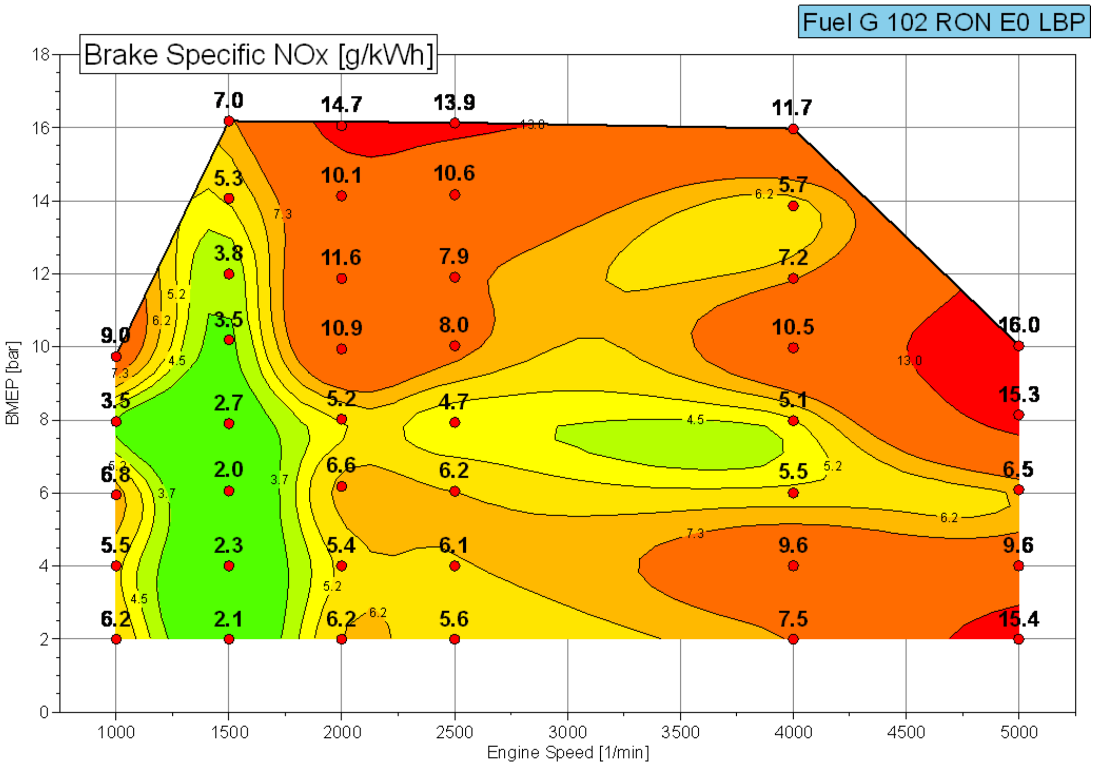

Figure 12: Brake Specific NOx Emissions

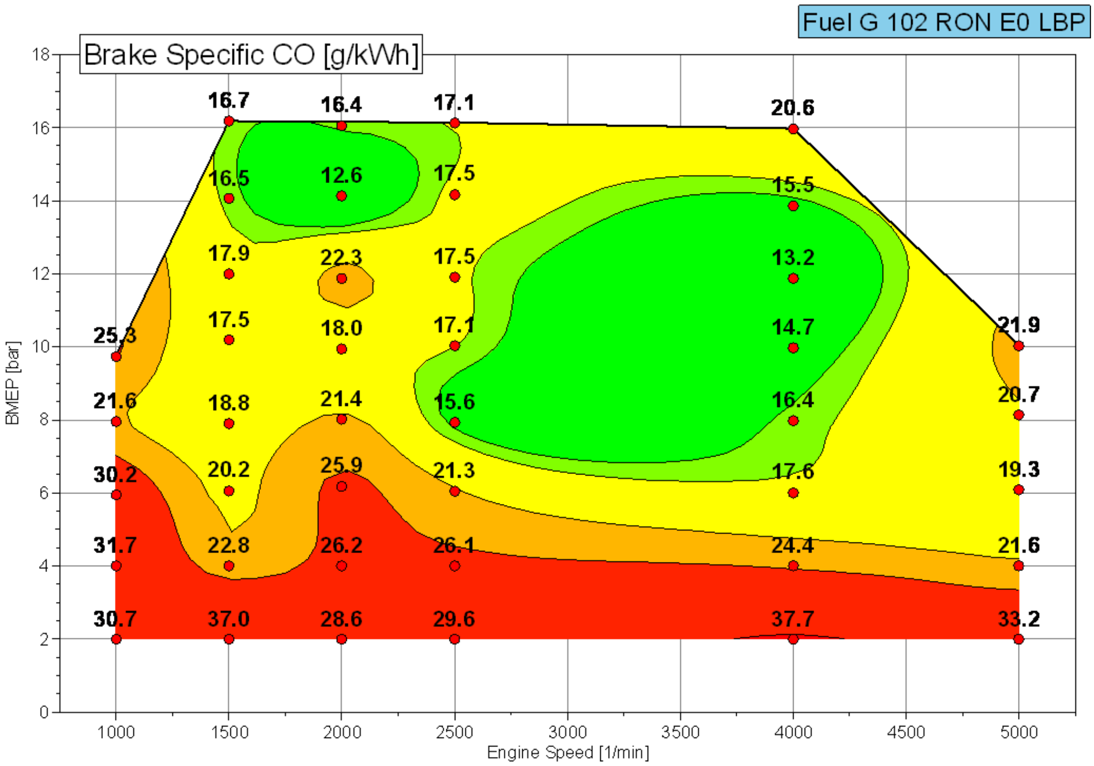

Figure 13: Brake Specific Carbon Monoxide Emissions

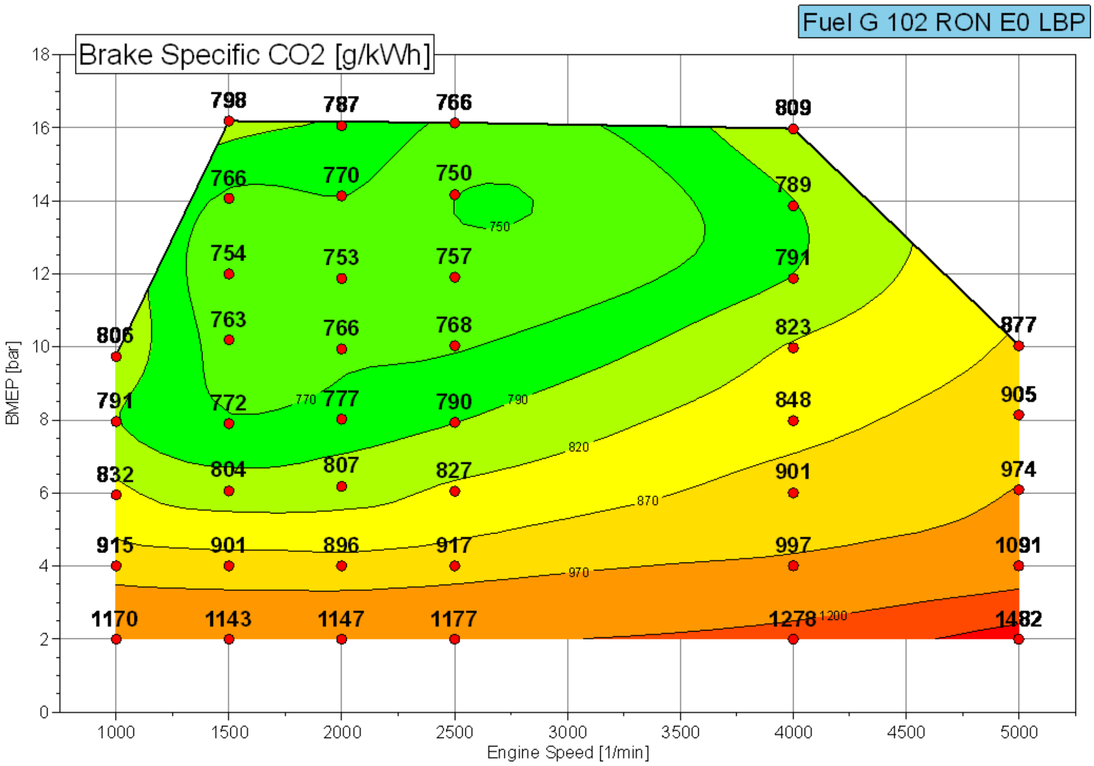

Figure 14: Brake Specific Carbon Dioxide Emissions

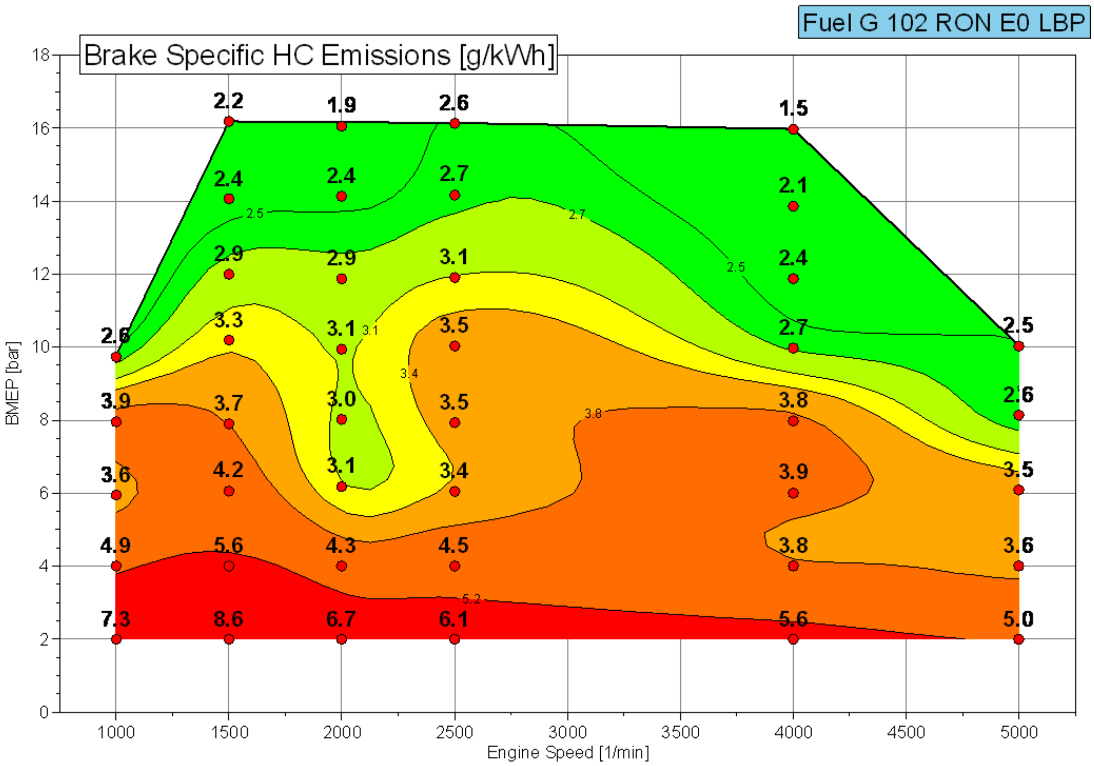

Figure 15: Brake Specific Hydrocarbon Emissions

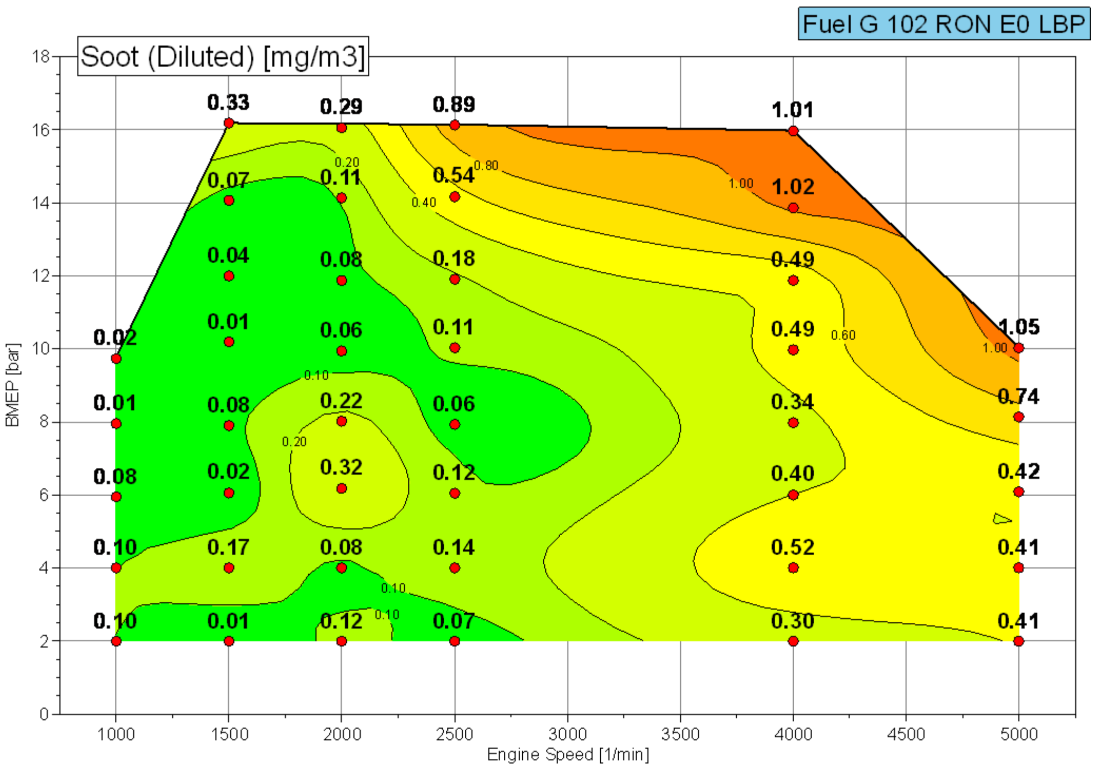

Figure 16: Particulate Soot Emissions

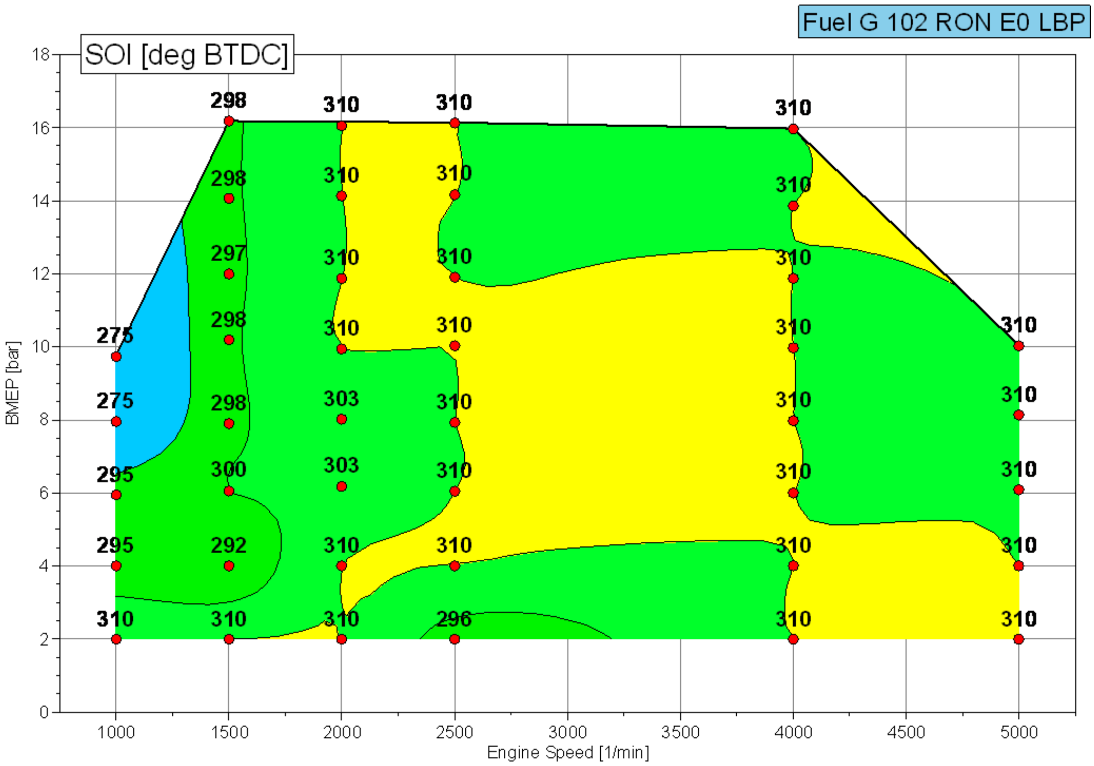

Figure 17: Start of Injection

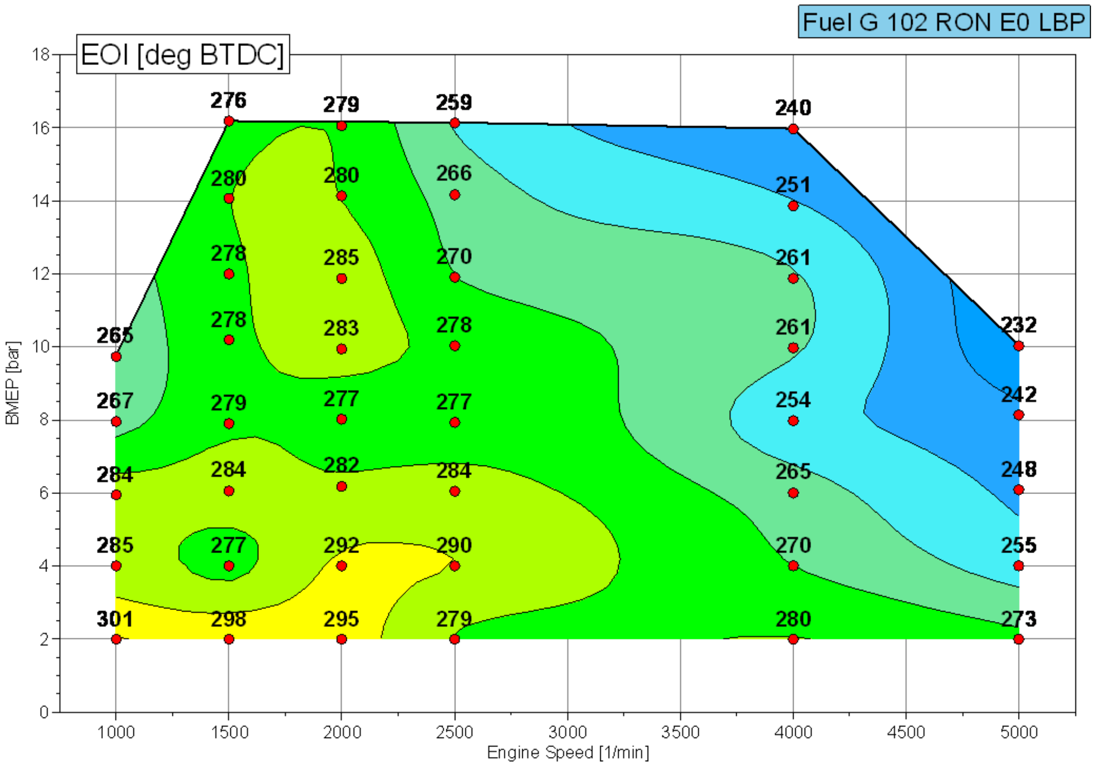

Figure 18: End of Injection

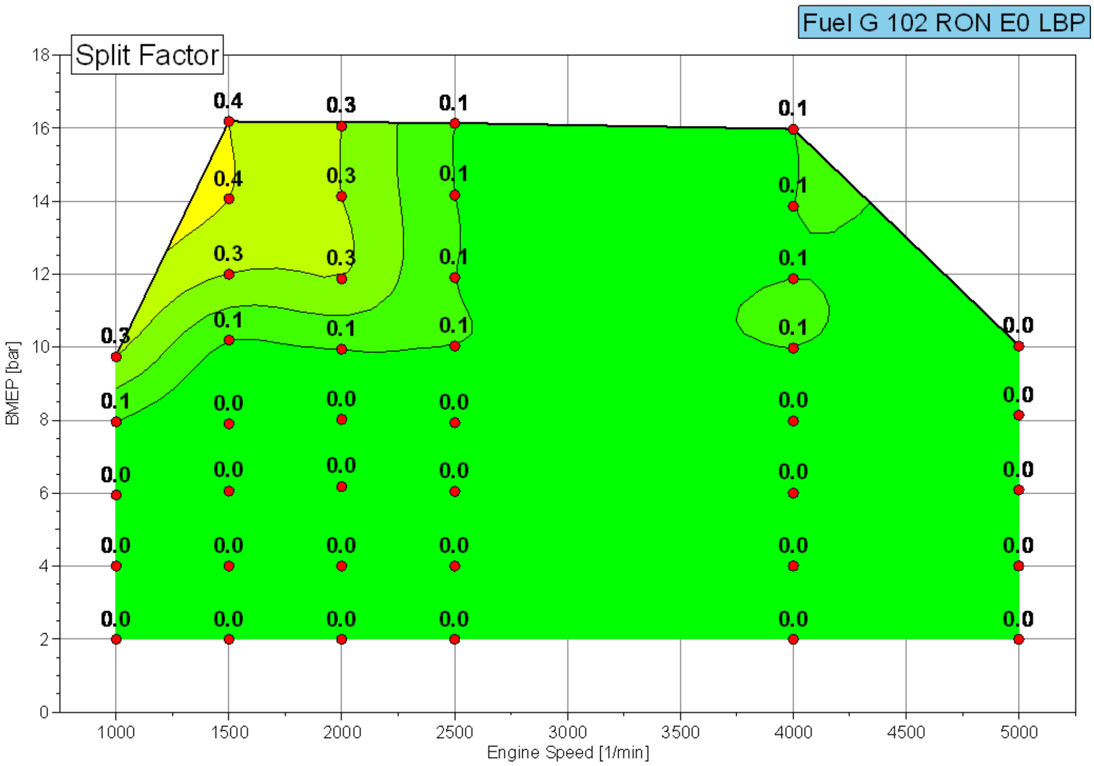

Figure 19: Injection Split Factor

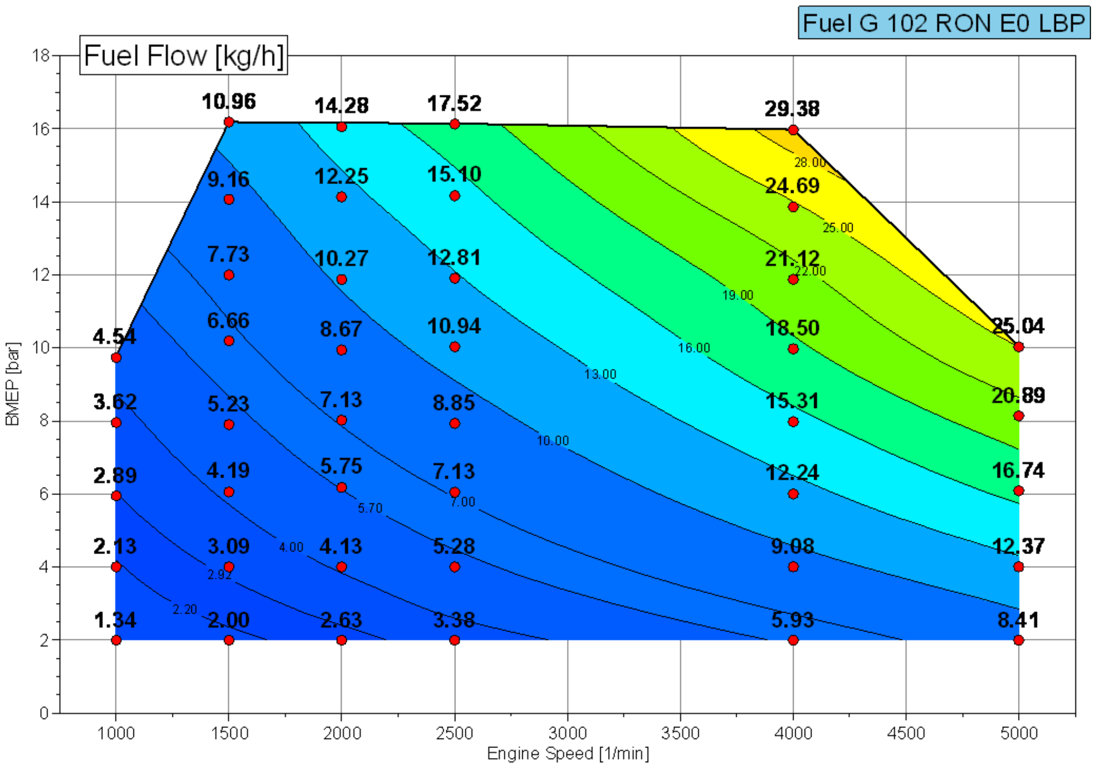

Figure 20: Fuel Flow

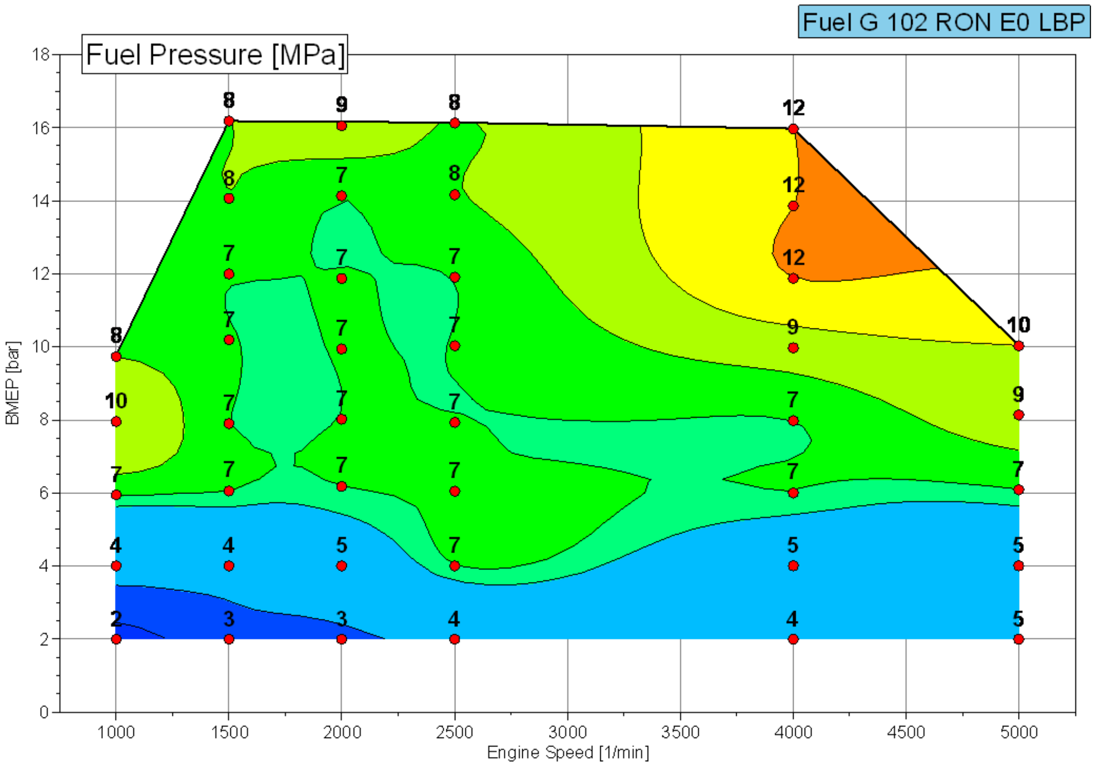

Figure 21: Fuel Rail Pressure

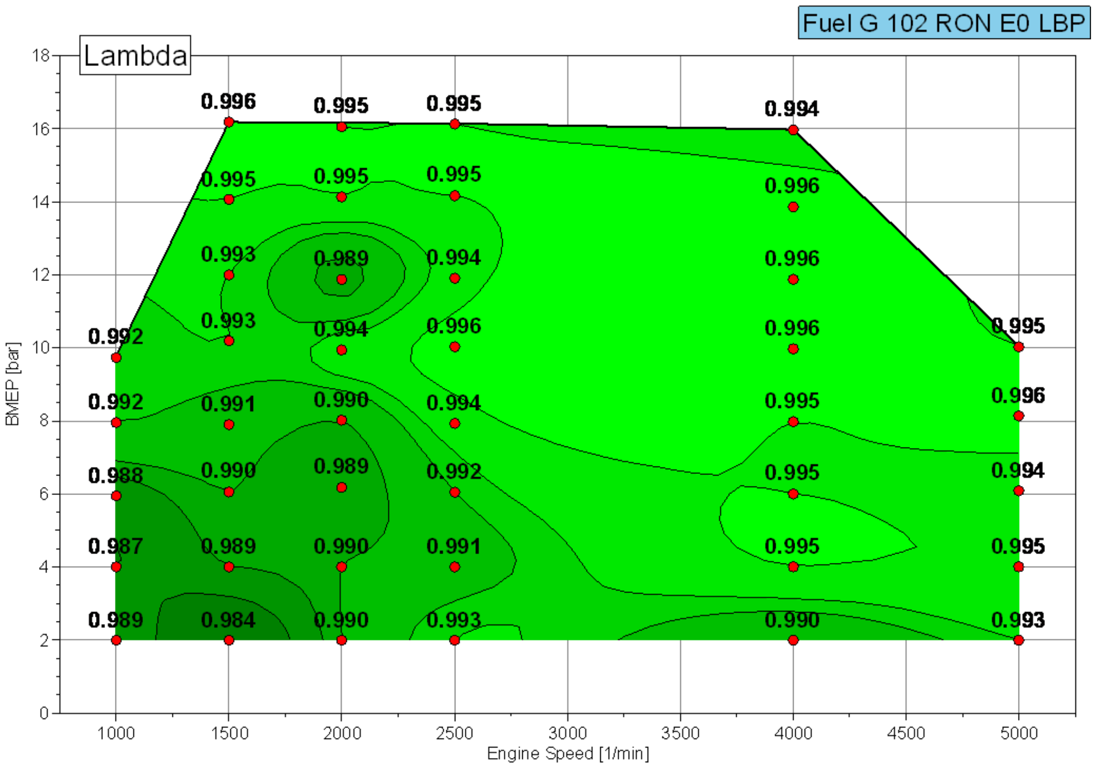

Figure 22: Lambda

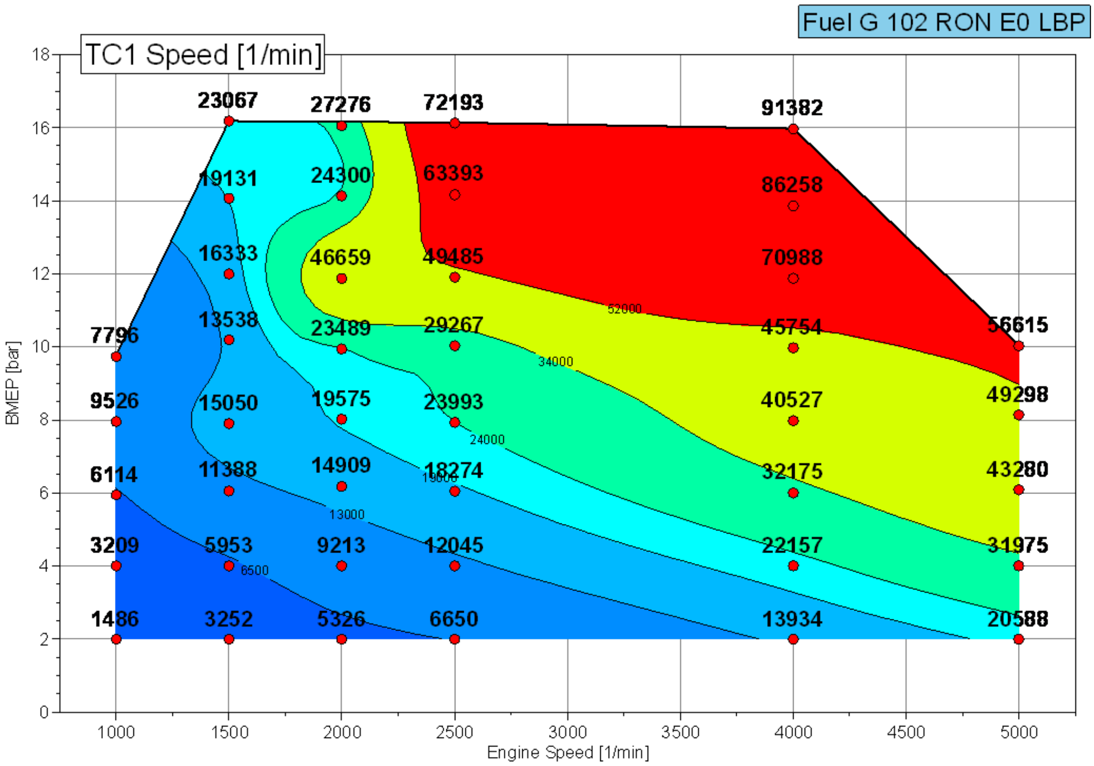

Figure 23: Low Pressure Turbocharger Speed

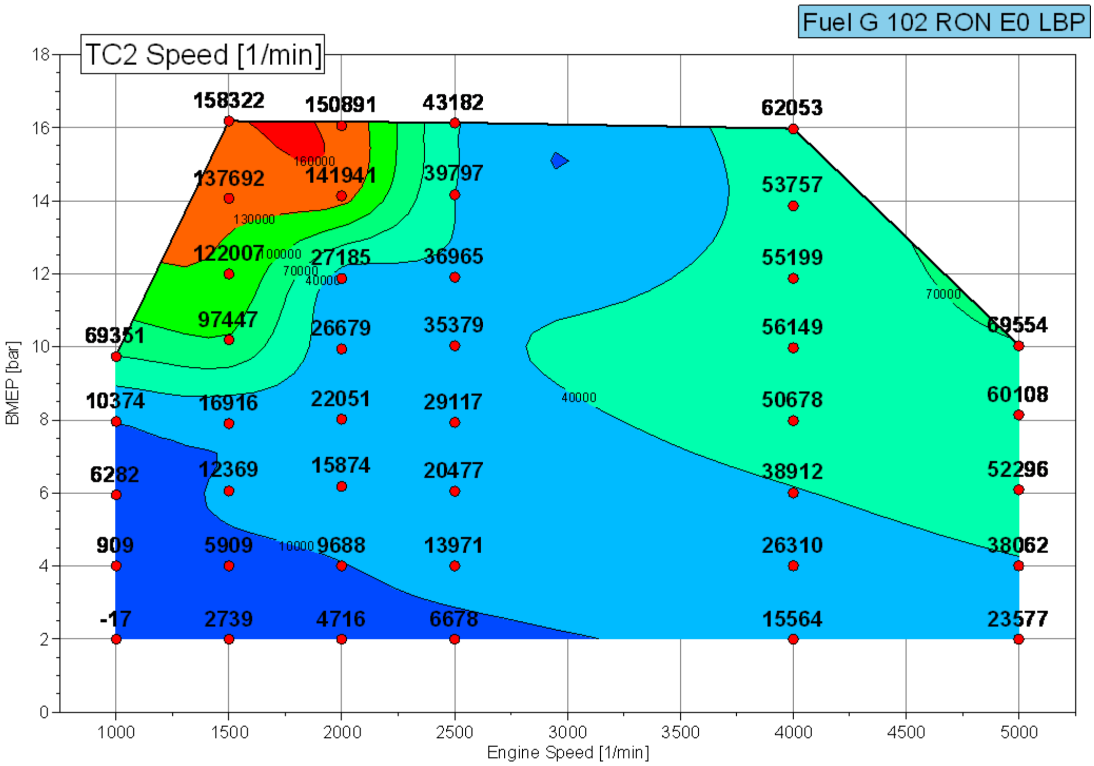

Figure 24: High Pressure Turbocharge Speed

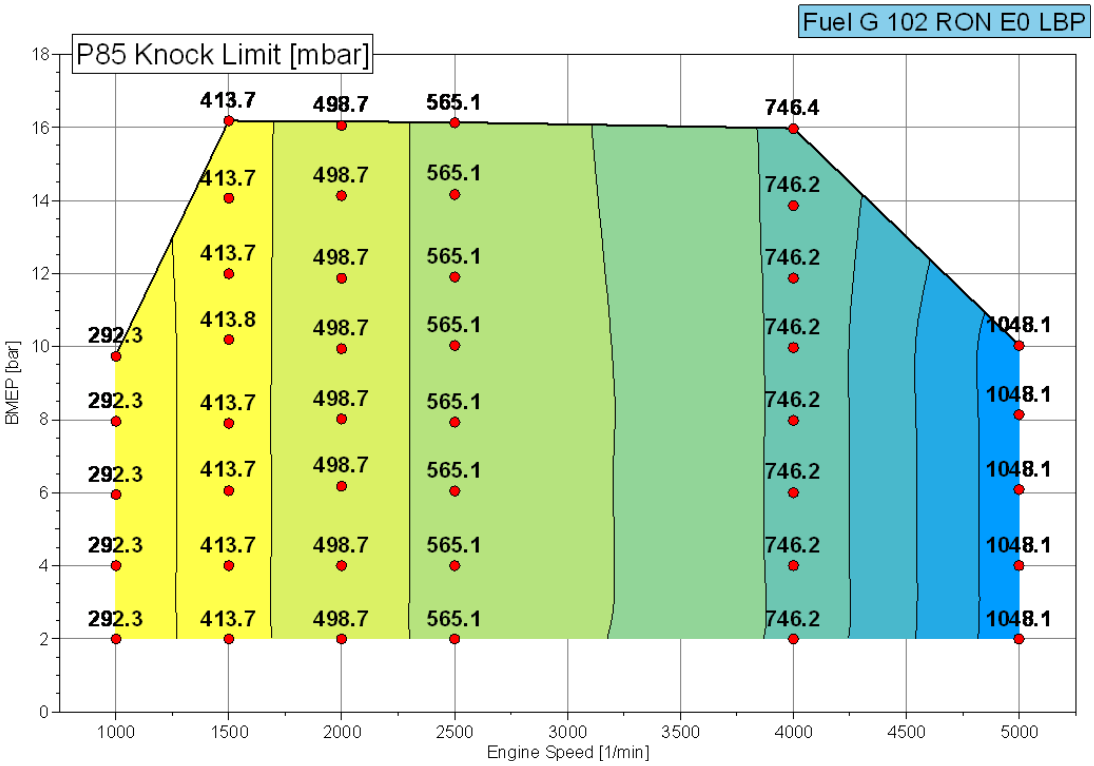

Figure 25: P85 Knock Limit

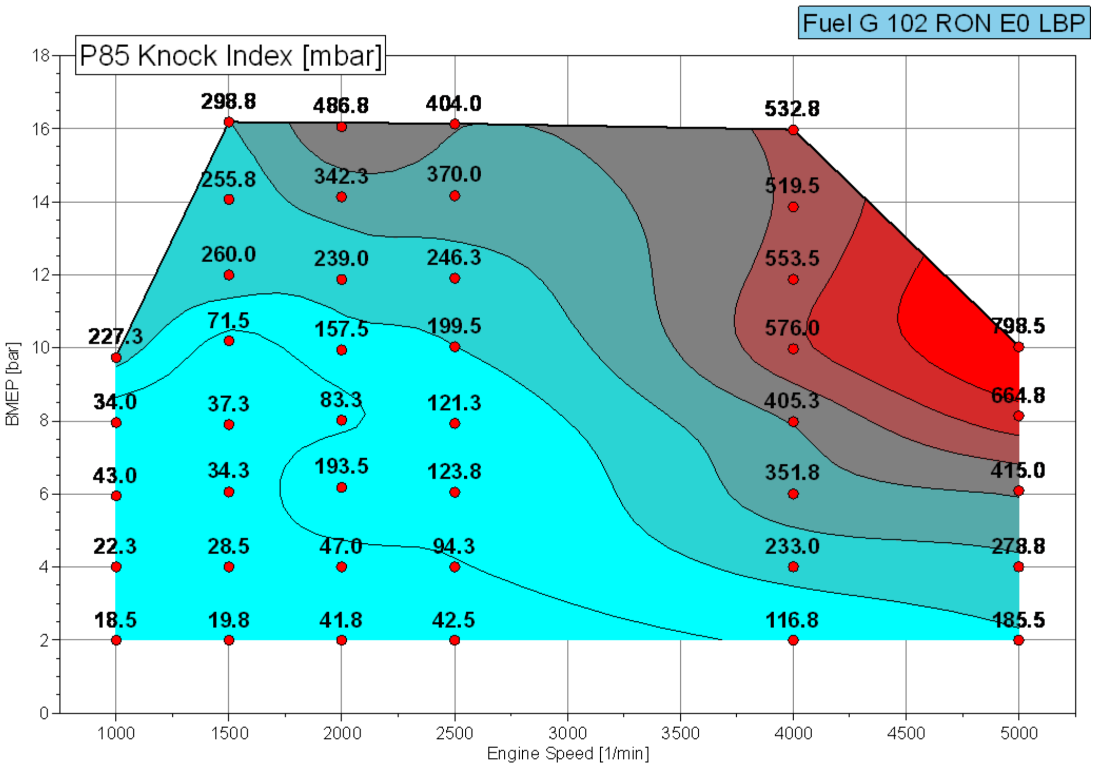

Figure 26: Averaged P85 Knock Index

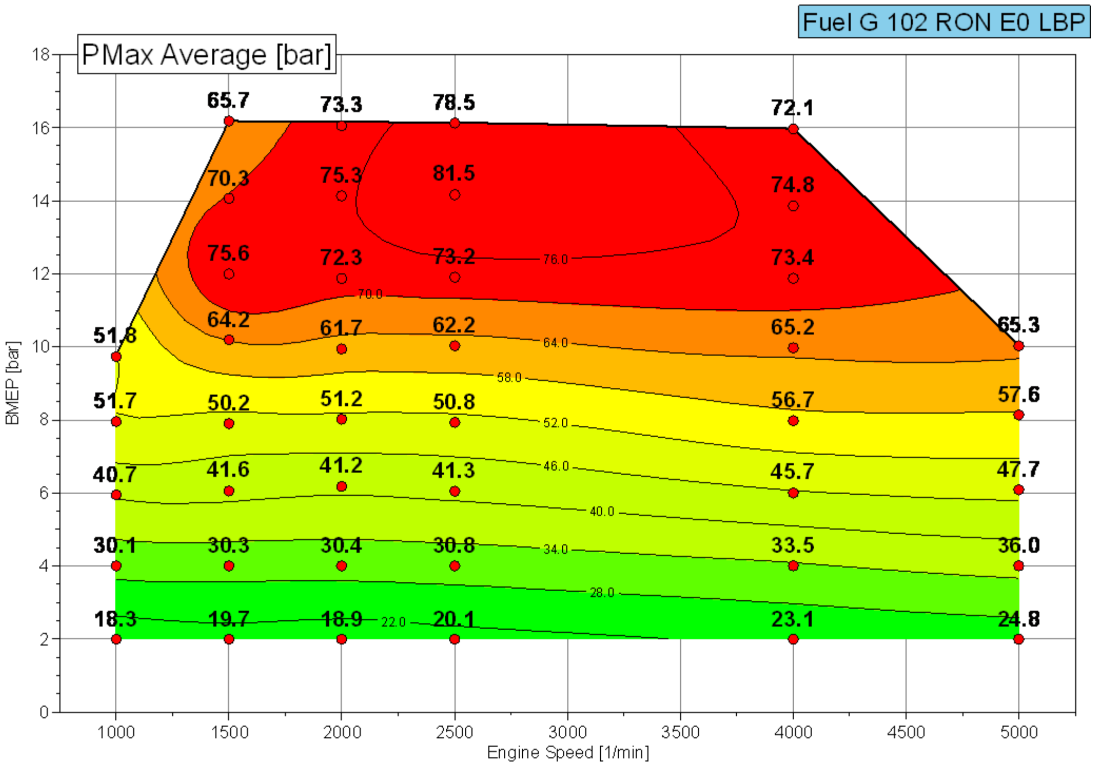

Figure 27: Averaged Max Pressure for Cylinders 1-4

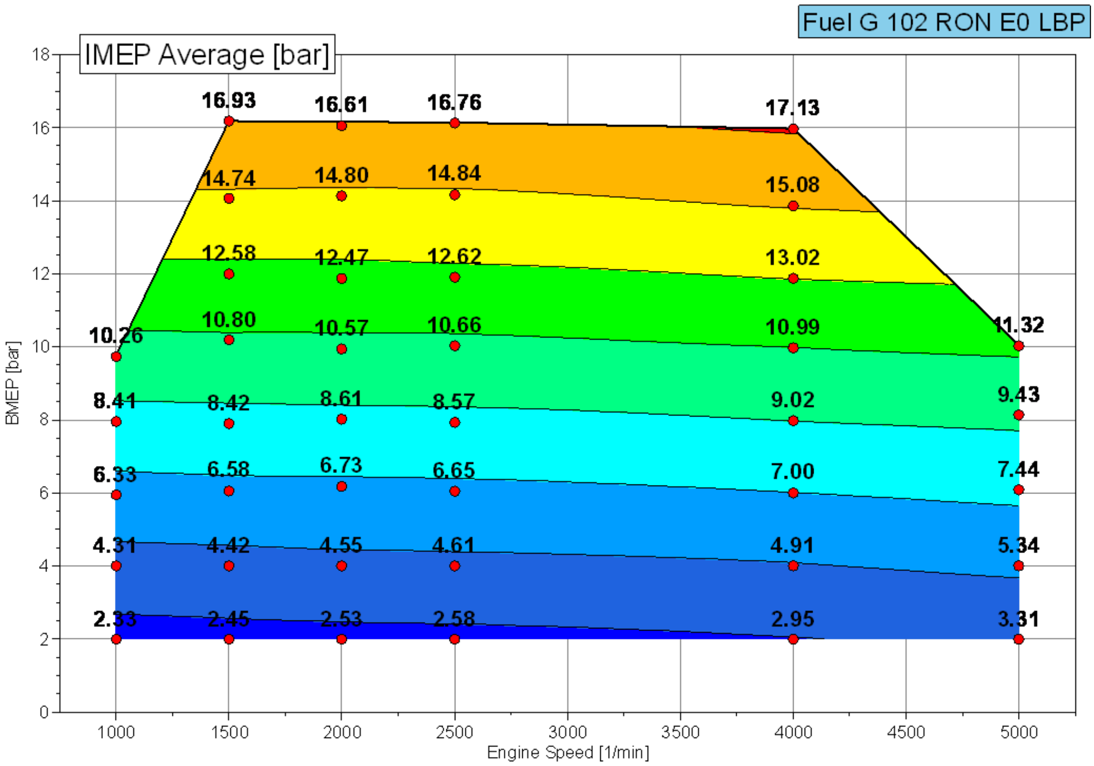

Figure 28: Indicated Mean Effective Pressure

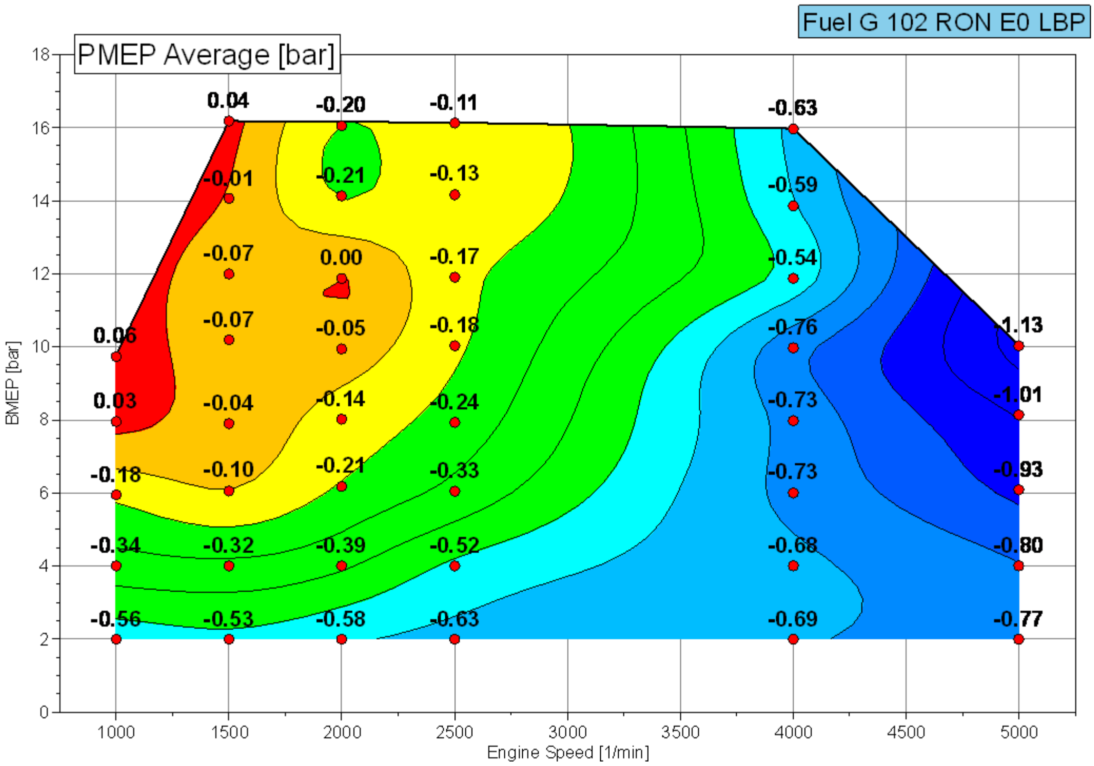

Figure 29: Pumping Mean Effective Pressure

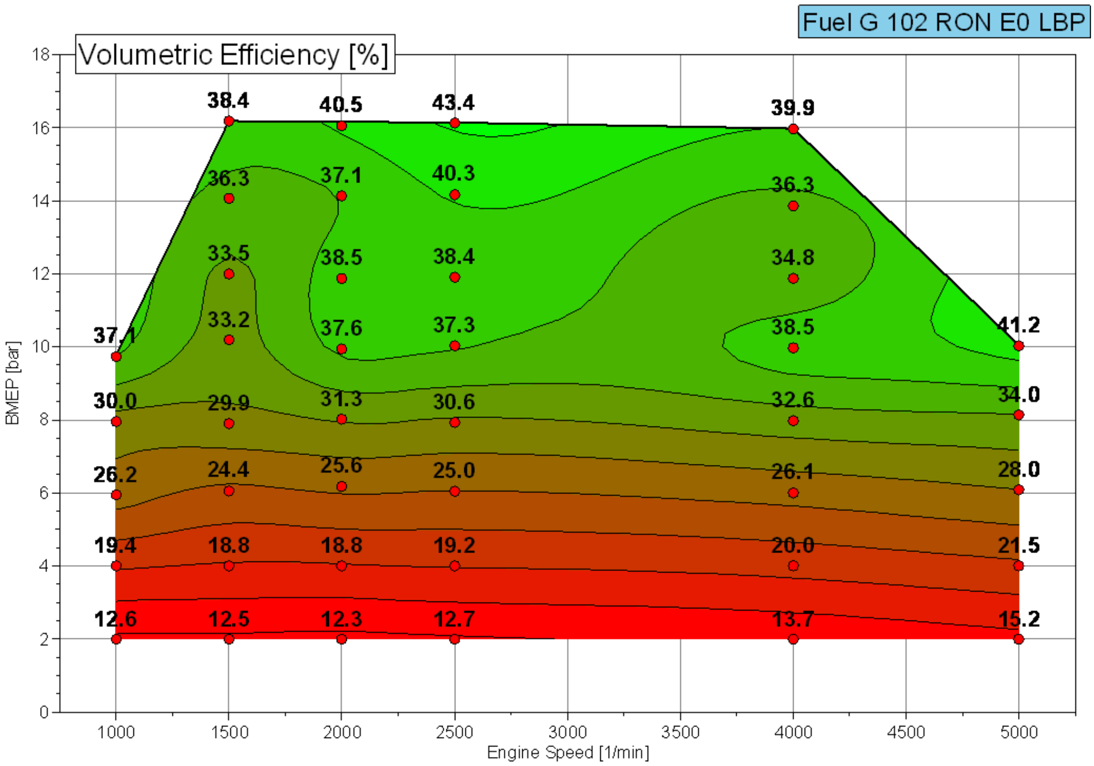

Figure 30: Calculated Volumetric Efficiency

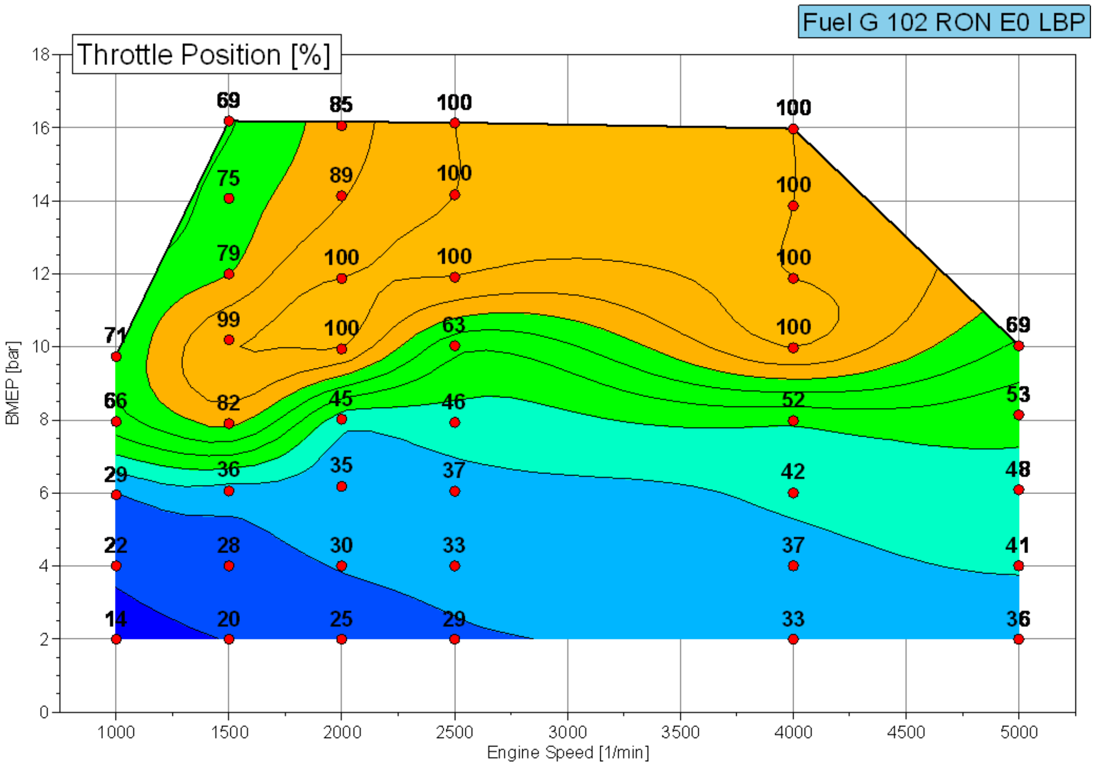

Figure 31: Throttle Position

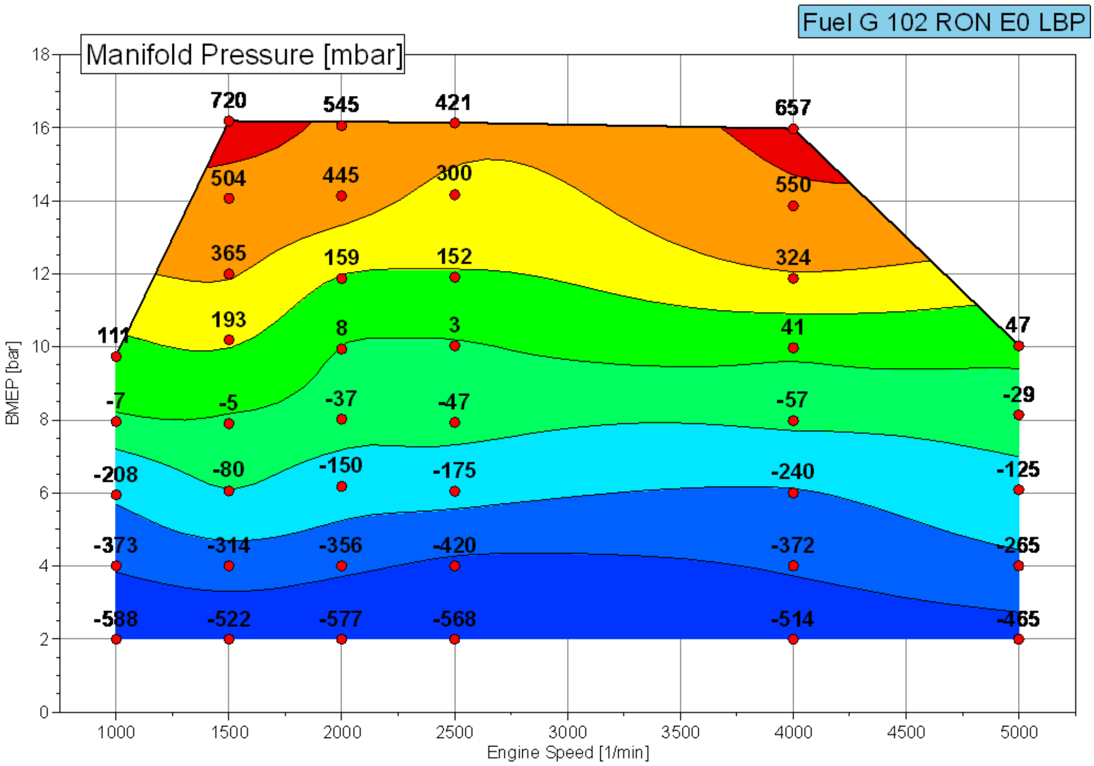

Figure 32: Intake Manifold Pressure

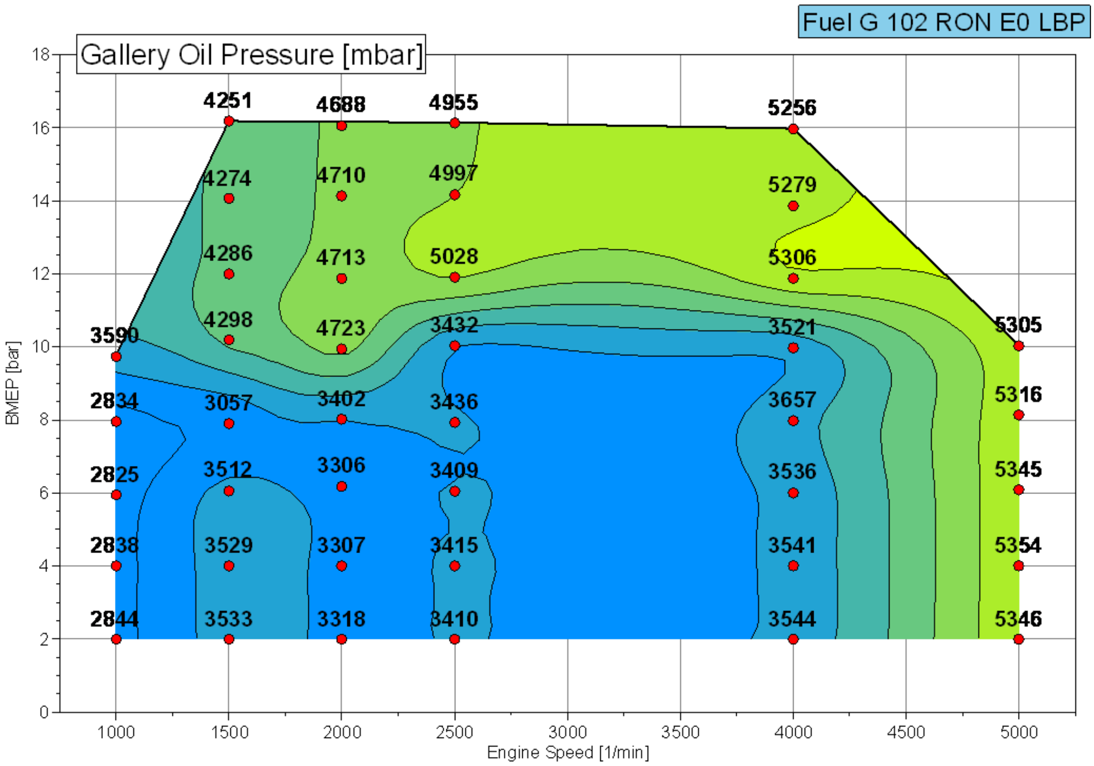

Figure 33: Gallery Oil Pressure

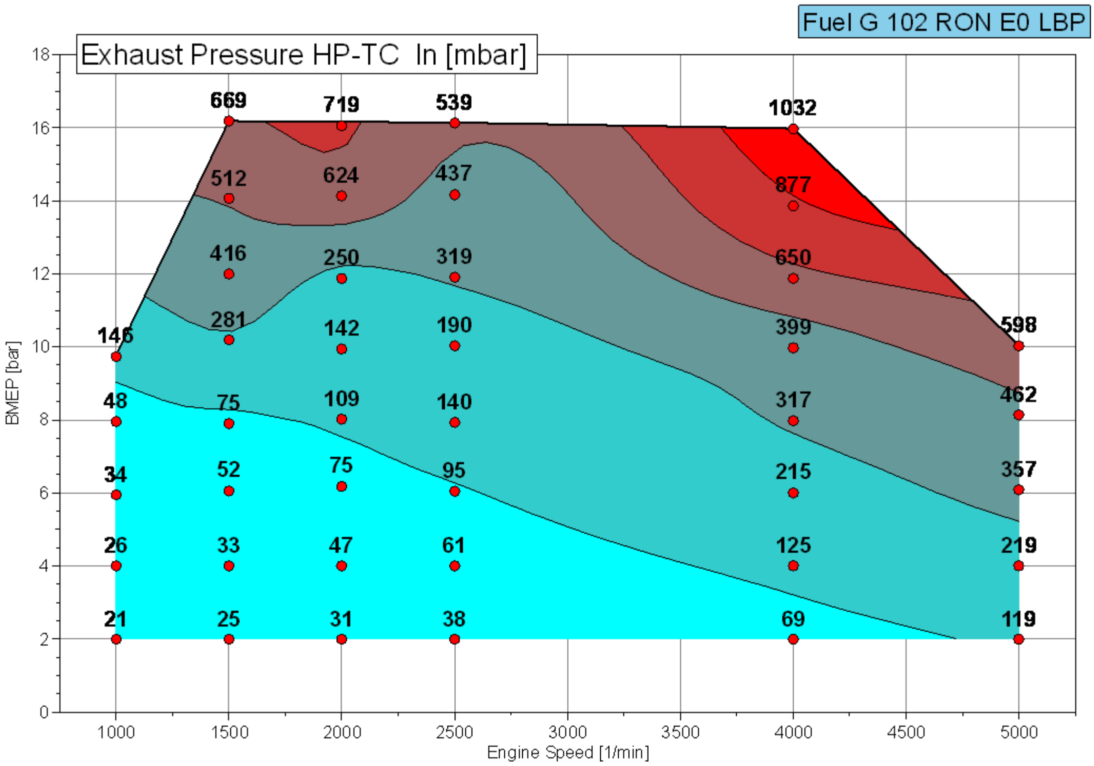

Figure 34: Exhaust Pressure High Pressure Turbocharger In

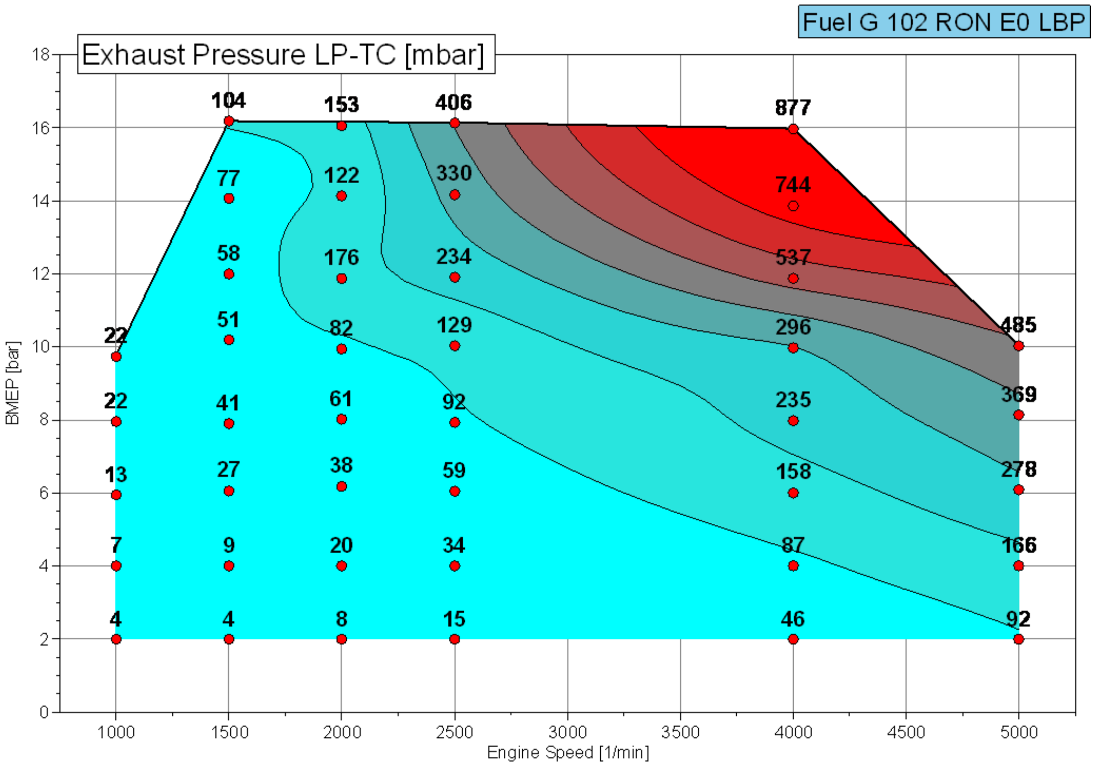

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

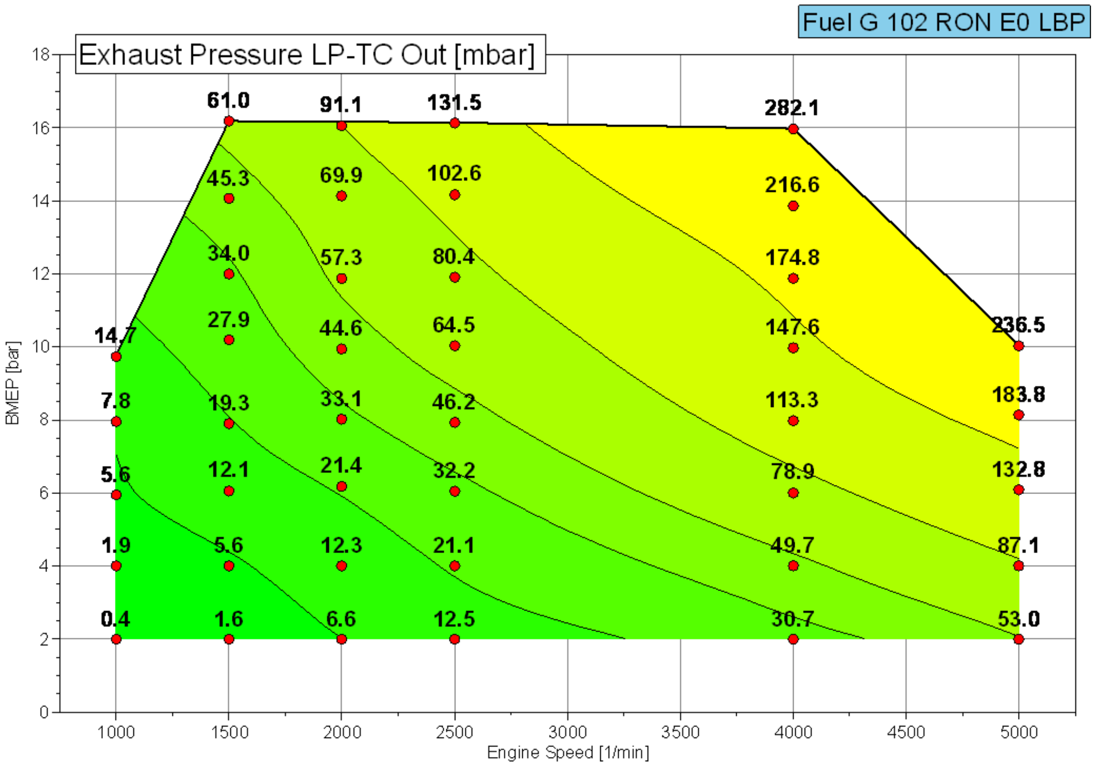

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

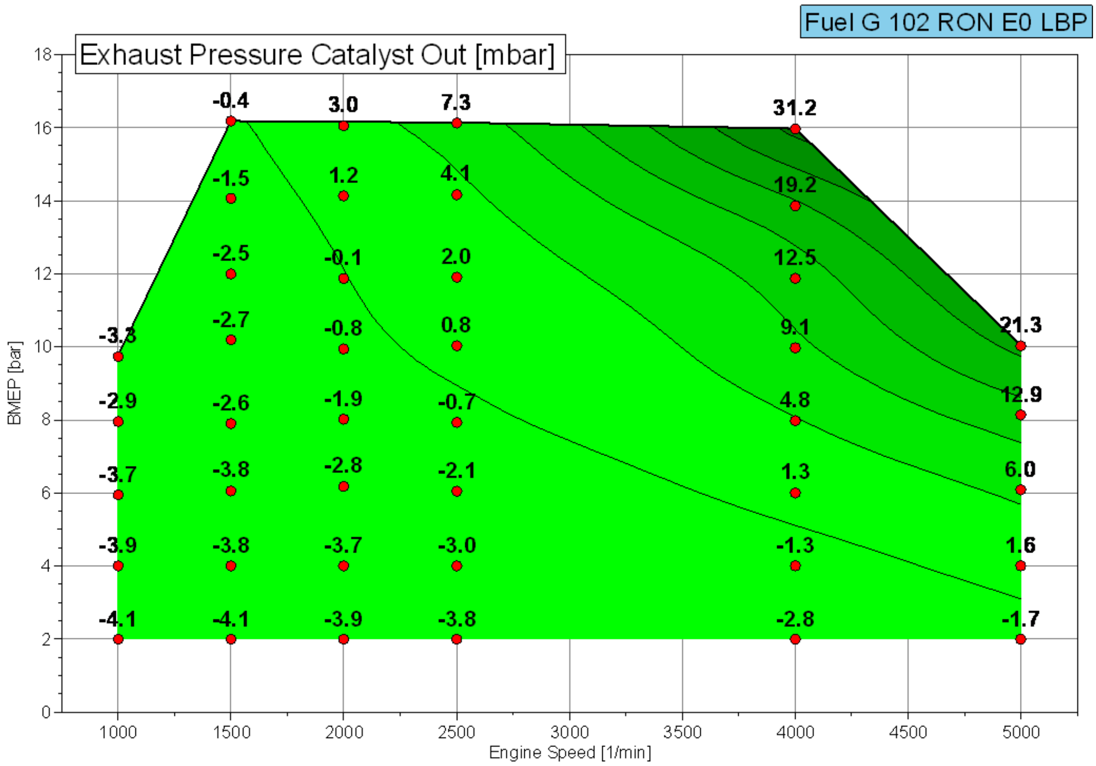

Figure 37: Exhaust Pressure Catalyst Out

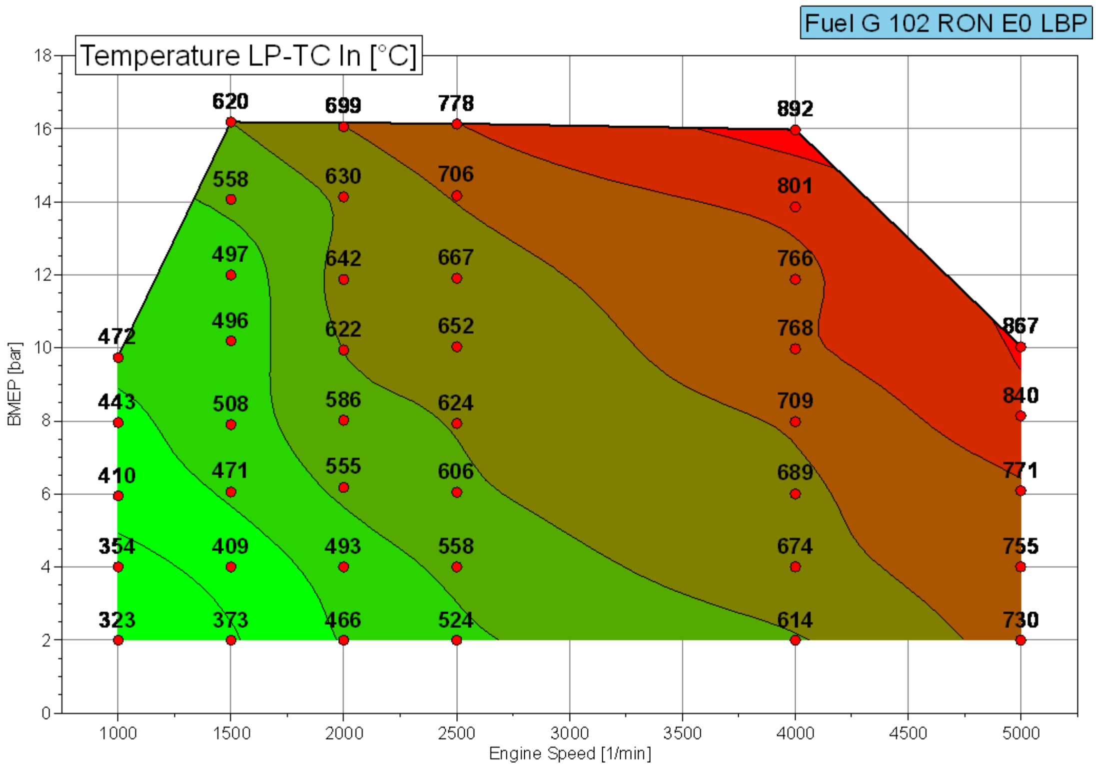

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

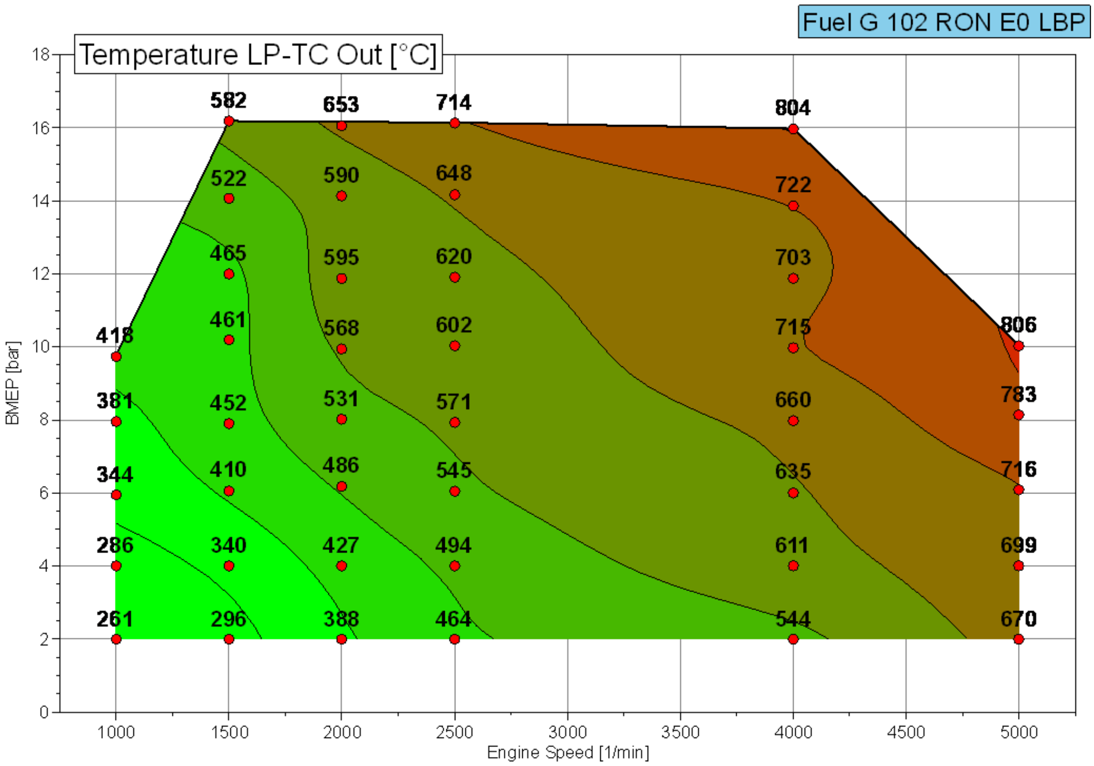

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

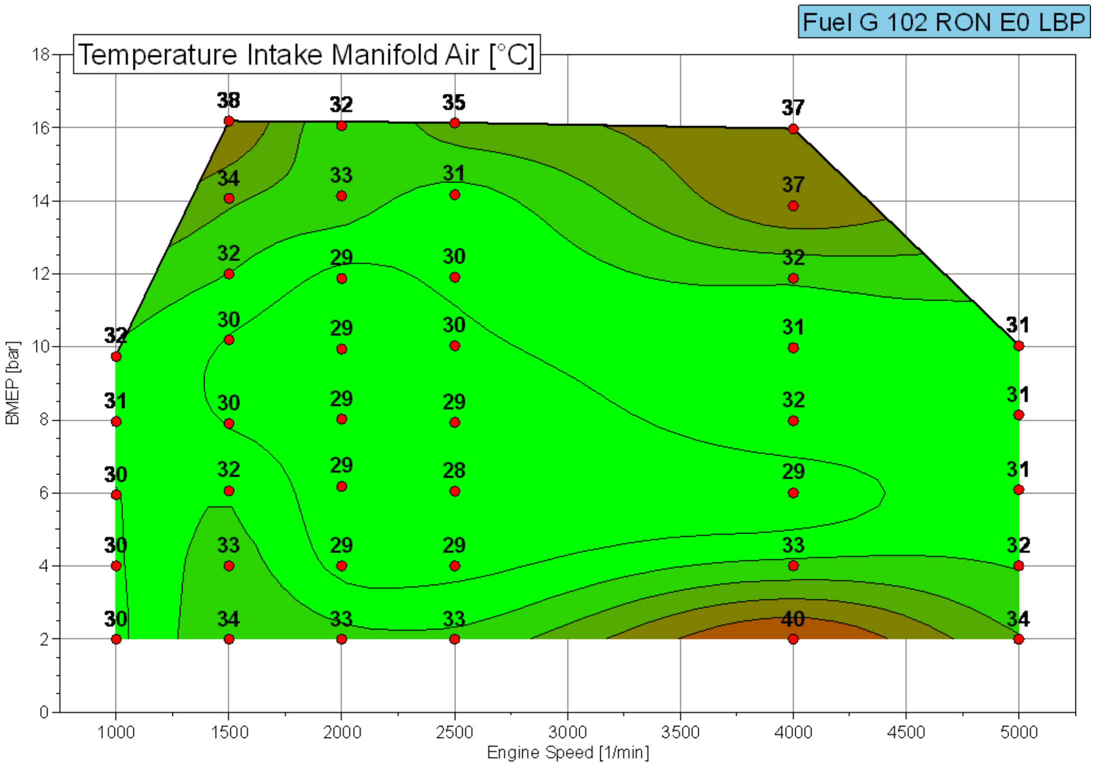

Figure 40: Intake Manifold Air Temperature

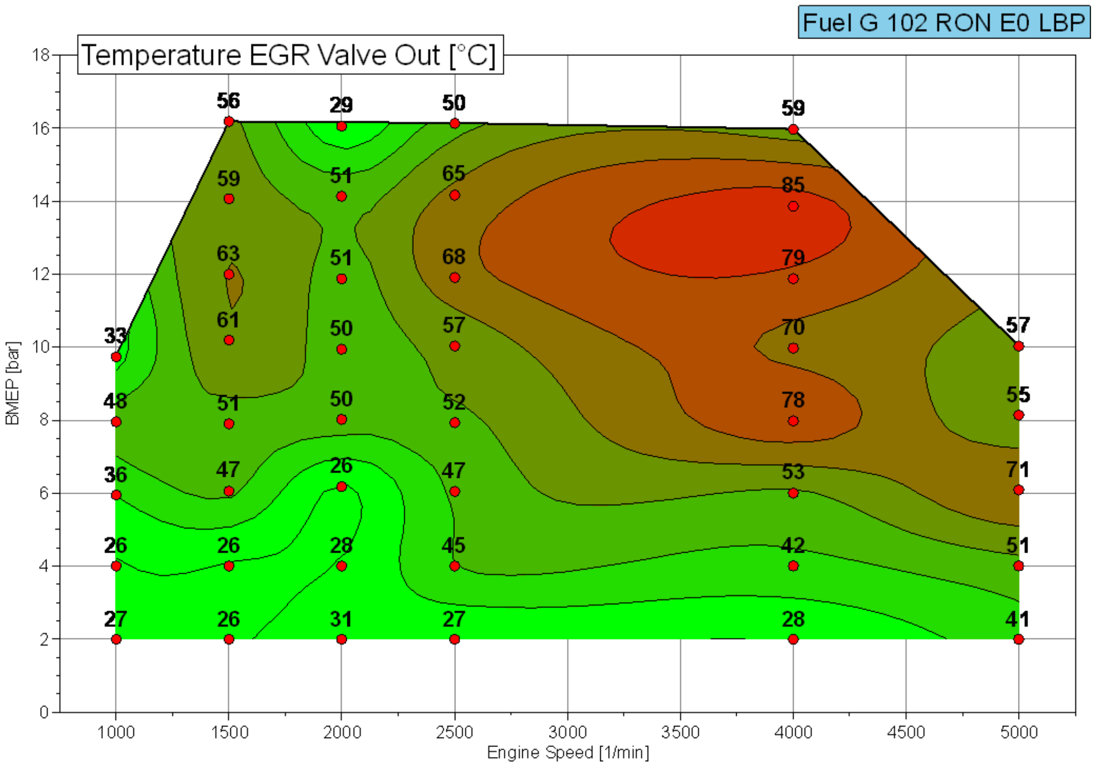

Figure 41: EGR Valve Out Temperature

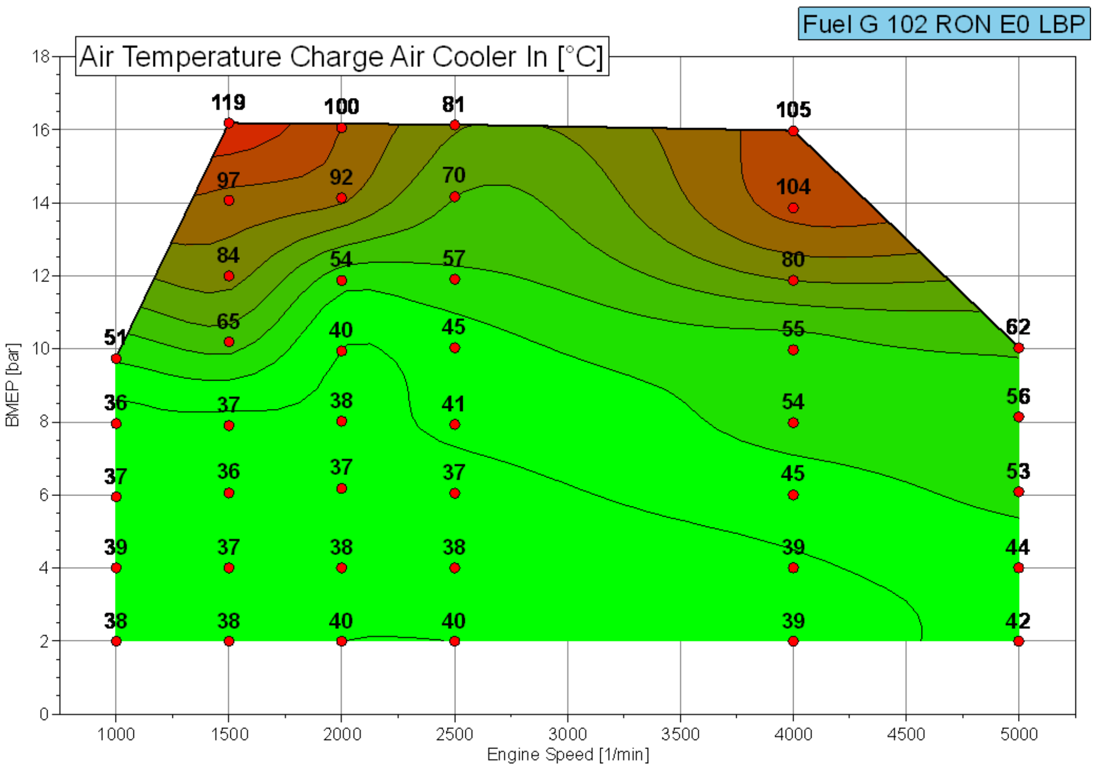

Figure 42: Charge Air Cooler Inlet Air Temperature

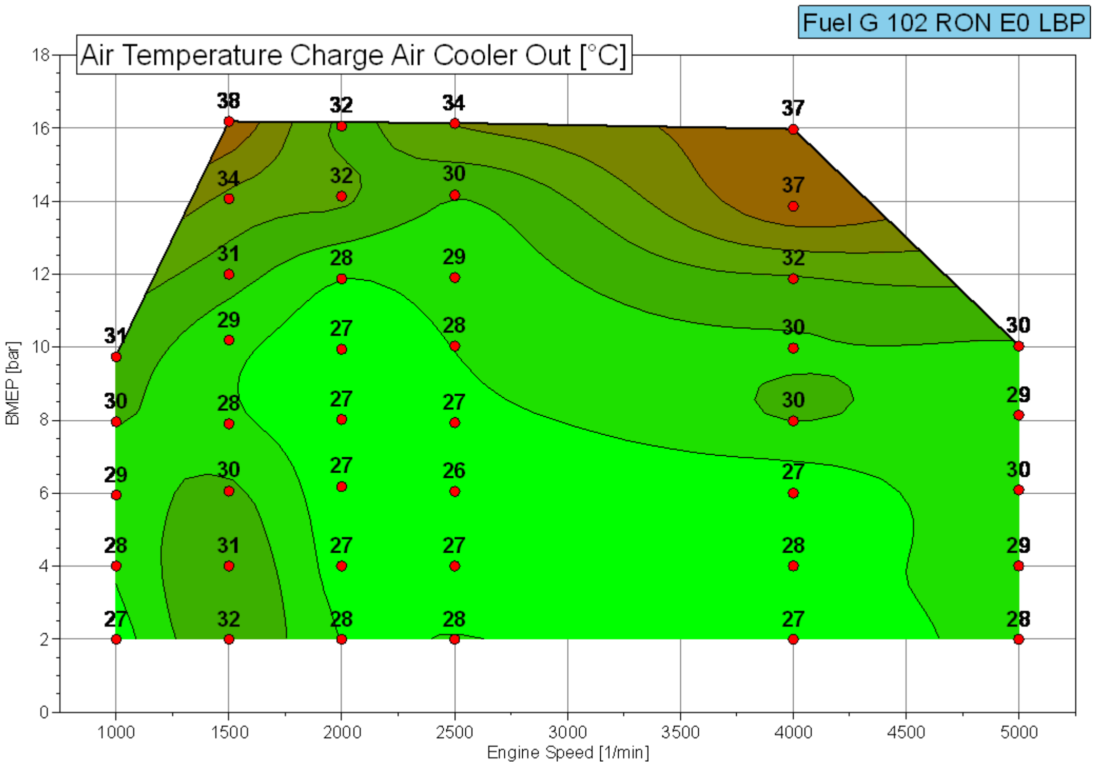

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel H Calibration Results

102 Ron 0% Ethanol High Boiling Point

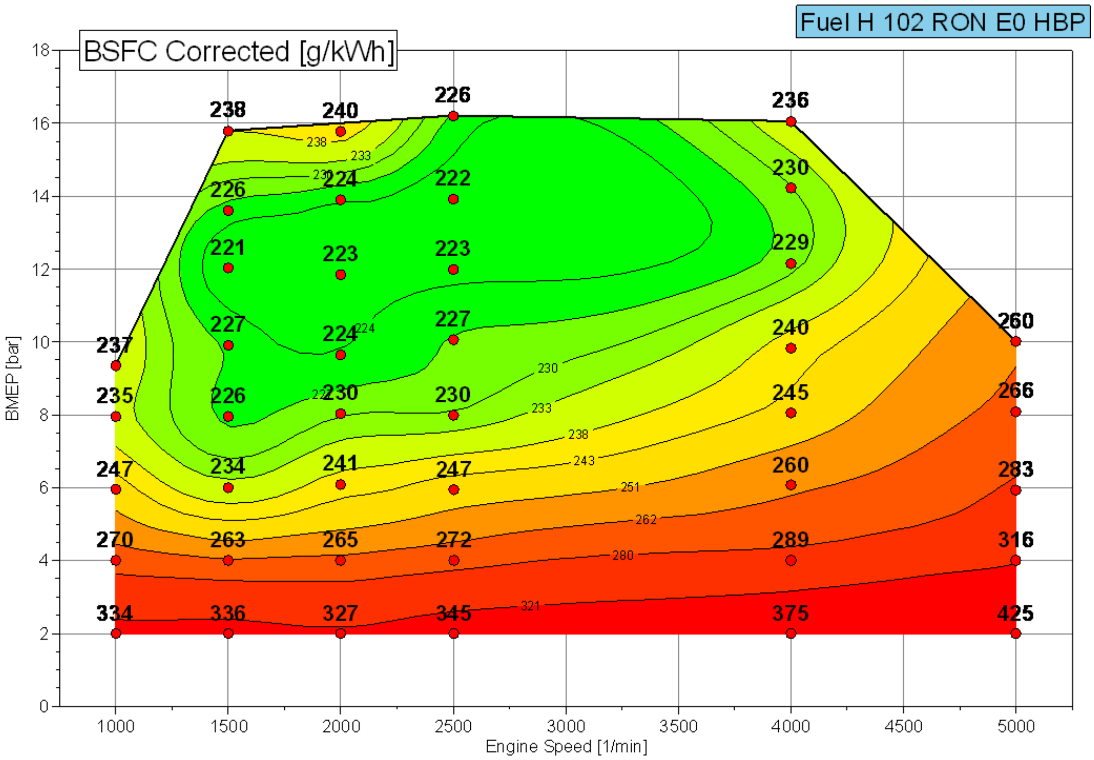

Figure 1: Brake Specific Fuel Consumption

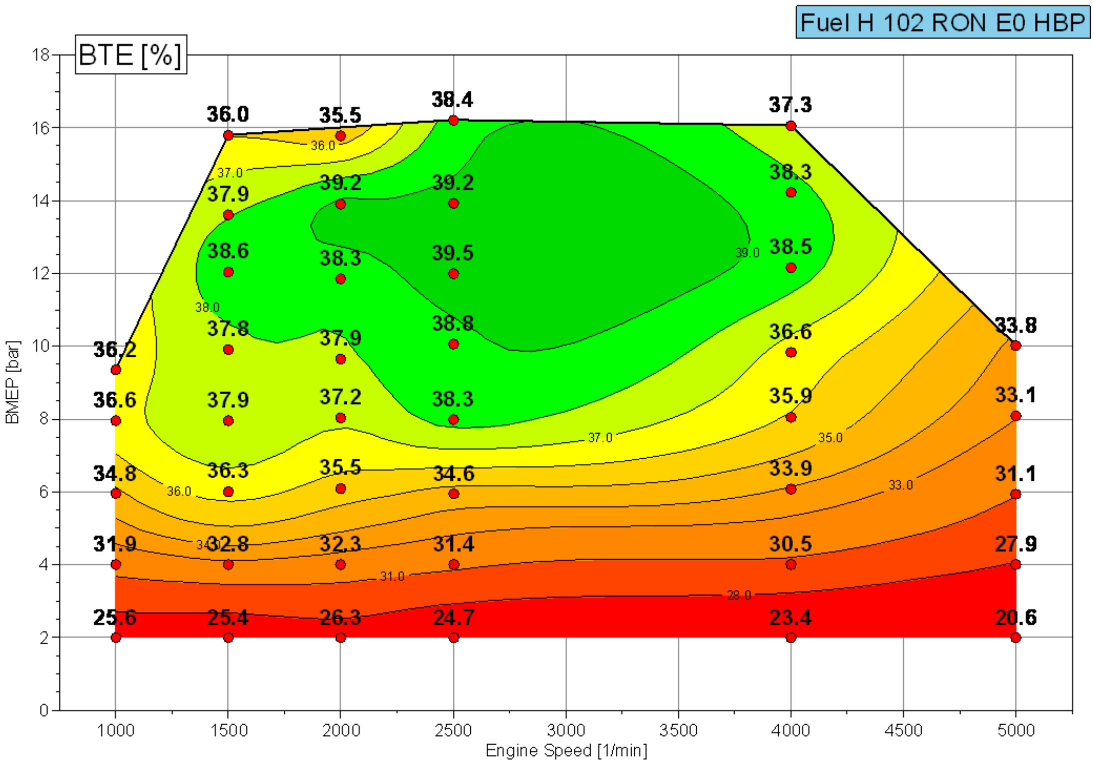

Figure 2: Brake Thermal Efficiency

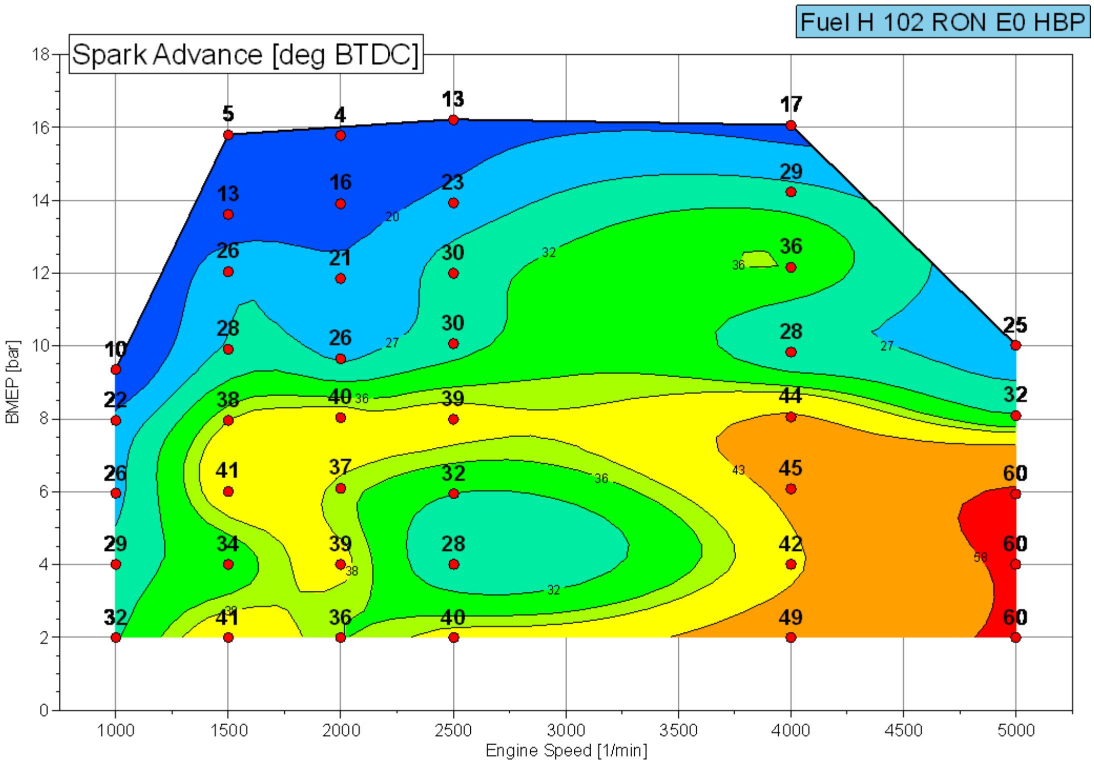

Figure 3: Spark Advance

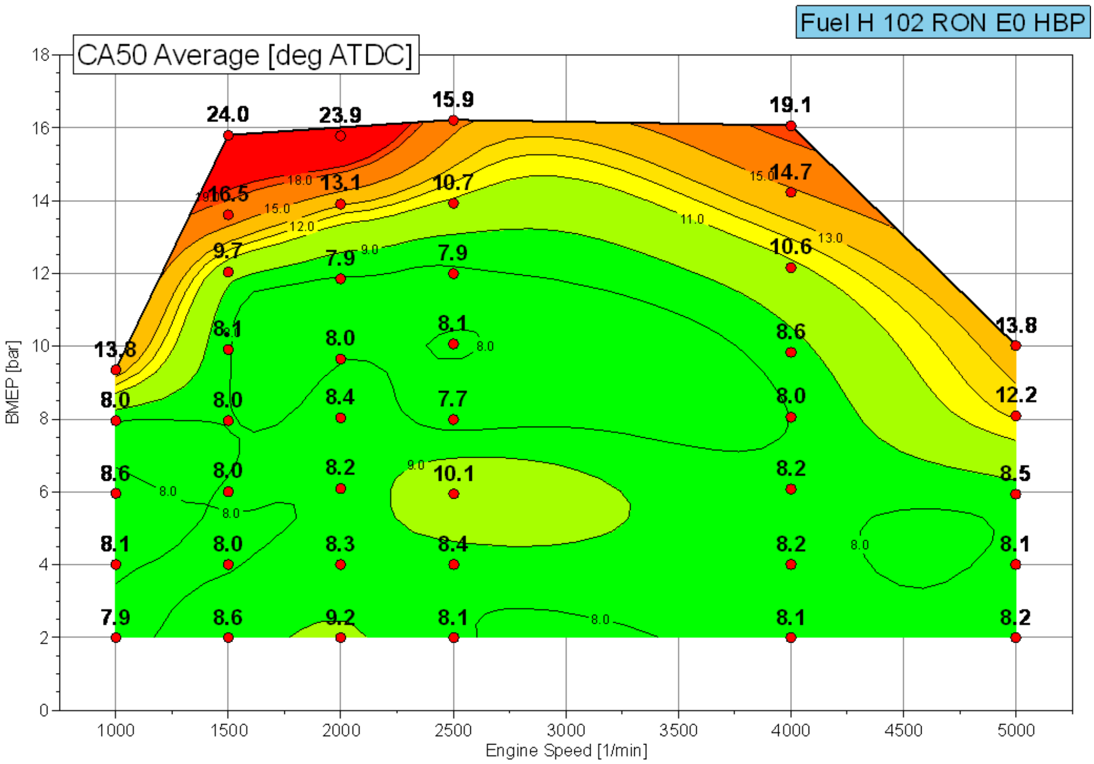

Figure 4: CA50 Average of Cylinders 1-4

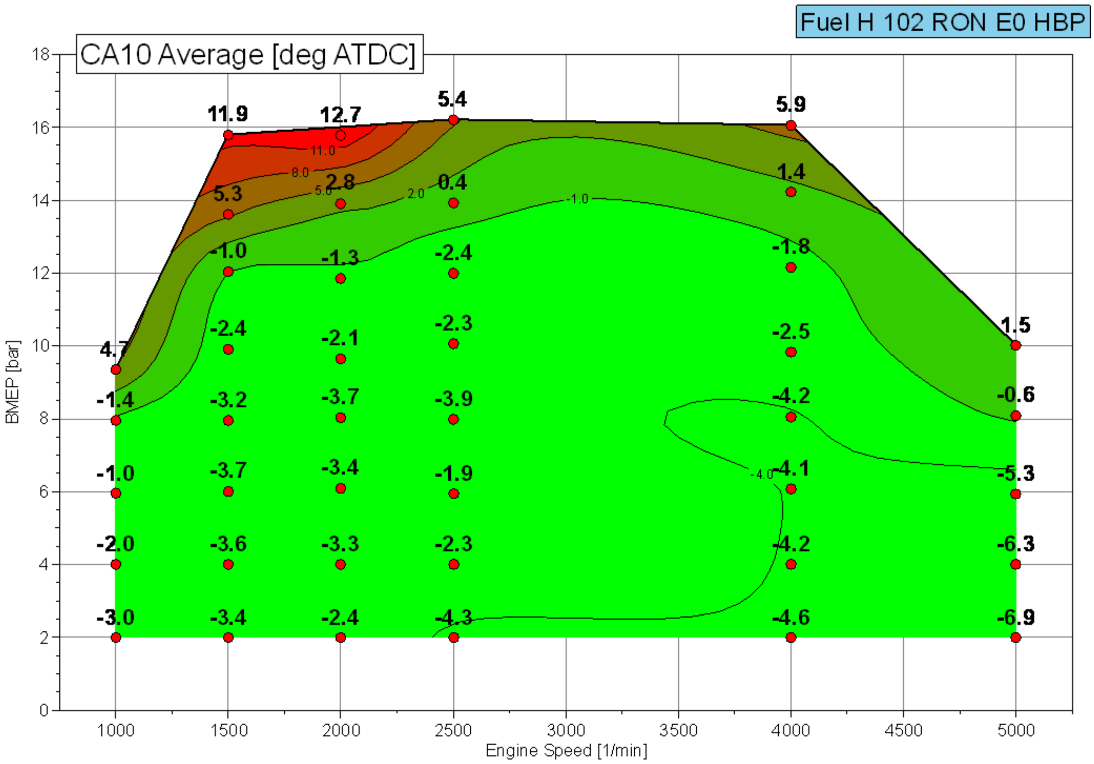

Figure 5: CA10 Average of Cylinders 1-4

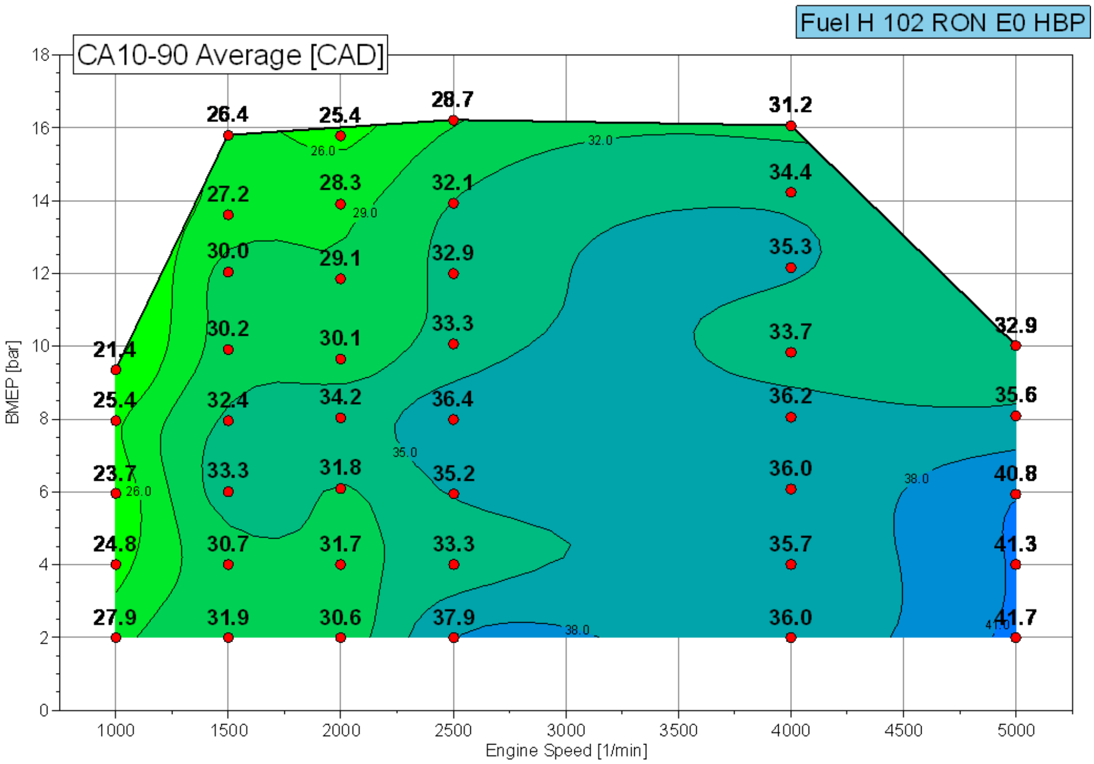

Figure 6: CA10-90 Average of Cylinders 1-4

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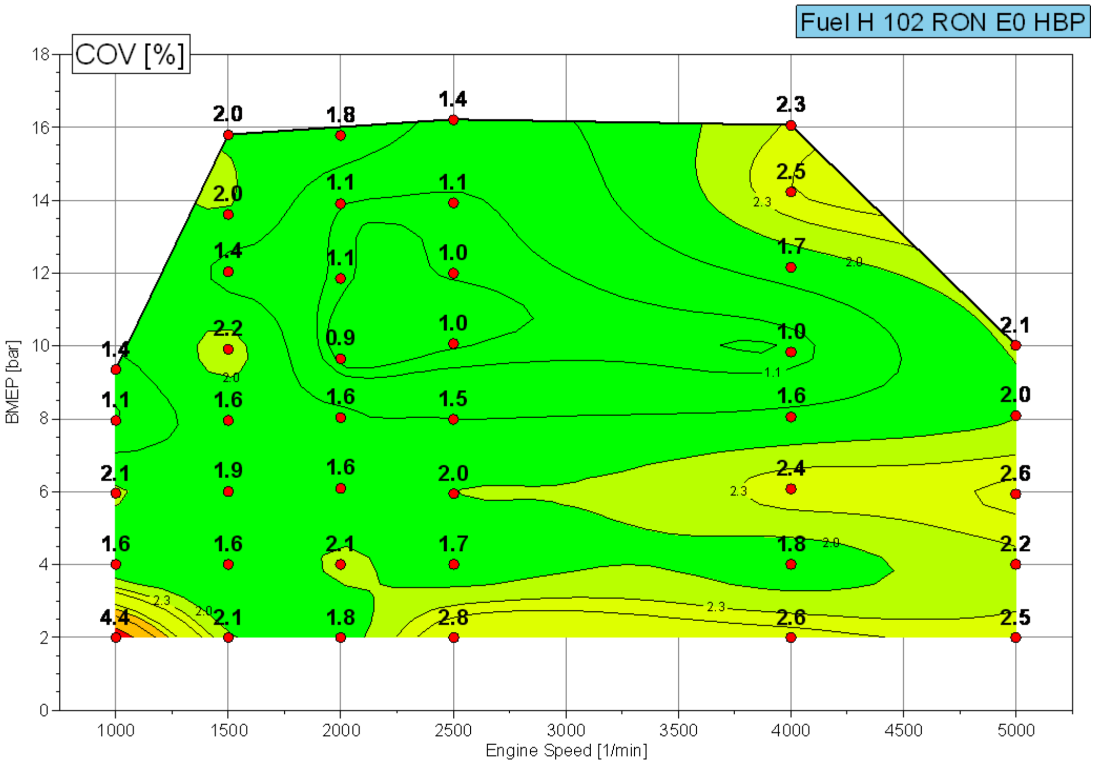

Figure 7: Coefficient of Variation Average of Cylinders 1-4

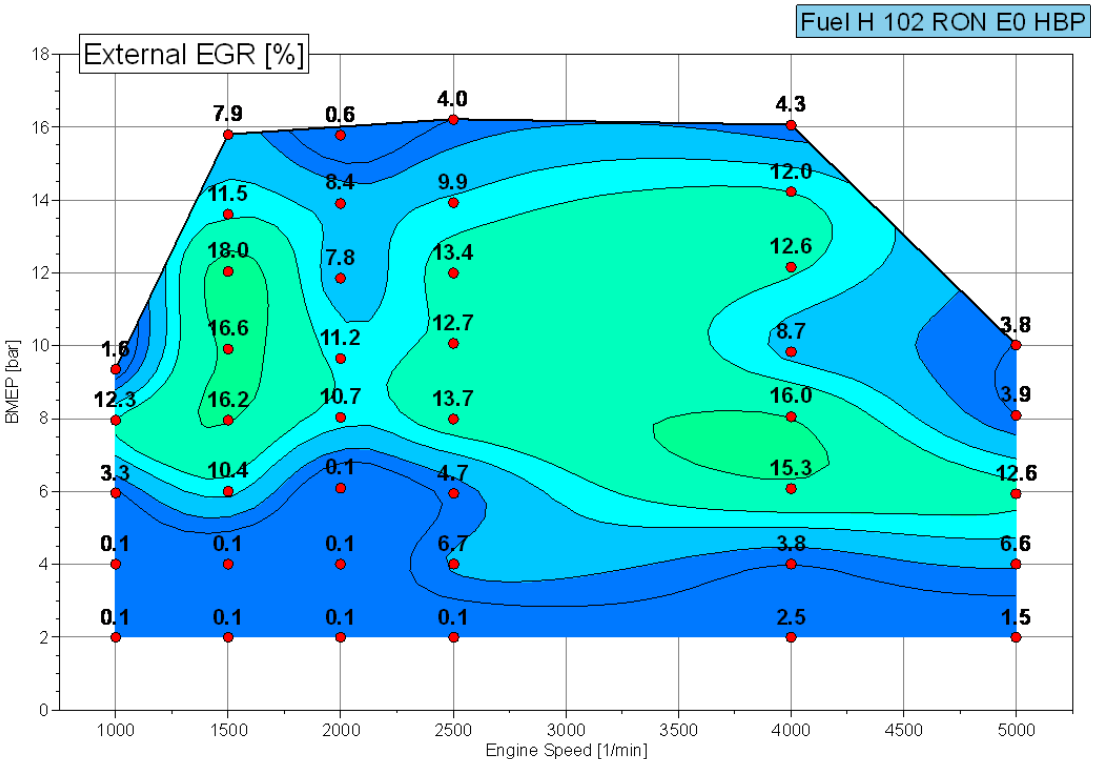

Figure 8: External EGR Percent of Intake Air

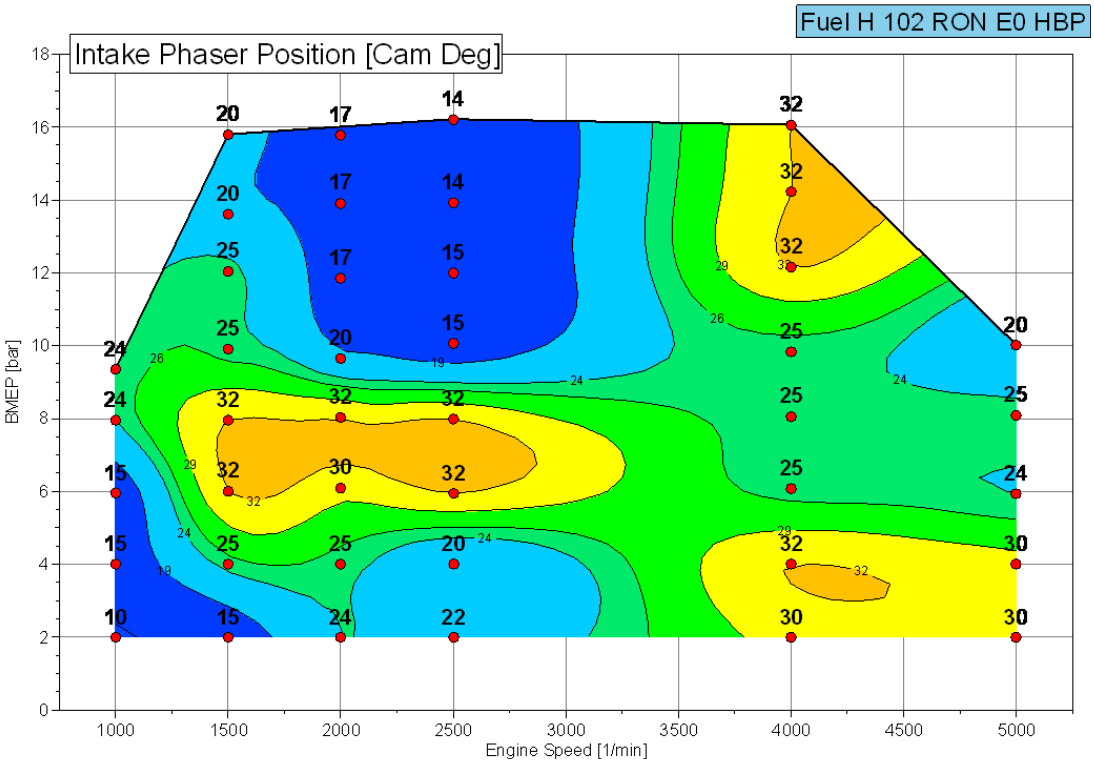

Figure 9: Intake Camshaft Phaser Position

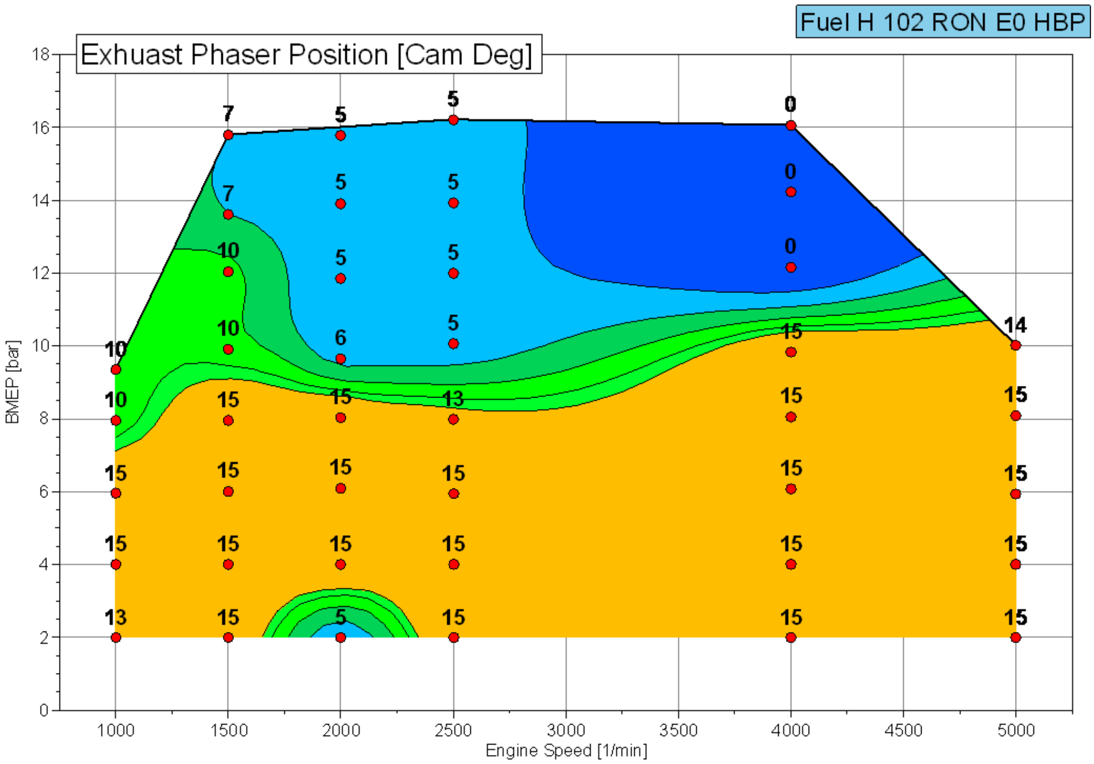

Figure 10: Exhaust Camshaft Phaser Position

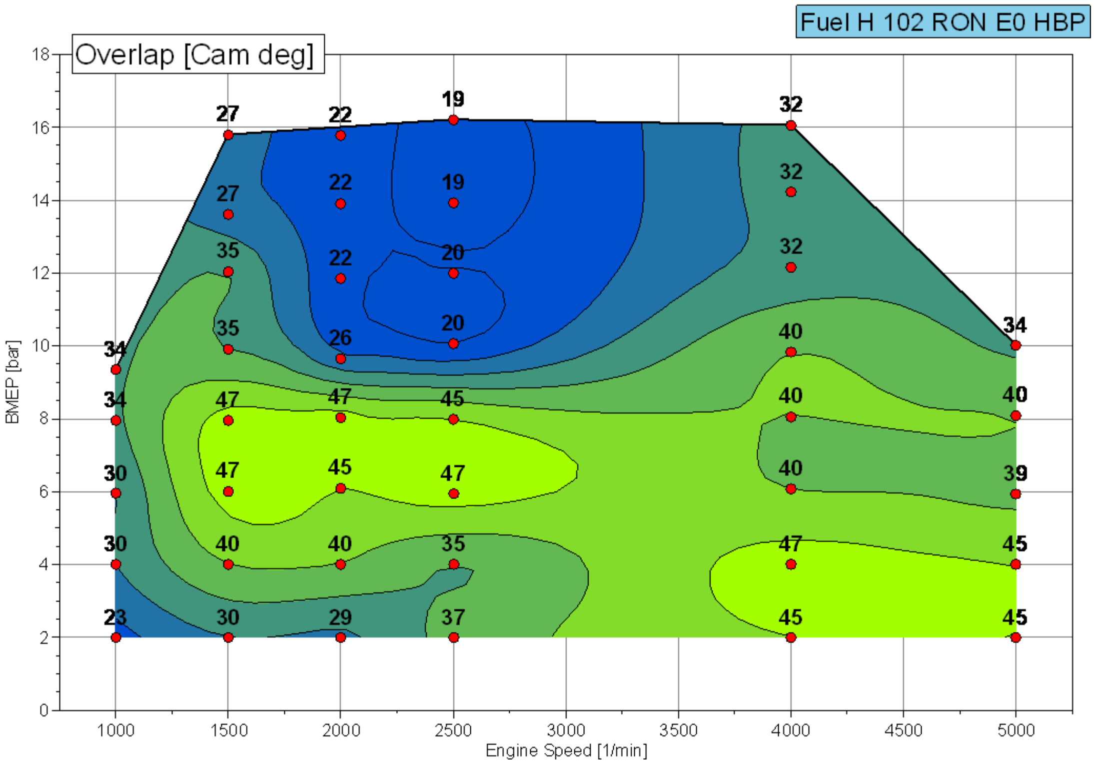

Figure 11: Camshaft Overlap

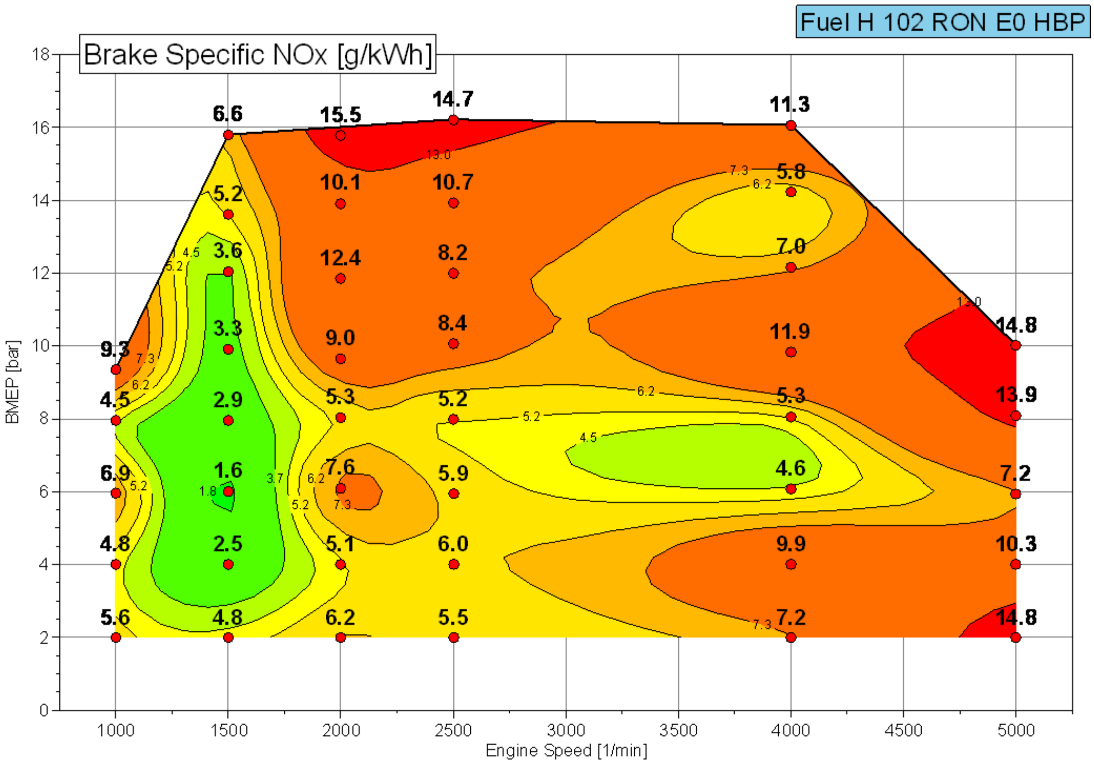

Figure 12: Brake Specific NOx Emissions

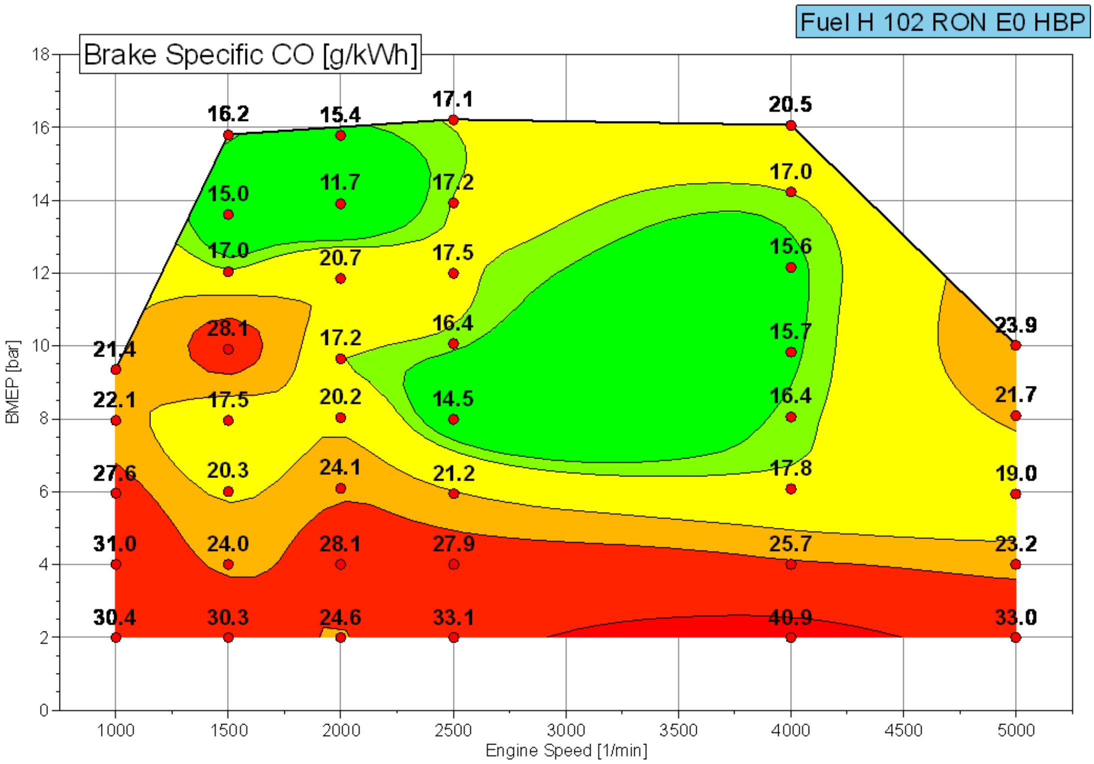

Figure 13: Brake Specific Carbon Monoxide Emissions

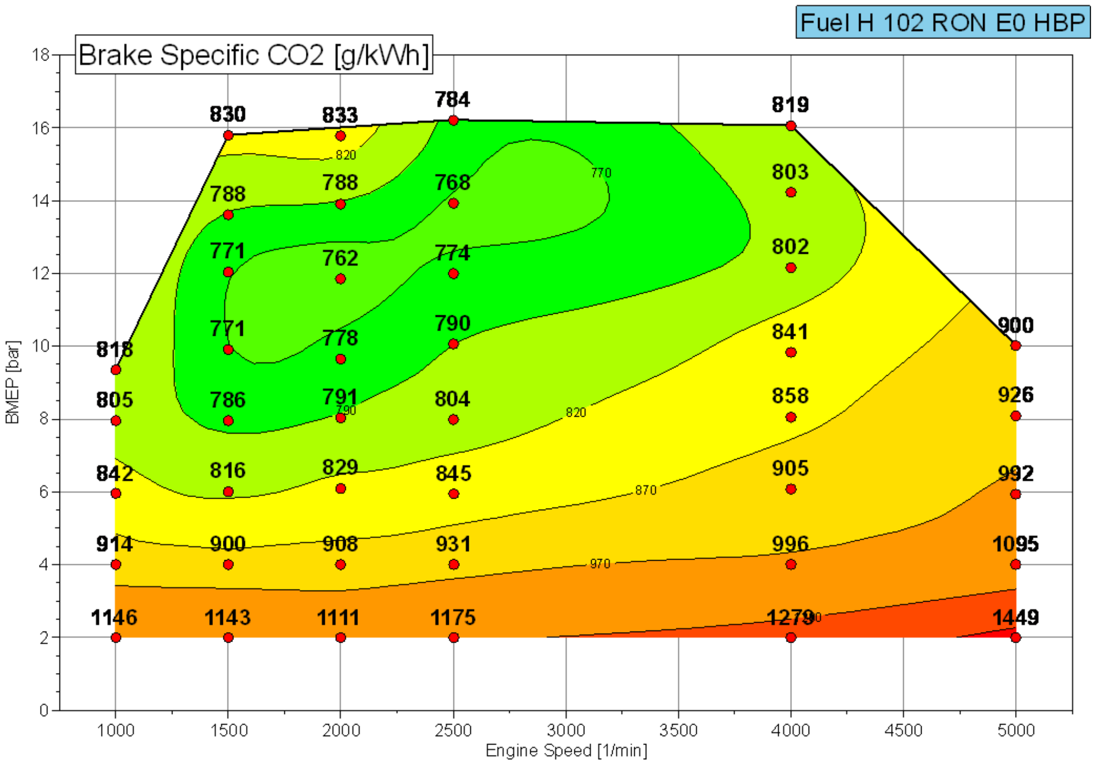

Figure 14: Brake Specific Carbon Dioxide Emissions

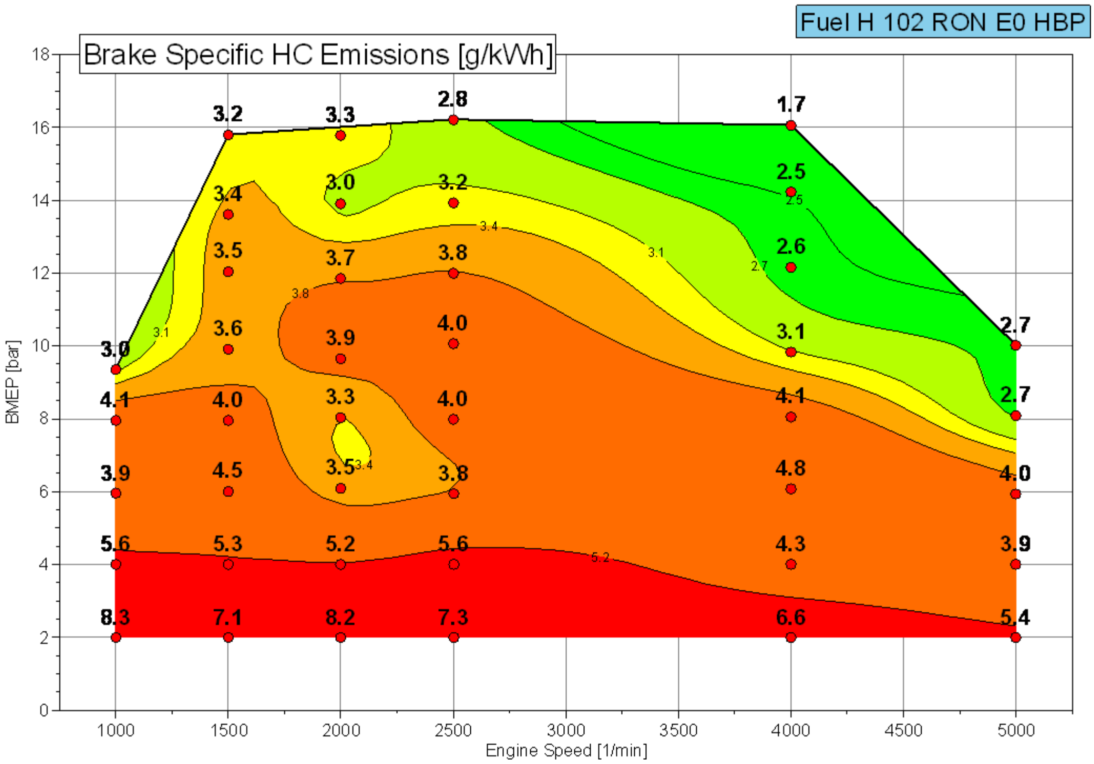

Figure 15: Brake Specific Hydrocarbon Emissions

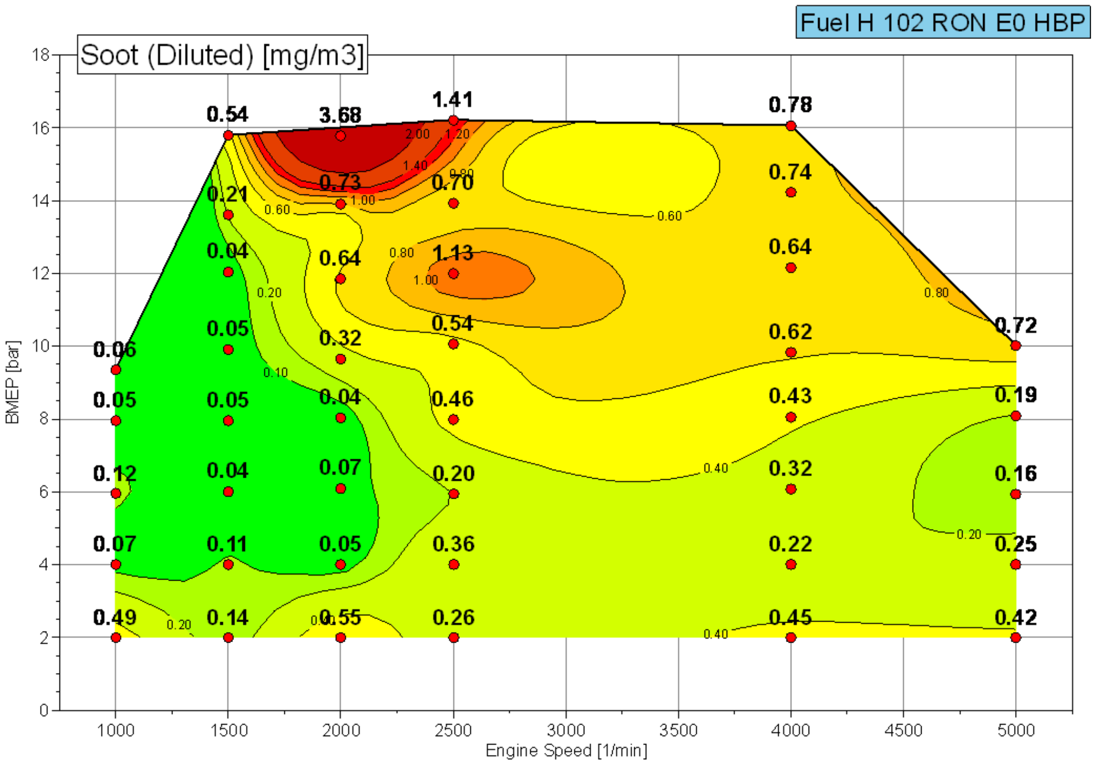

Figure 16: Particulate Soot Emissions

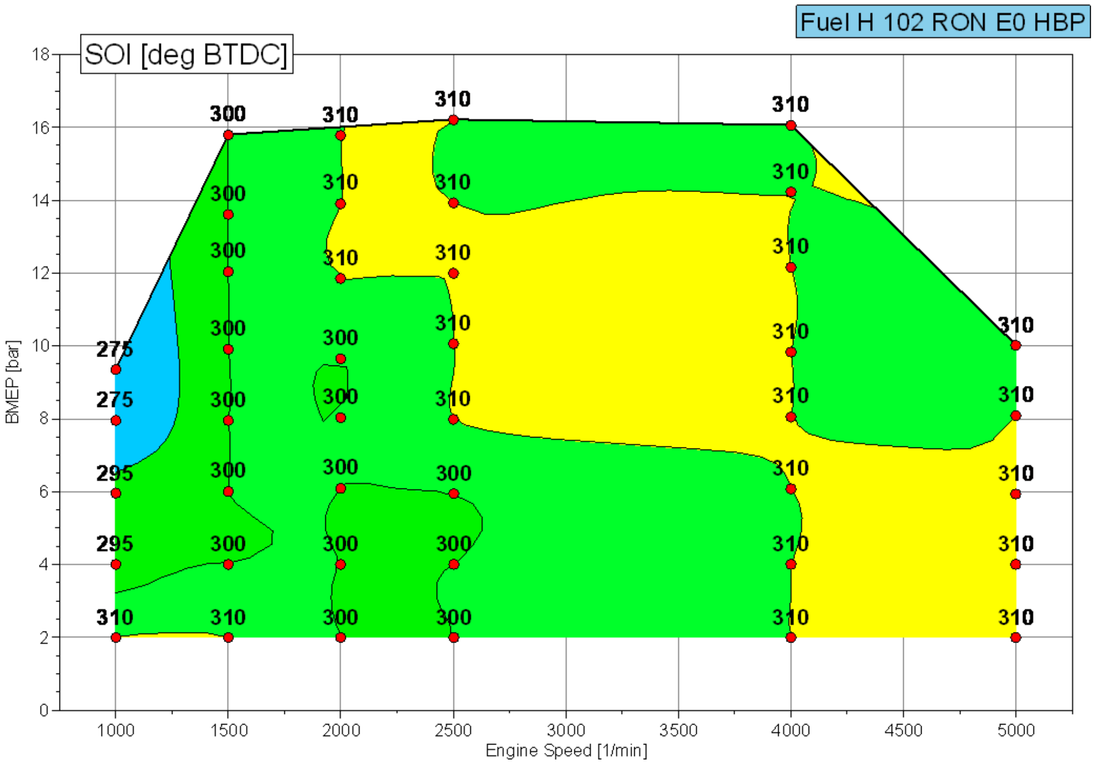

Figure 17: Start of Injection

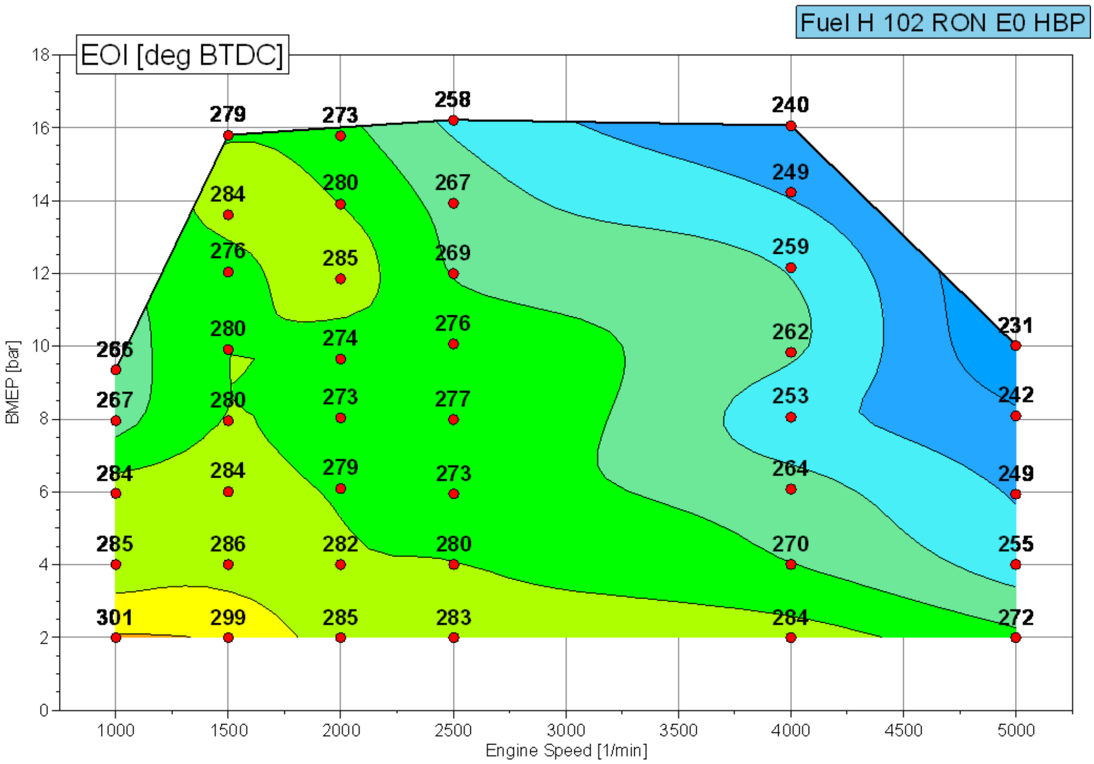

Figure 18: End of Injection

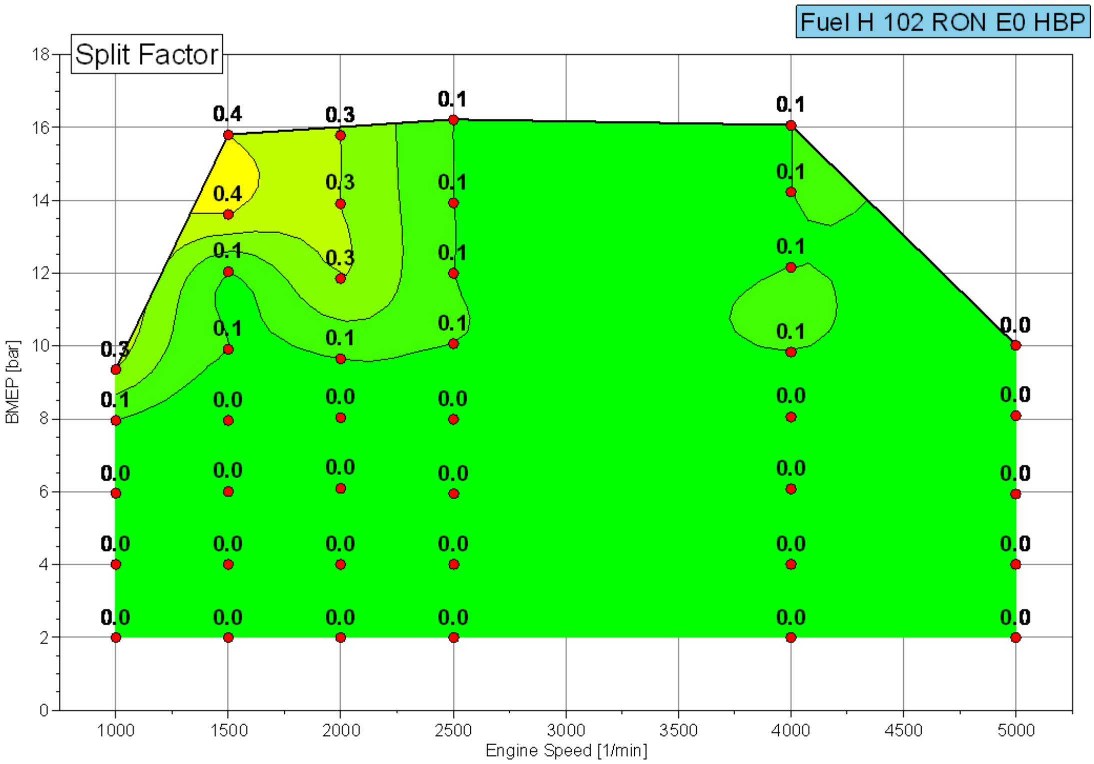

Figure 19: Injection Split Factor

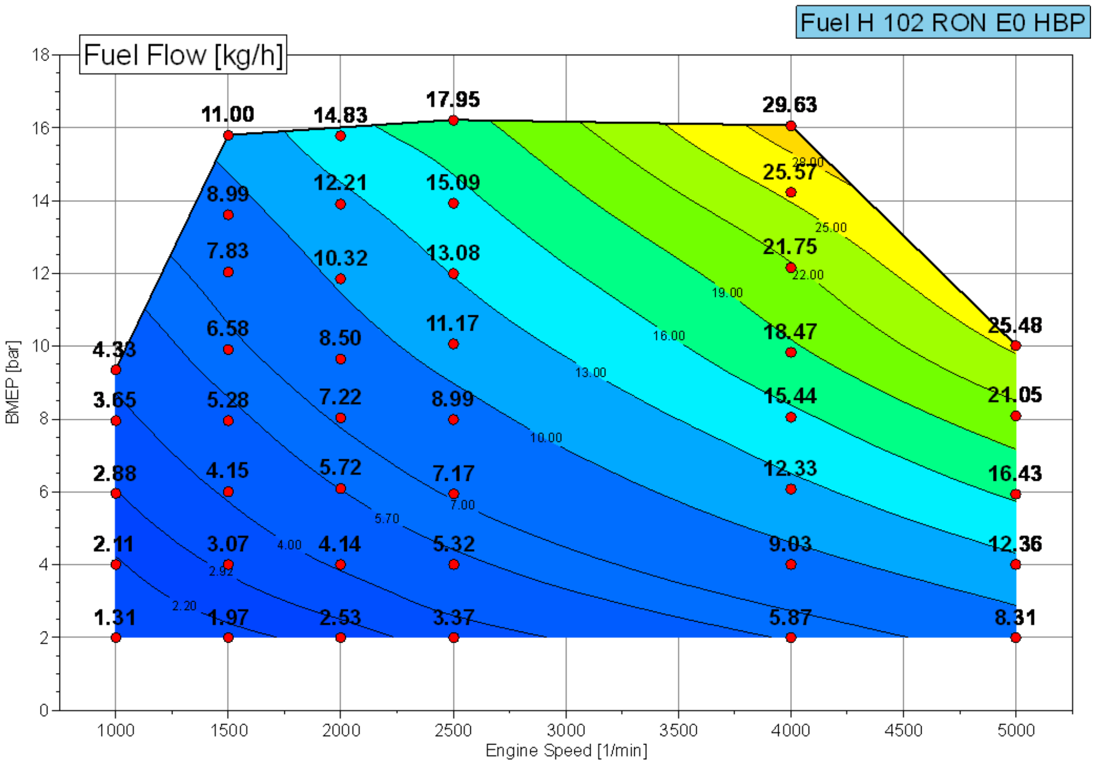

Figure 20: Fuel Flow

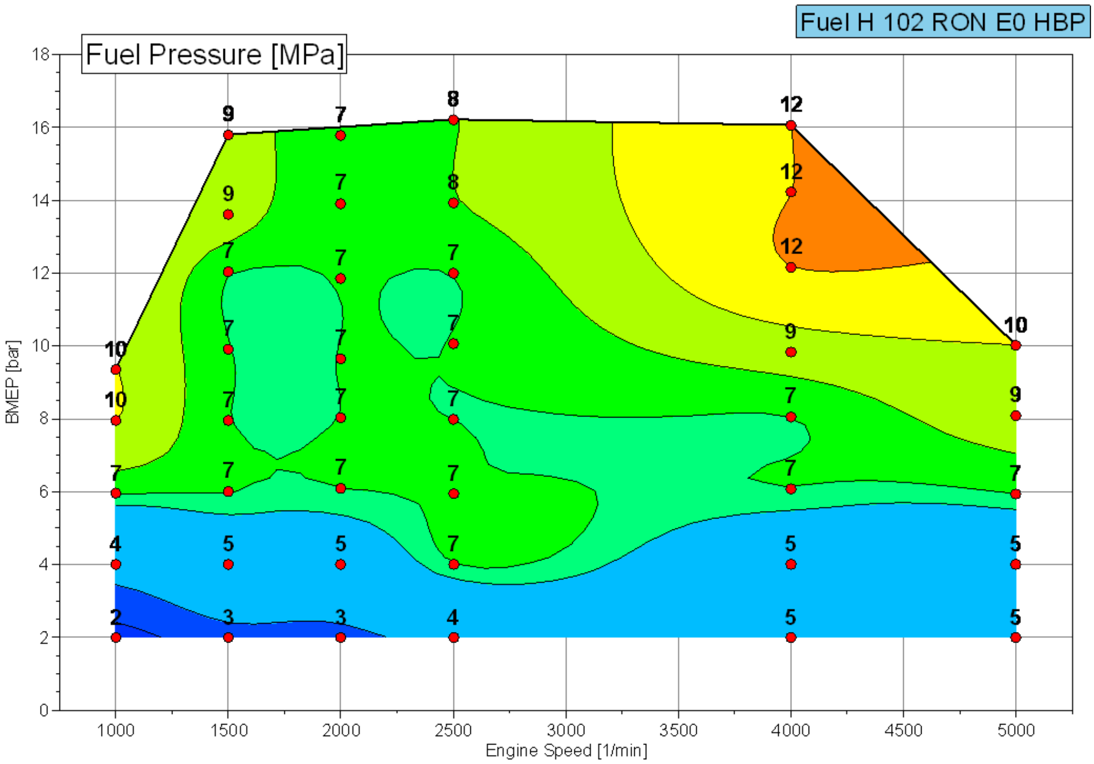

Figure 21: Fuel Rail Pressure

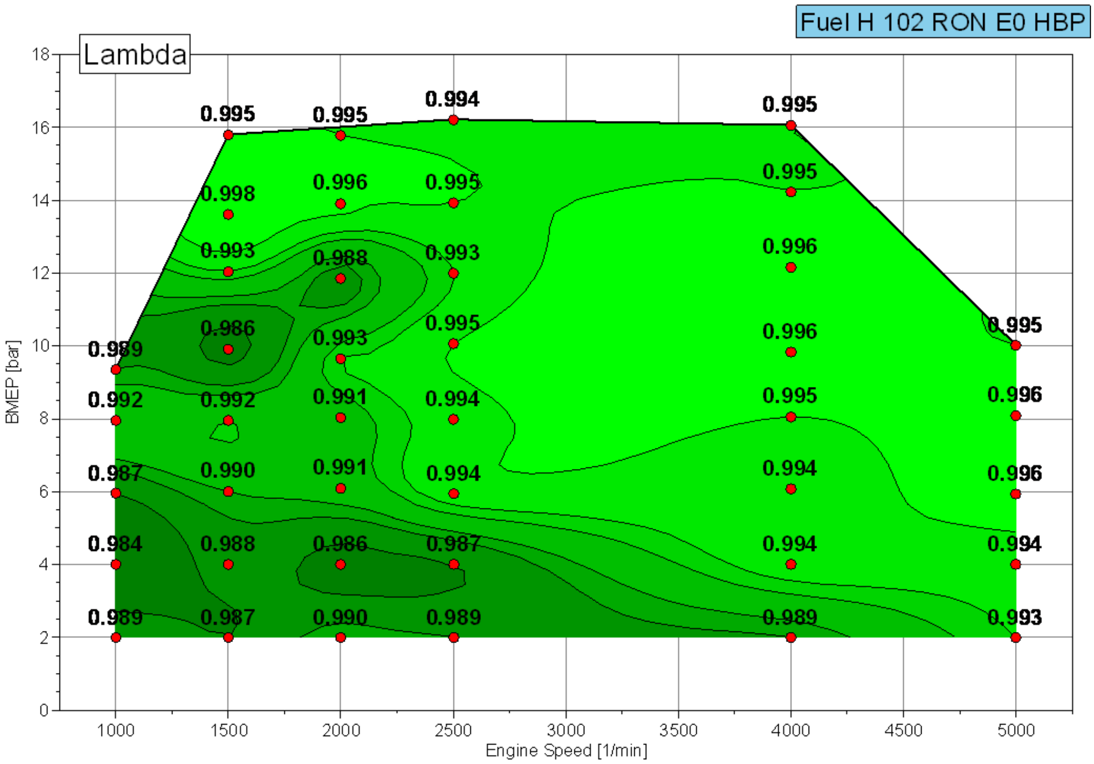

Figure 22: Lambda

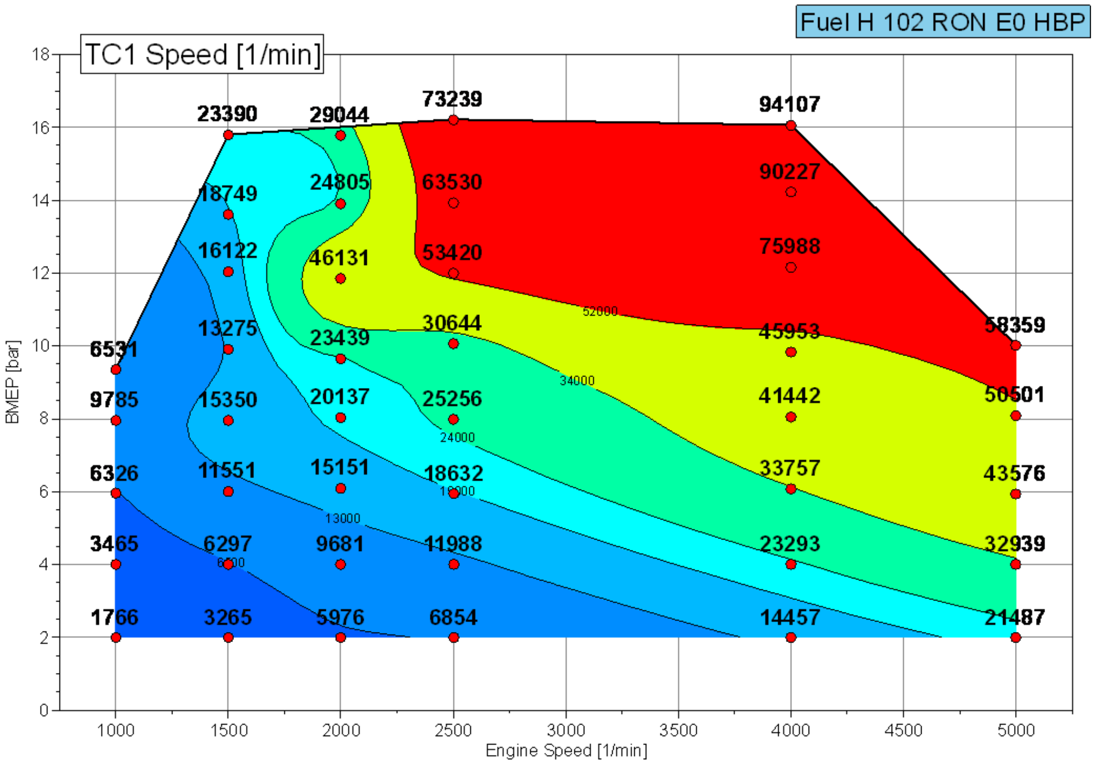

Figure 23: Low Pressure Turbocharger Speed

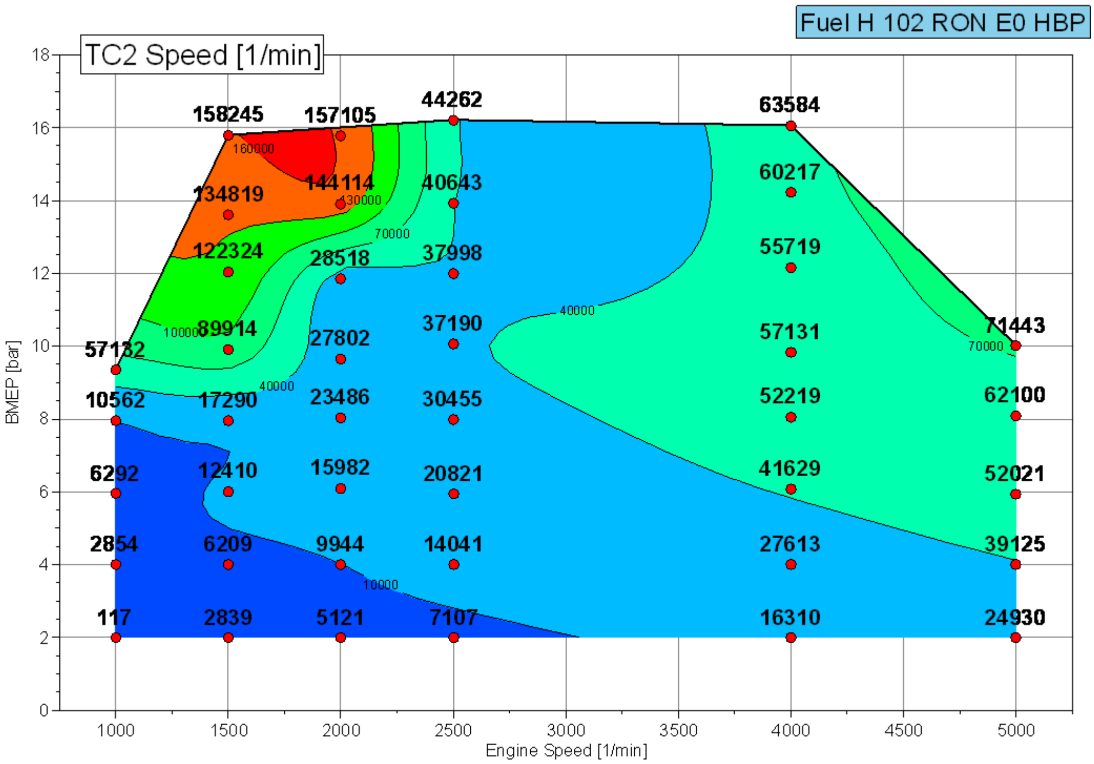

Figure 24: High Pressure Turbocharge Speed

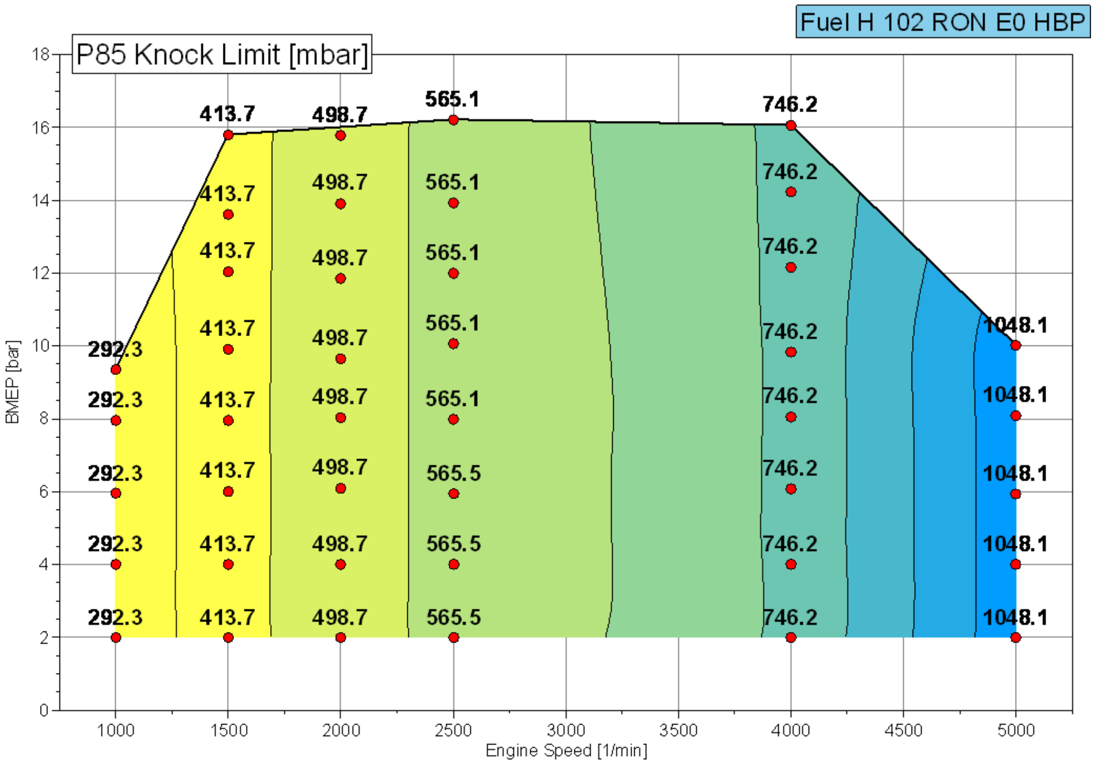

Figure 25: P85 Knock Limit

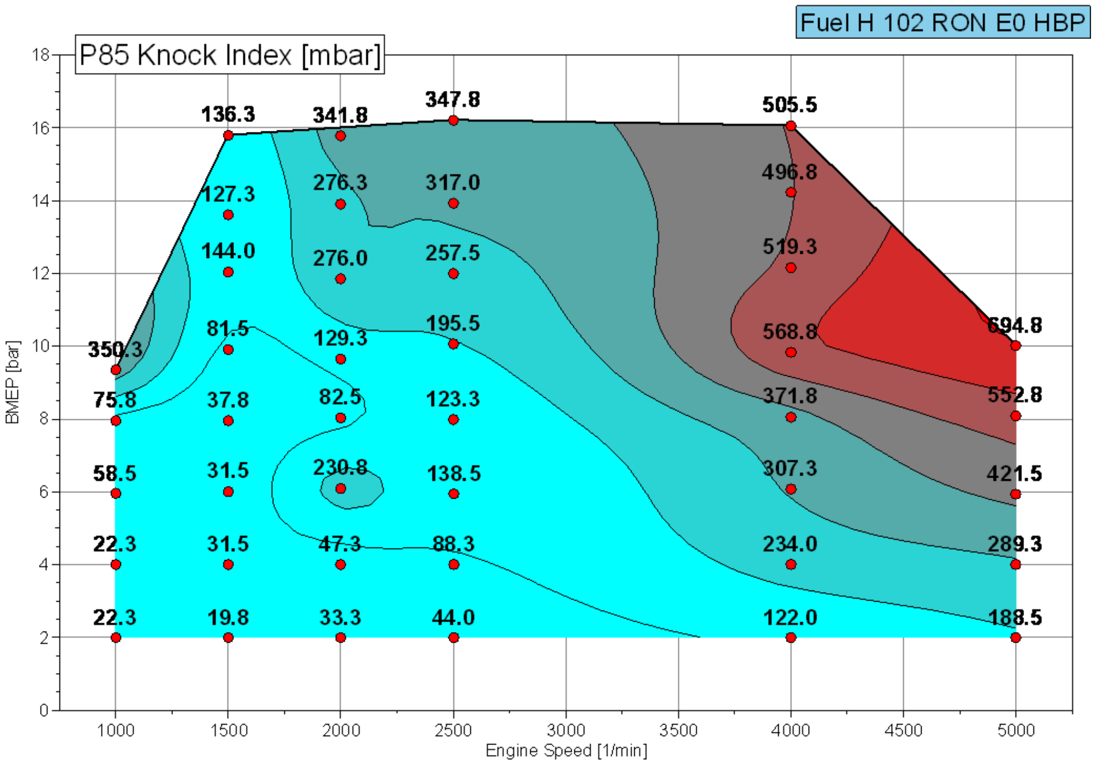

Figure 26: Averaged P85 Knock Index

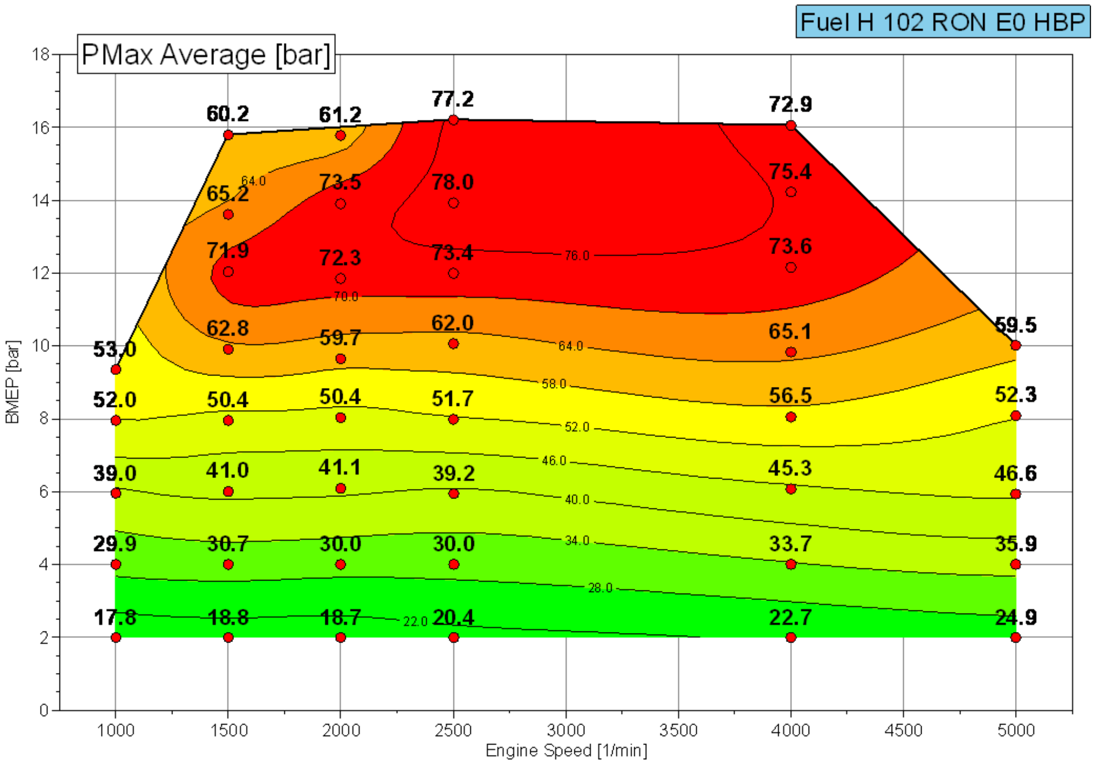

Figure 27: Averaged Max Pressure for Cylinders 1-4

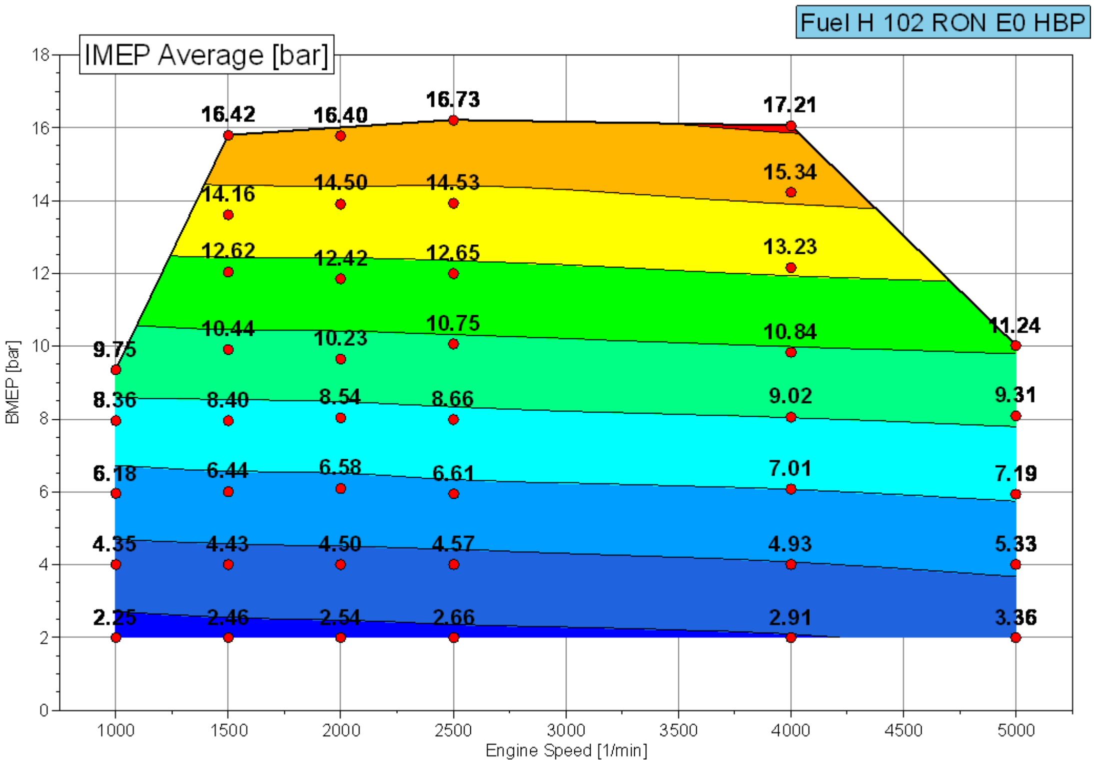

Figure 28: Indicated Mean Effective Pressure

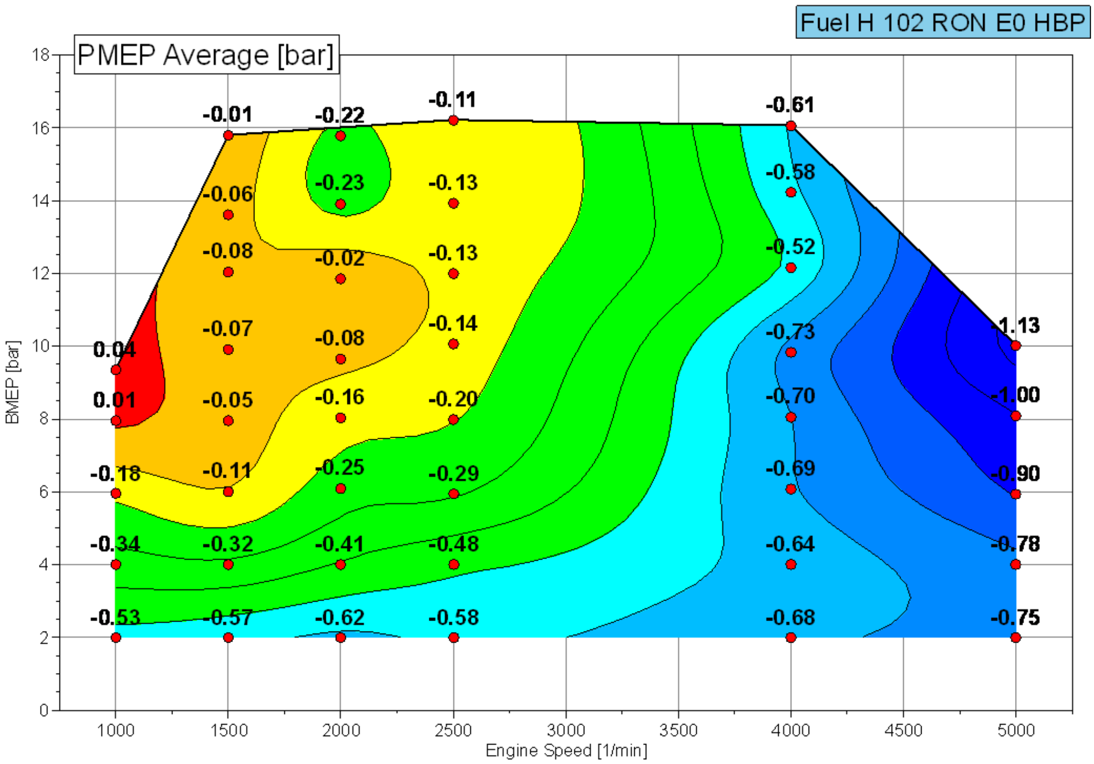

Figure 29: Pumping Mean Effective Pressure

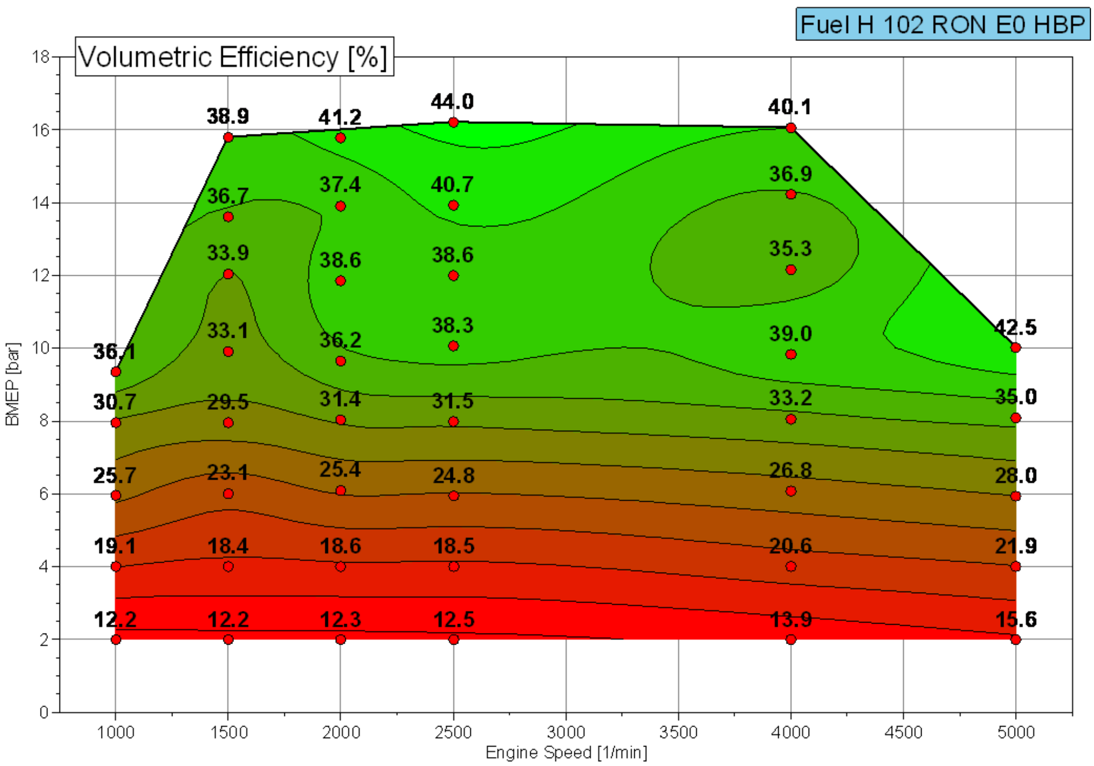

Figure 30: Calculated Volumetric Efficiency

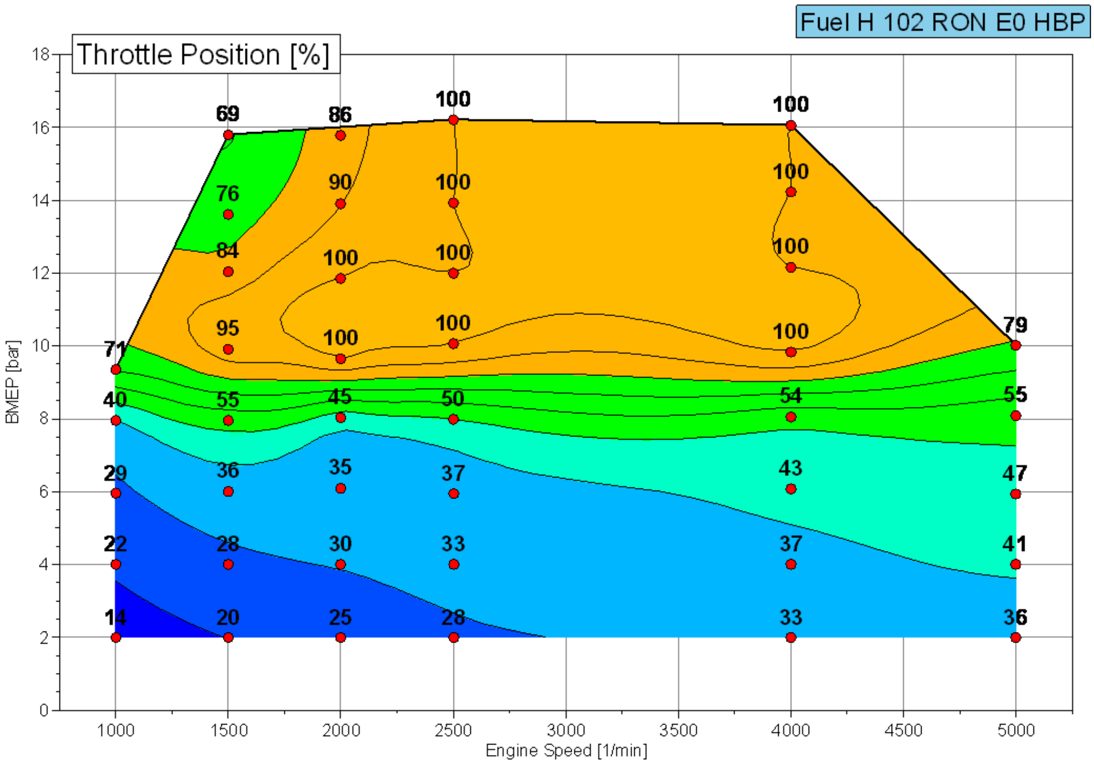

Figure 31: Throttle Position

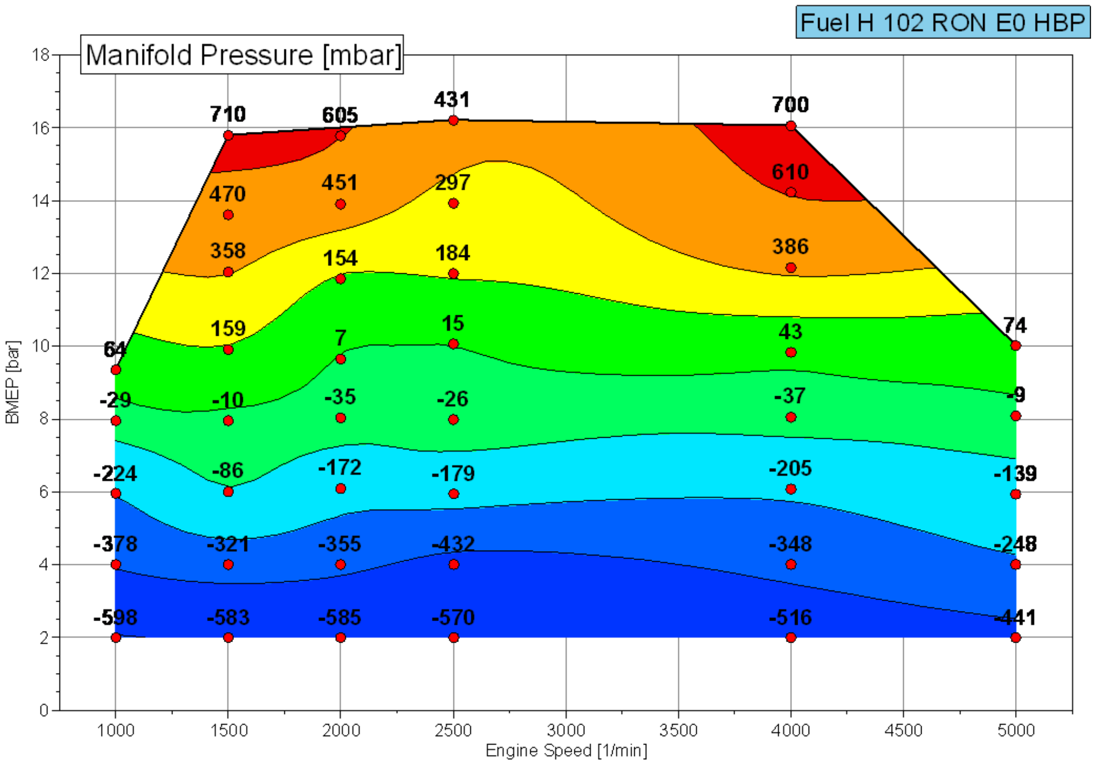

Figure 32: Intake Manifold Pressure

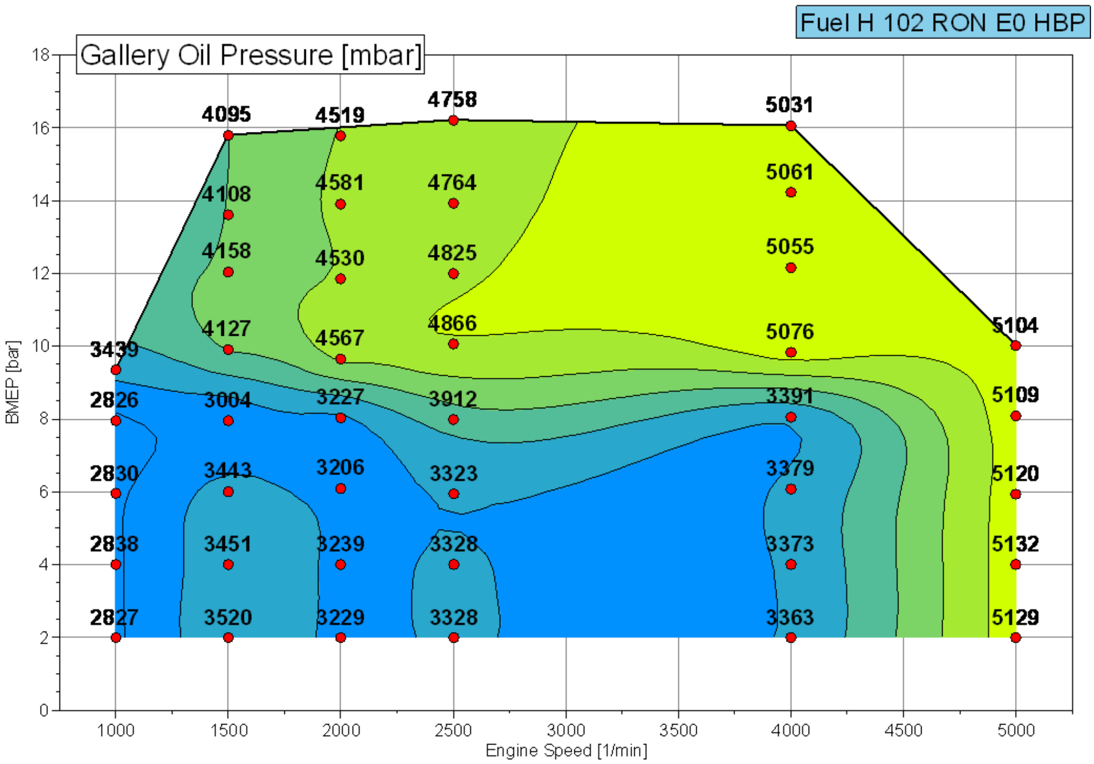

Figure 33: Gallery Oil Pressure

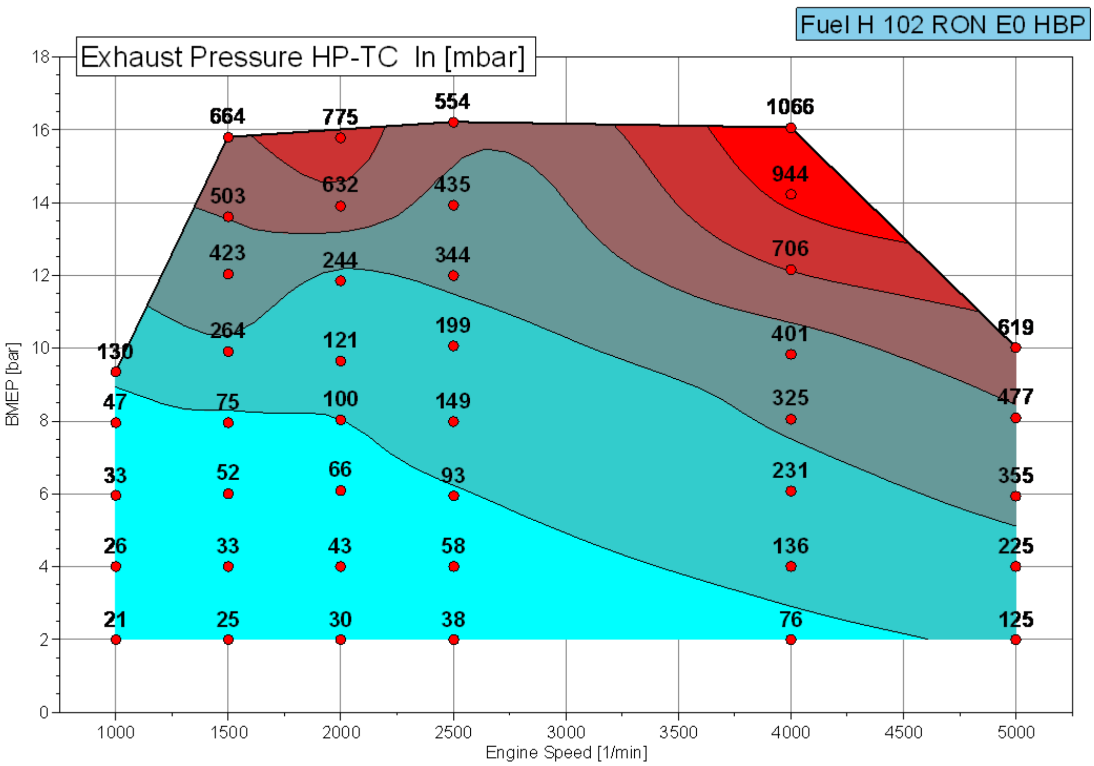

Figure 34: Exhaust Pressure High Pressure Turbocharger In

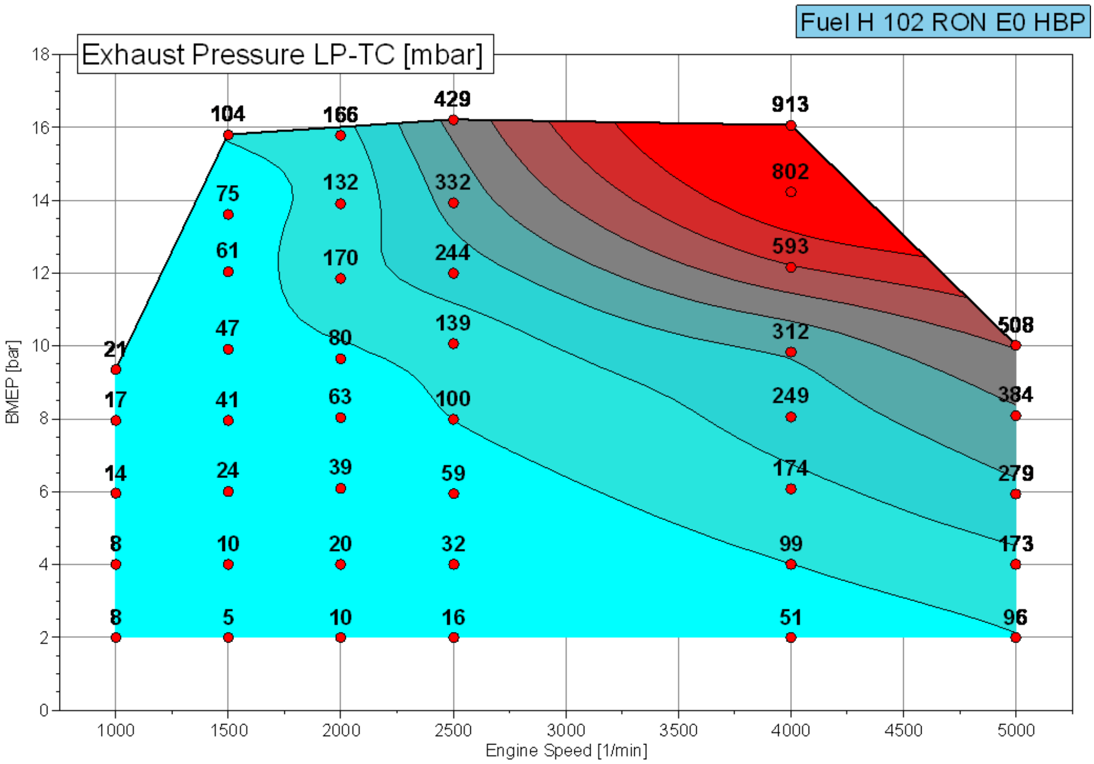

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

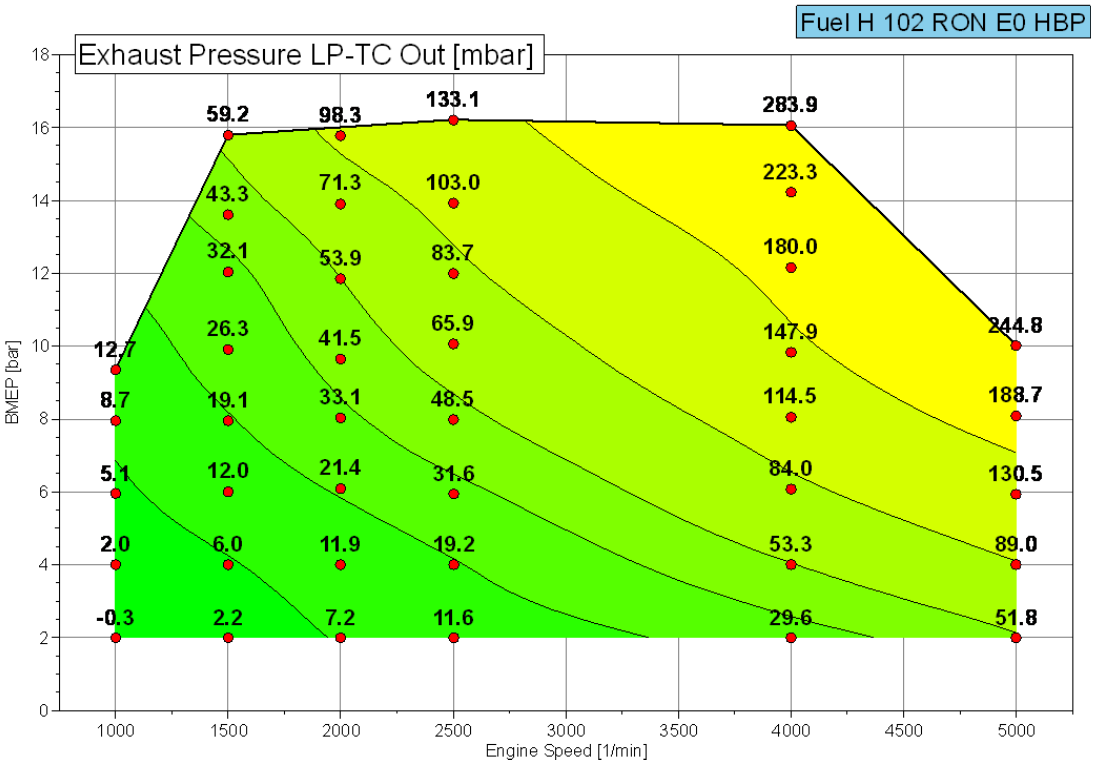

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

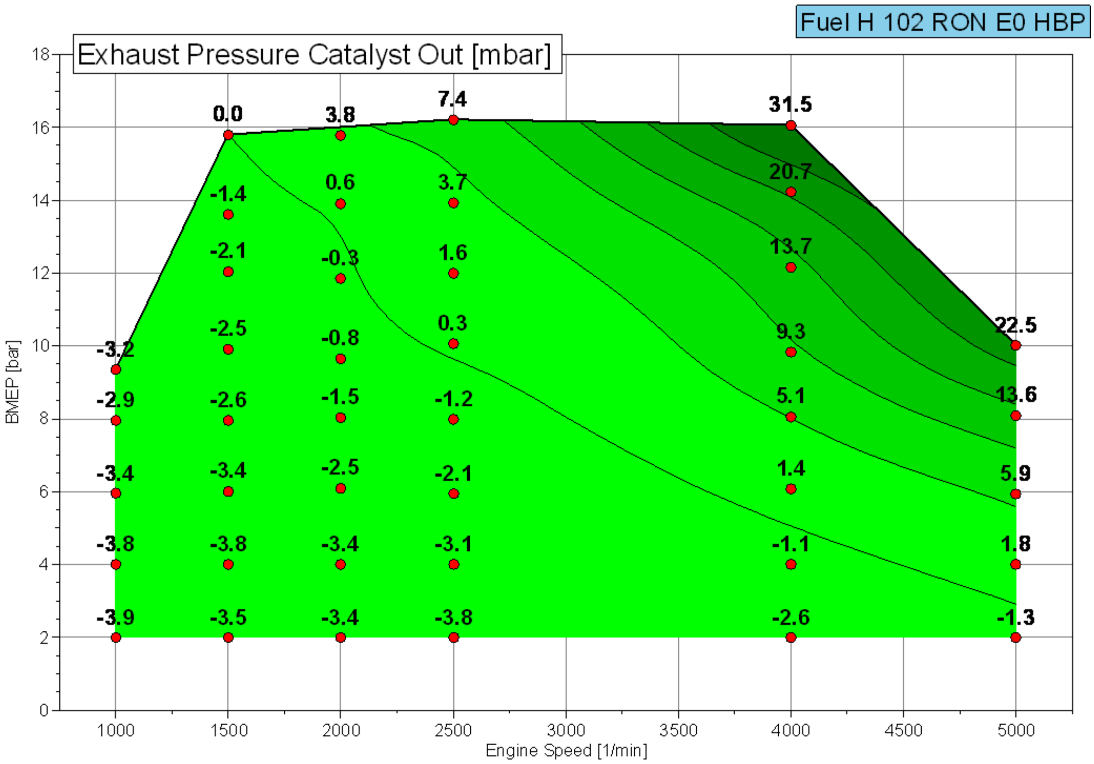

Figure 37: Exhaust Pressure Catalyst Out

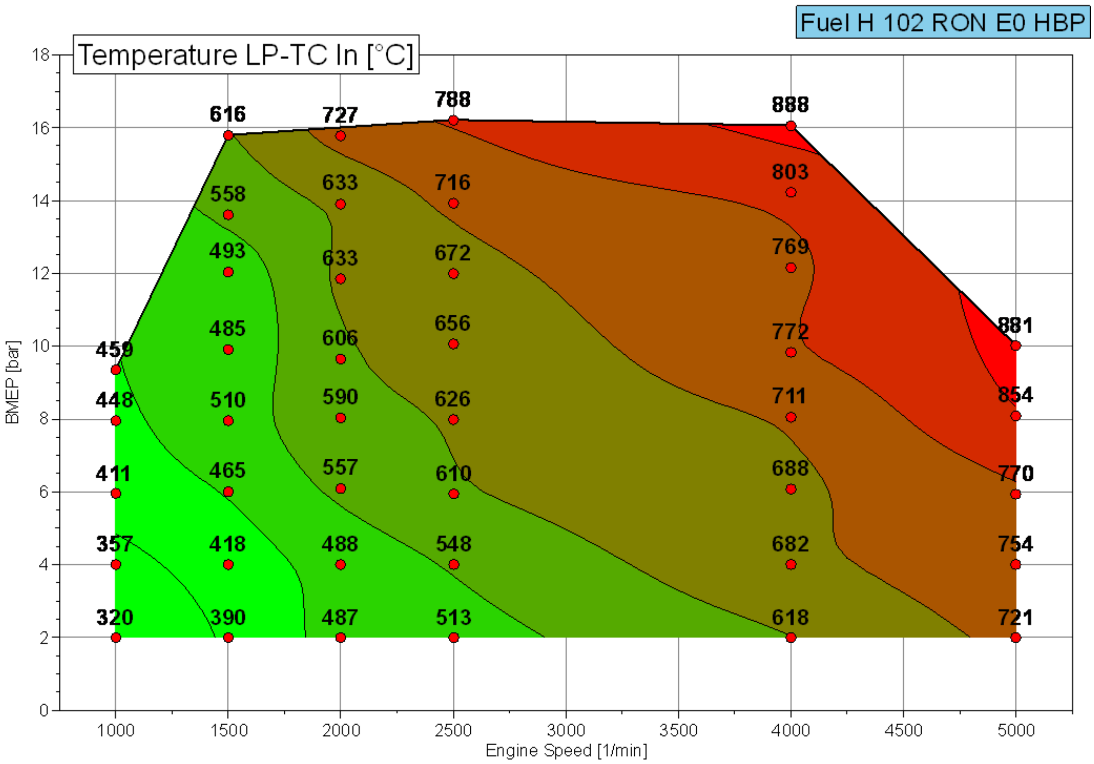

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

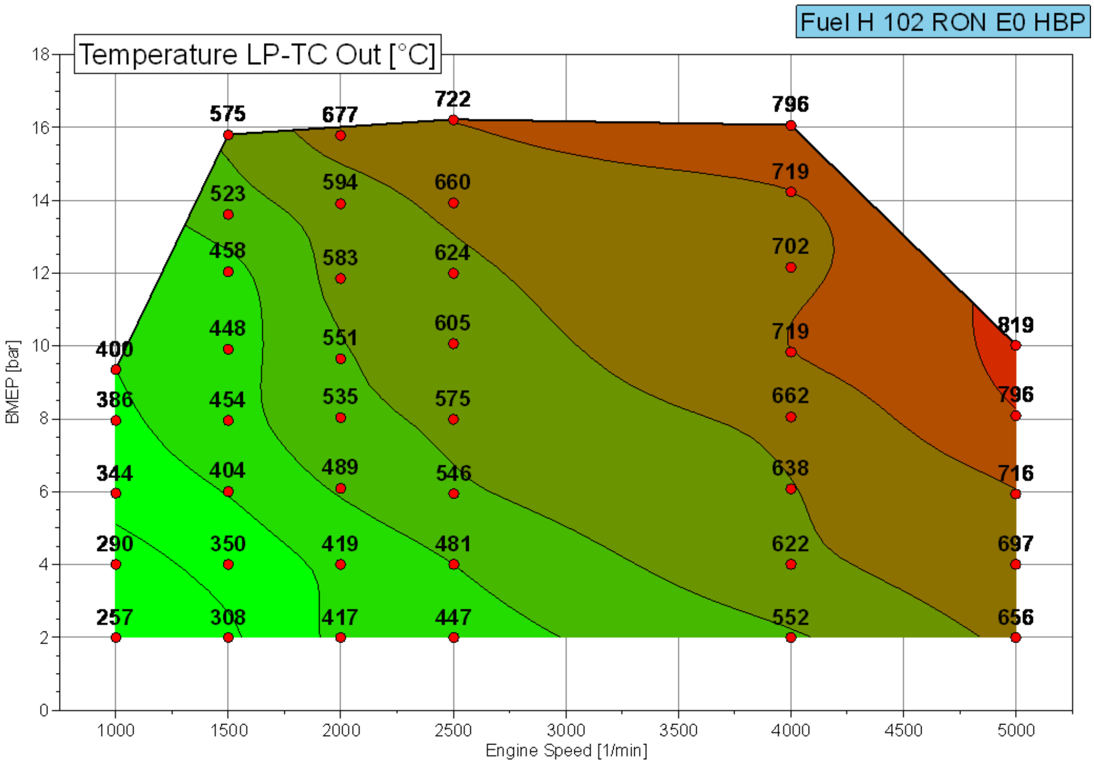

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

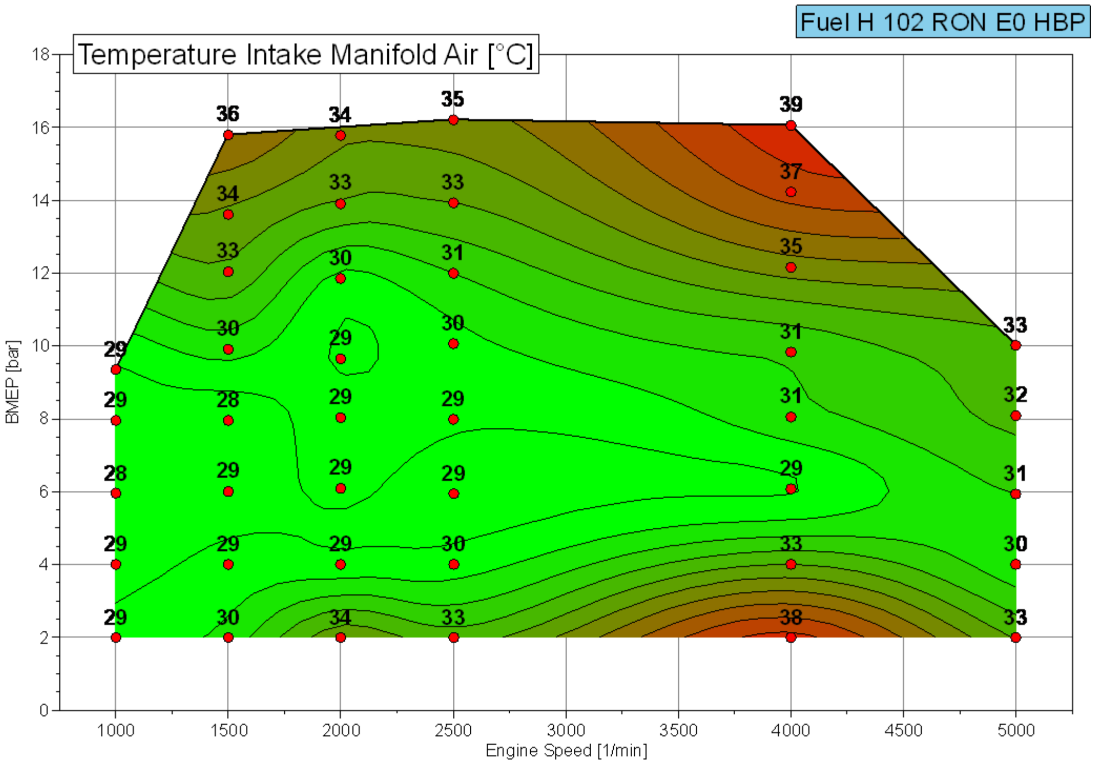

Figure 40: Intake Manifold Air Temperature

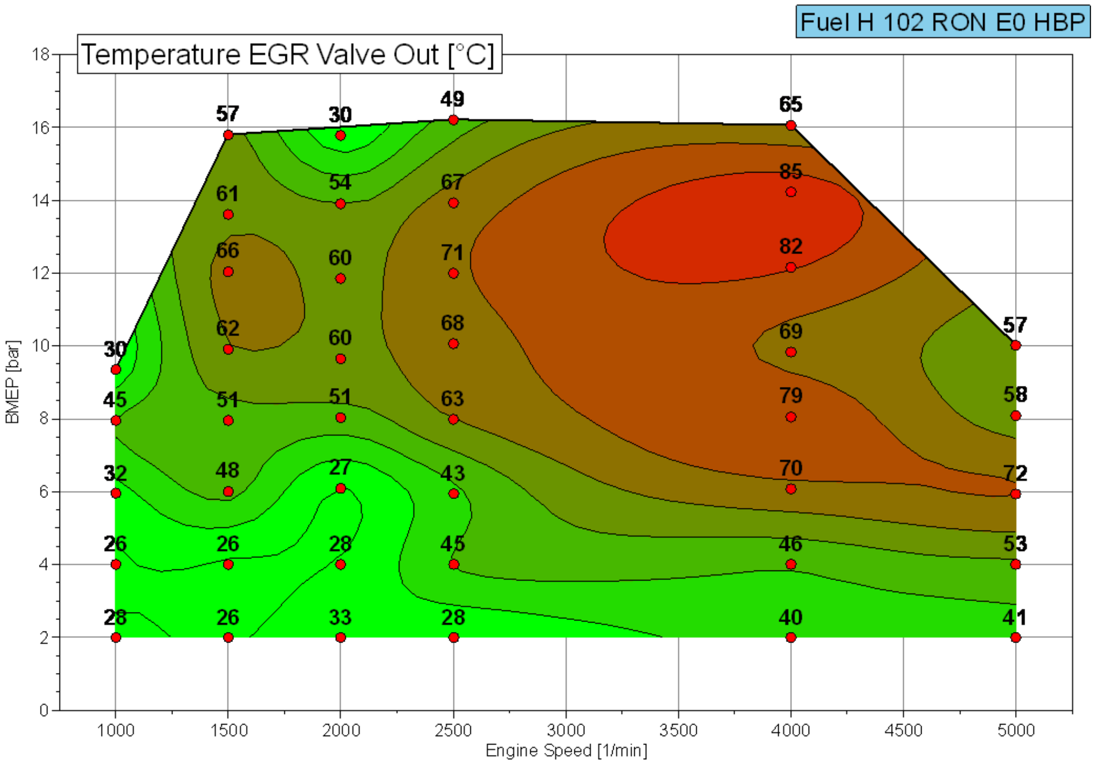

Figure 41: EGR Valve Out Temperature

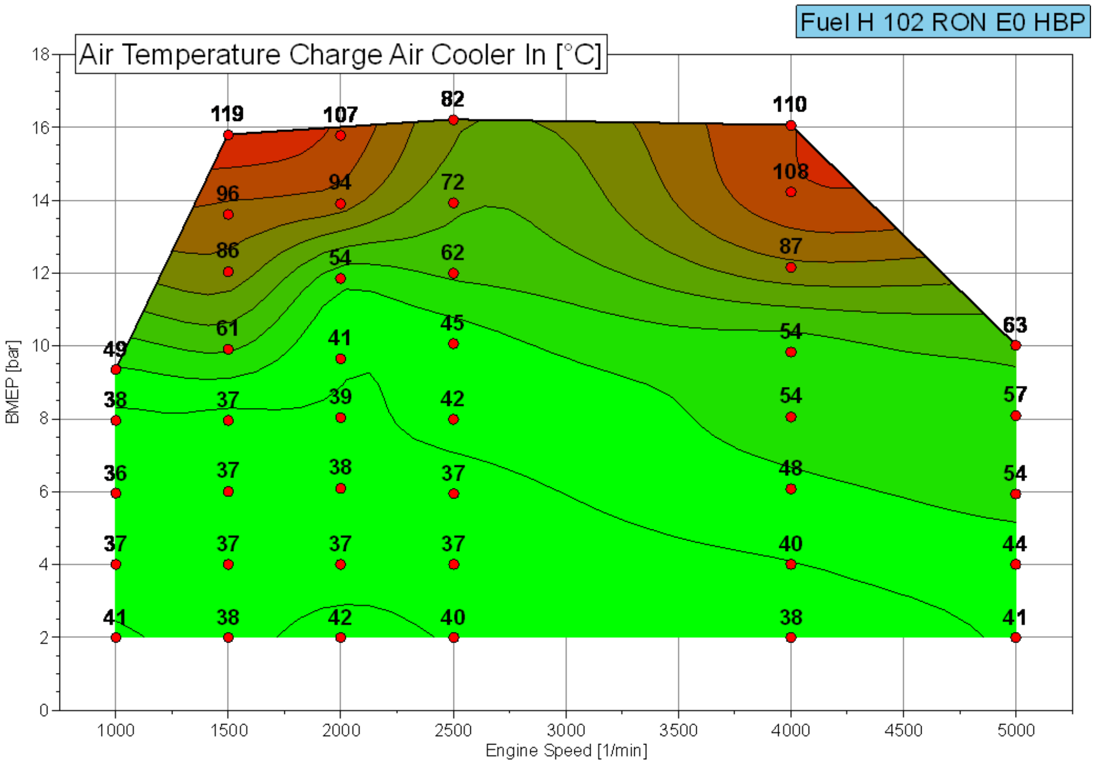

Figure 42: Charge Air Cooler Inlet Air Temperature

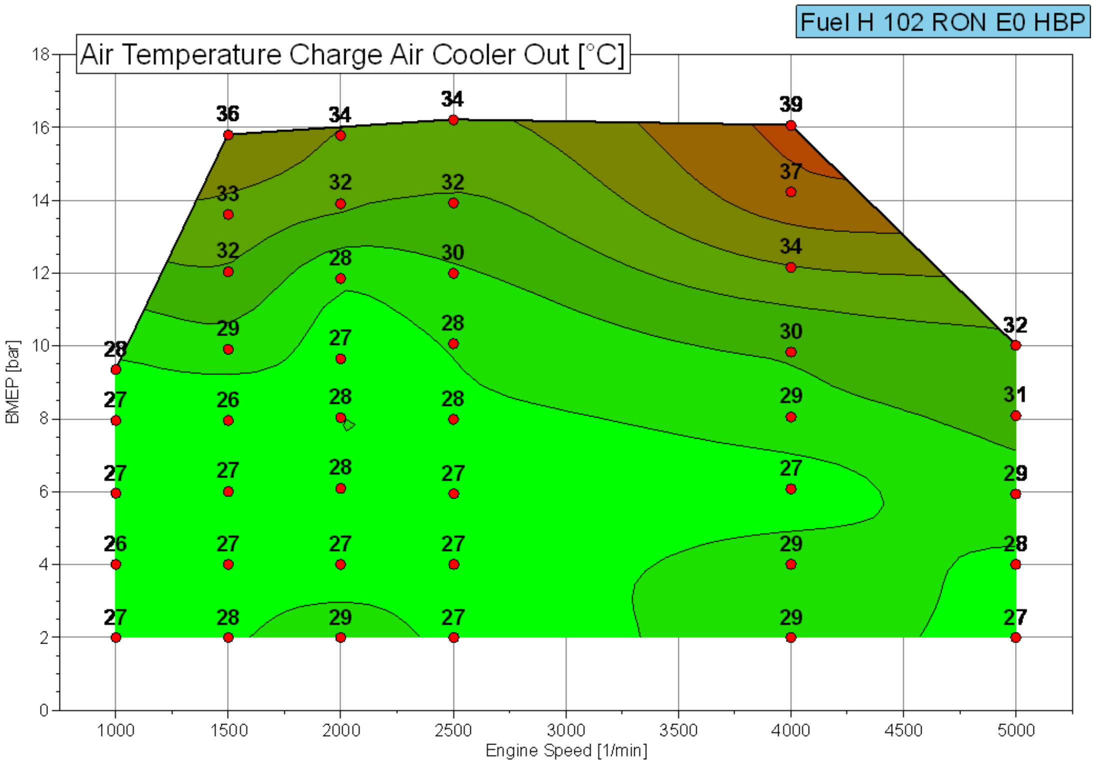

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel I Calibration Results

102 Ron 10% Ethanol Low Boiling Point

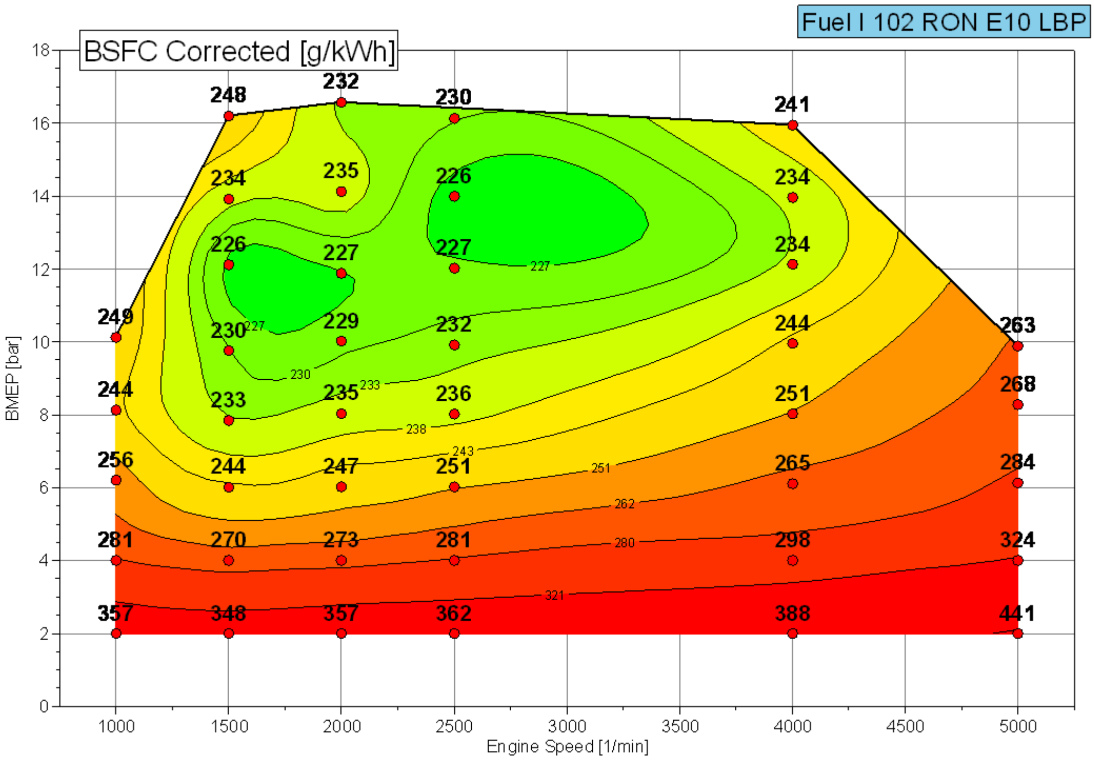

Figure 1: Brake Specific Fuel Consumption

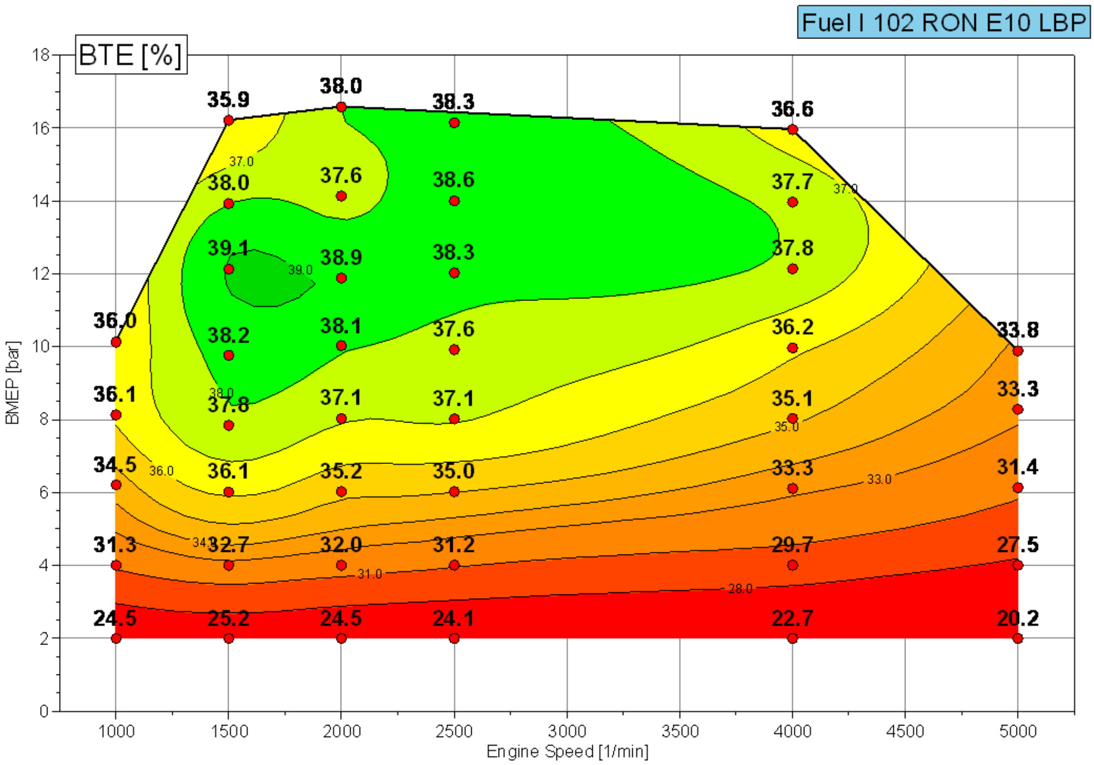

Figure 2: Brake Thermal Efficiency

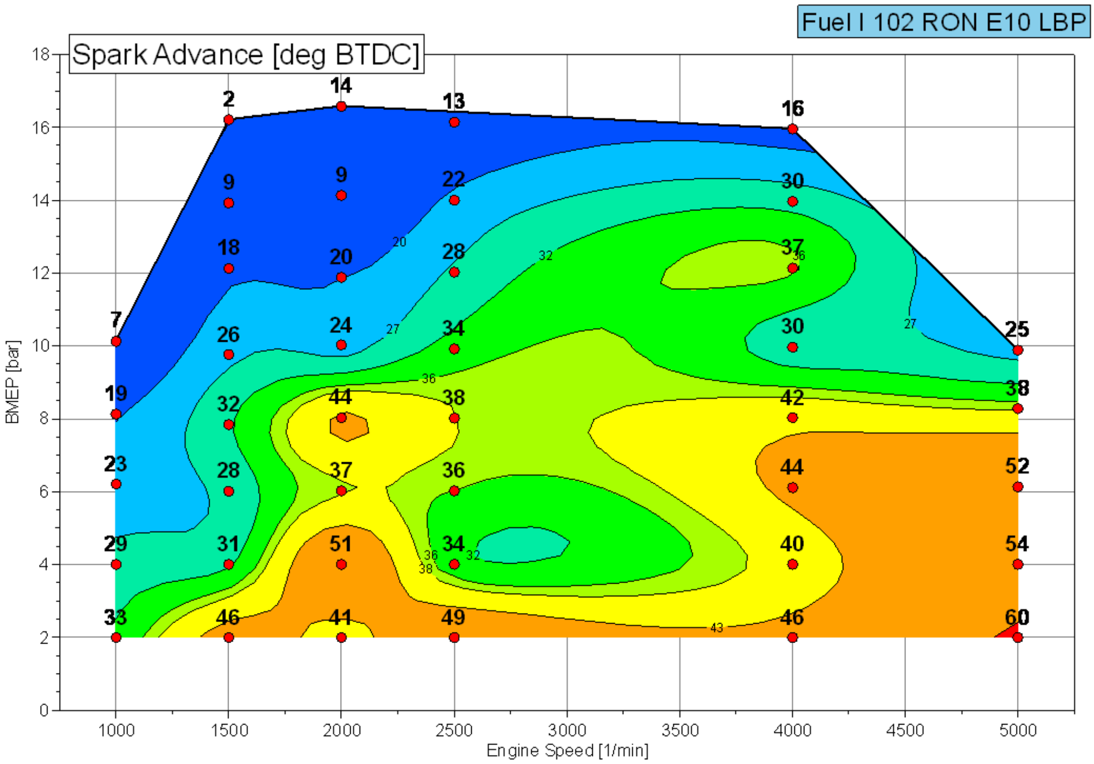

Figure 3: Spark Advance

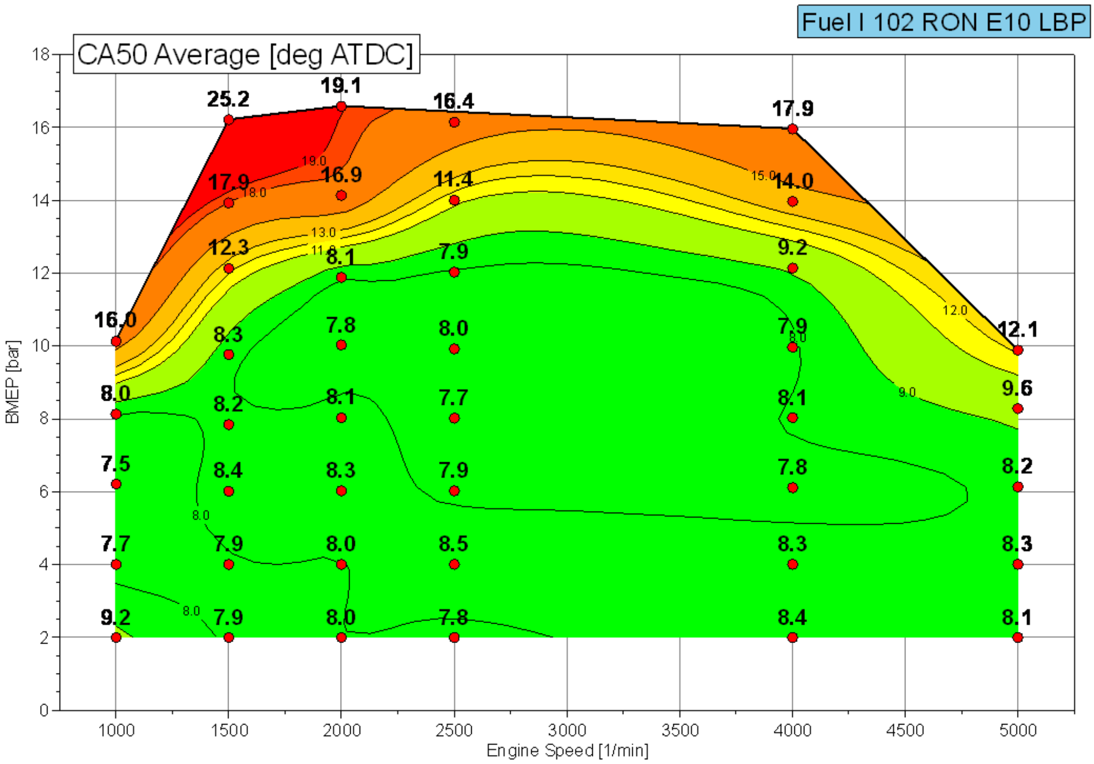

Figure 4: CA50 Average of Cylinders 1-4

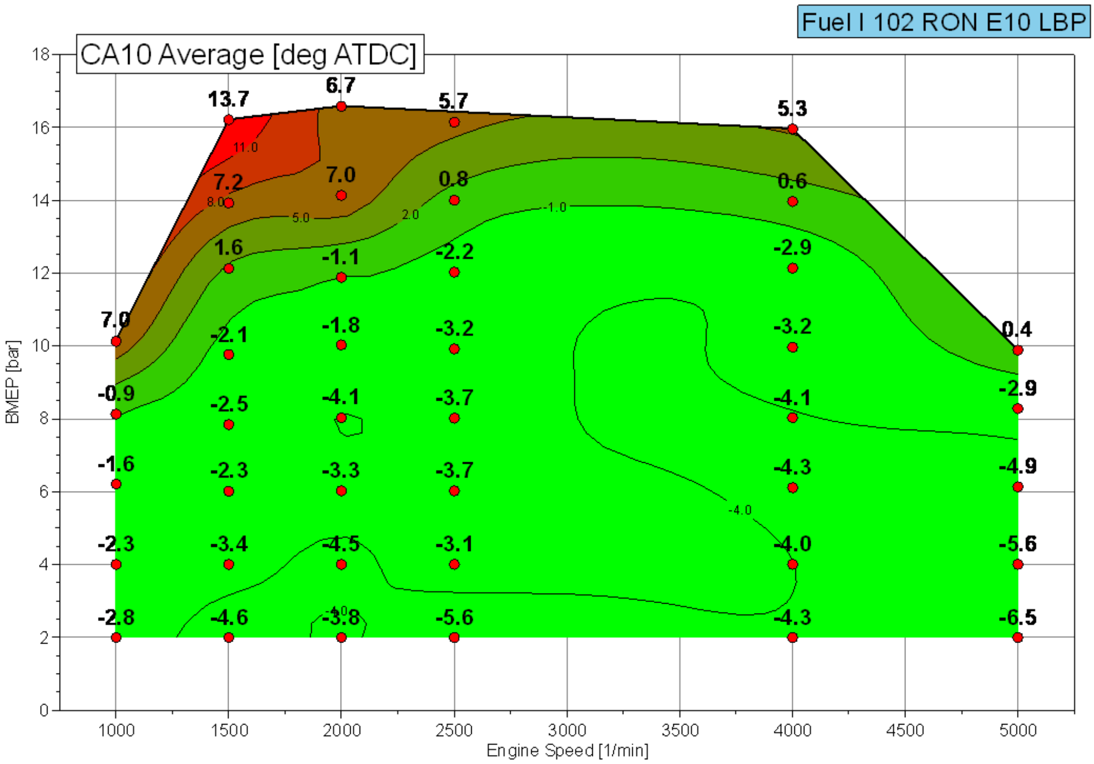

Figure 5: CA10 Average of Cylinders 1-4

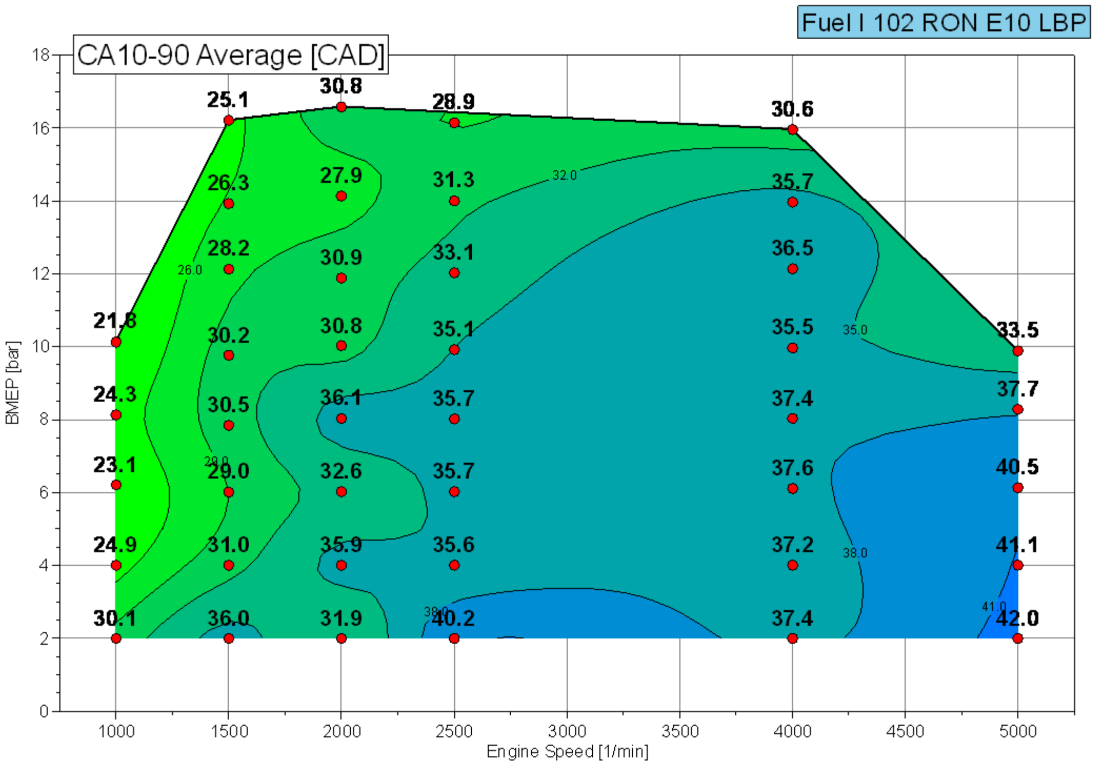

Figure 6: CA10-90 Average of Cylinders 1-4

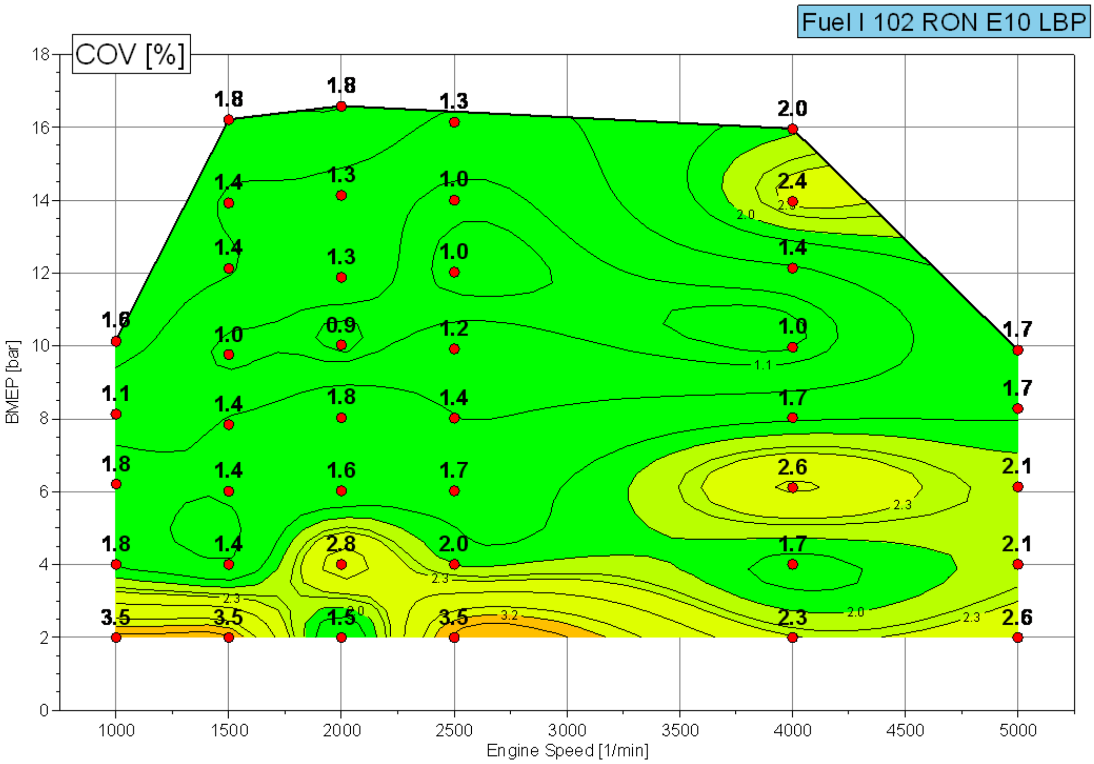

Figure 7: Coefficient of Variation Average of Cylinders 1-4

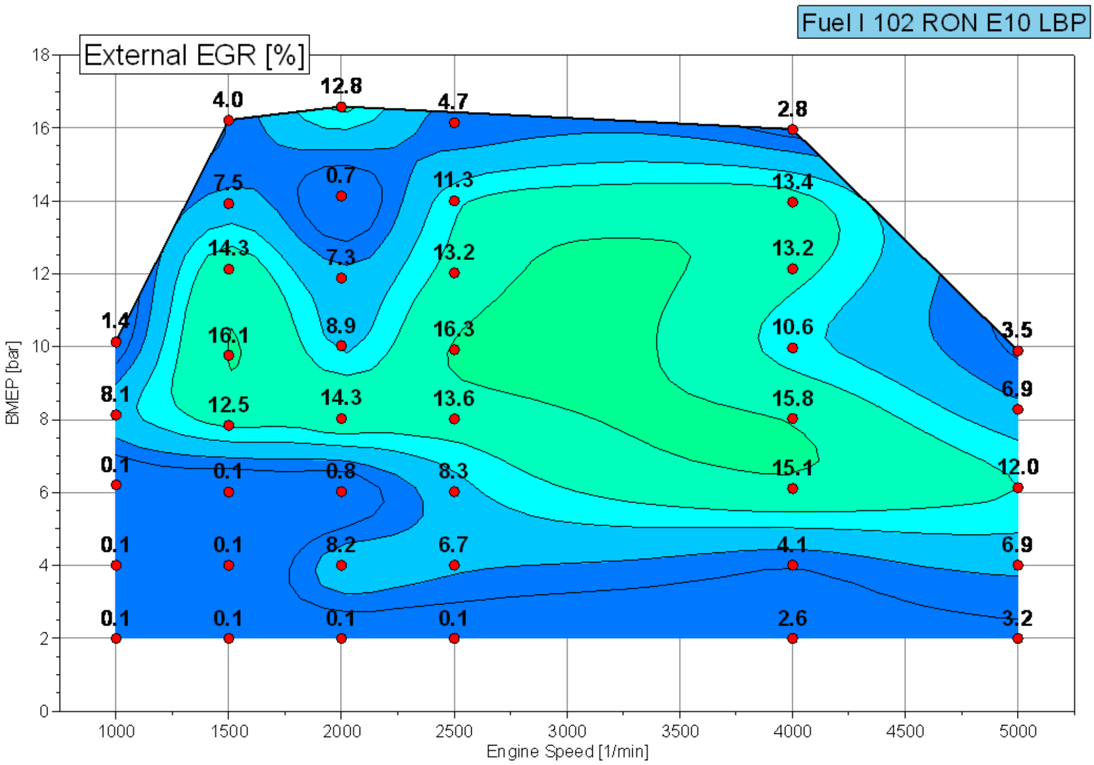

Figure 8: External EGR Percent of Intake Air

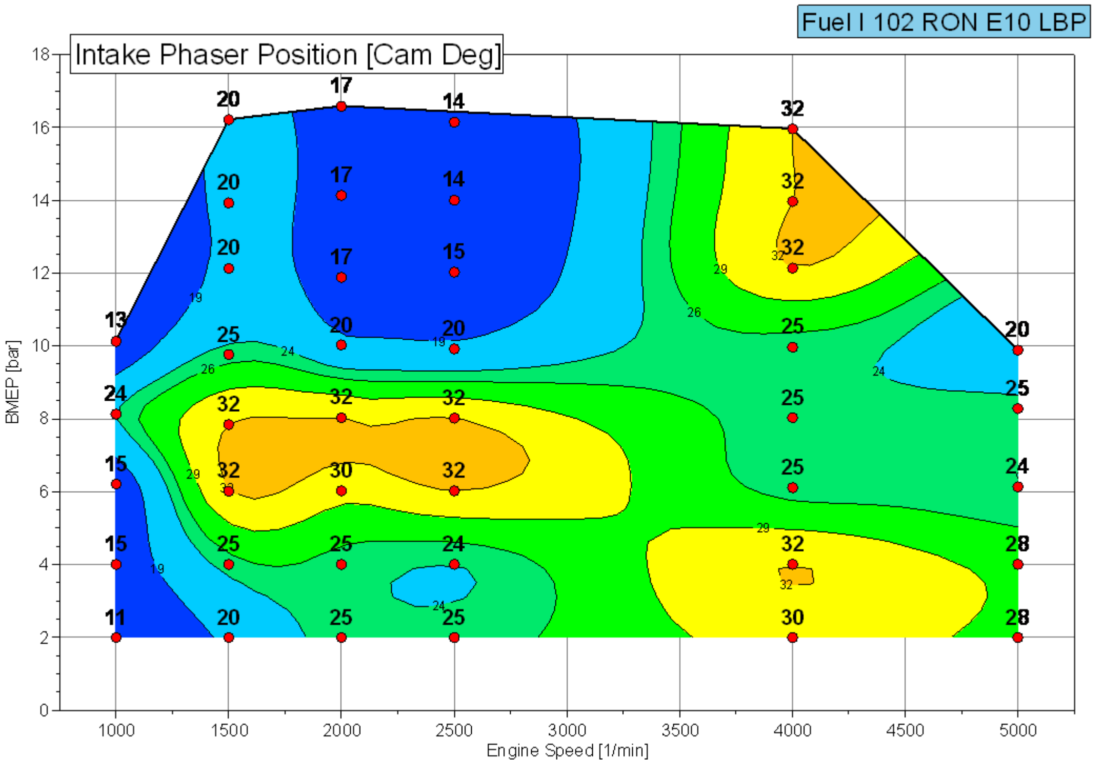

Figure 9: Intake Camshaft Phaser Position

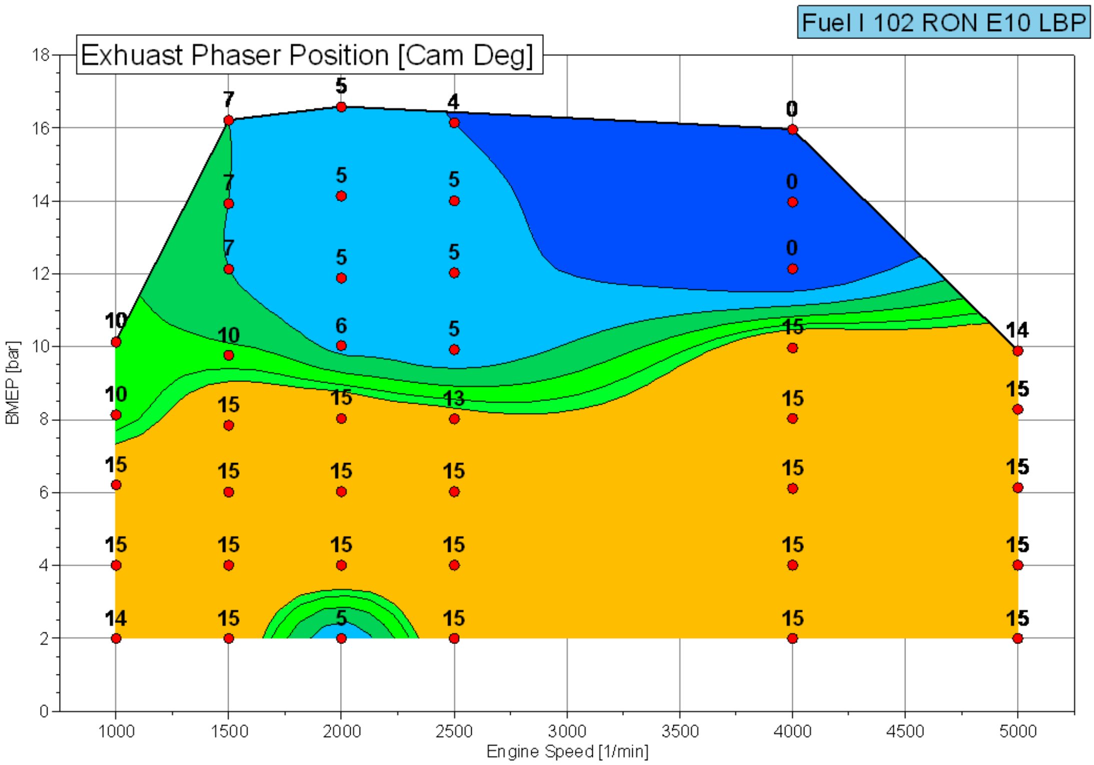

Figure 10: Exhaust Camshaft Phaser Position

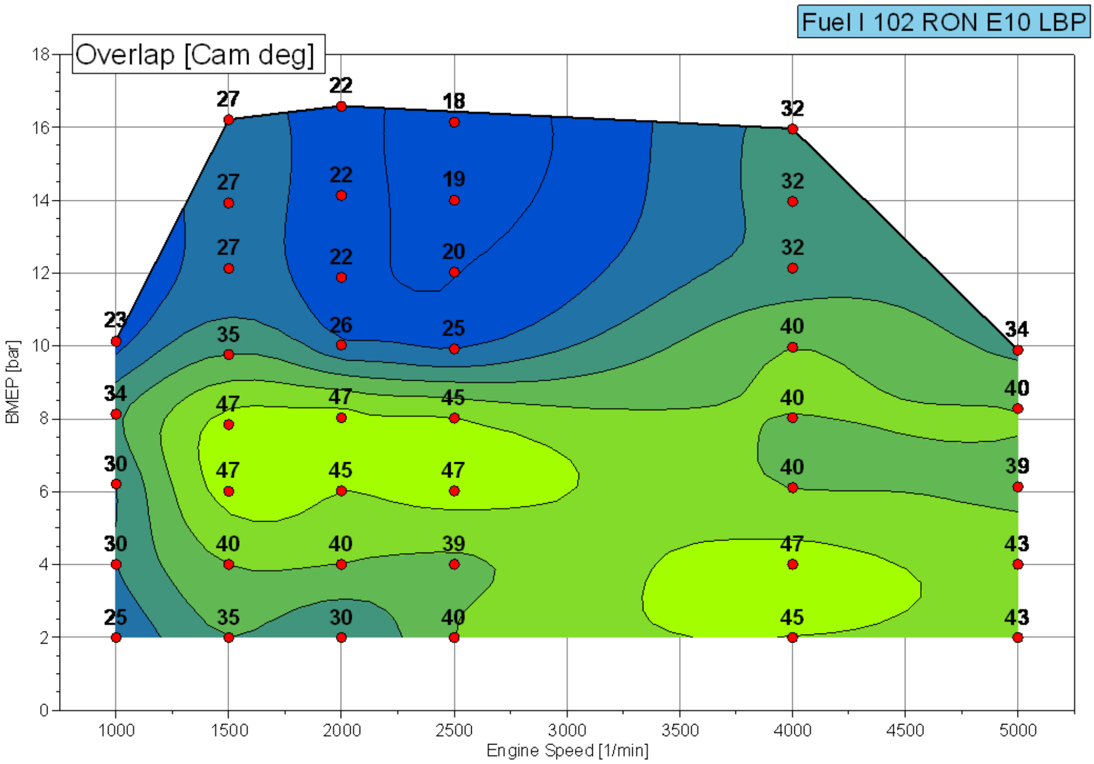

Figure 11: Camshaft Overlap

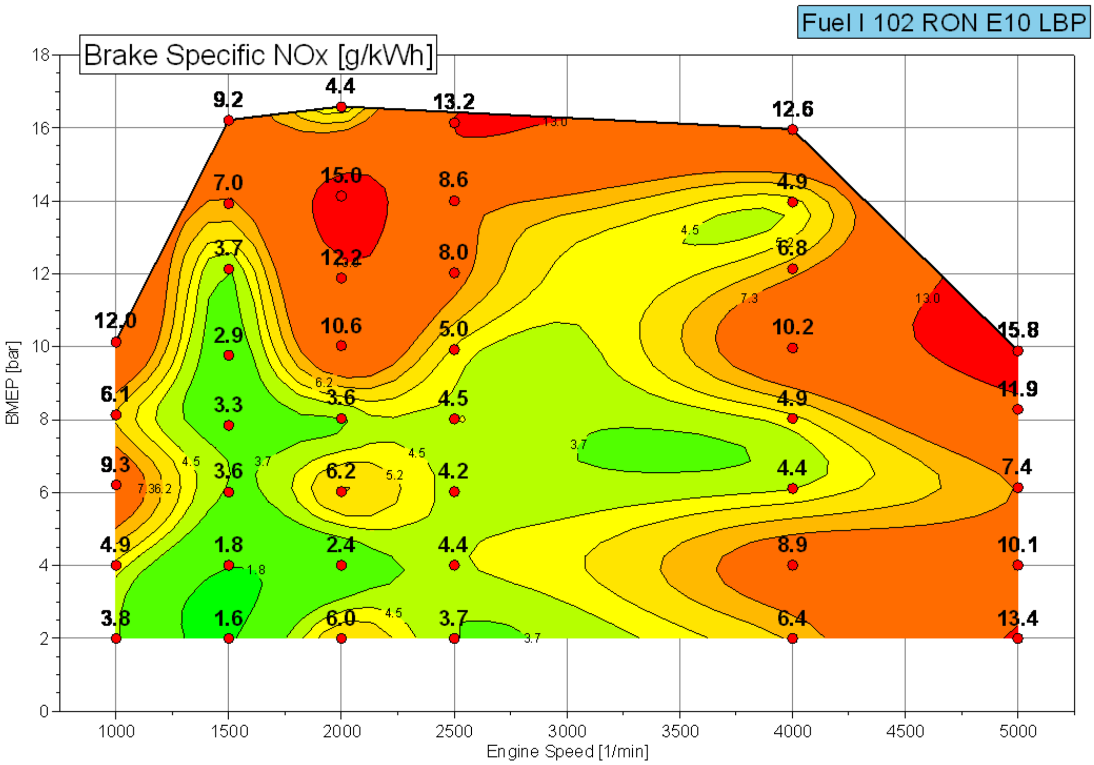

Figure 12: Brake Specific NOx Emissions

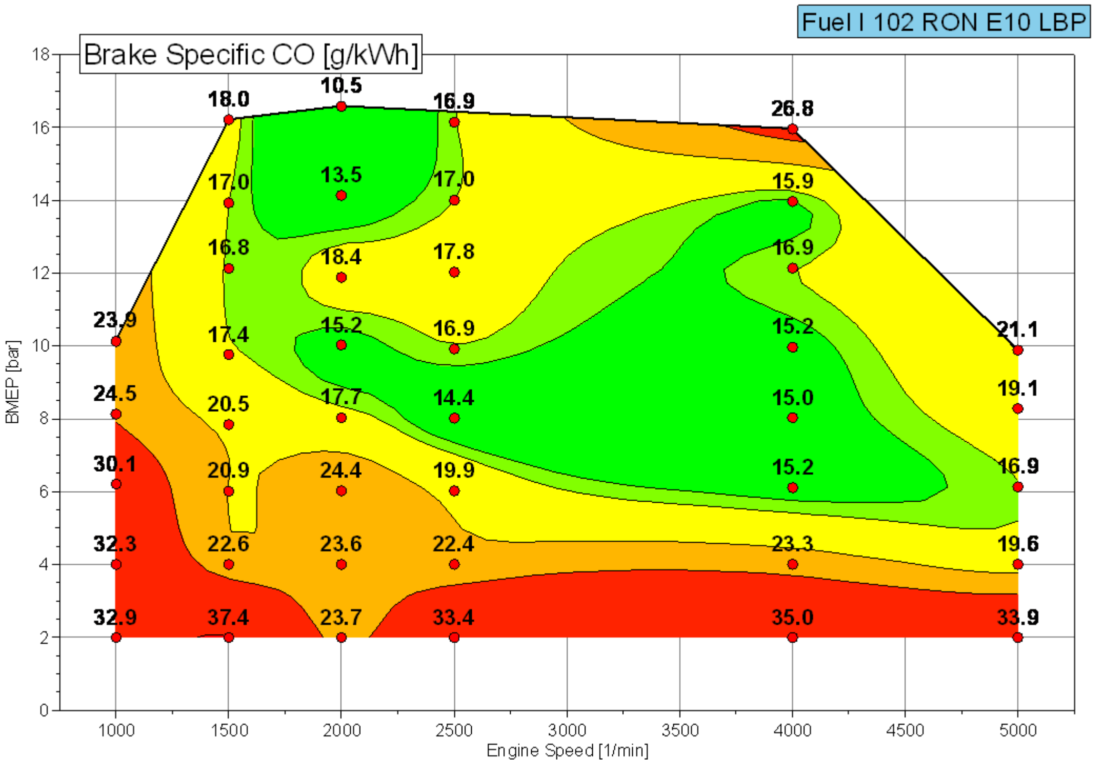

Figure 13: Brake Specific Carbon Monoxide Emissions

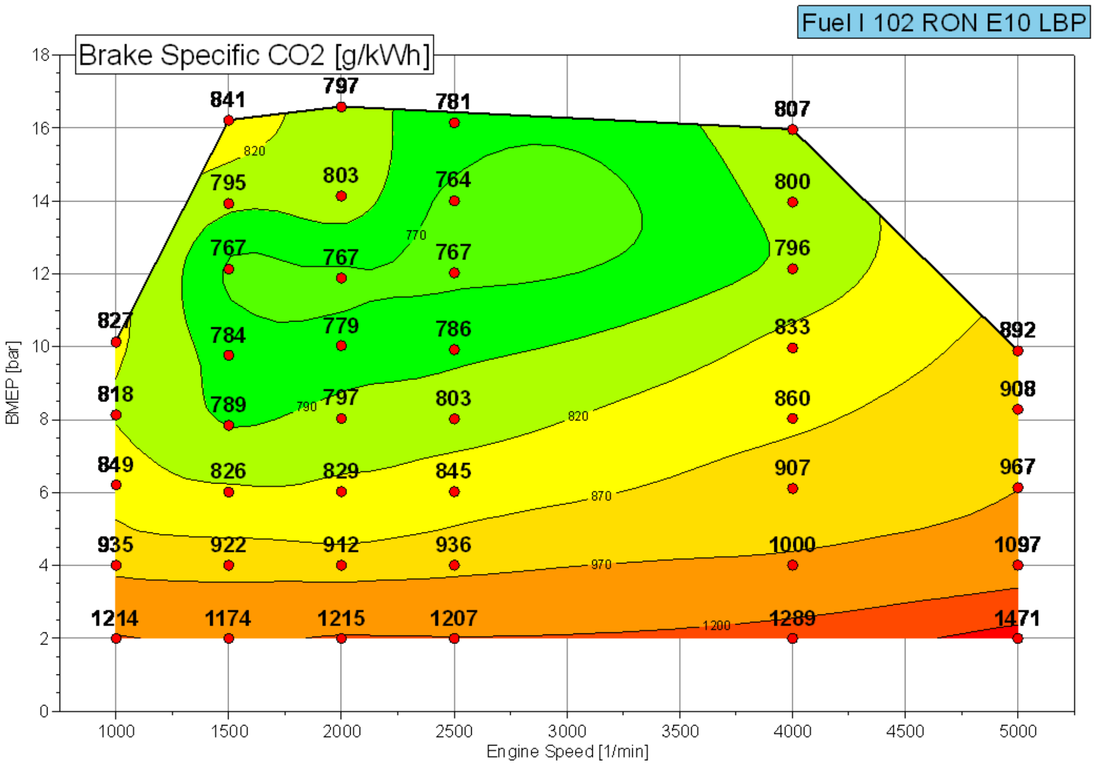

Figure 14: Brake Specific Carbon Dioxide Emissions

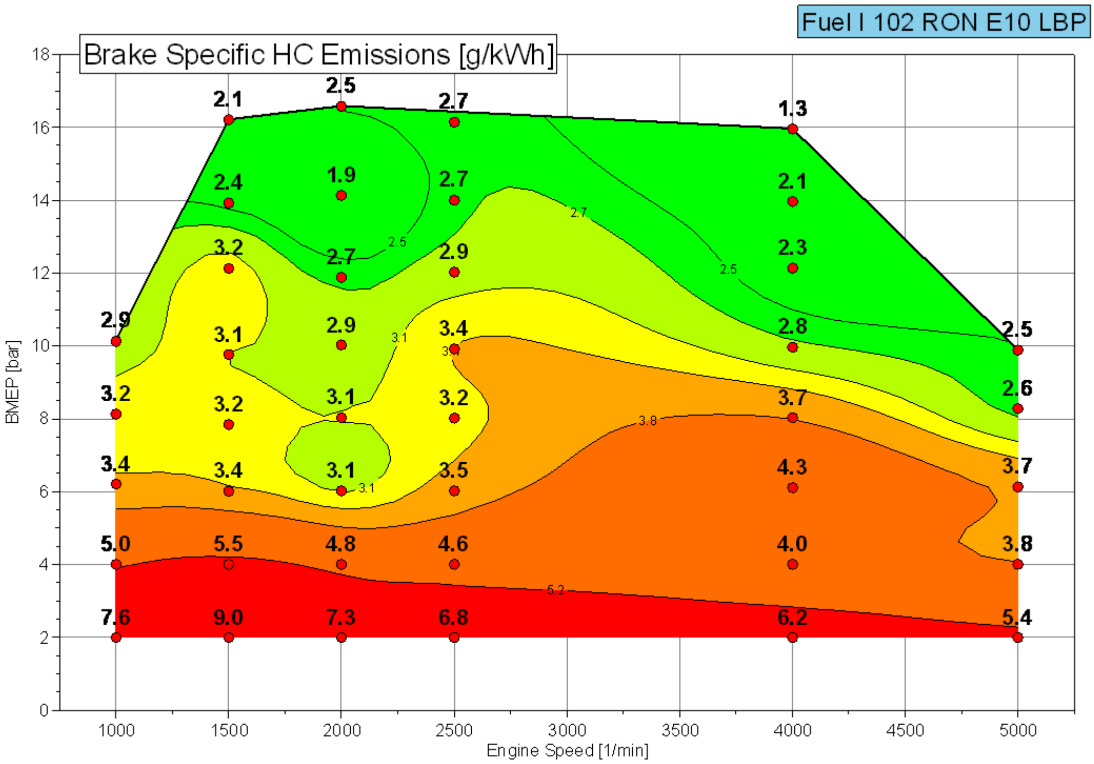

Figure 15: Brake Specific Hydrocarbon Emissions

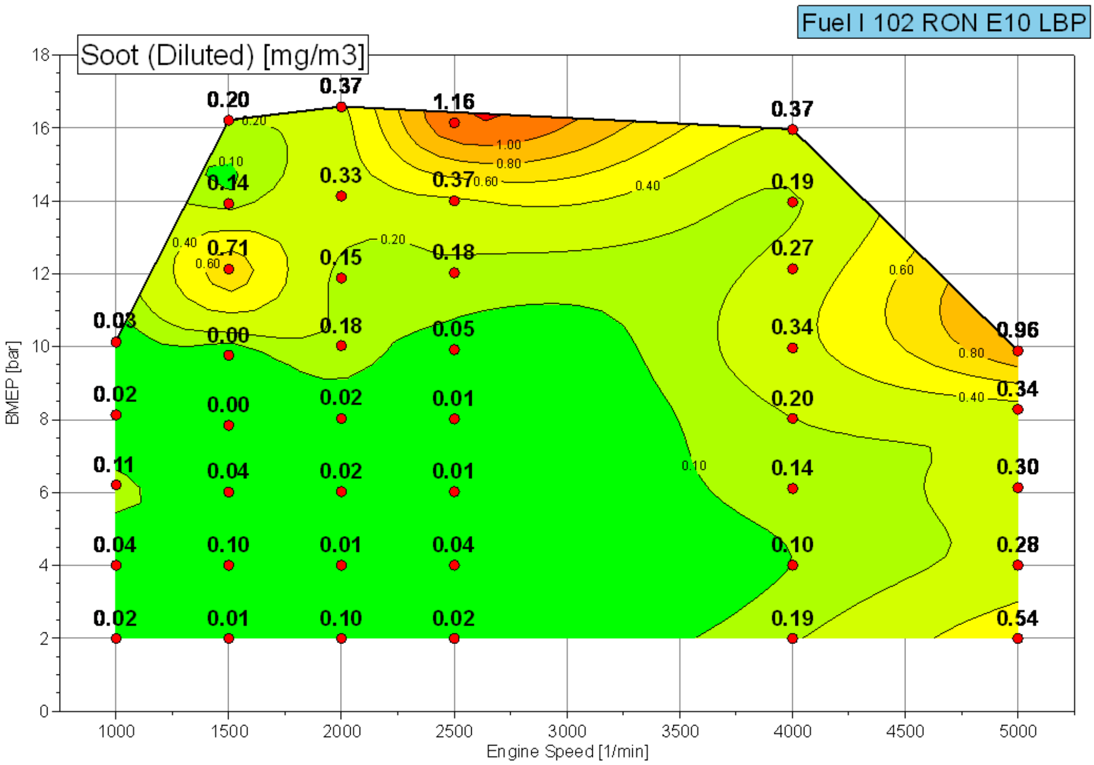

Figure 16: Particulate Soot Emissions

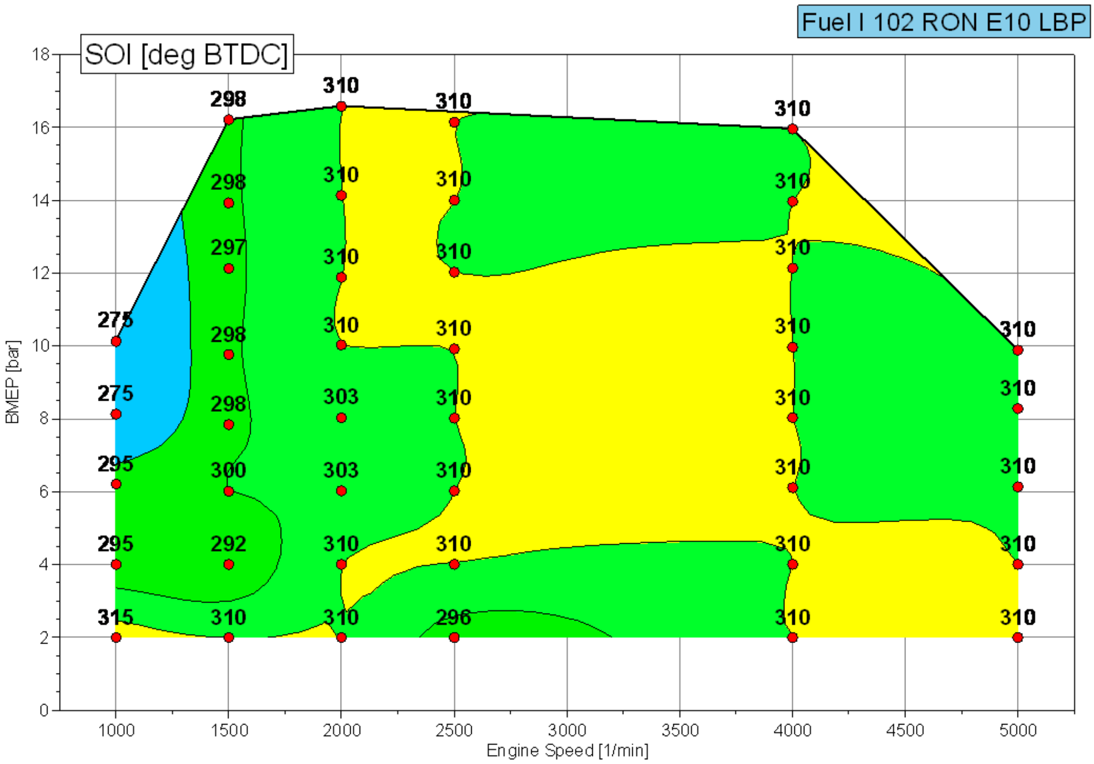

Figure 17: Start of Injection

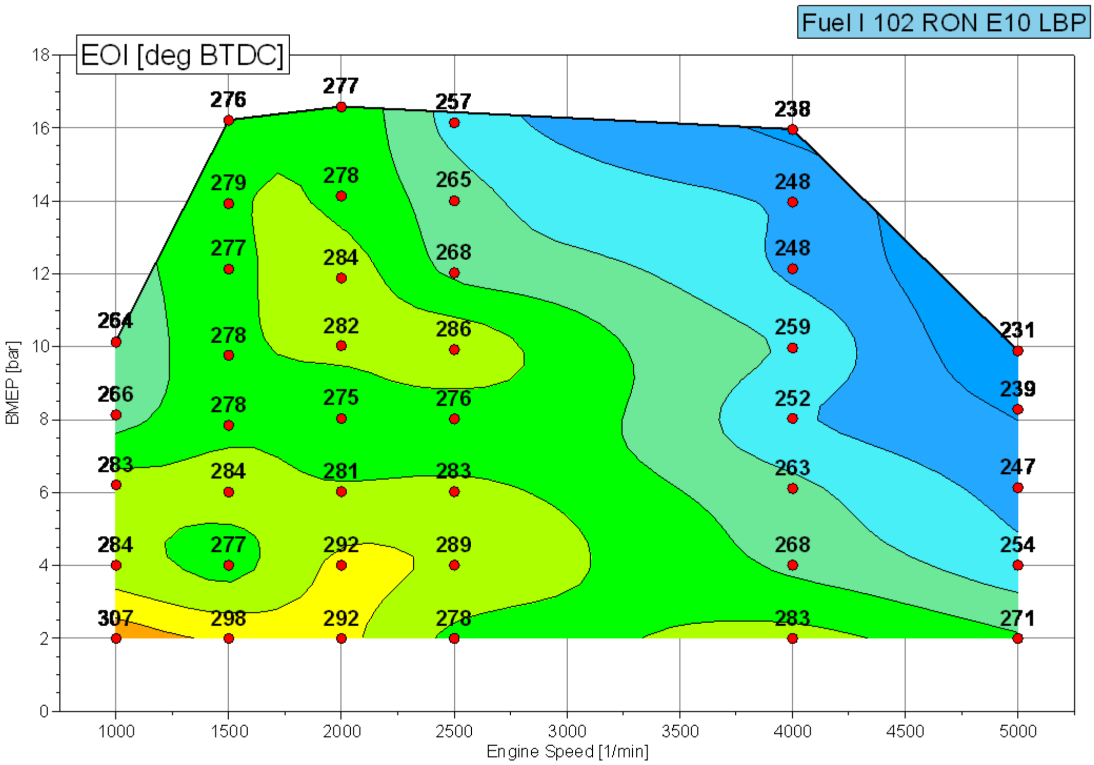

Figure 18: End of Injection

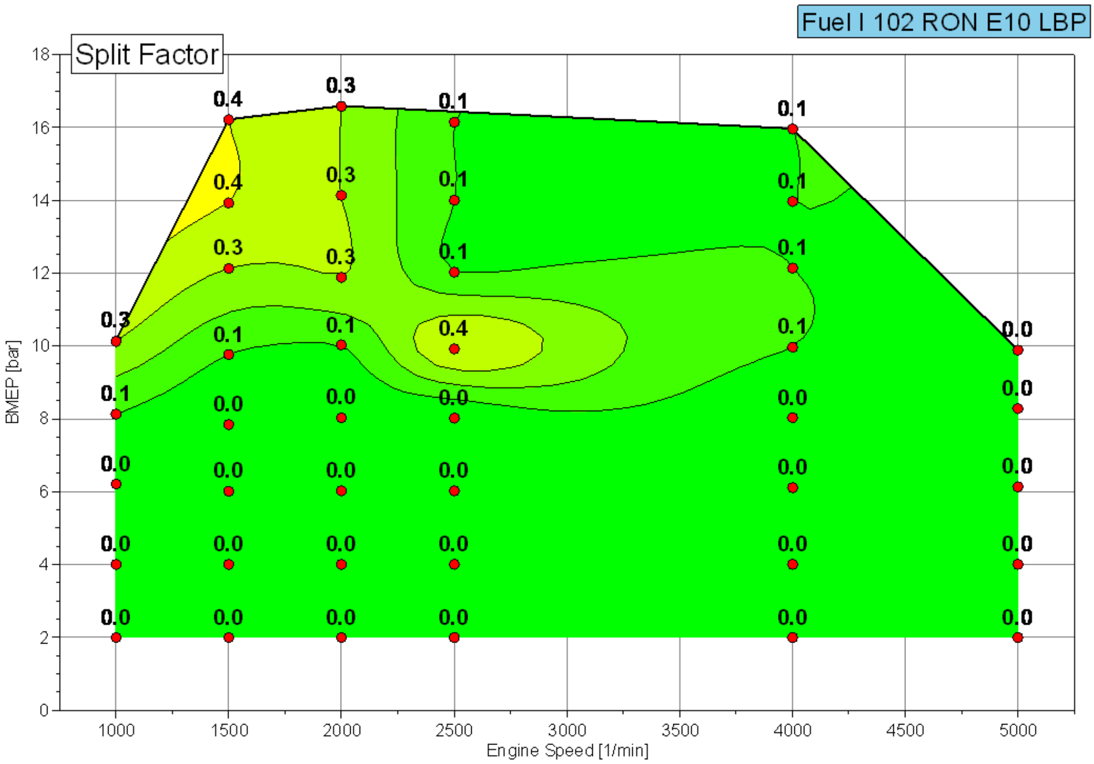

Figure 19: Injection Split Factor

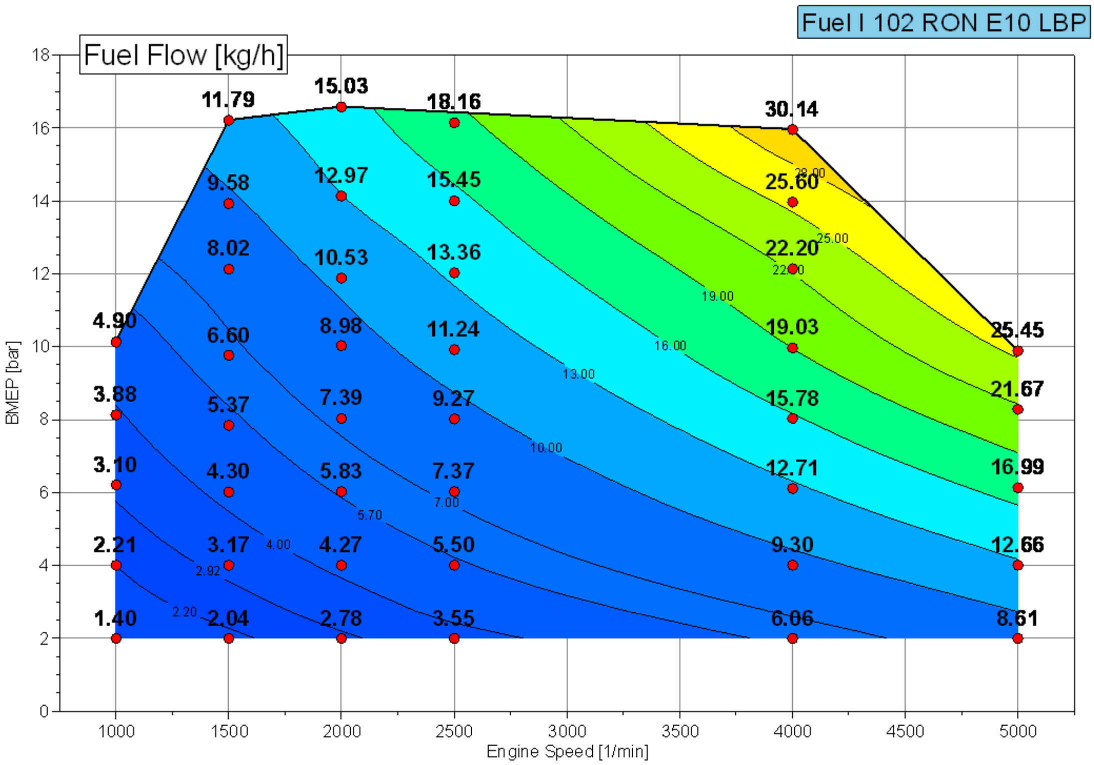

Figure 20: Fuel Flow

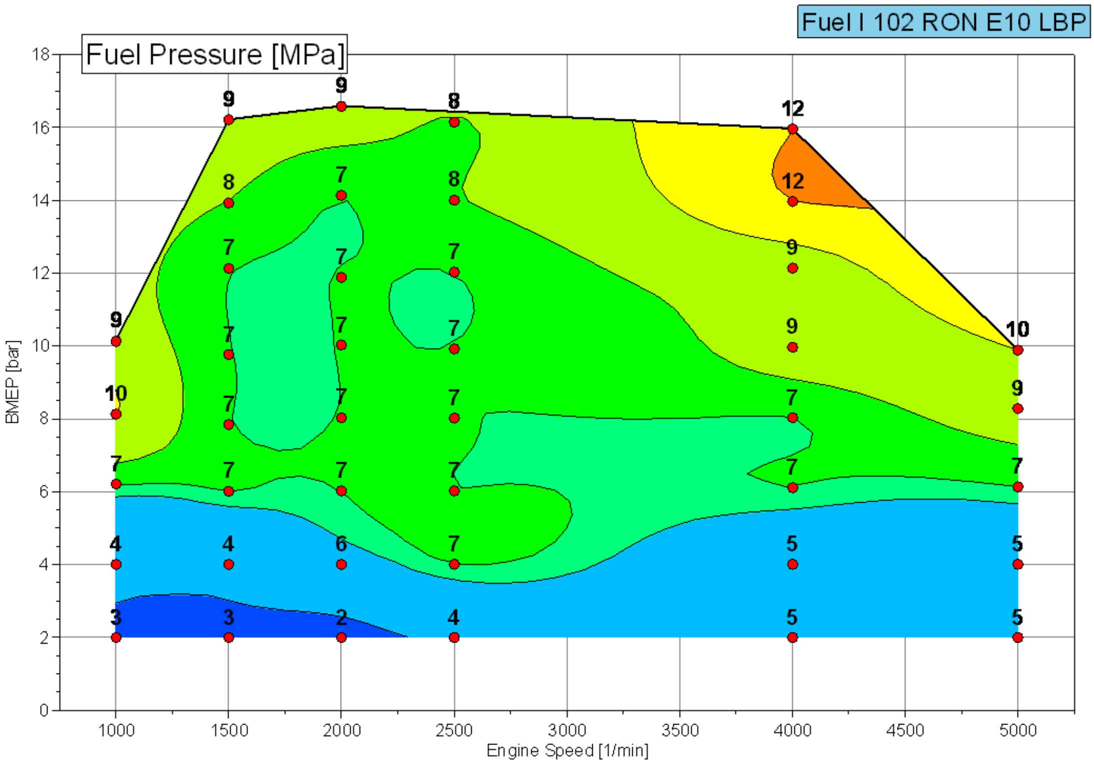

Figure 21: Fuel Rail Pressure

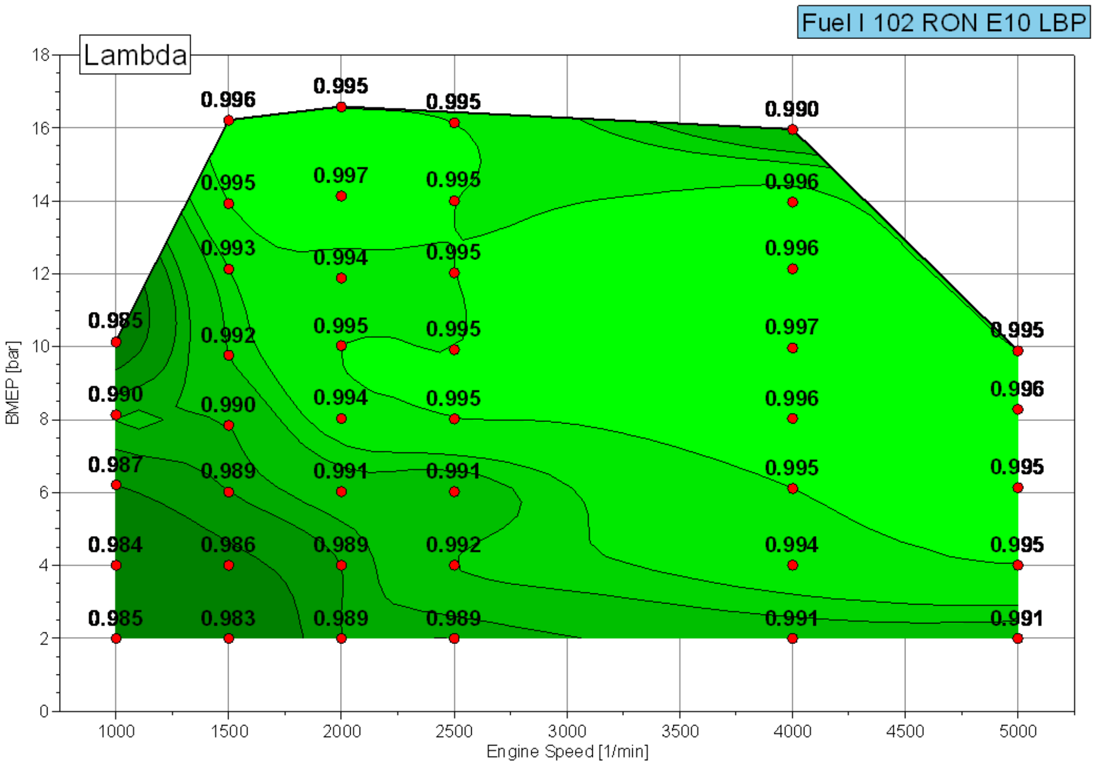

Figure 22: Lambda

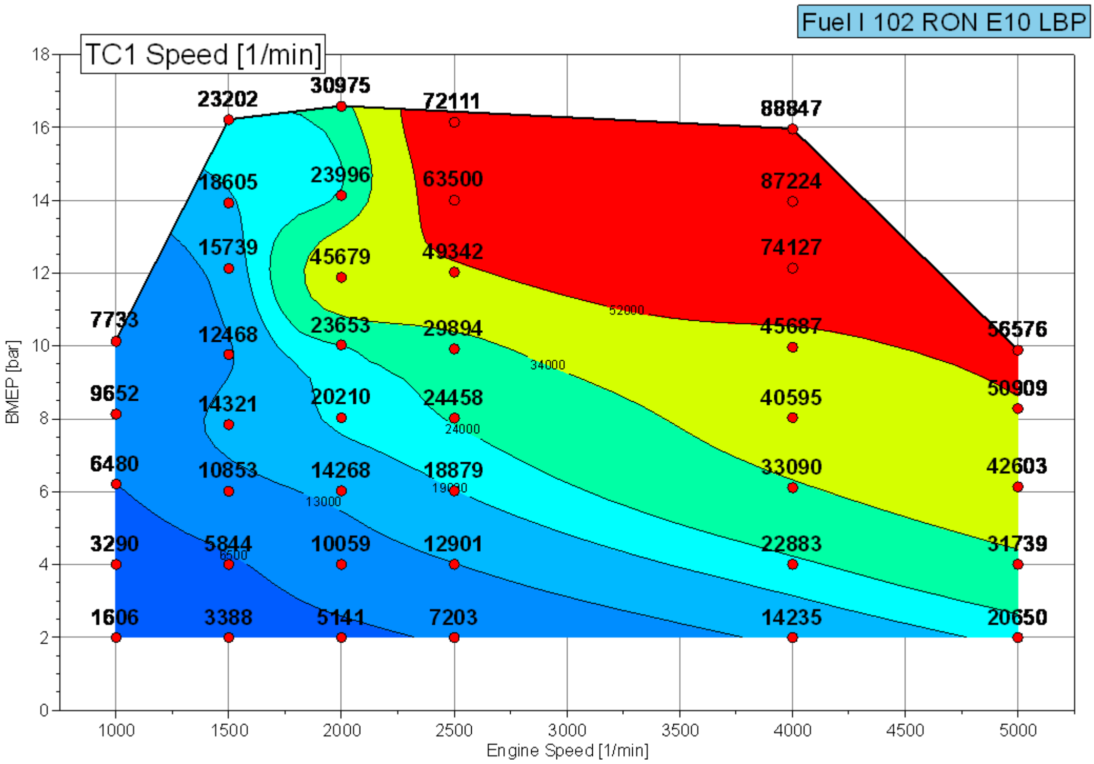

Figure 23: Low Pressure Turbocharger Speed

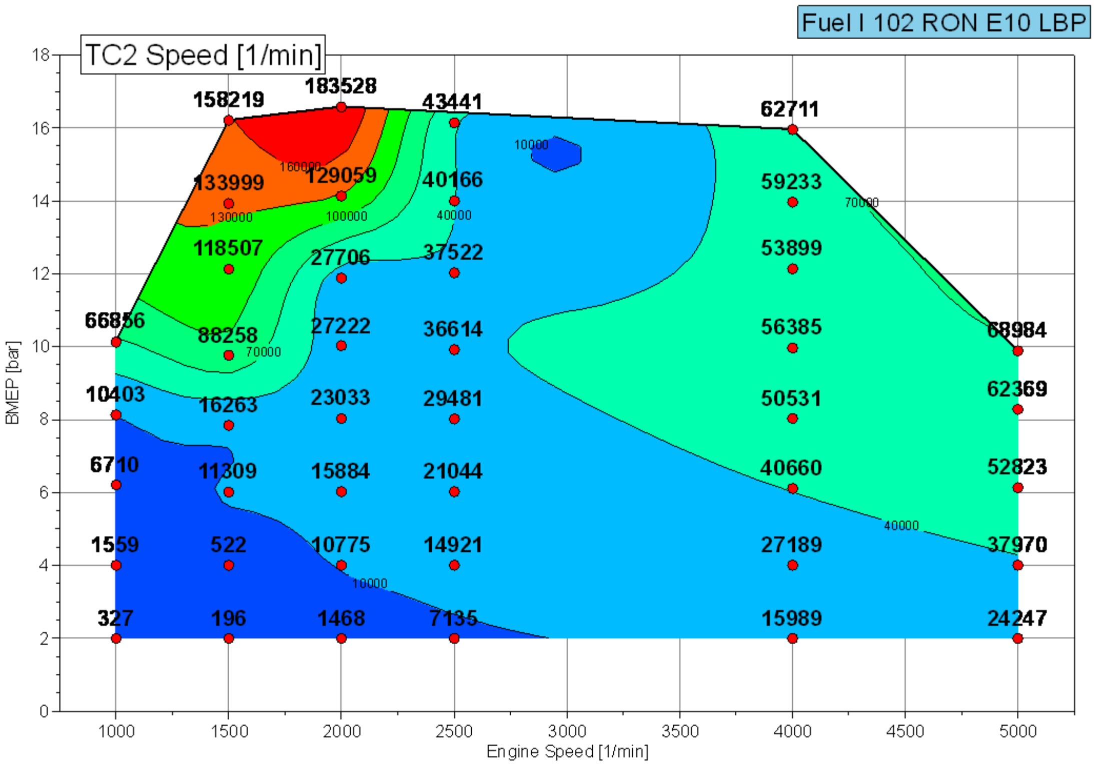

Figure 24: High Pressure Turbocharge Speed

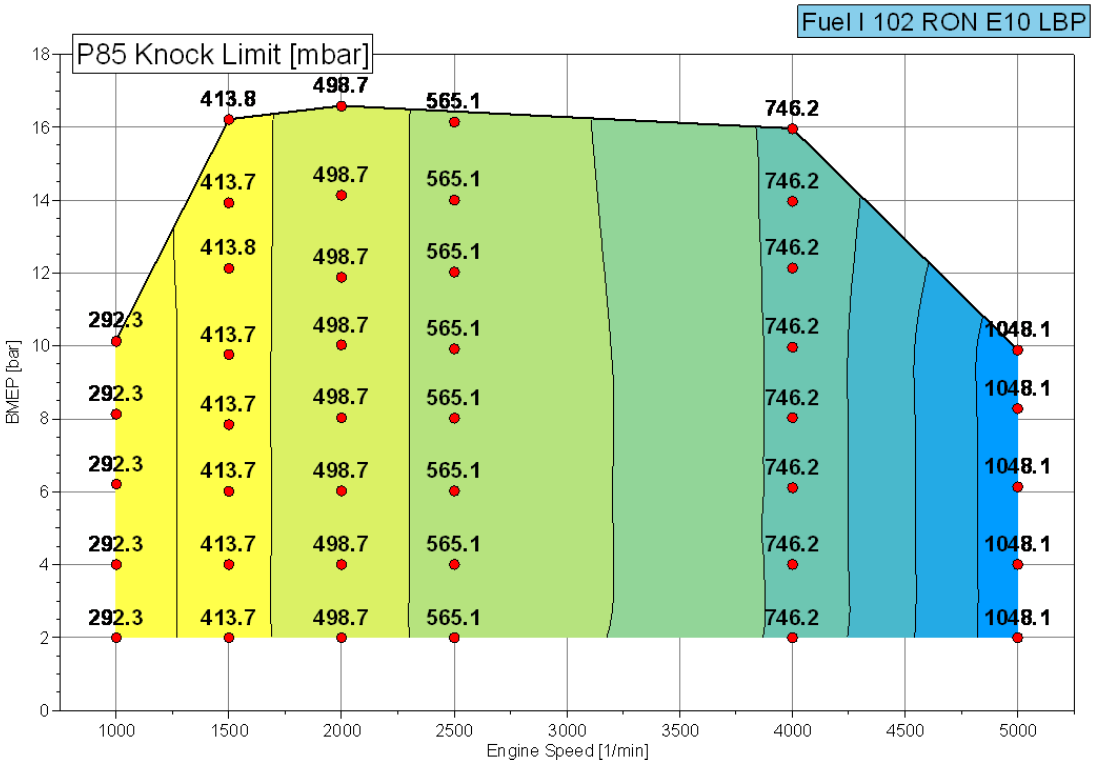

Figure 25: P85 Knock Limit

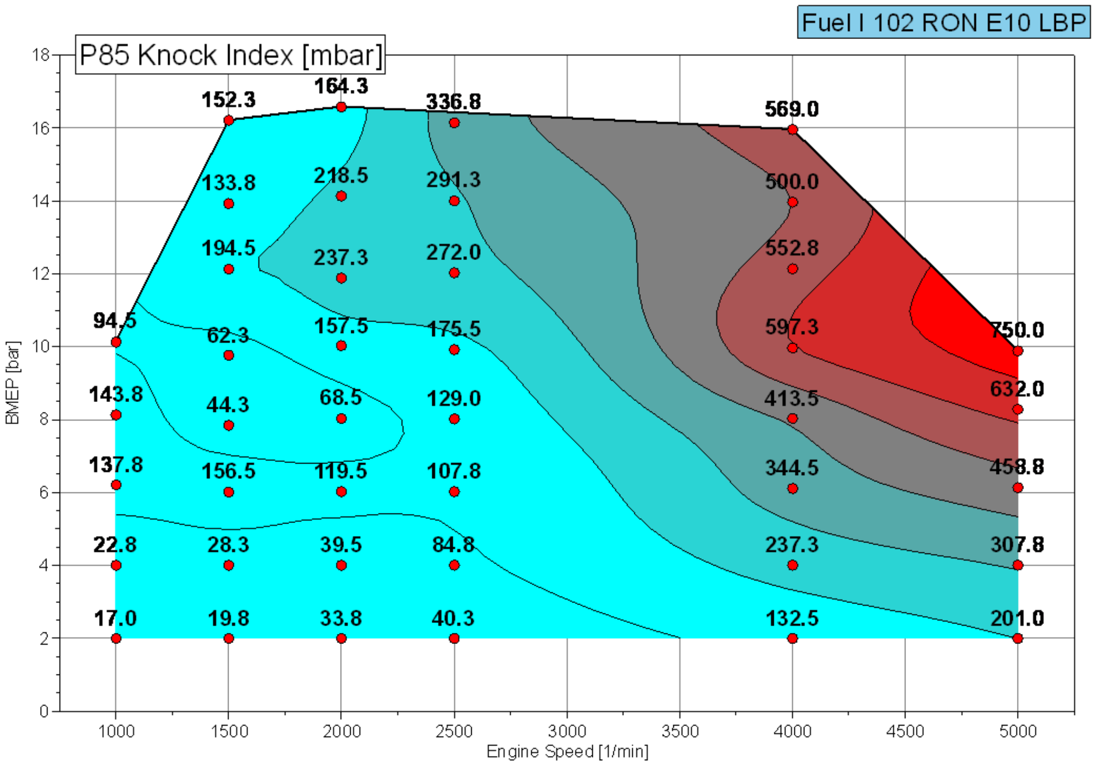

Figure 26: Averaged P85 Knock Index

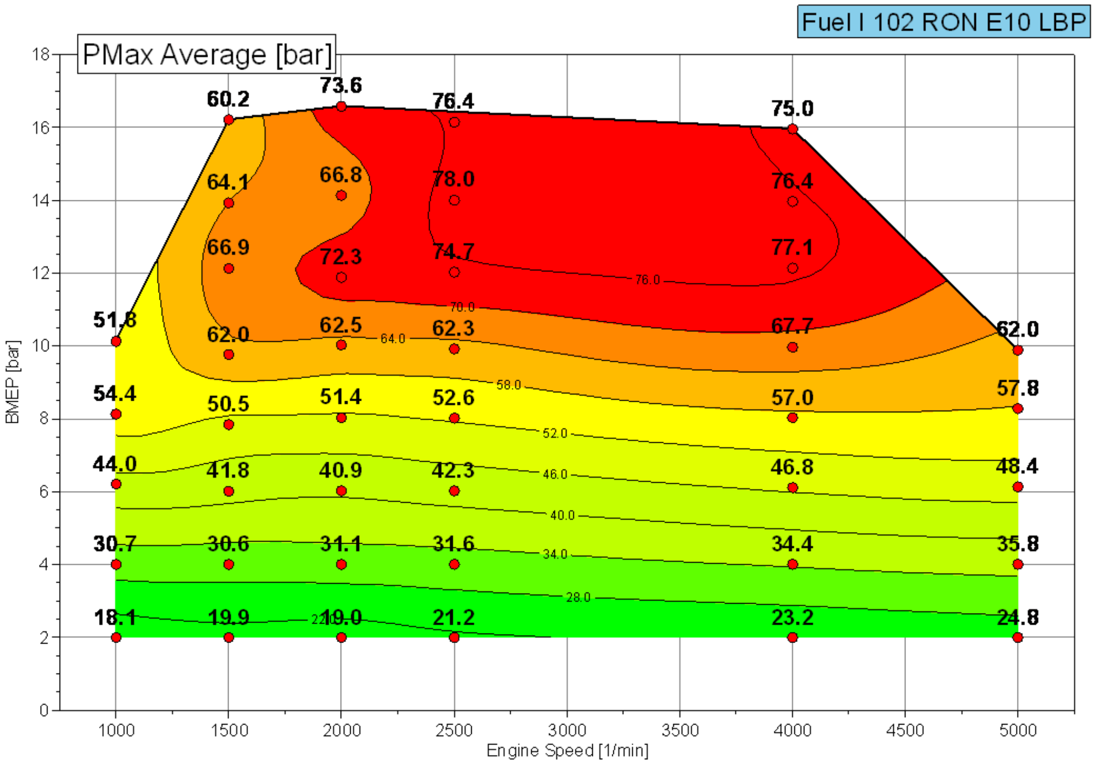

Figure 27: Averaged Max Pressure for Cylinders 1-4

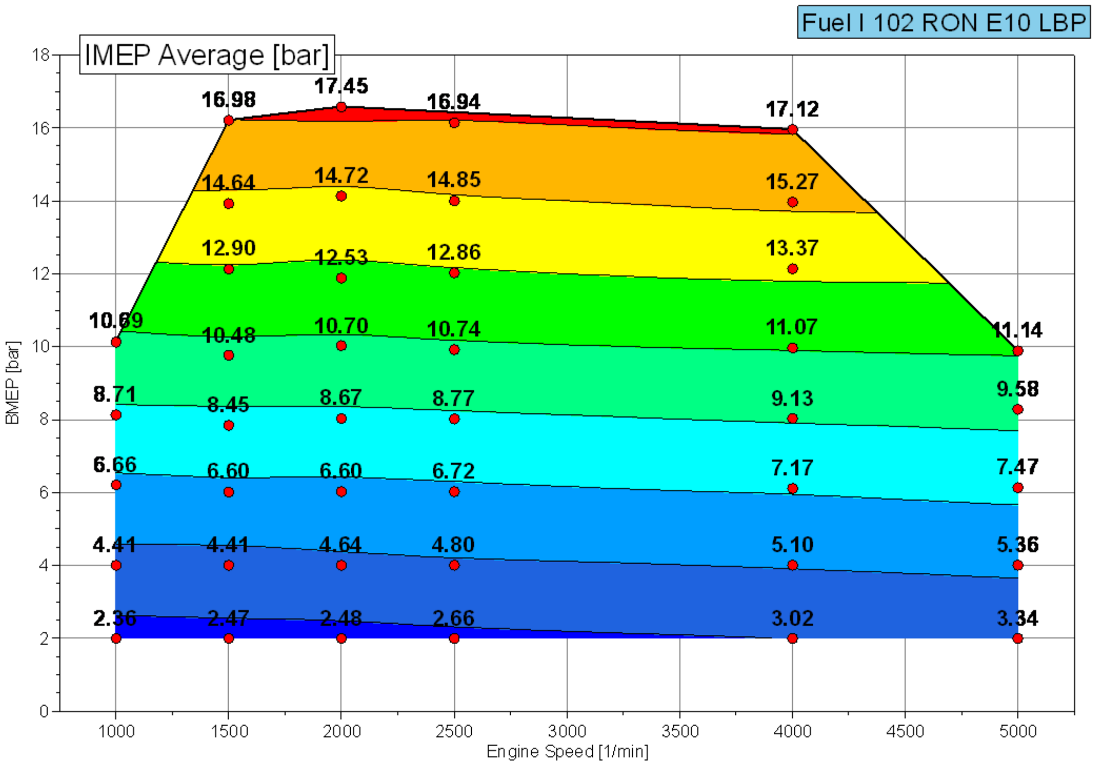

Figure 28: Indicated Mean Effective Pressure

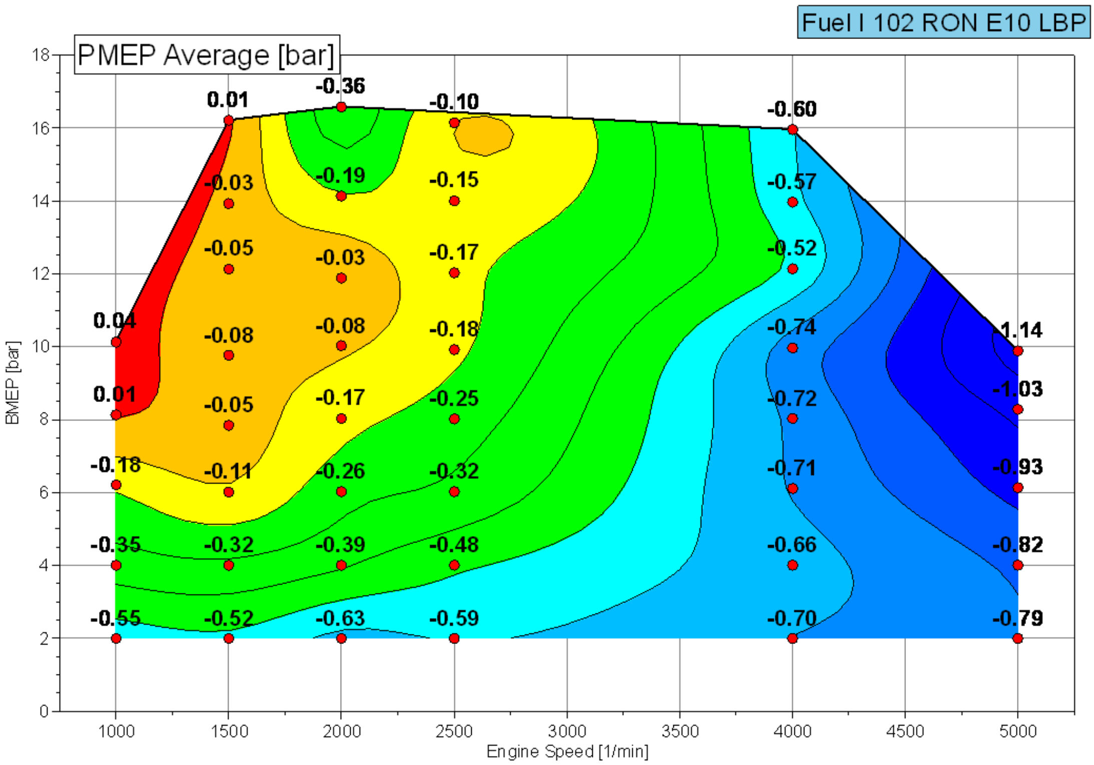

Figure 29: Pumping Mean Effective Pressure

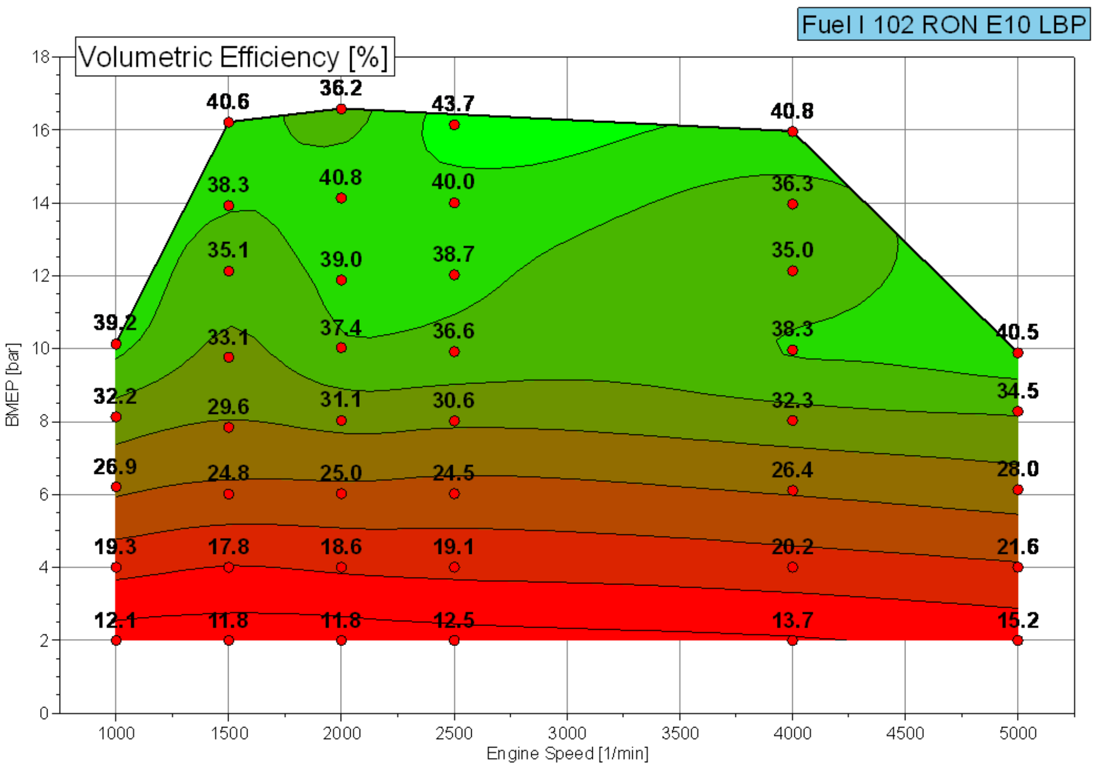

Figure 30: Calculated Volumetric Efficiency

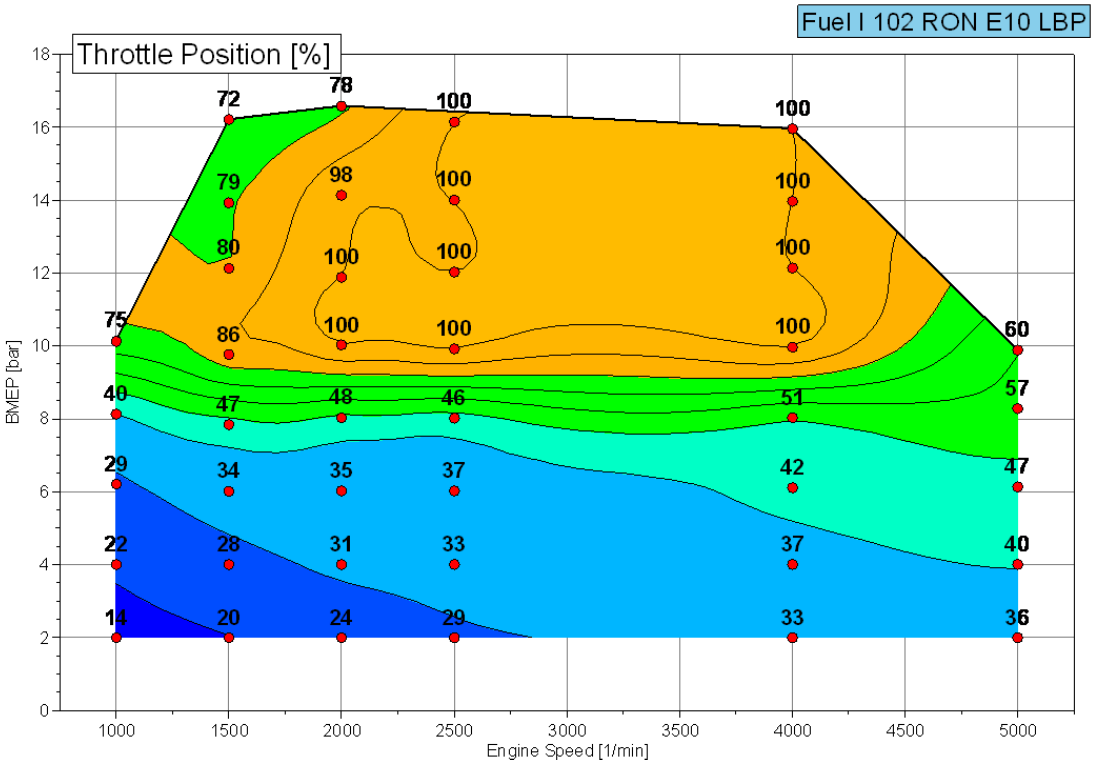

Figure 31: Throttle Position

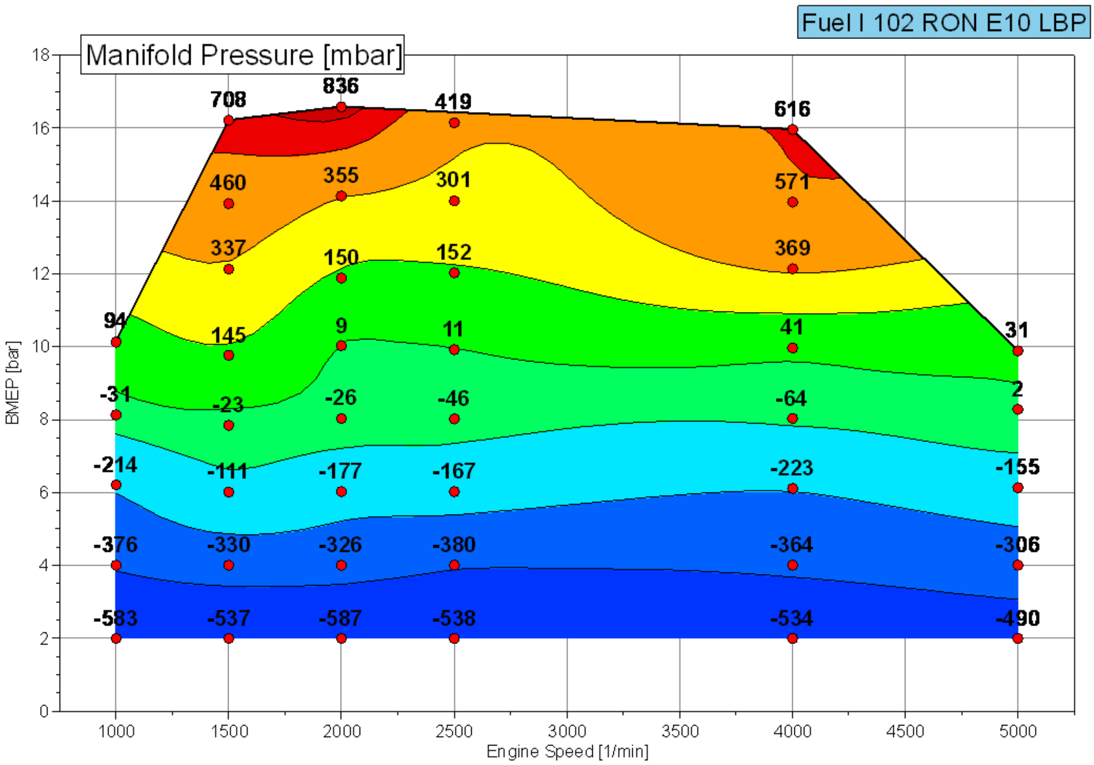

Figure 32: Intake Manifold Pressure

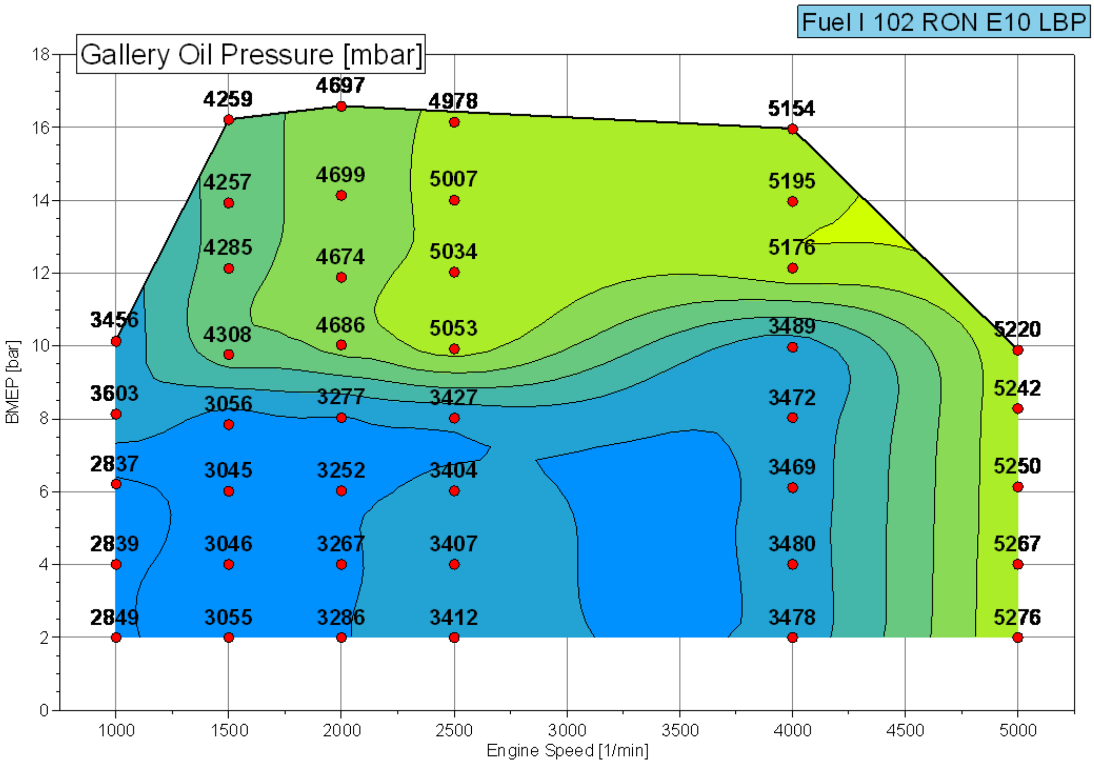

Figure 33: Gallery Oil Pressure

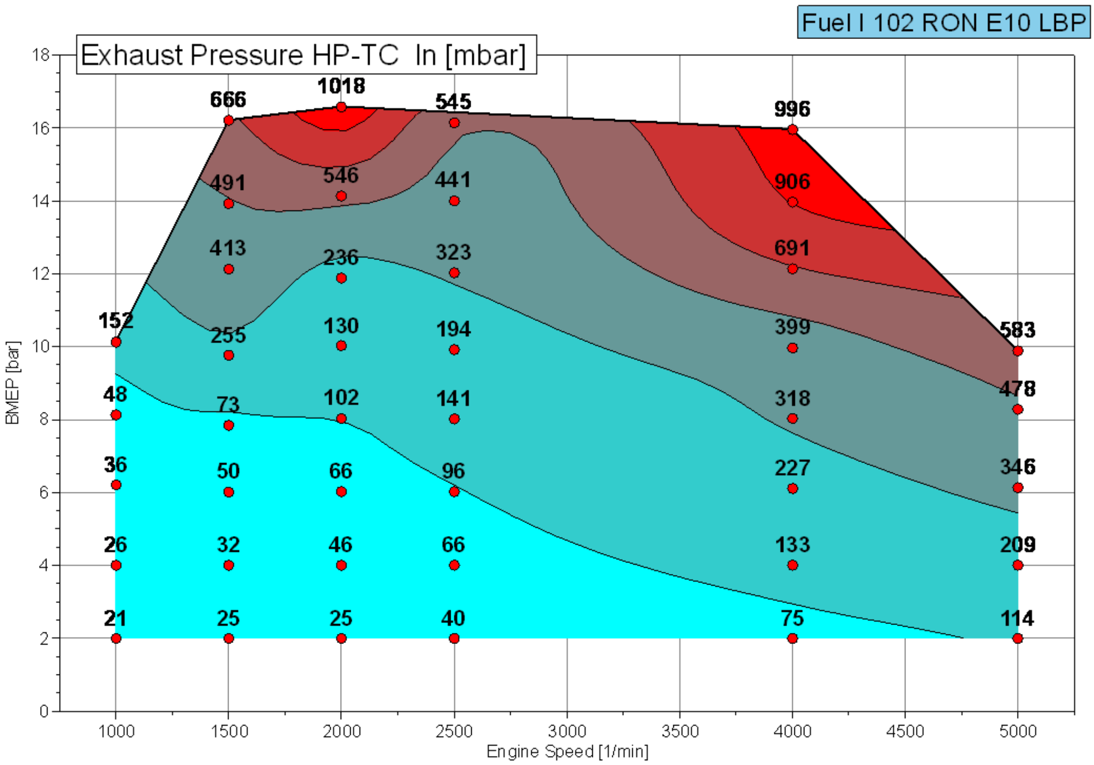

Figure 34: Exhaust Pressure High Pressure Turbocharger In

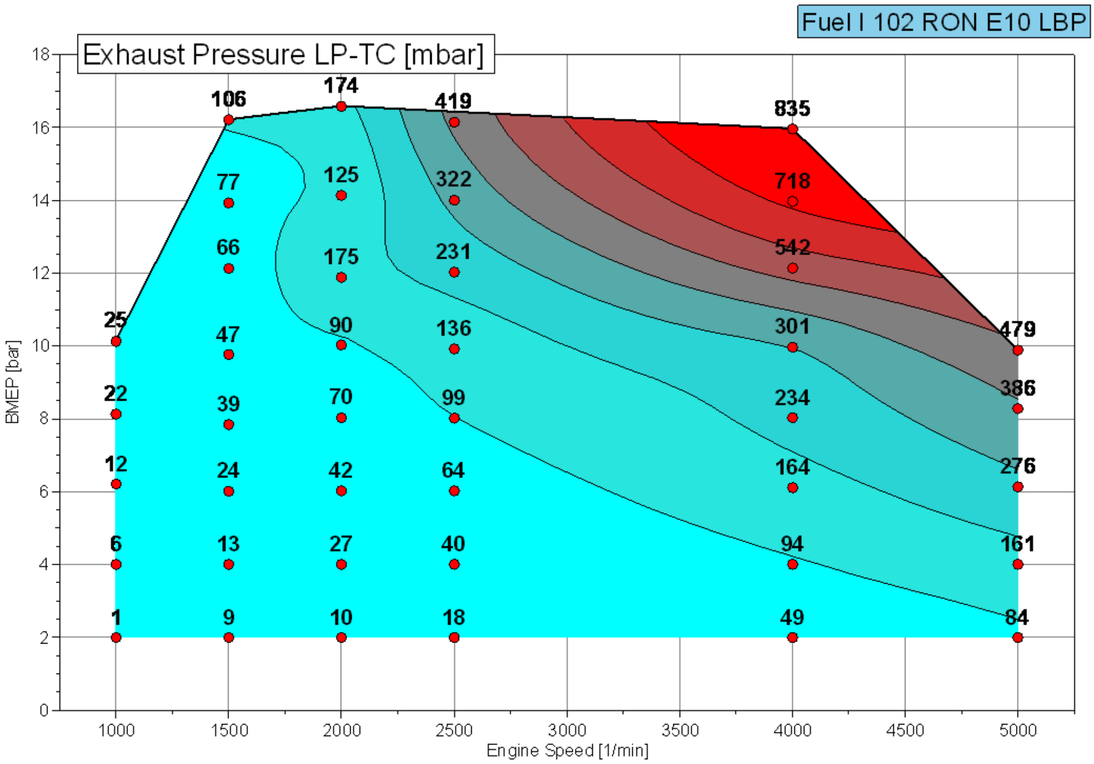

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

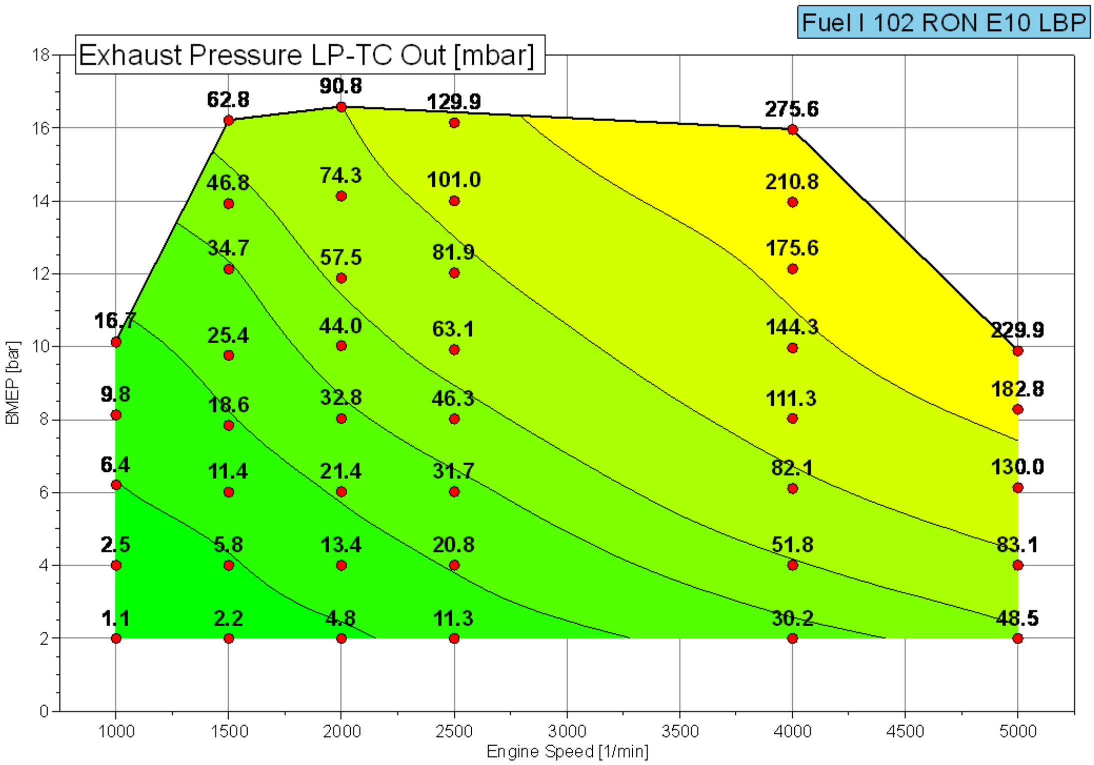

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

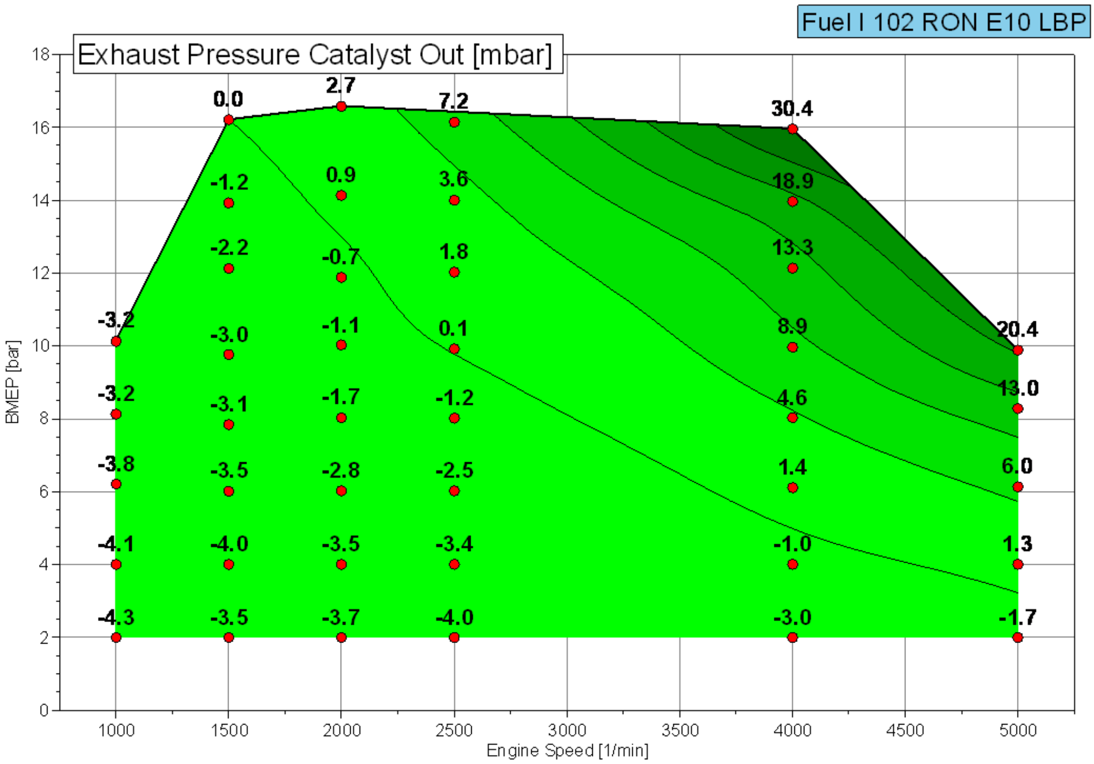

Figure 37: Exhaust Pressure Catalyst Out

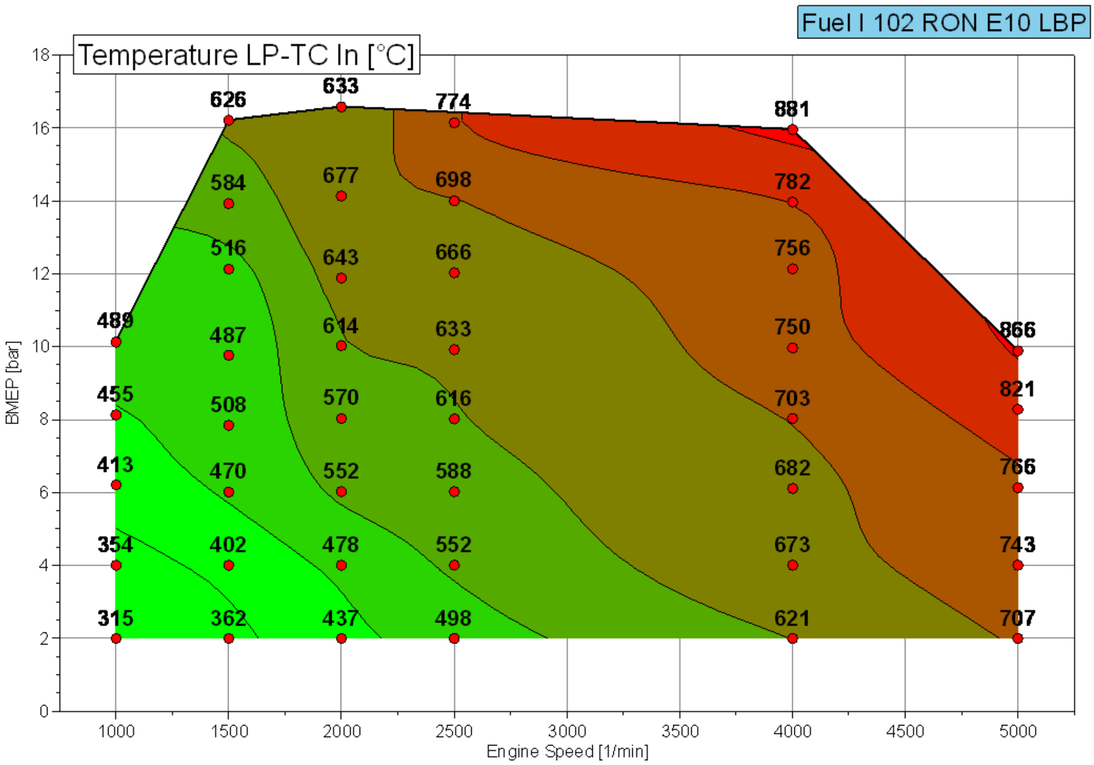

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

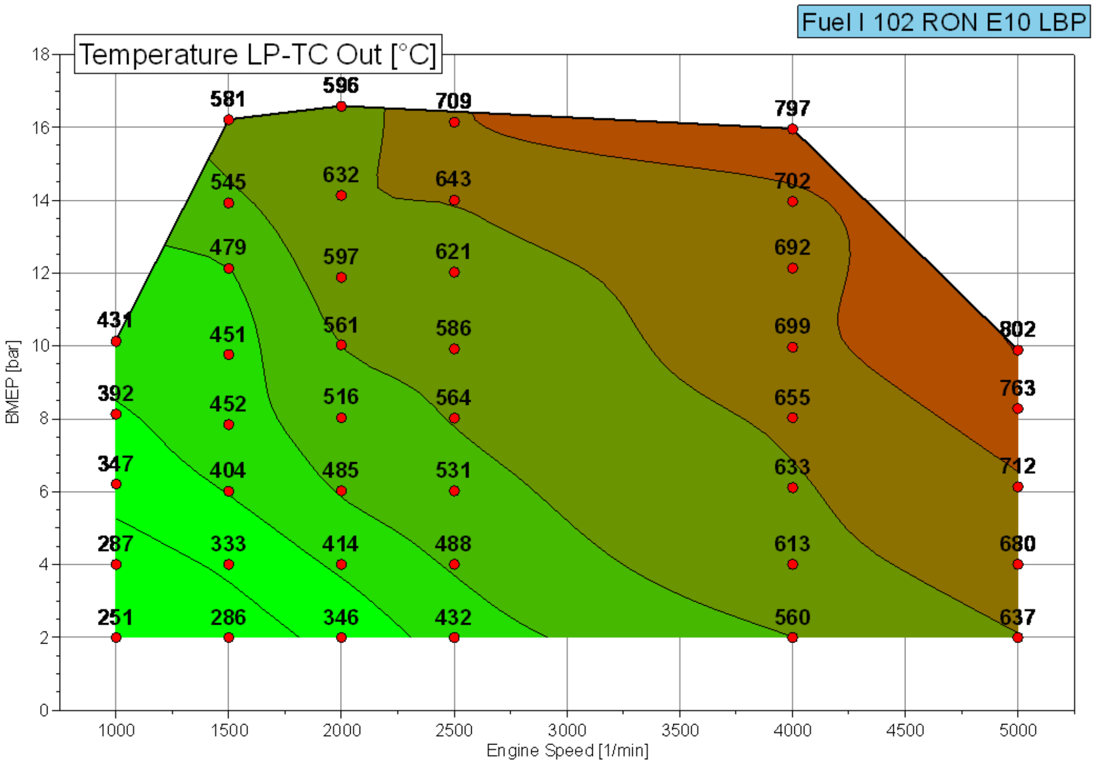

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

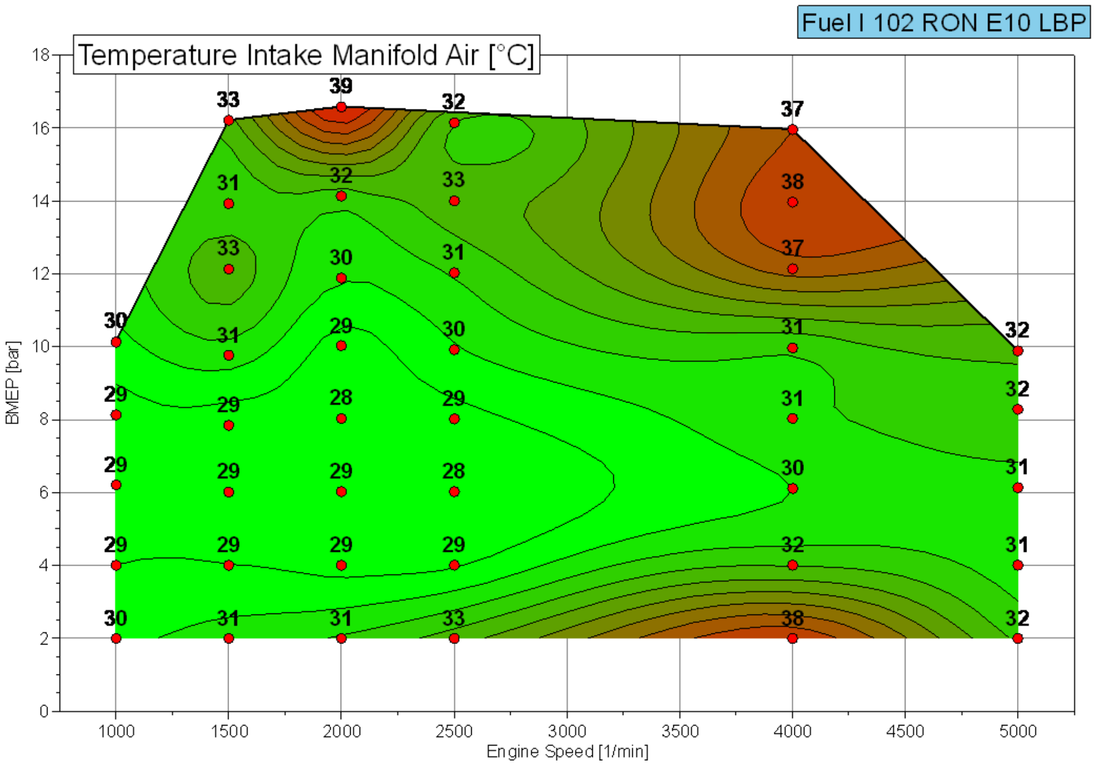

Figure 40: Intake Manifold Air Temperature

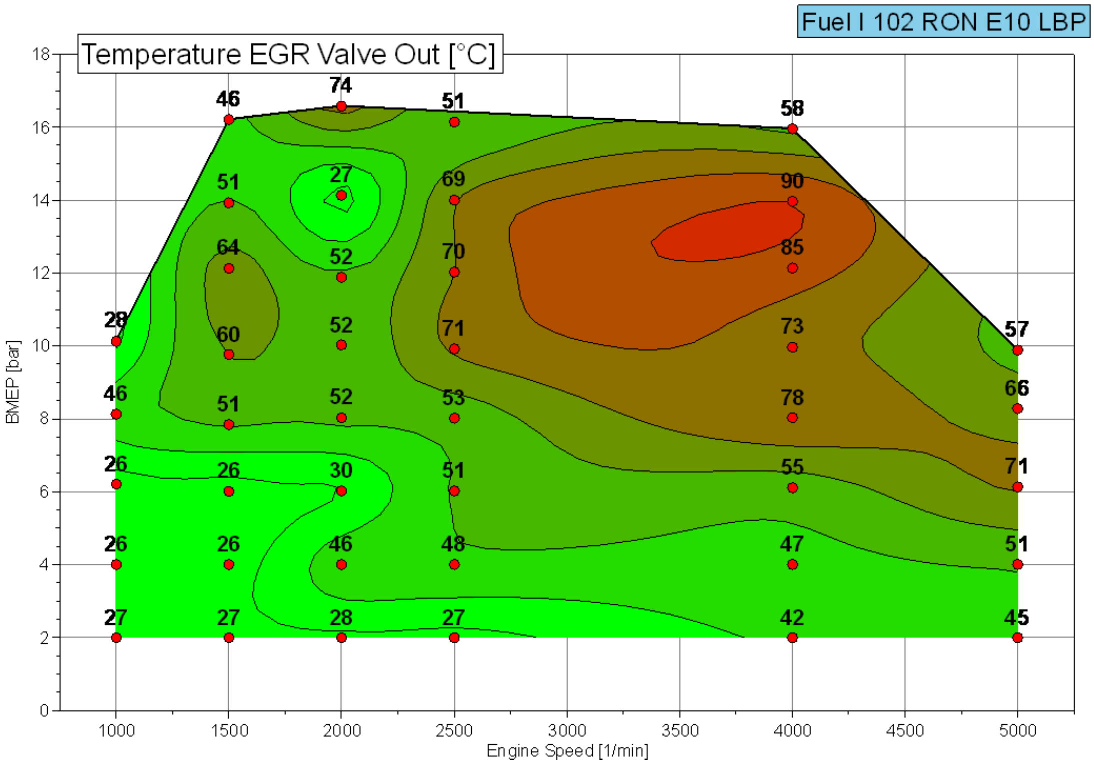

Figure 41: EGR Valve Out Temperature

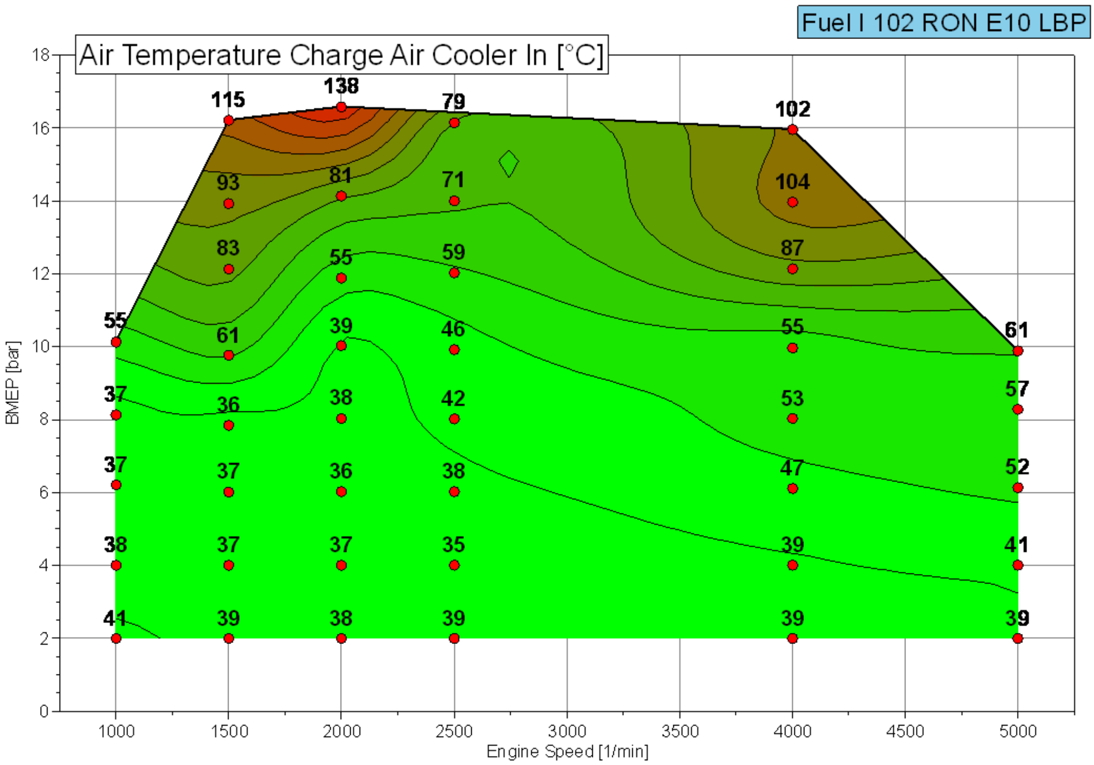

Figure 42: Charge Air Cooler Inlet Air Temperature

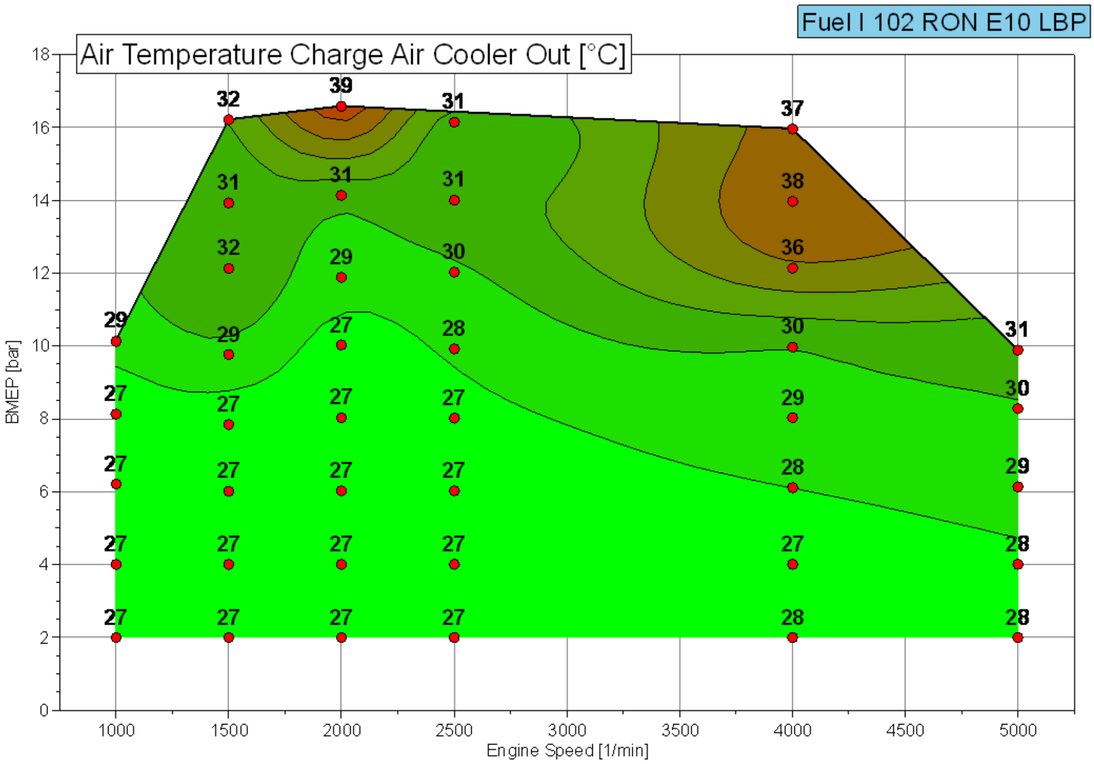

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel J Calibration Results

102 Ron 10% Ethanol High Boiling Point

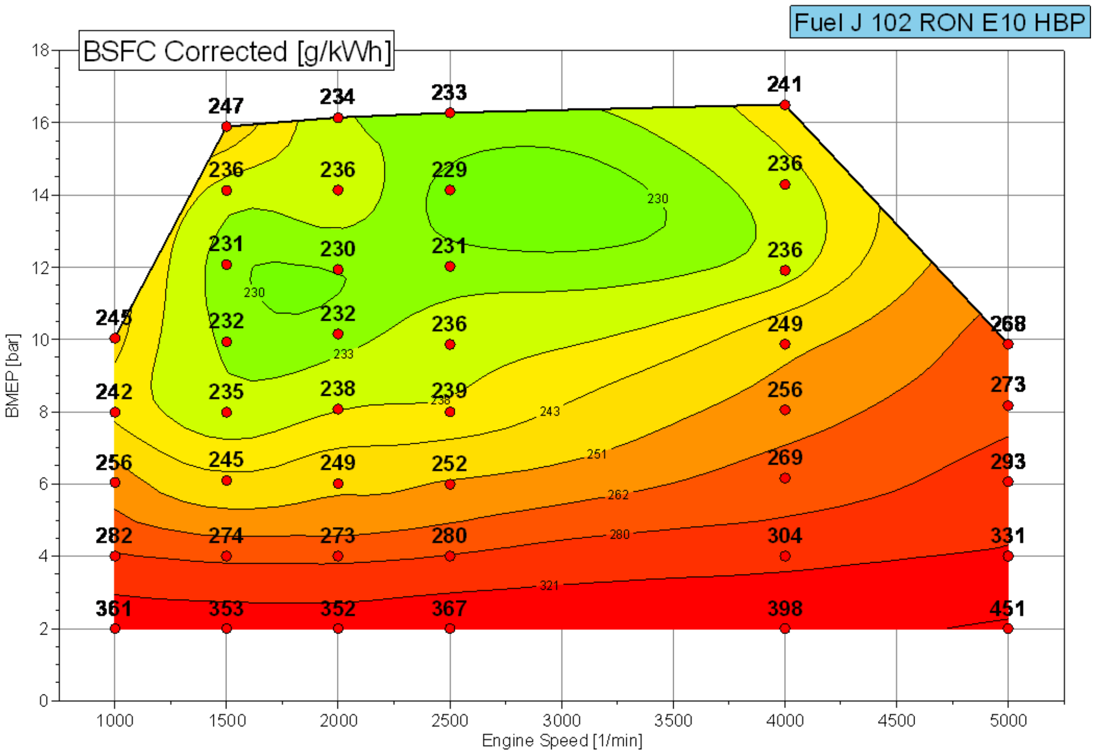

Figure 1: Brake Specific Fuel Consumption

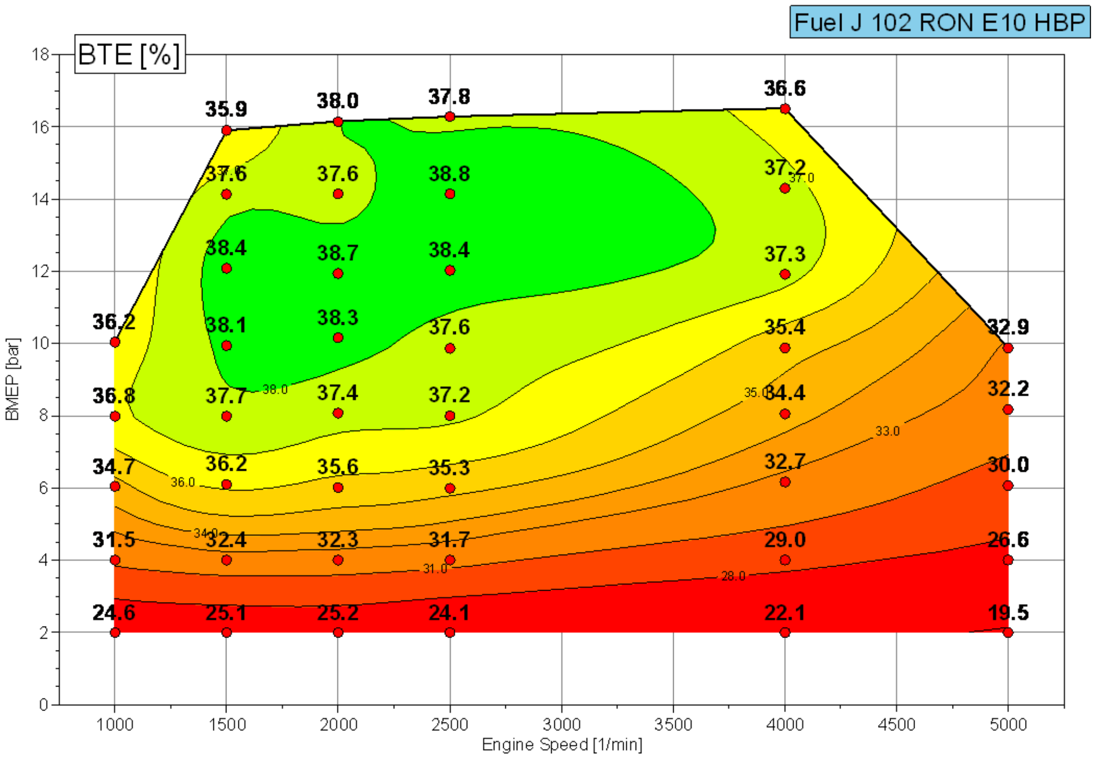

Figure 2: Brake Thermal Efficiency

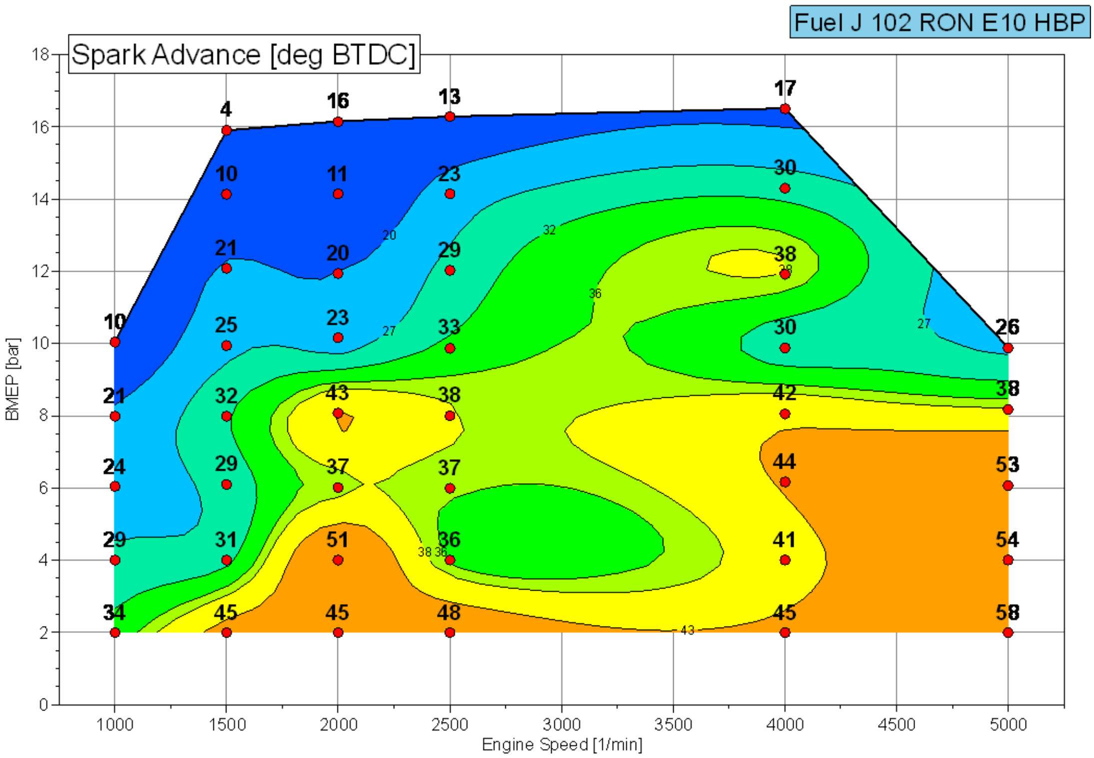

Figure 3: Spark Advance

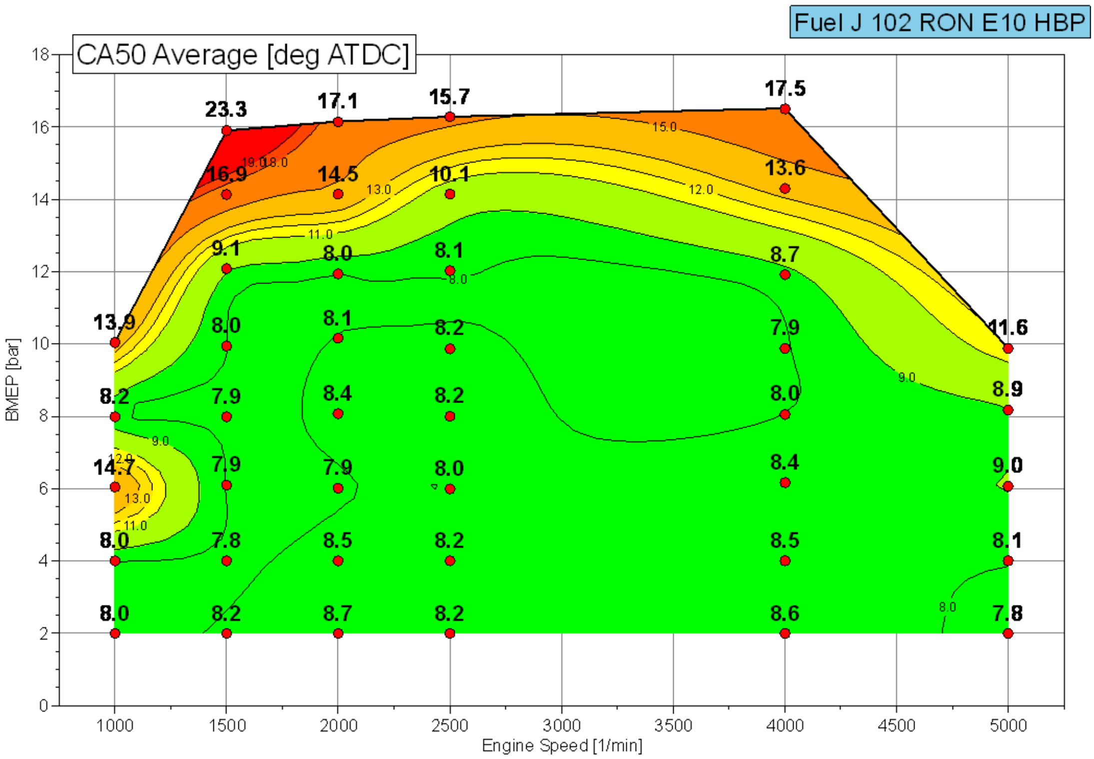

Figure 4: CA50 Average of Cylinders 1-4

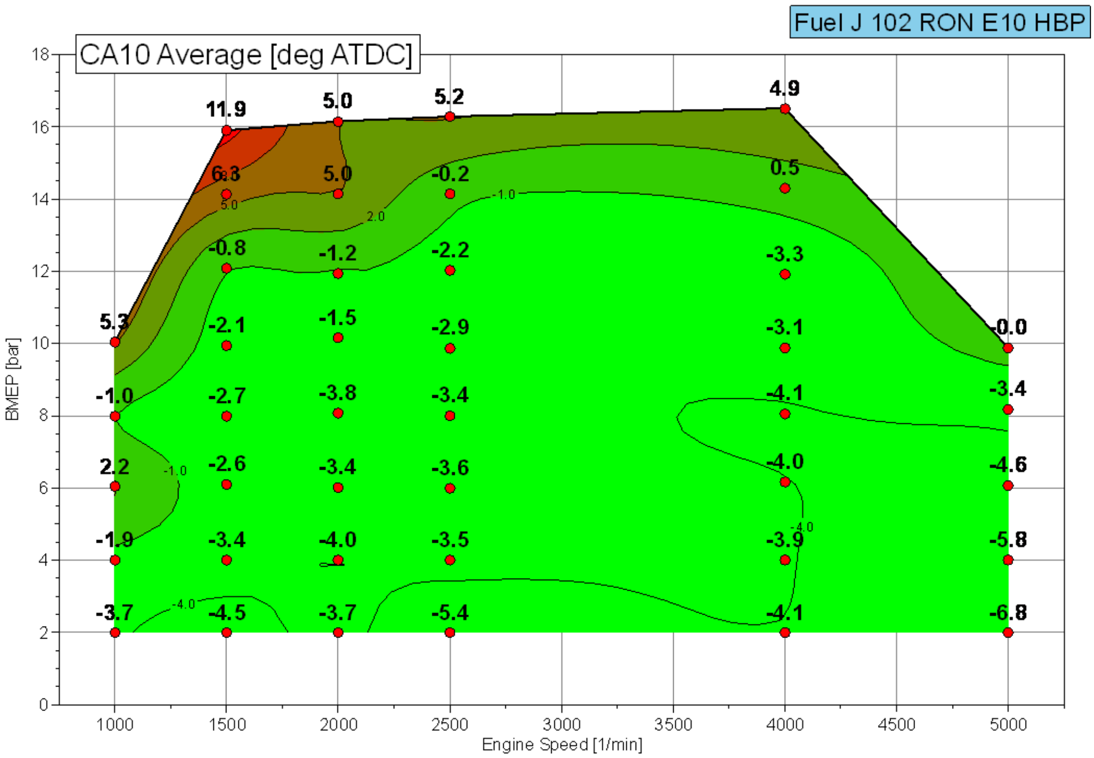

Figure 5: CA10 Average of Cylinders 1-4

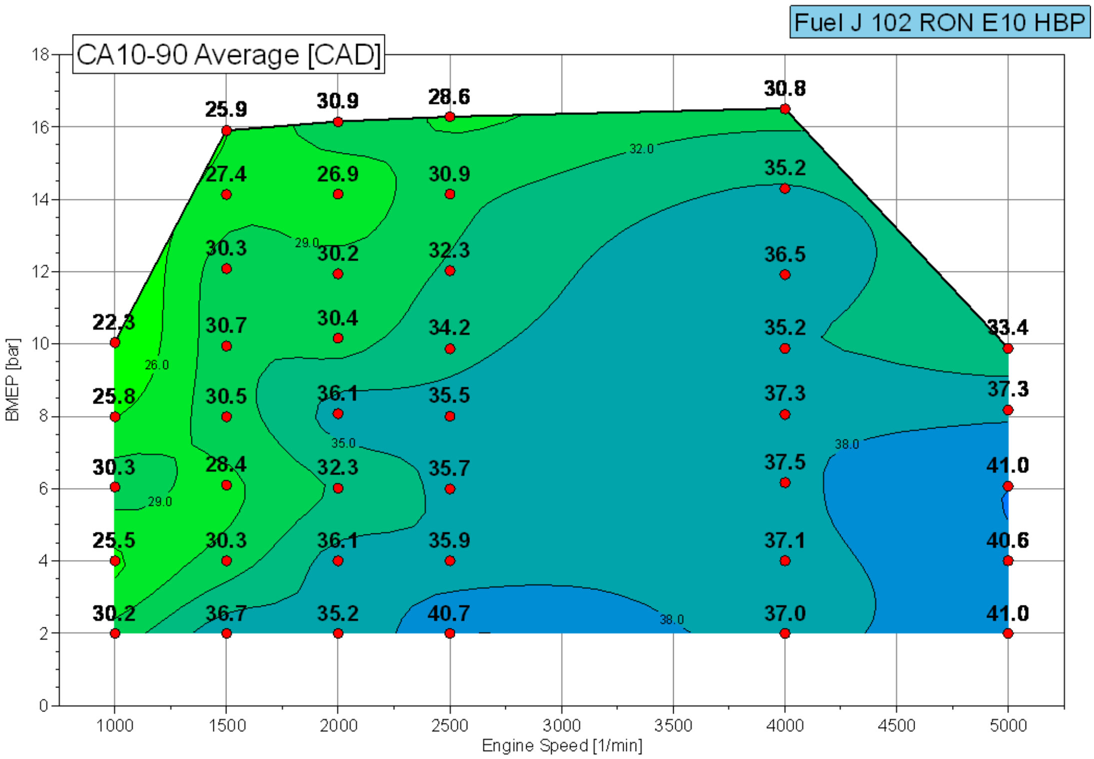

Figure 6: CA10-90 Average of Cylinders 1-4

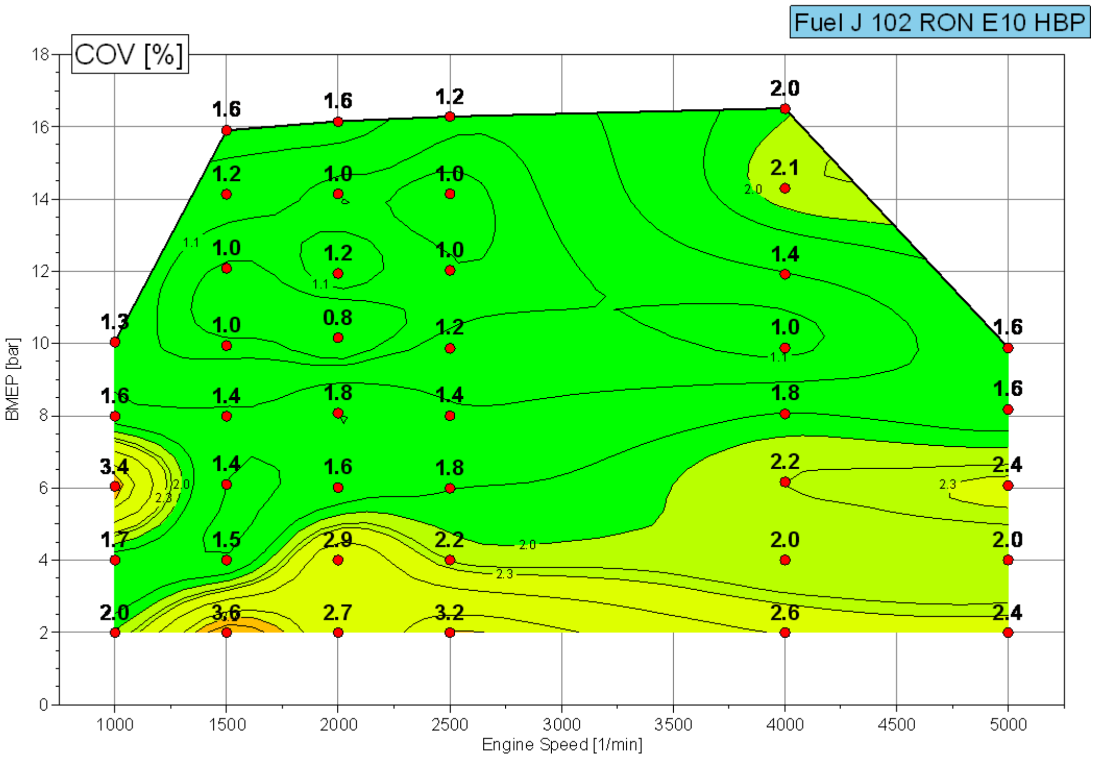

Figure 7: Coefficient of Variation Average of Cylinders 1-4

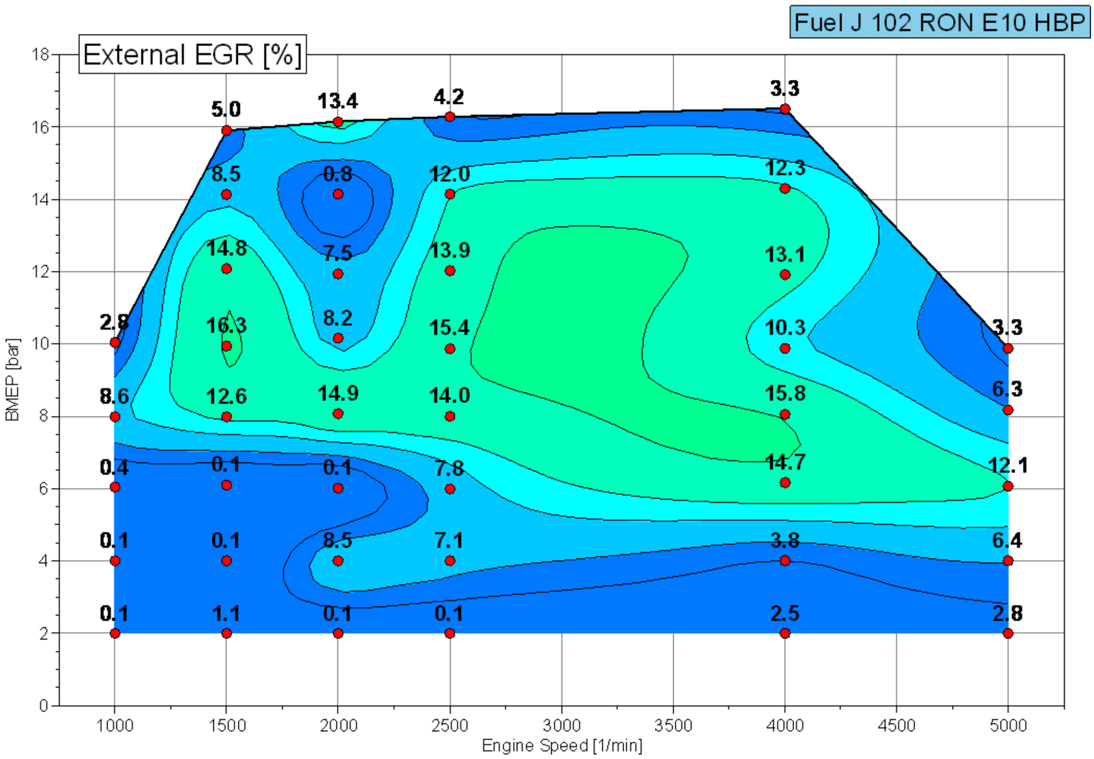

Figure 8: External EGR Percent of Intake Air

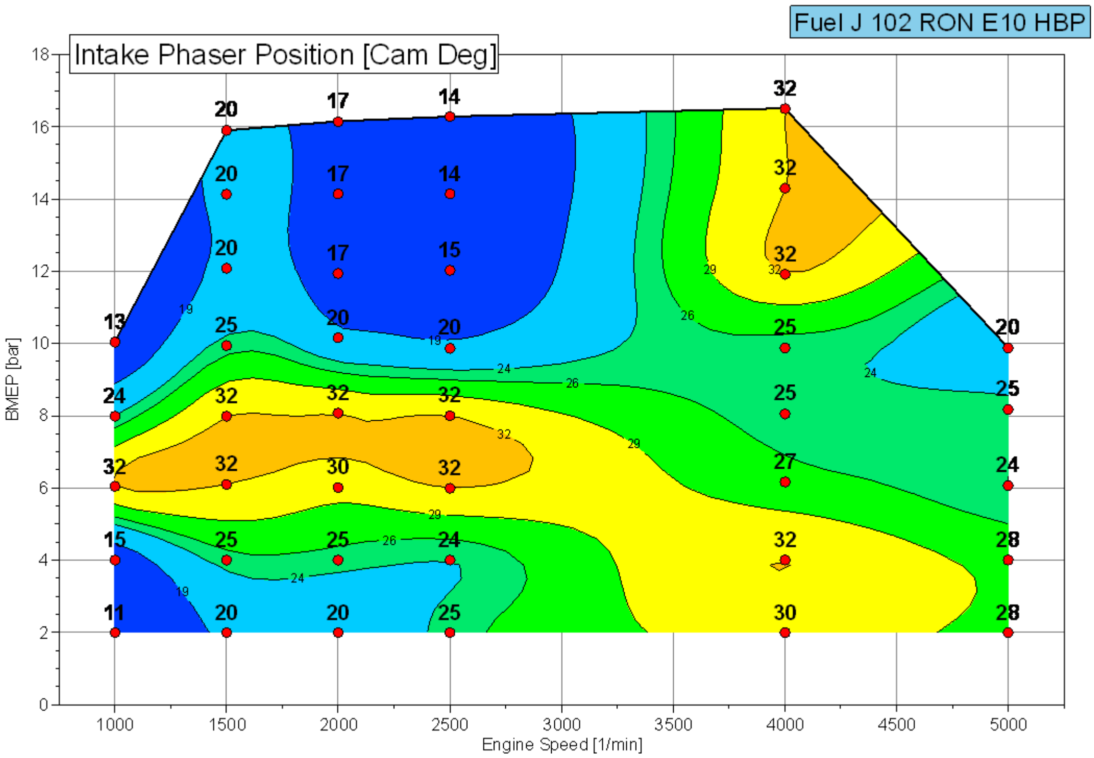

Figure 9: Intake Camshaft Phaser Position

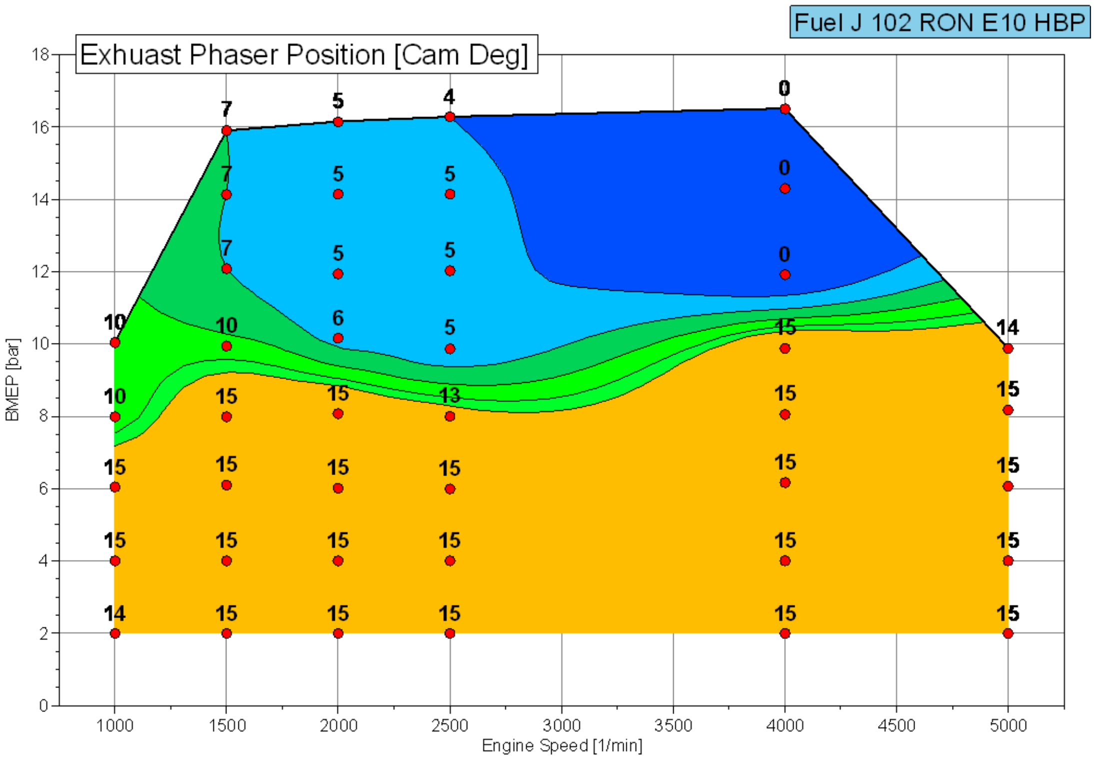

Figure 10: Exhaust Camshaft Phaser Position

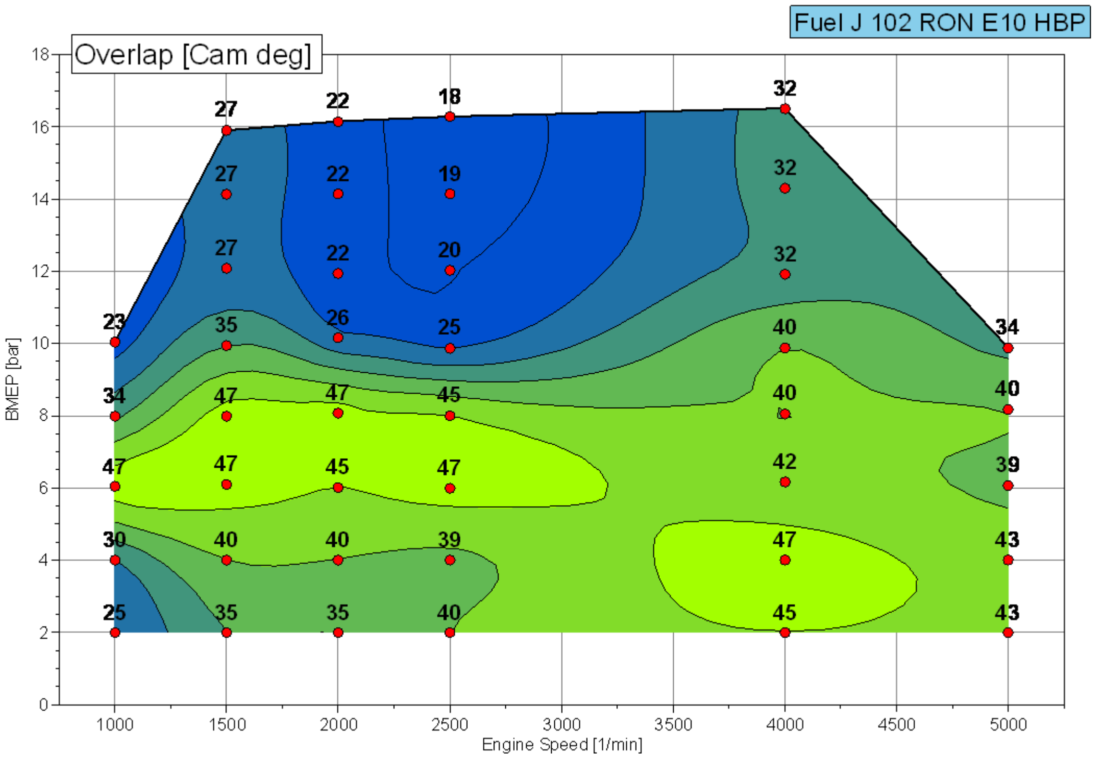

Figure 11: Camshaft Overlap

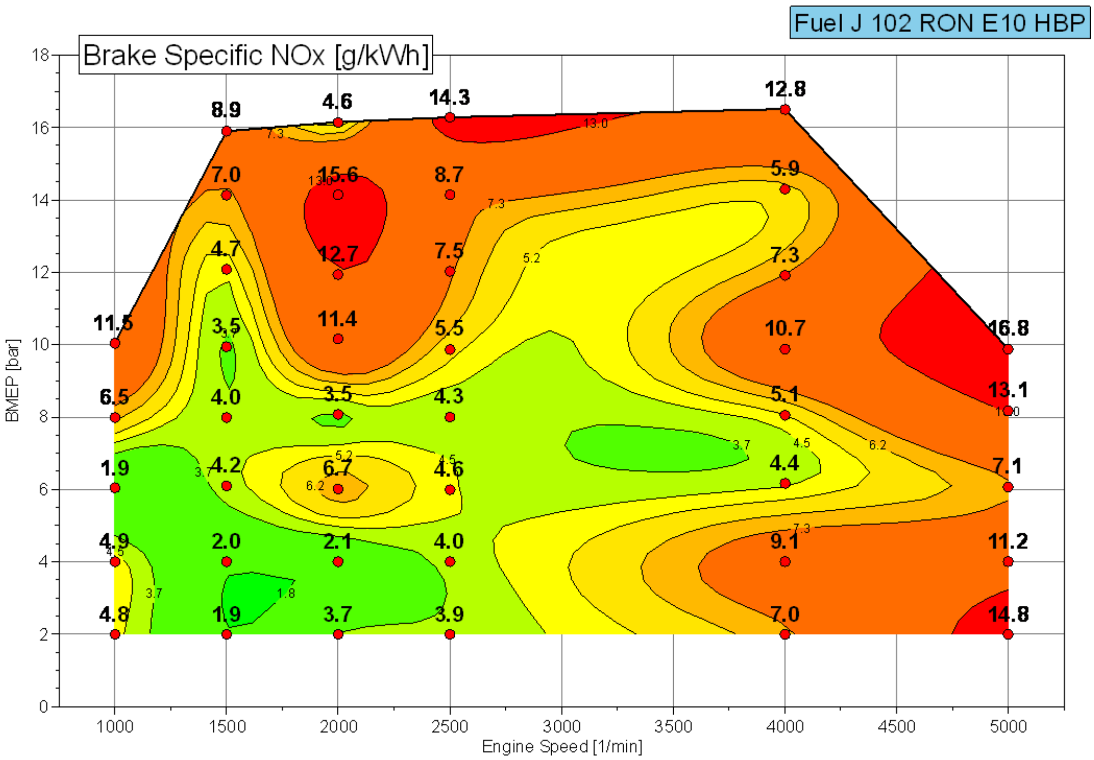

Figure 12: Brake Specific NOx Emissions

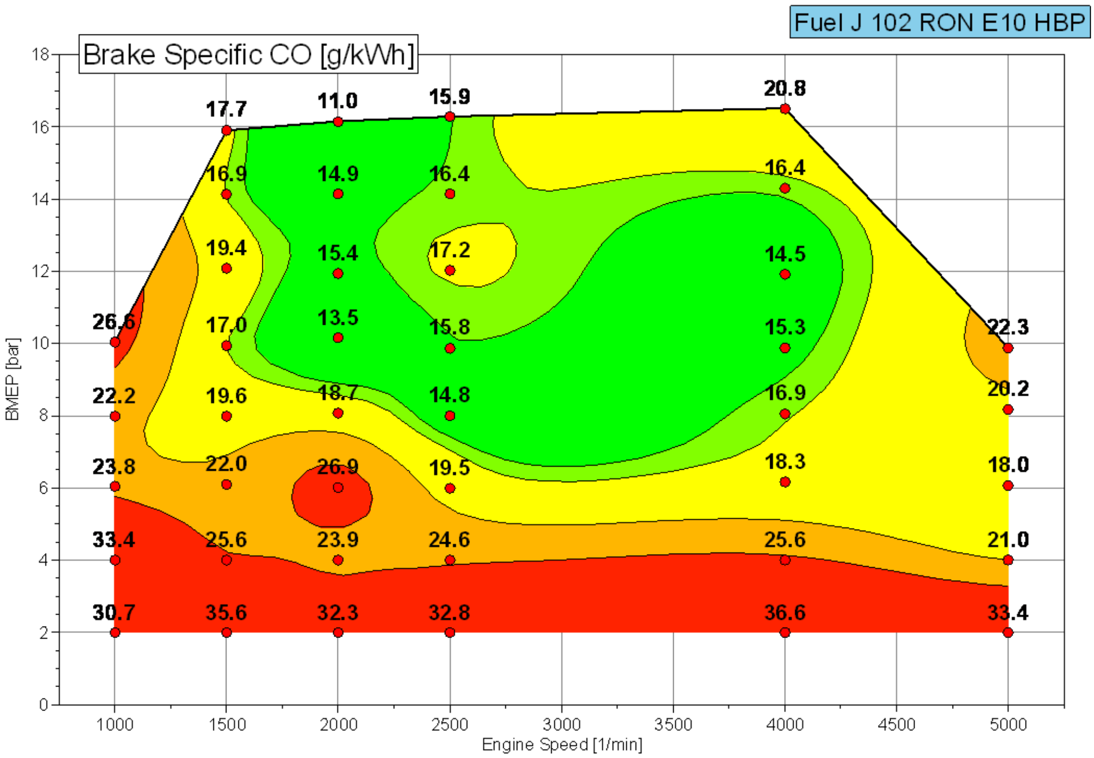

Figure 13: Brake Specific Carbon Monoxide Emissions

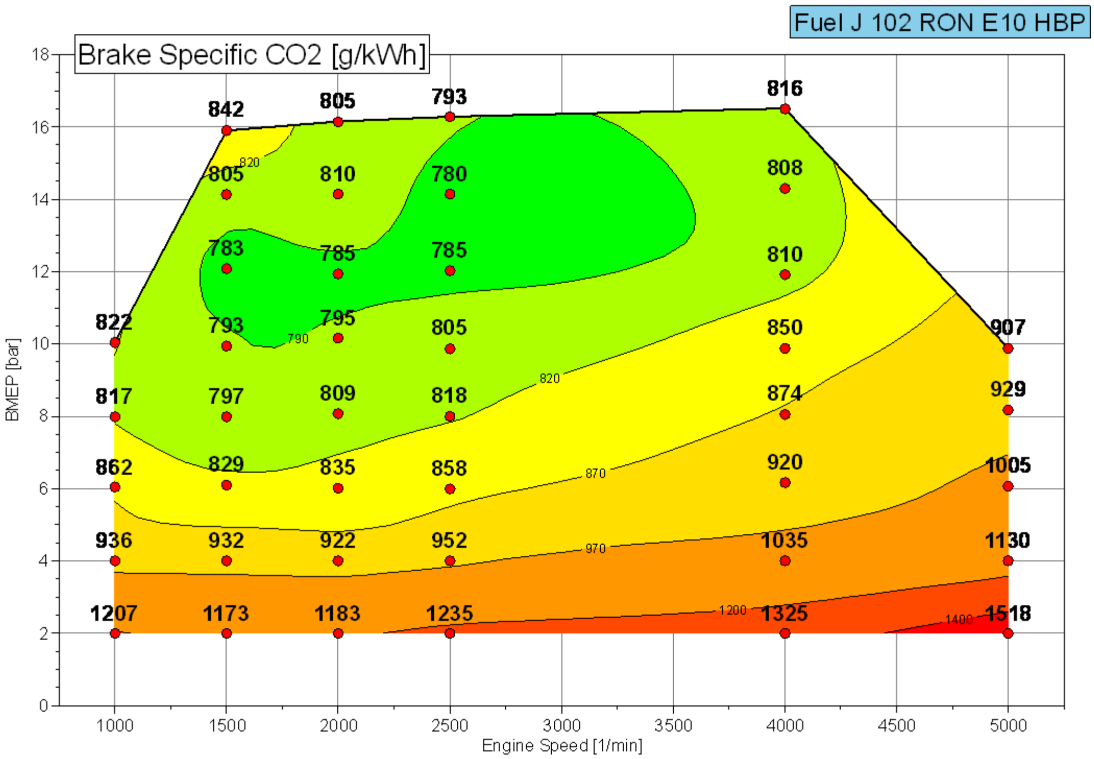

Figure 14: Brake Specific Carbon Dioxide Emissions

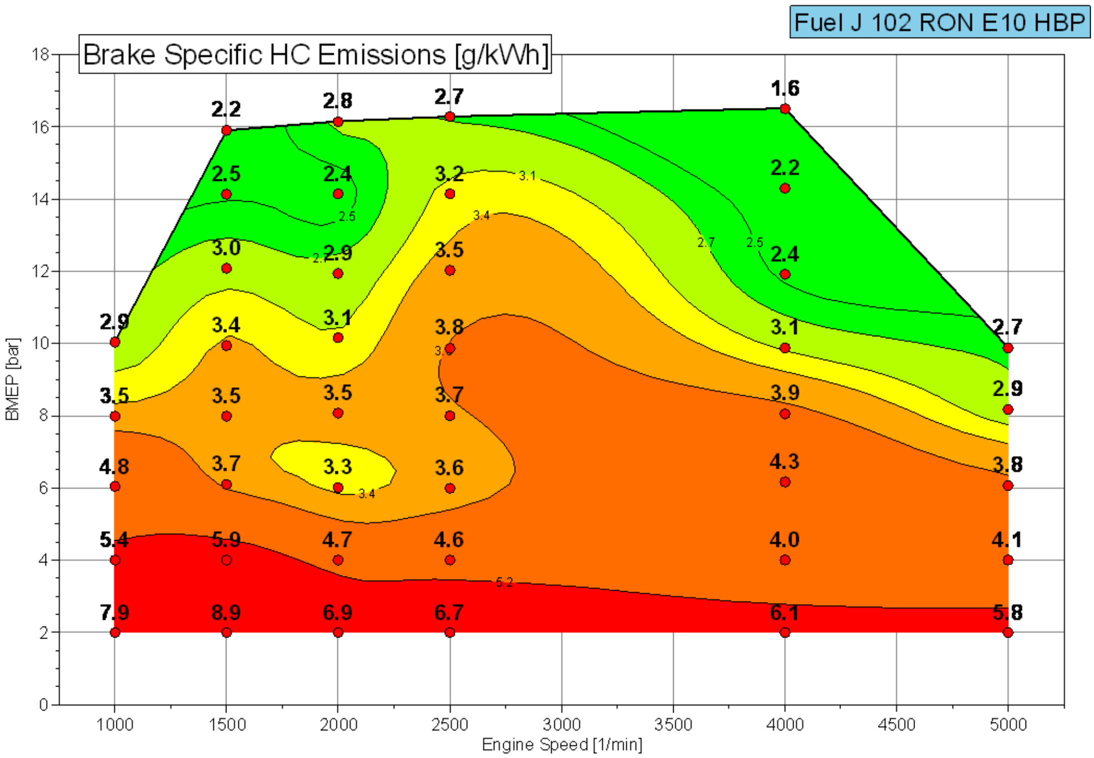

Figure 15: Brake Specific Hydrocarbon Emissions

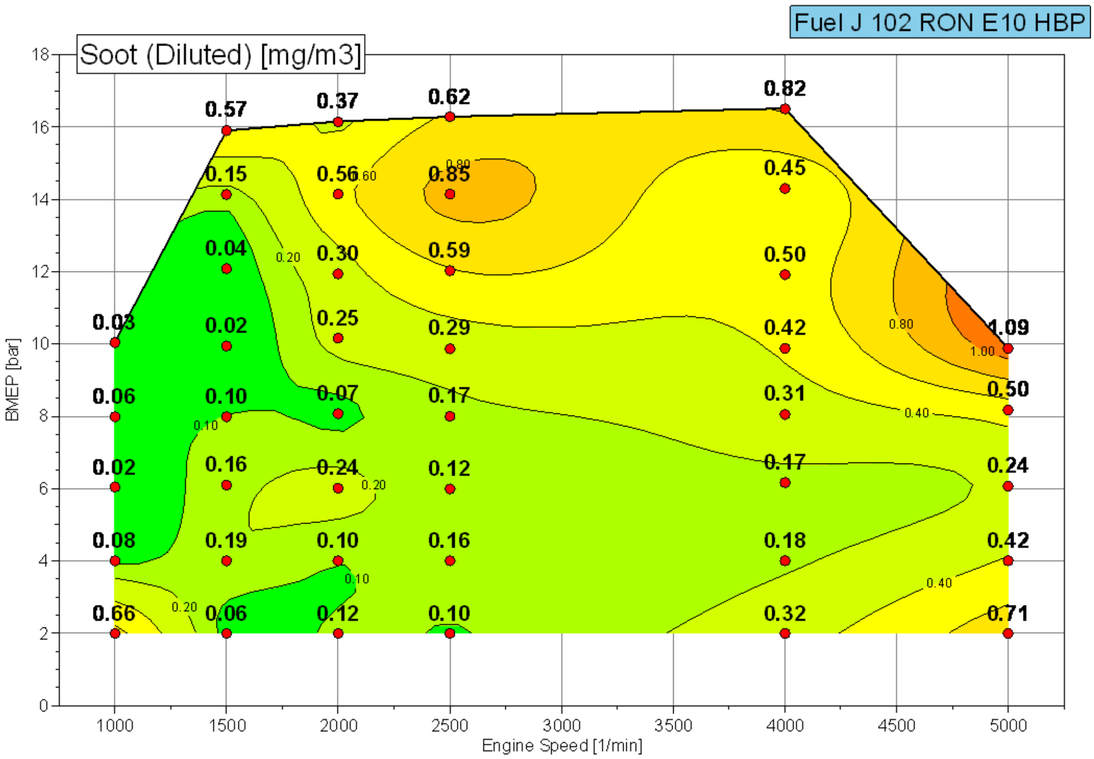

Figure 16: Particulate Soot Emissions

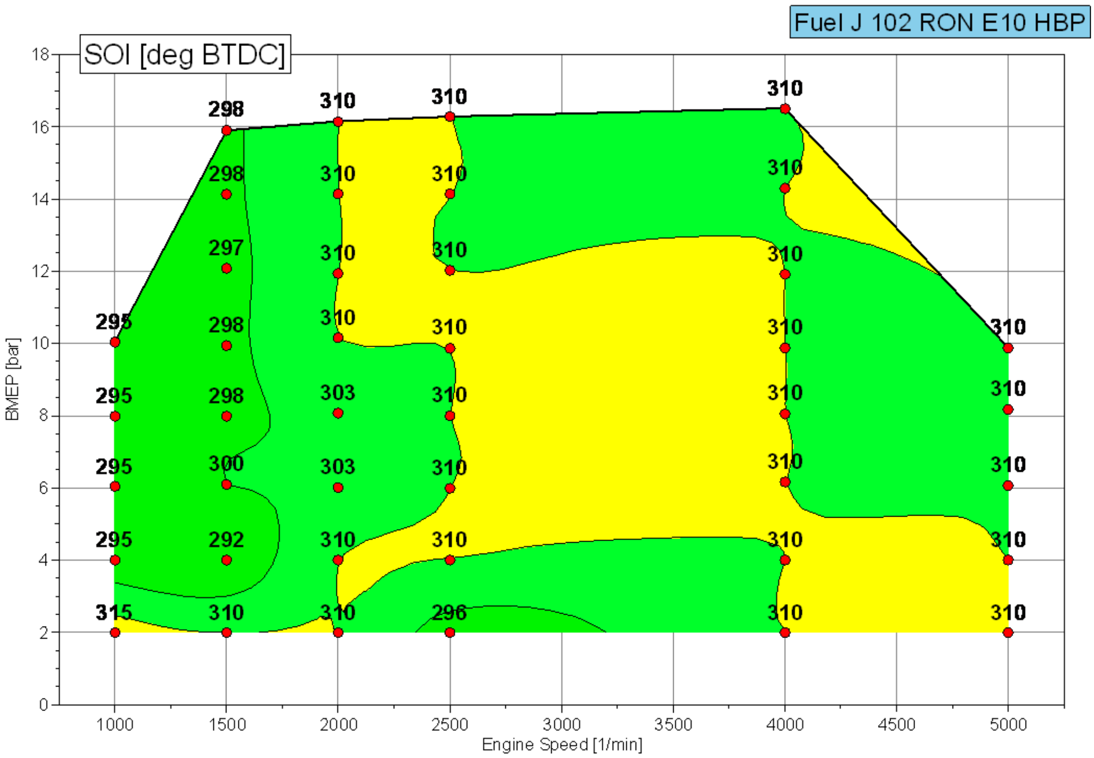

Figure 17: Start of Injection

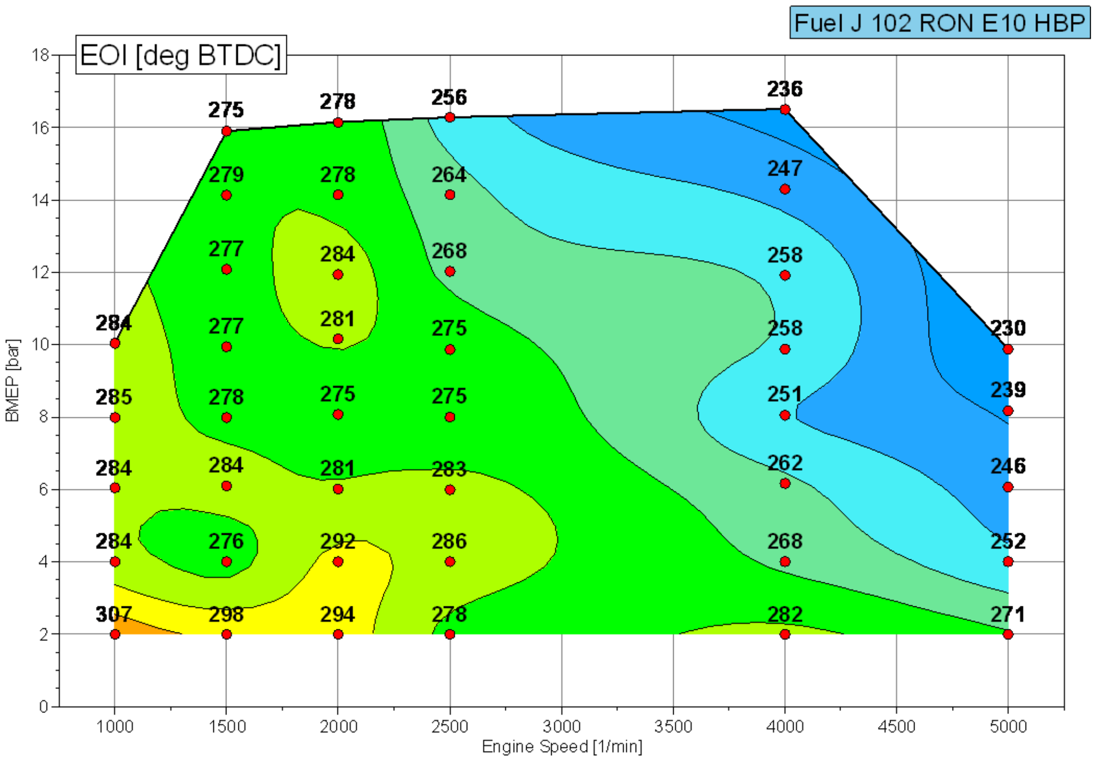

Figure 18: End of Injection

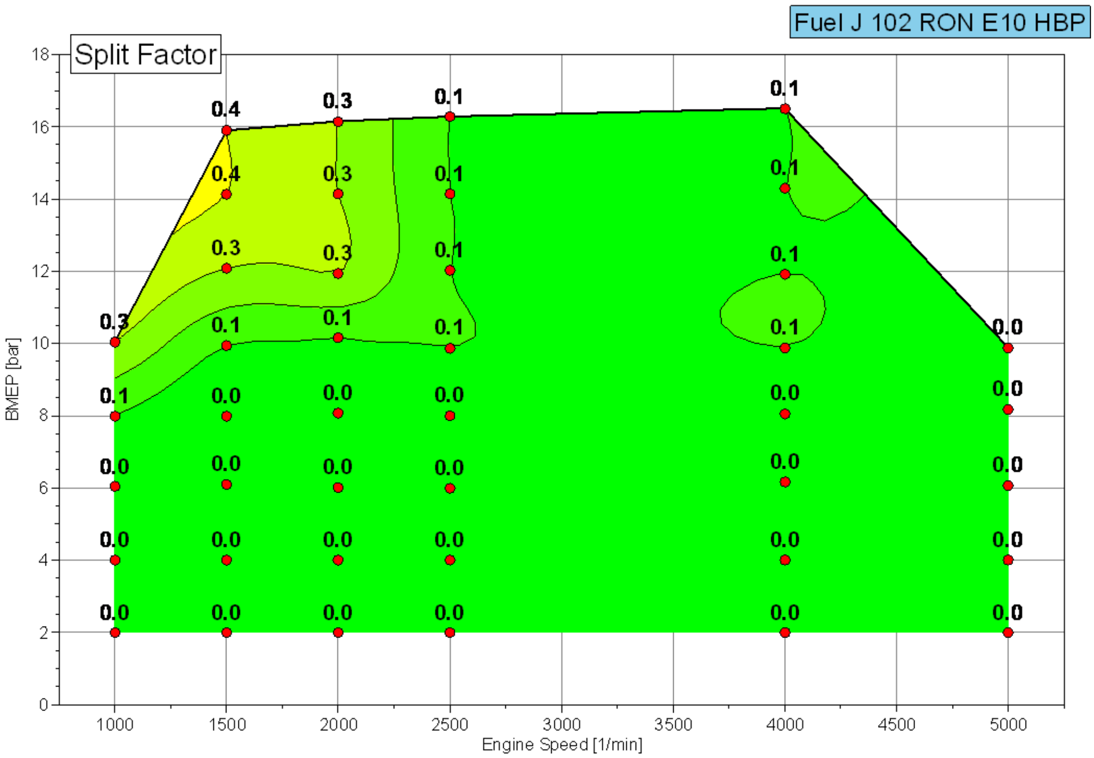

Figure 19: Injection Split Factor

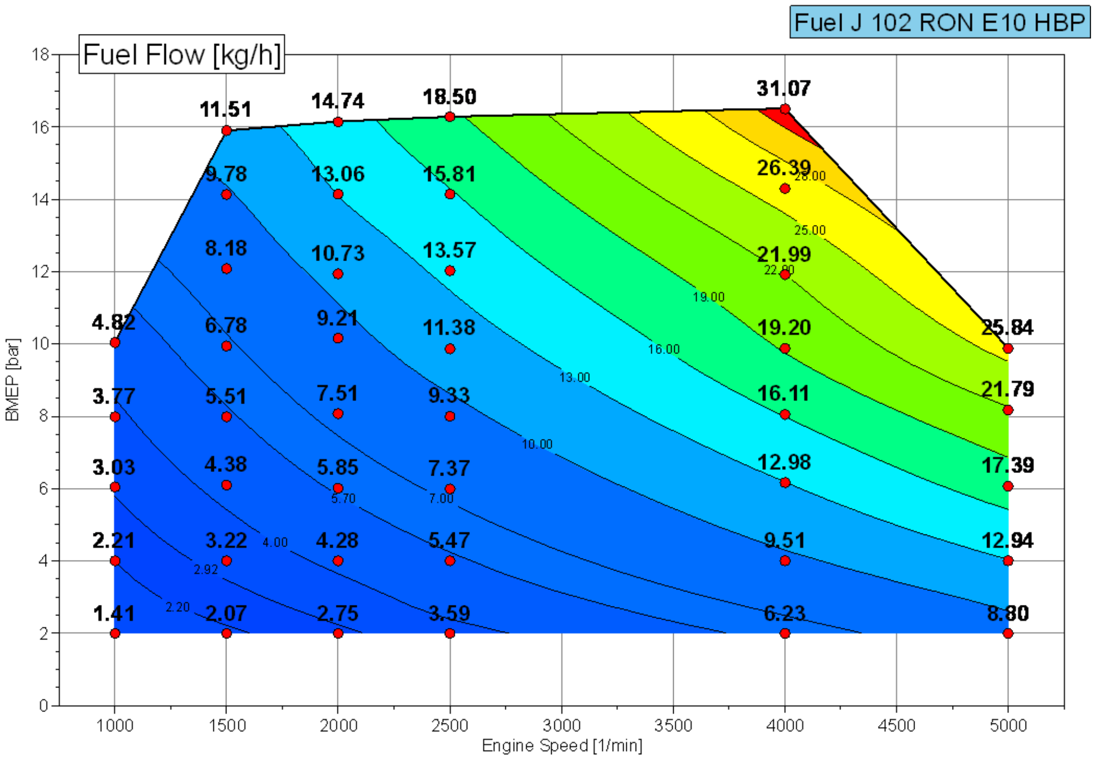

Figure 20: Fuel Flow

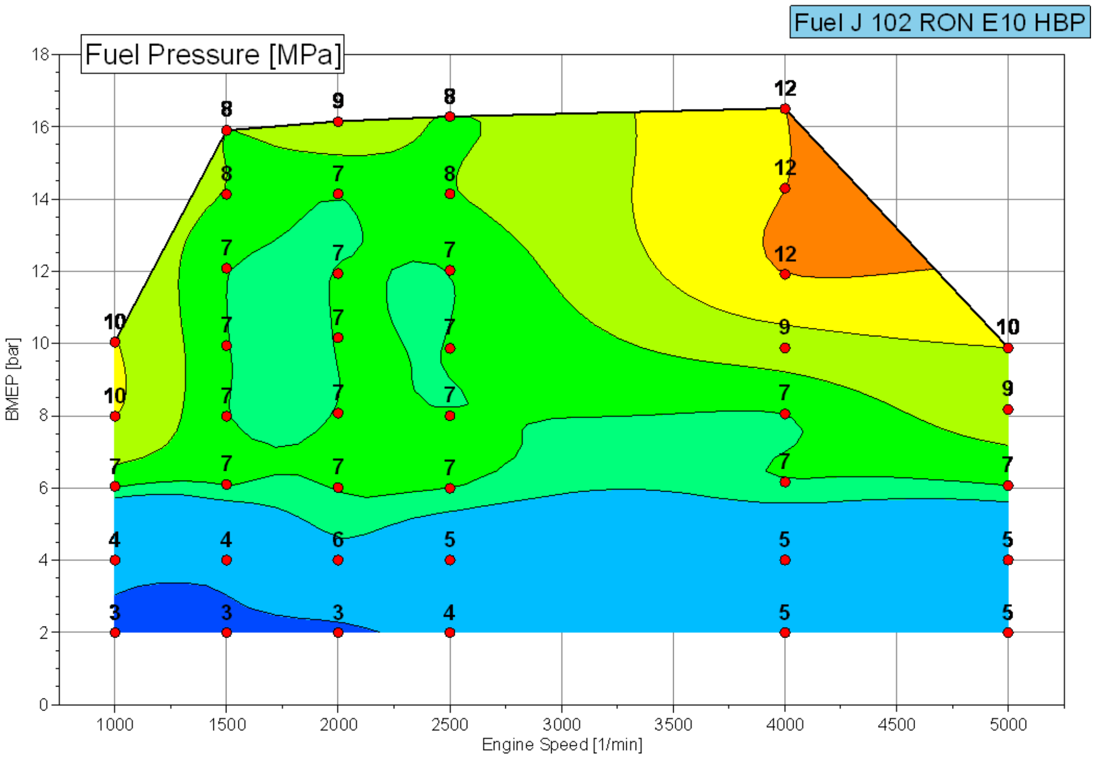

Figure 21: Fuel Rail Pressure

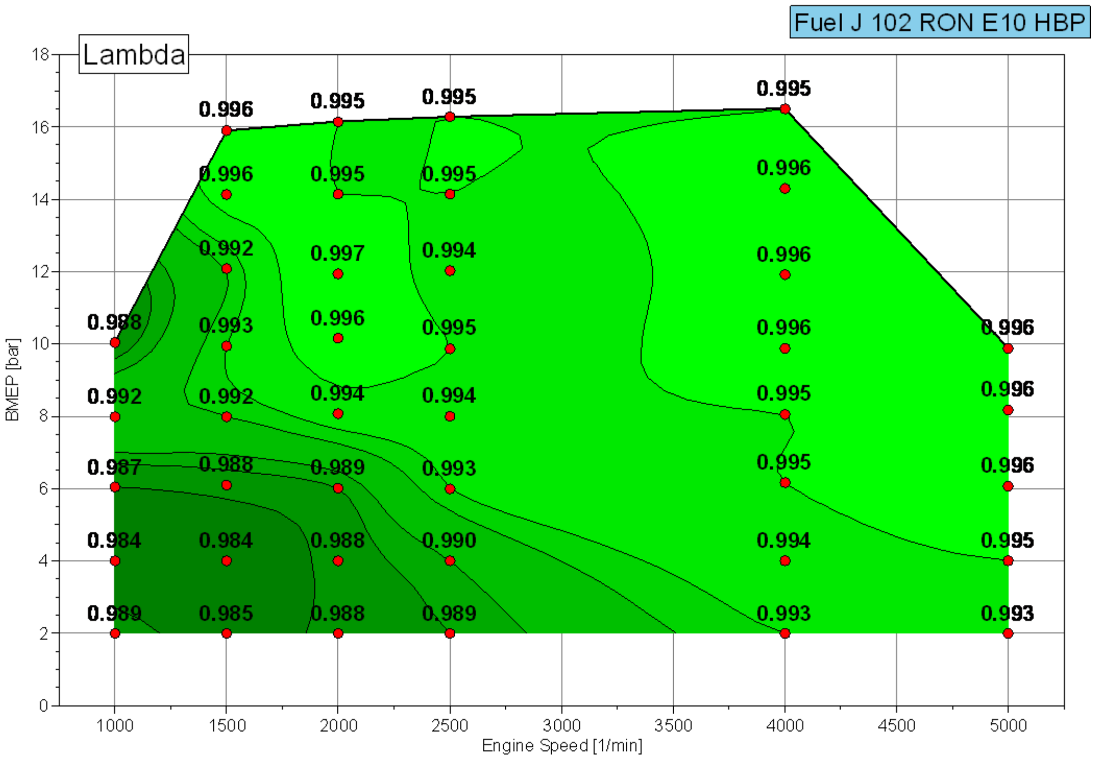

Figure 22: Lambda

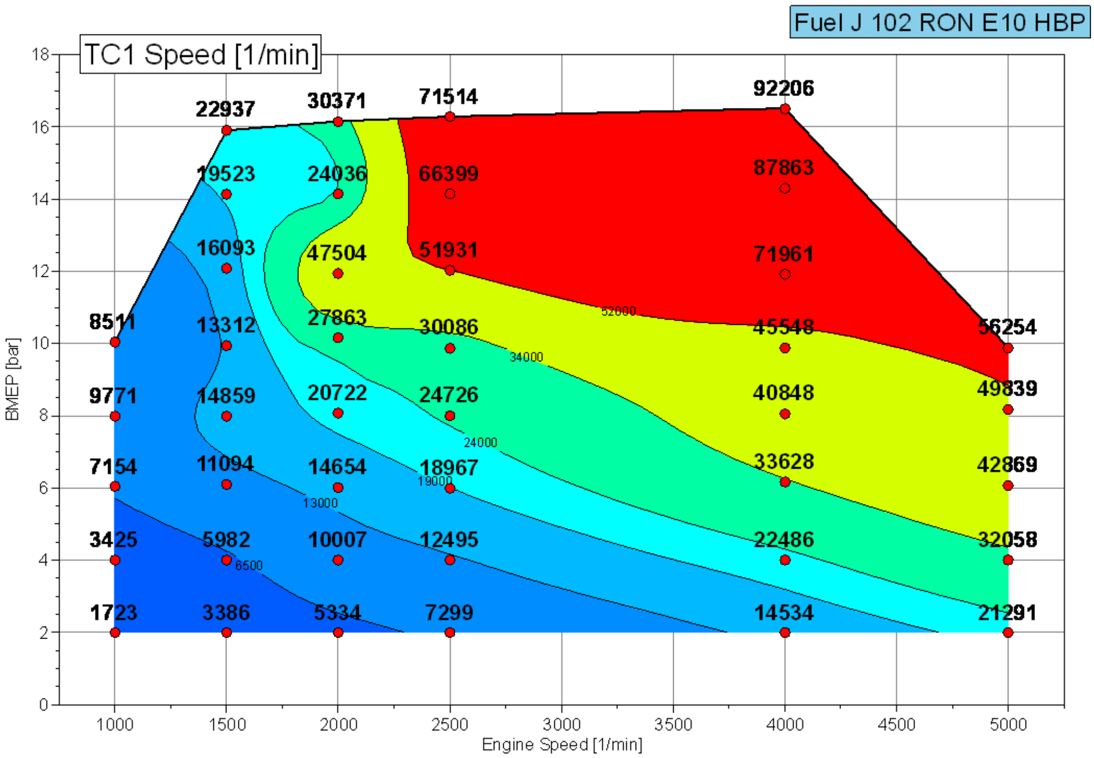

Figure 23: Low Pressure Turbocharger Speed

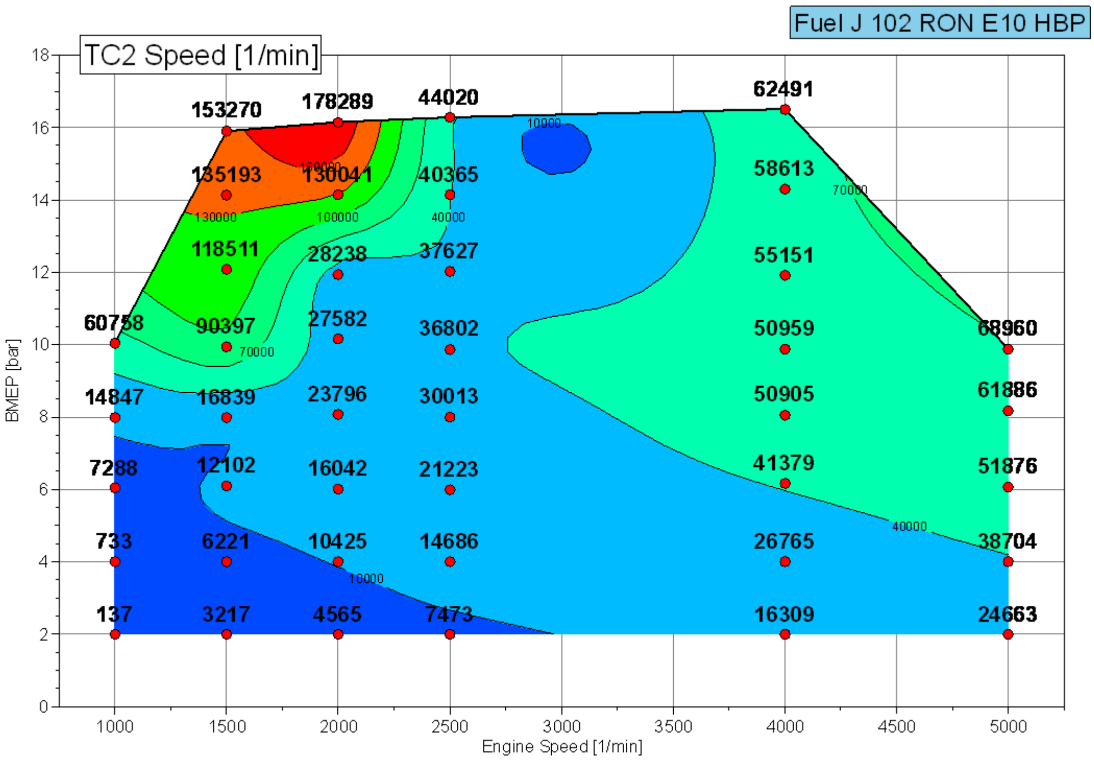

Figure 24: High Pressure Turbocharge Speed

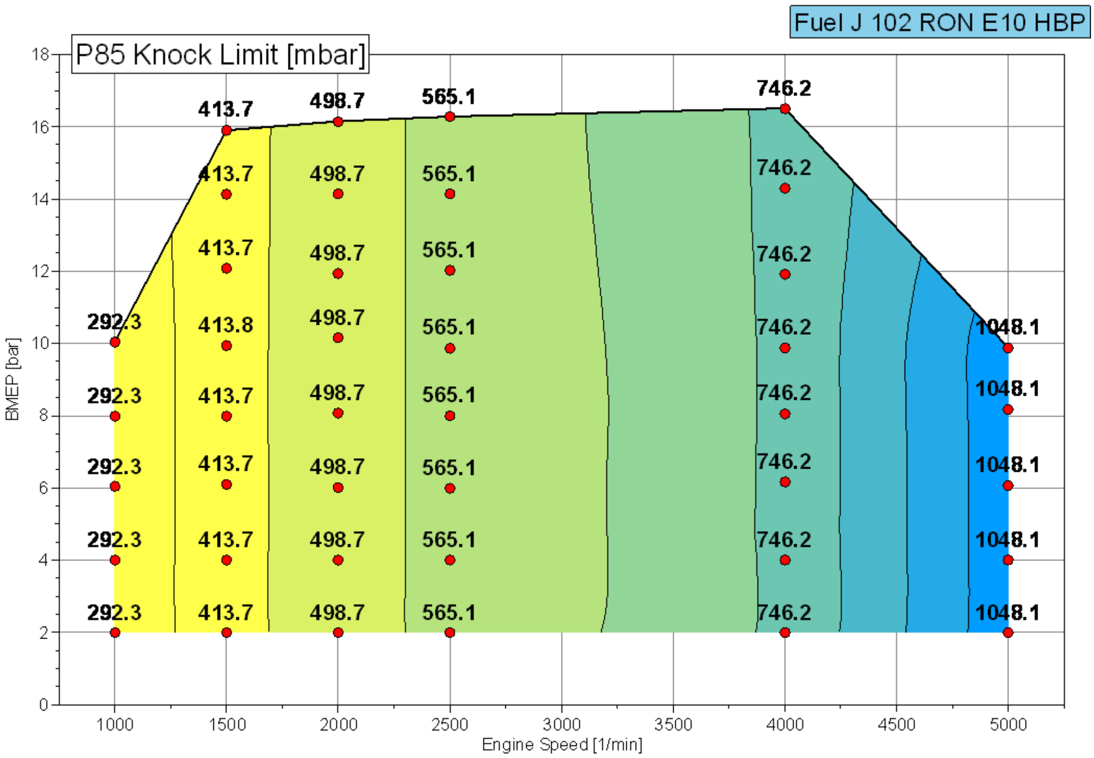

Figure 25: P85 Knock Limit

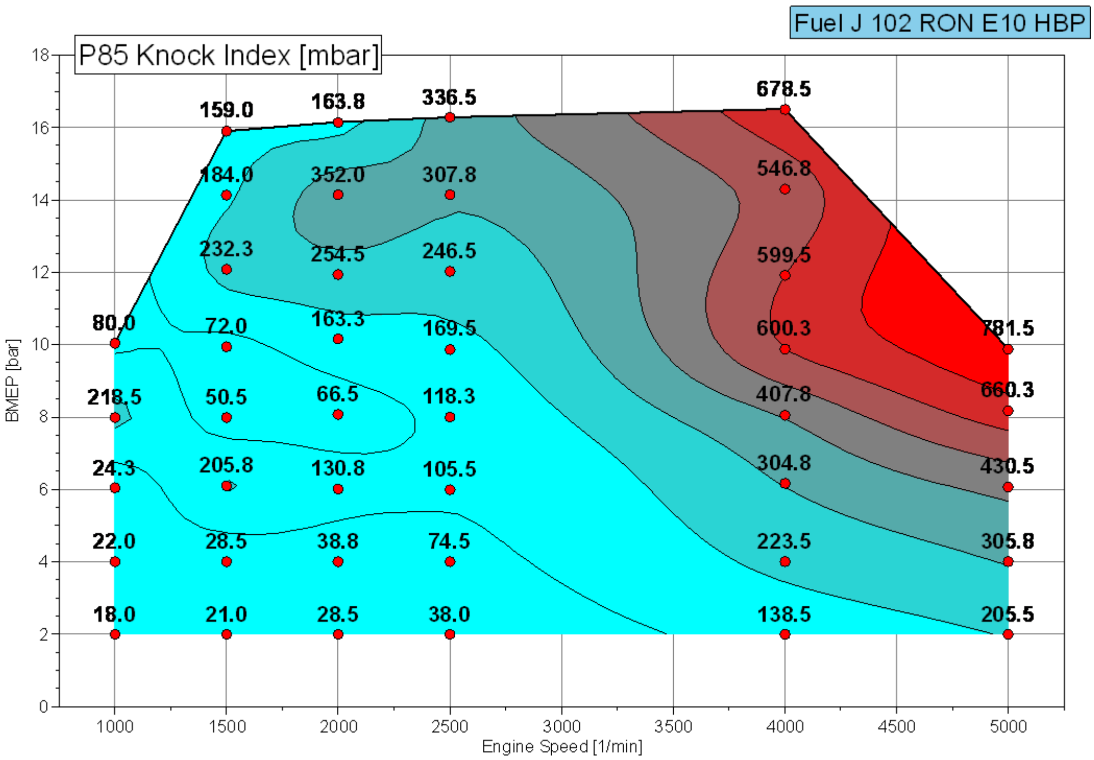

Figure 26: Averaged P85 Knock Index

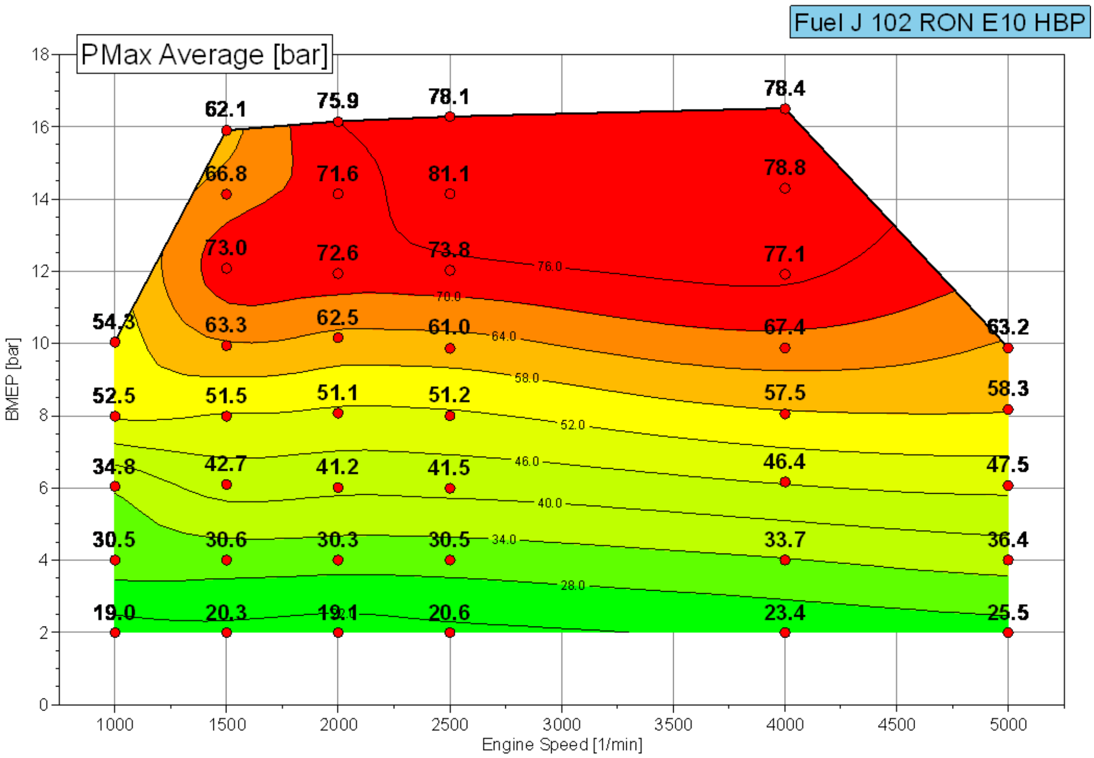

Figure 27: Averaged Max Pressure for Cylinders 1-4

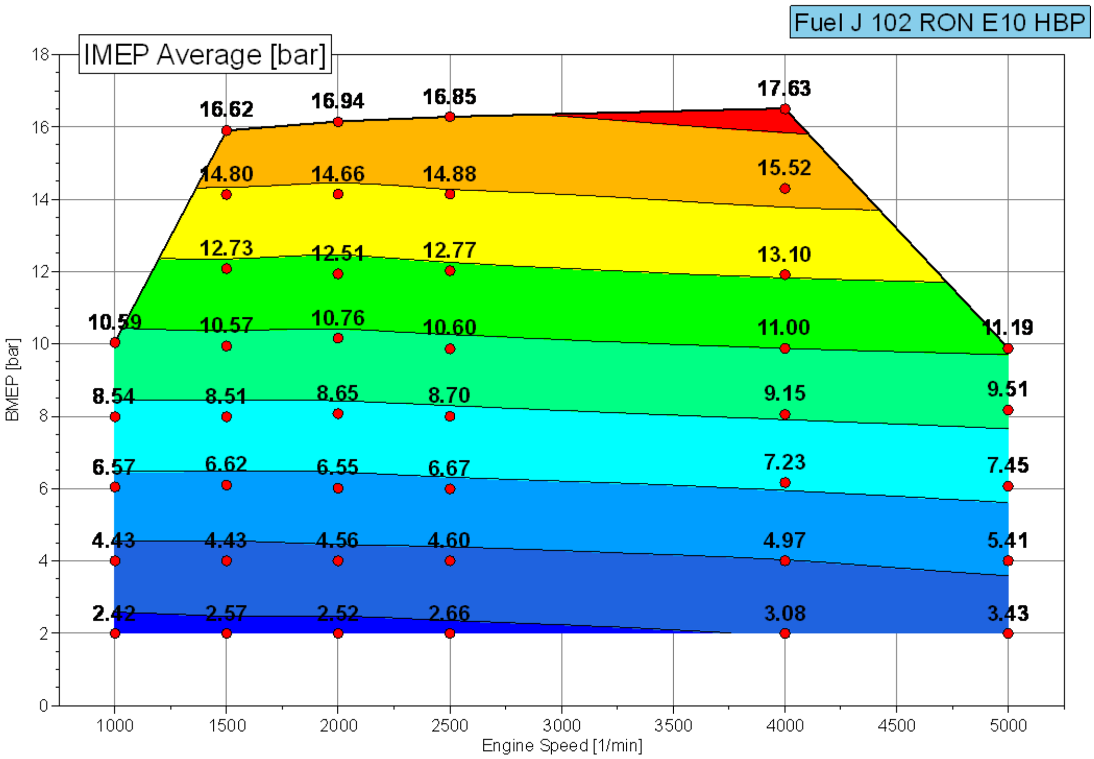

Figure 28: Indicated Mean Effective Pressure

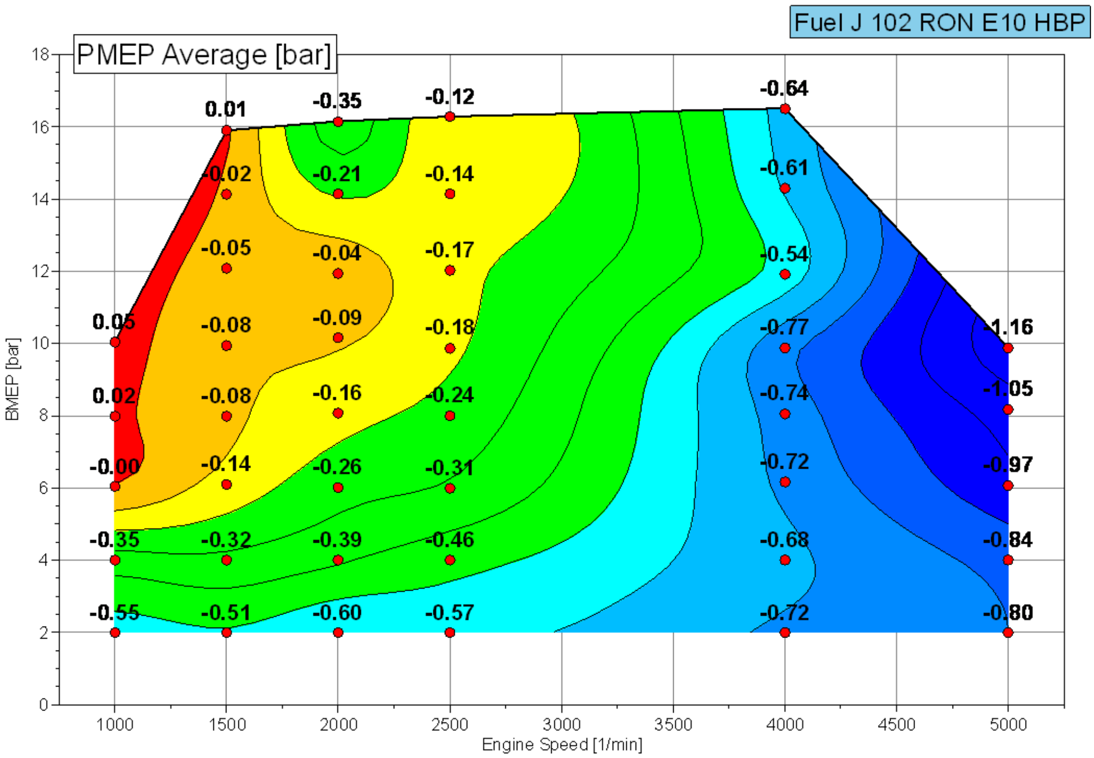

Figure 29: Pumping Mean Effective Pressure

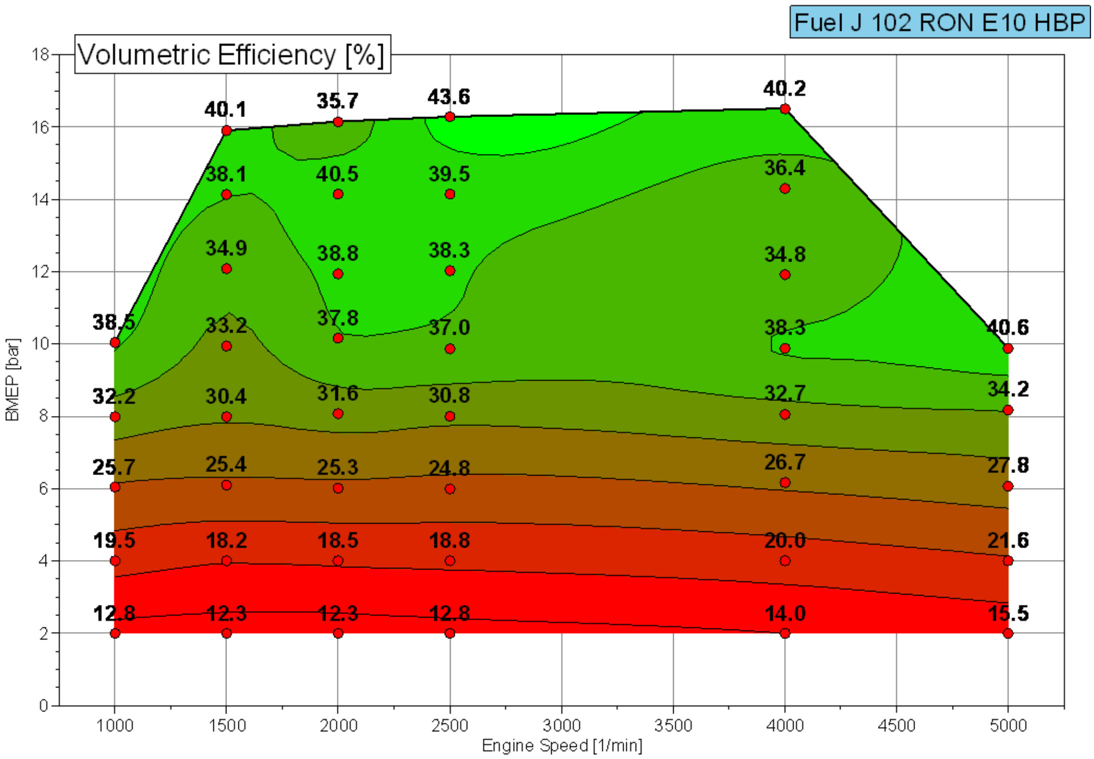

Figure 30: Calculated Volumetric Efficiency

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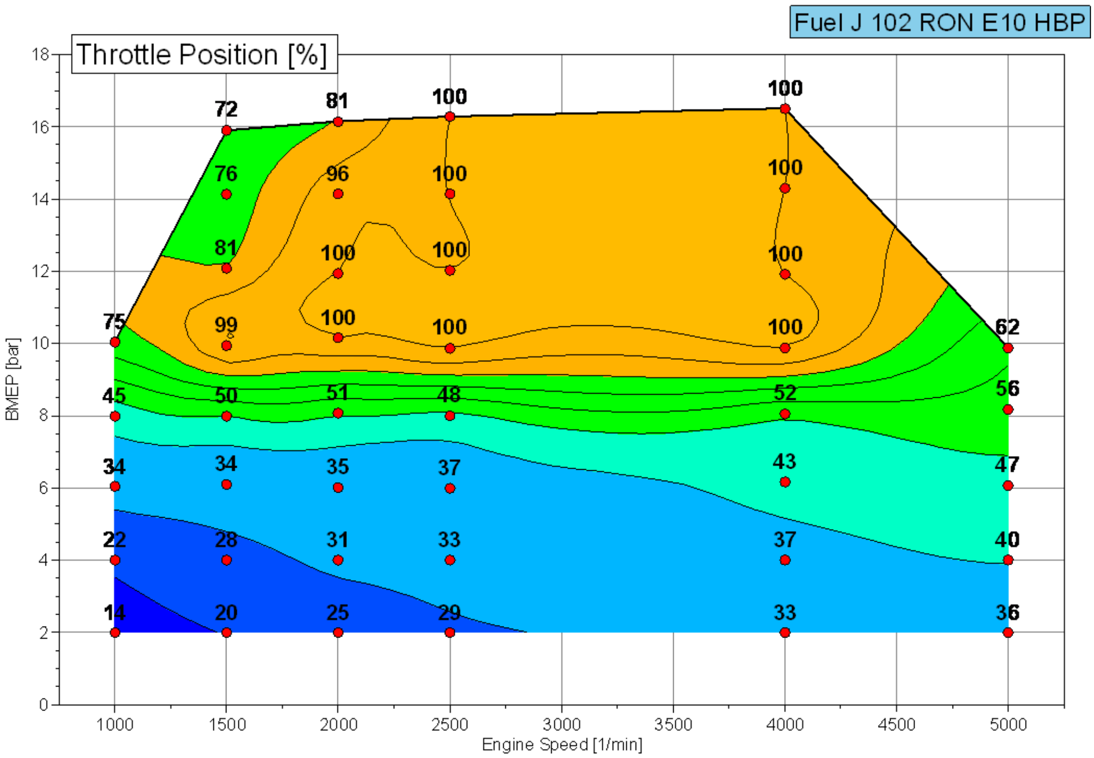

Figure 31: Throttle Position

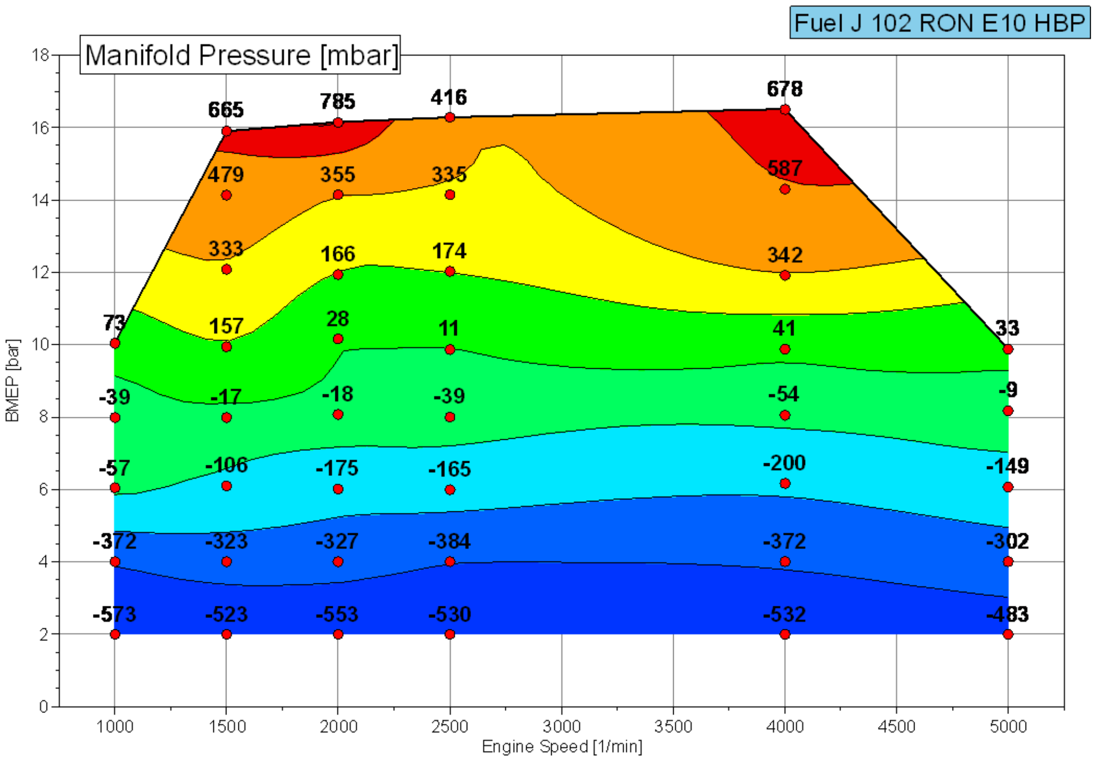

Figure 32: Intake Manifold Pressure

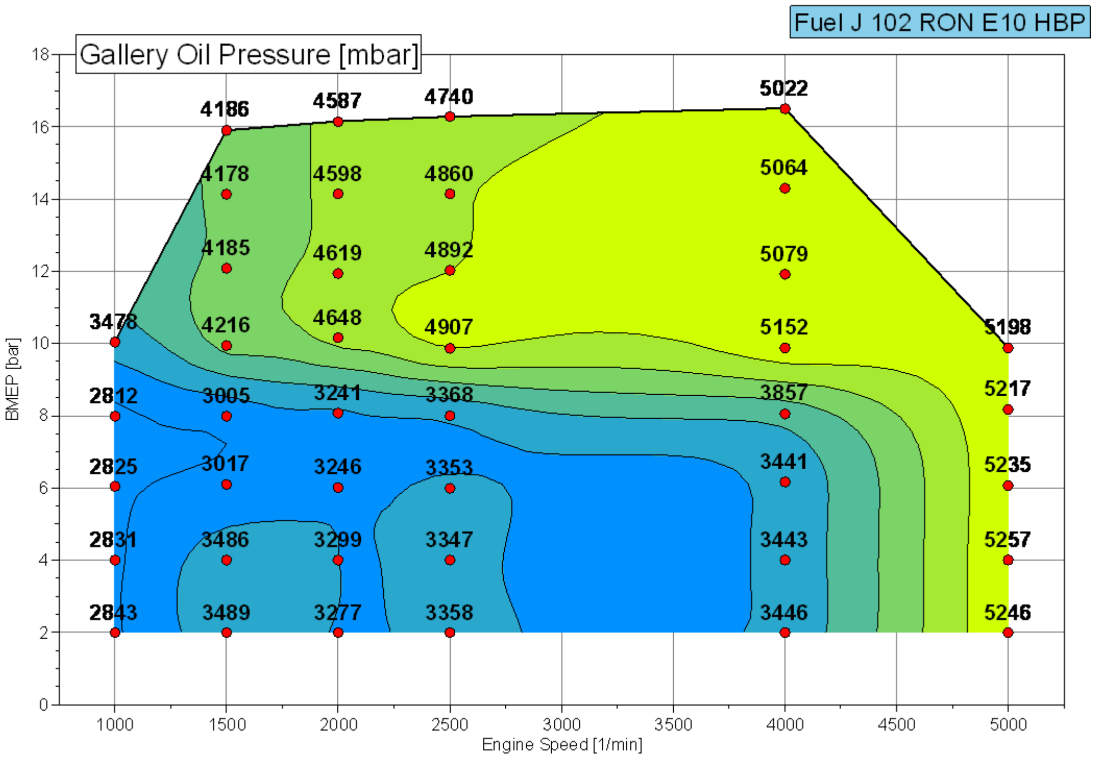

Figure 33: Gallery Oil Pressure

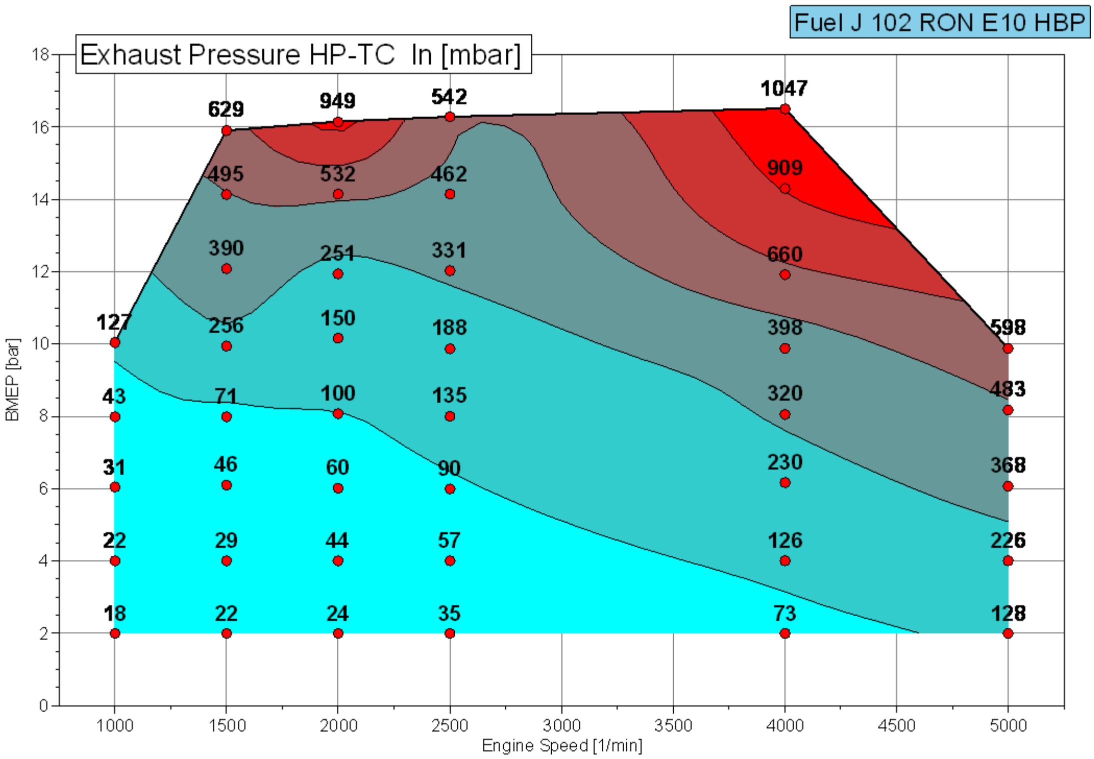

Figure 34: Exhaust Pressure High Pressure Turbocharger In

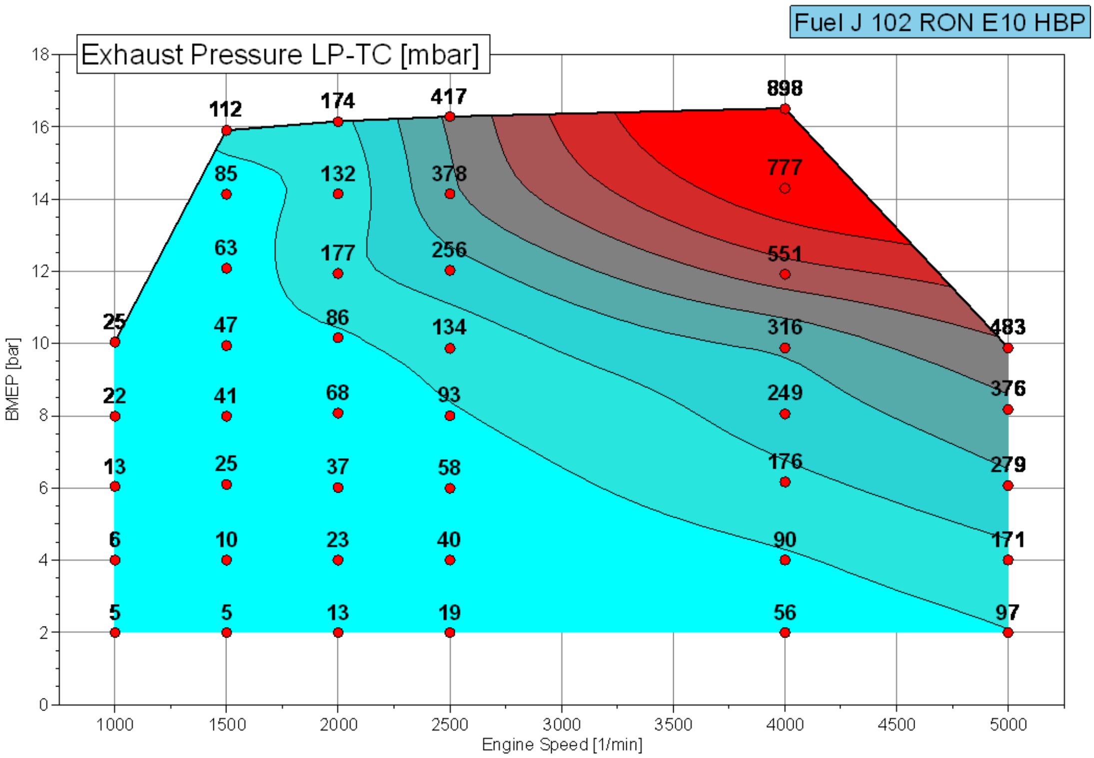

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

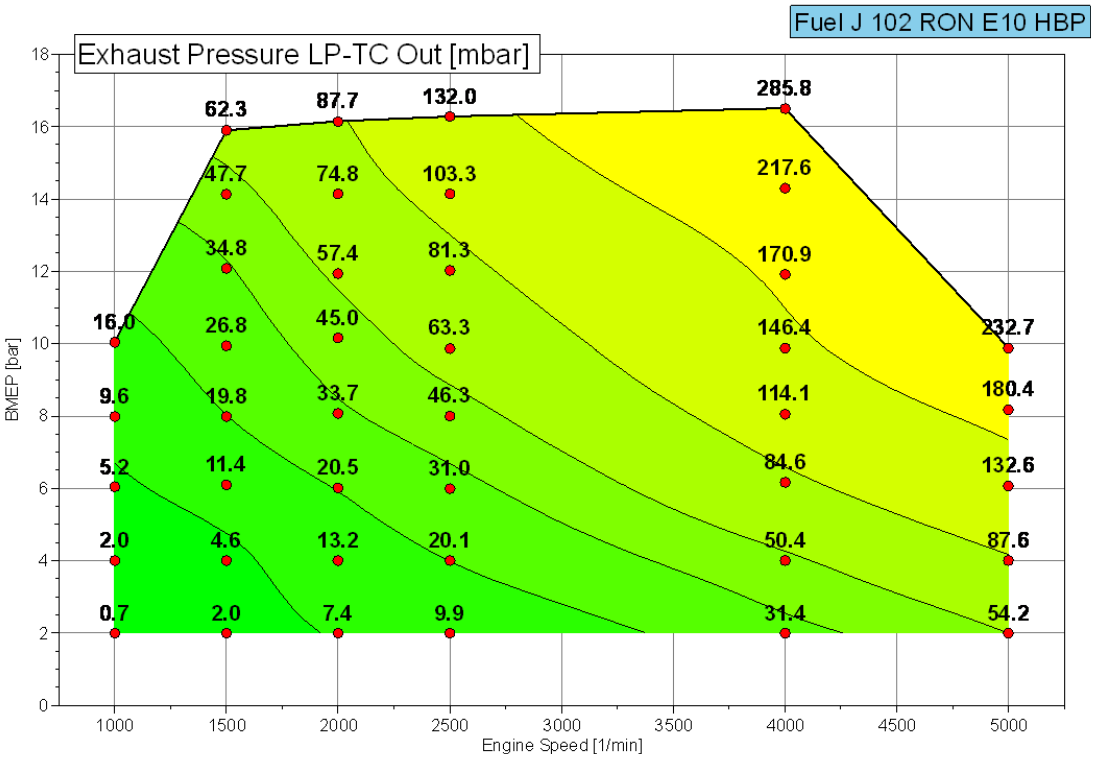

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

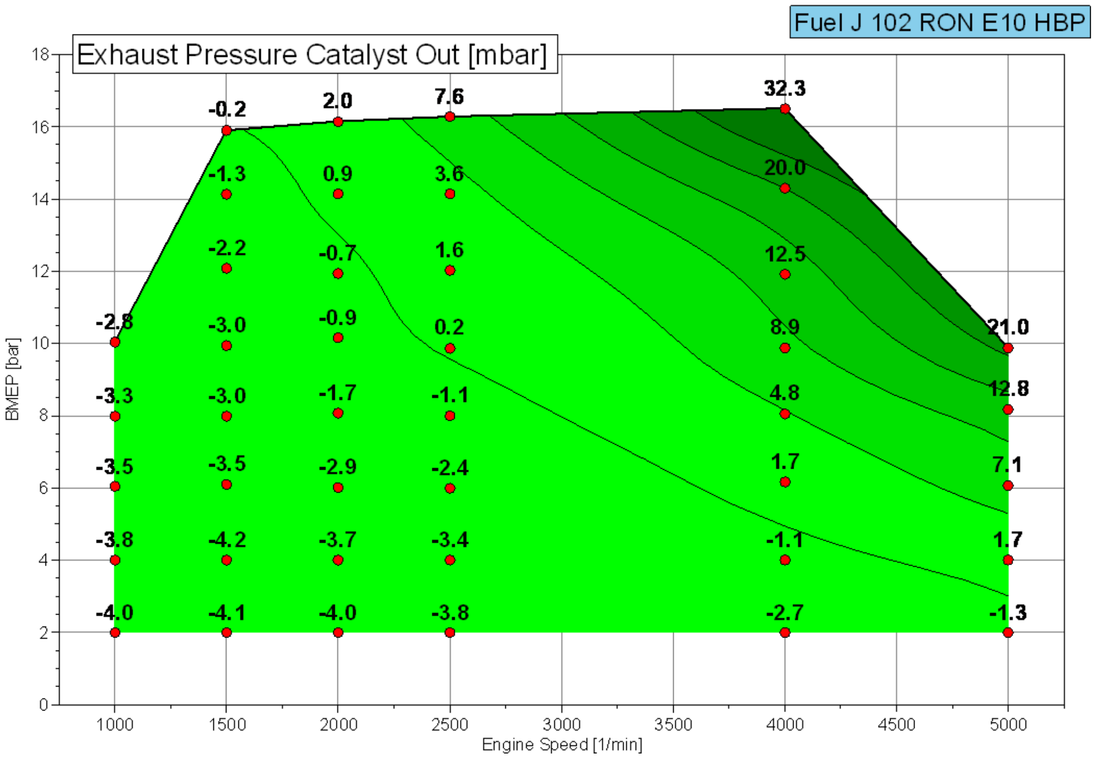

Figure 37: Exhaust Pressure Catalyst Out

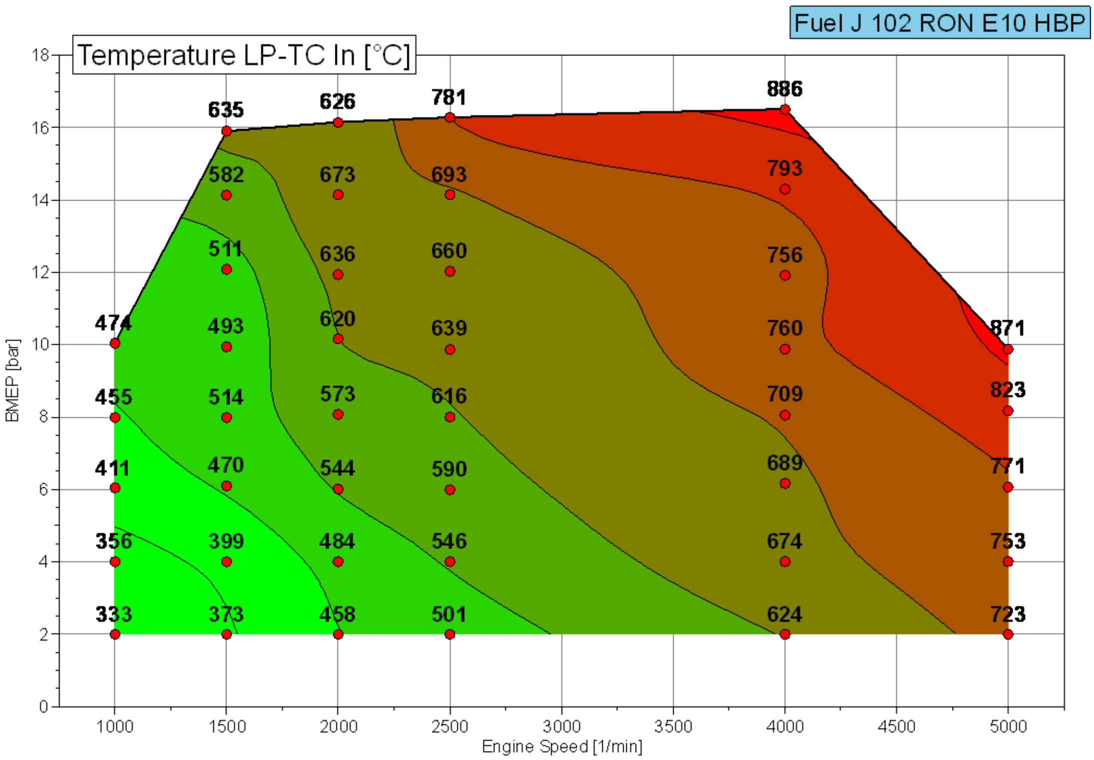

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

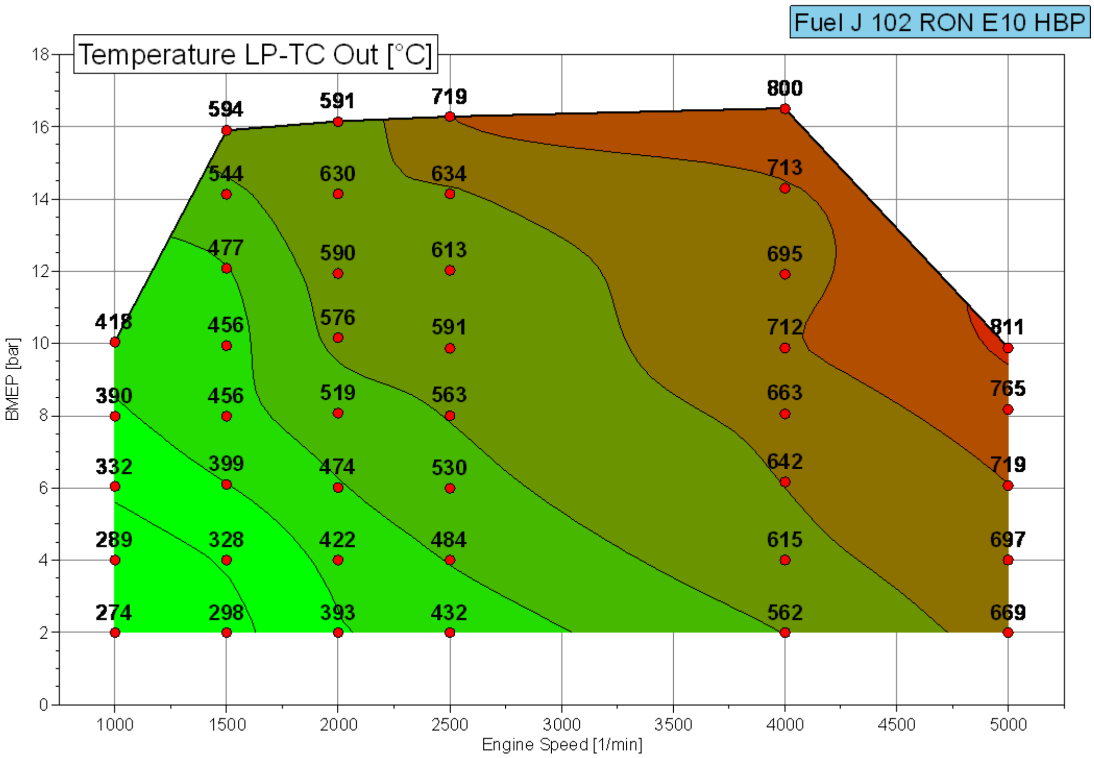

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

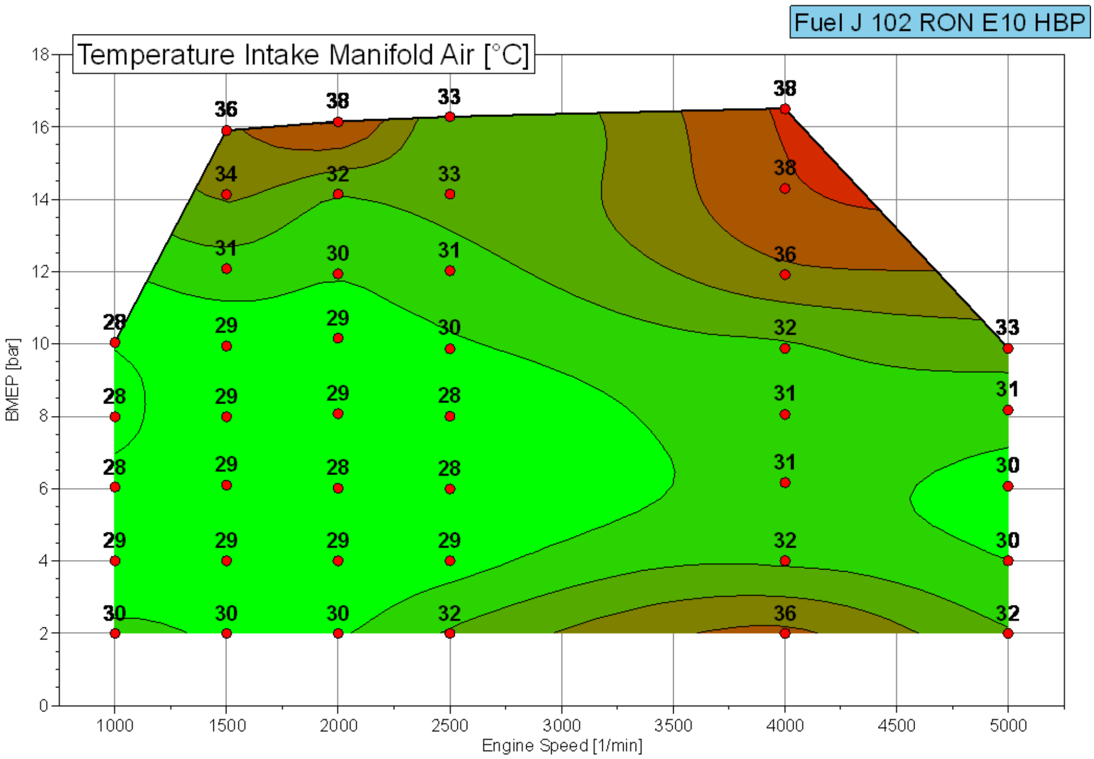

Figure 40: Intake Manifold Air Temperature

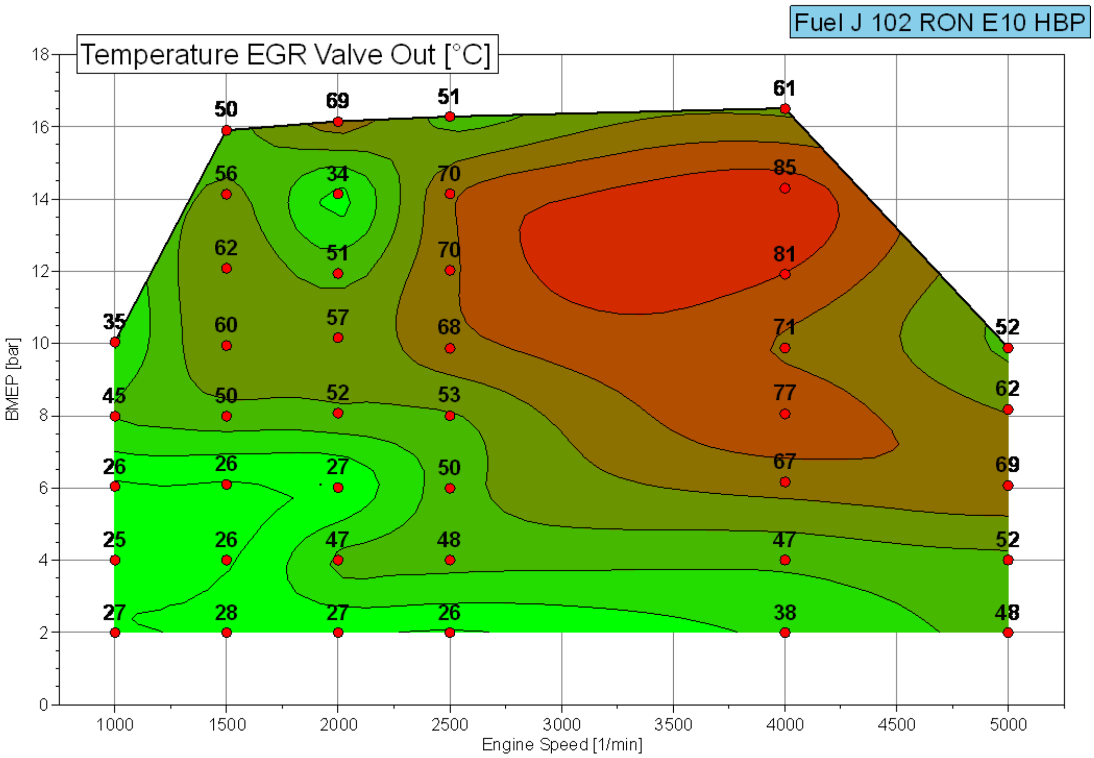

Figure 41: EGR Valve Out Temperature

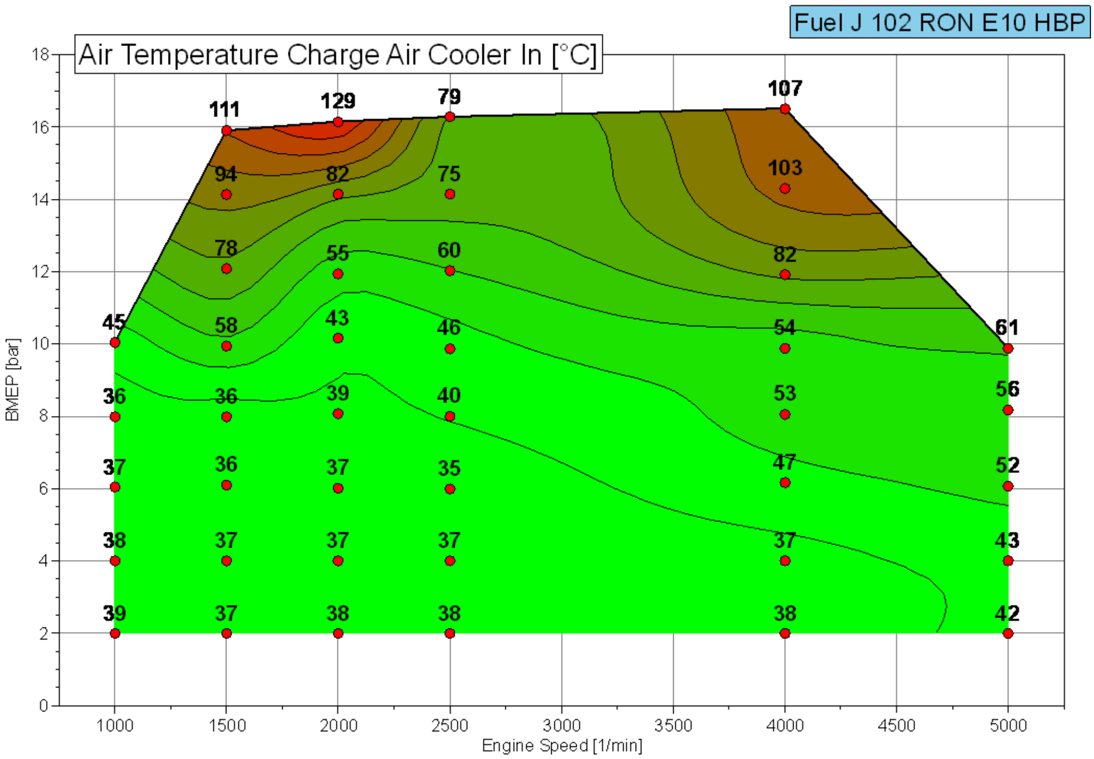

Figure 42: Charge Air Cooler Inlet Air Temperature

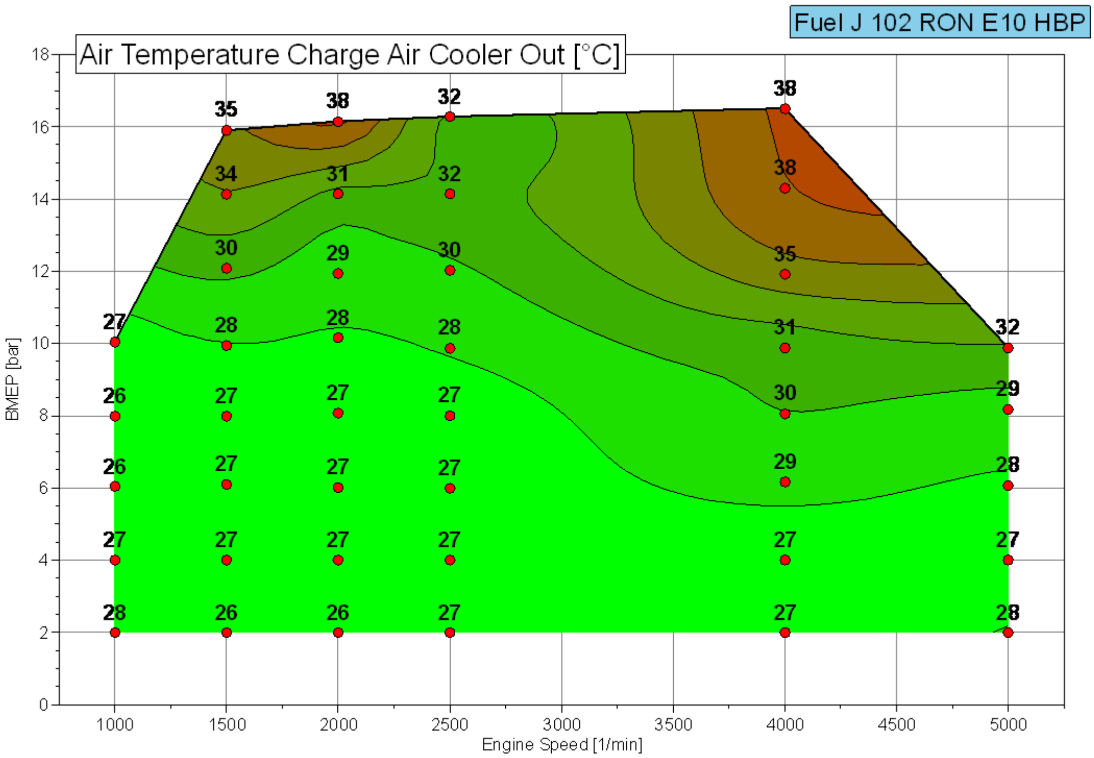

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel K Calibration Results

102 Ron 30% Ethanol Low Boiling Point

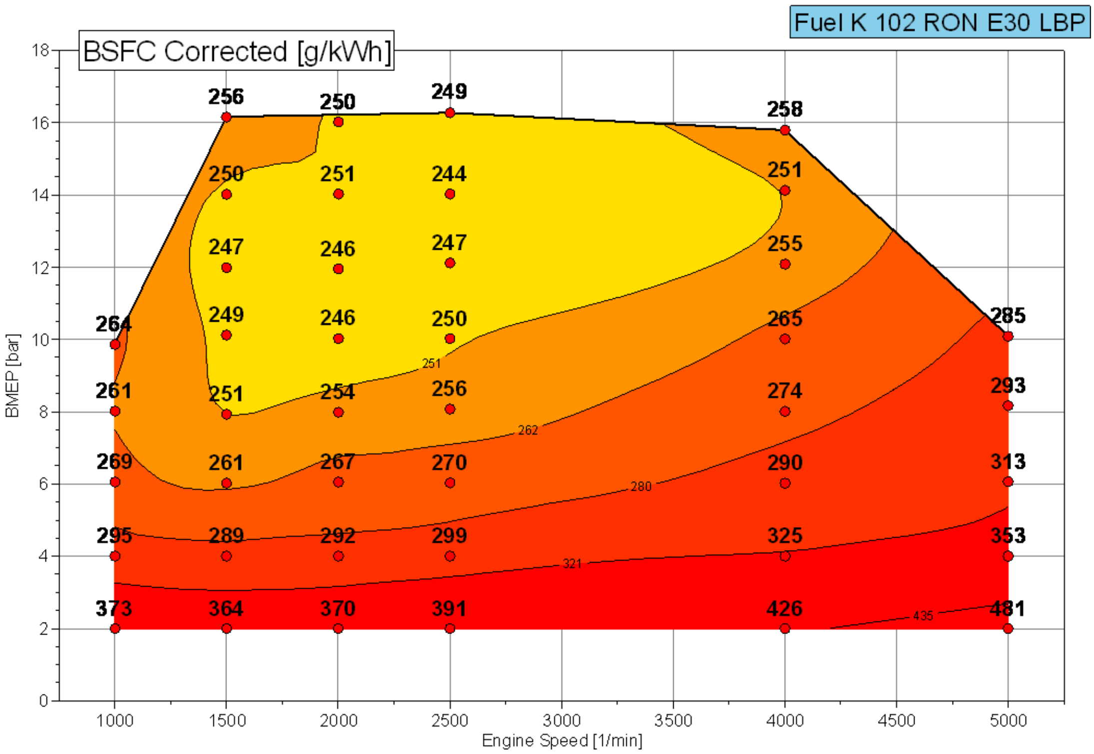

Figure 1: Brake Specific Fuel Consumption

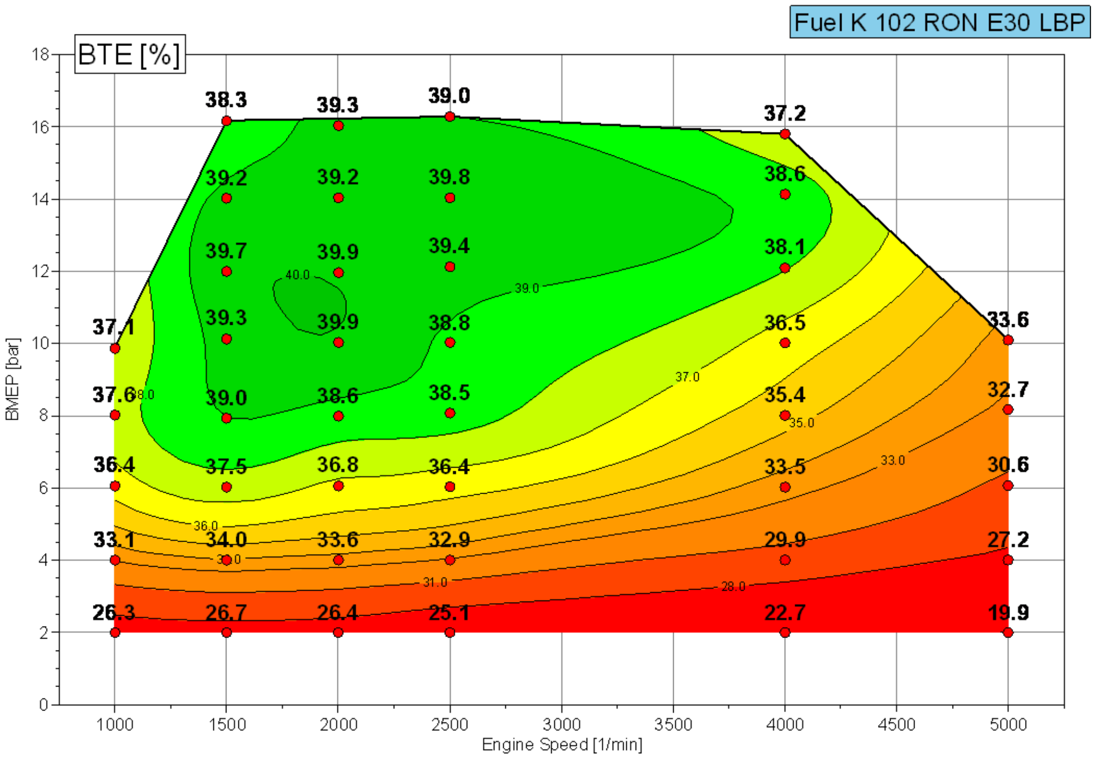

Figure 2: Brake Thermal Efficiency

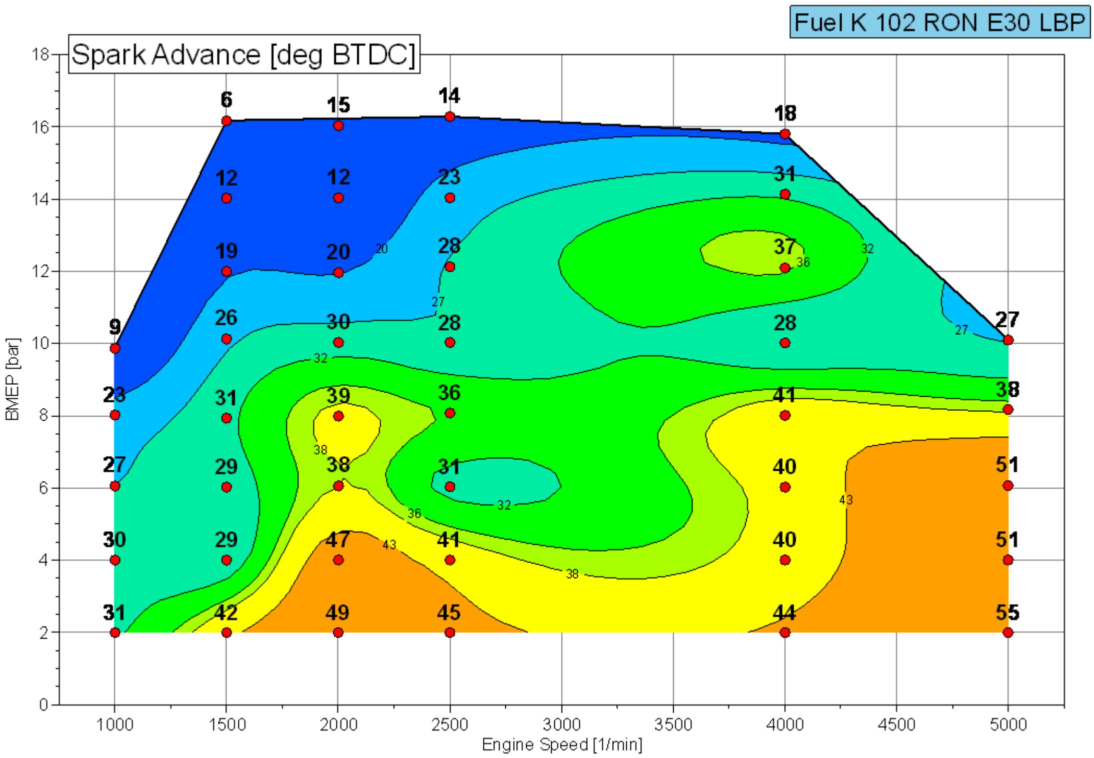

Figure 3: Spark Advance

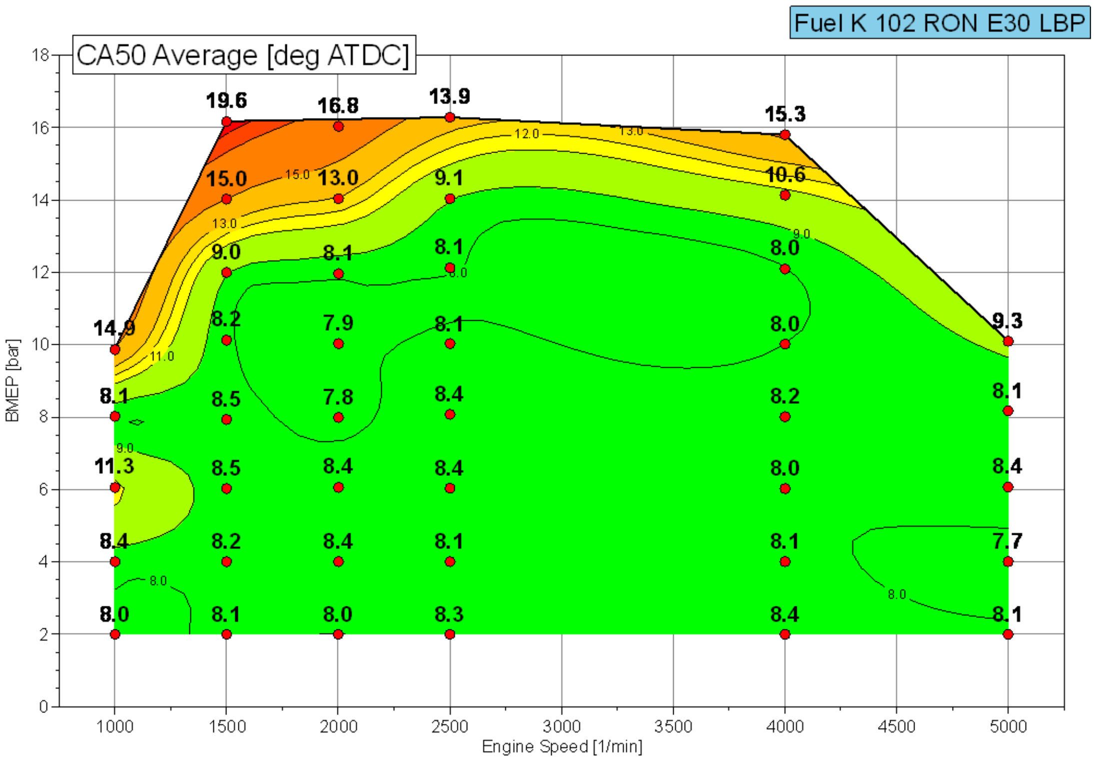

Figure 4: CA50 Average of Cylinders 1-4

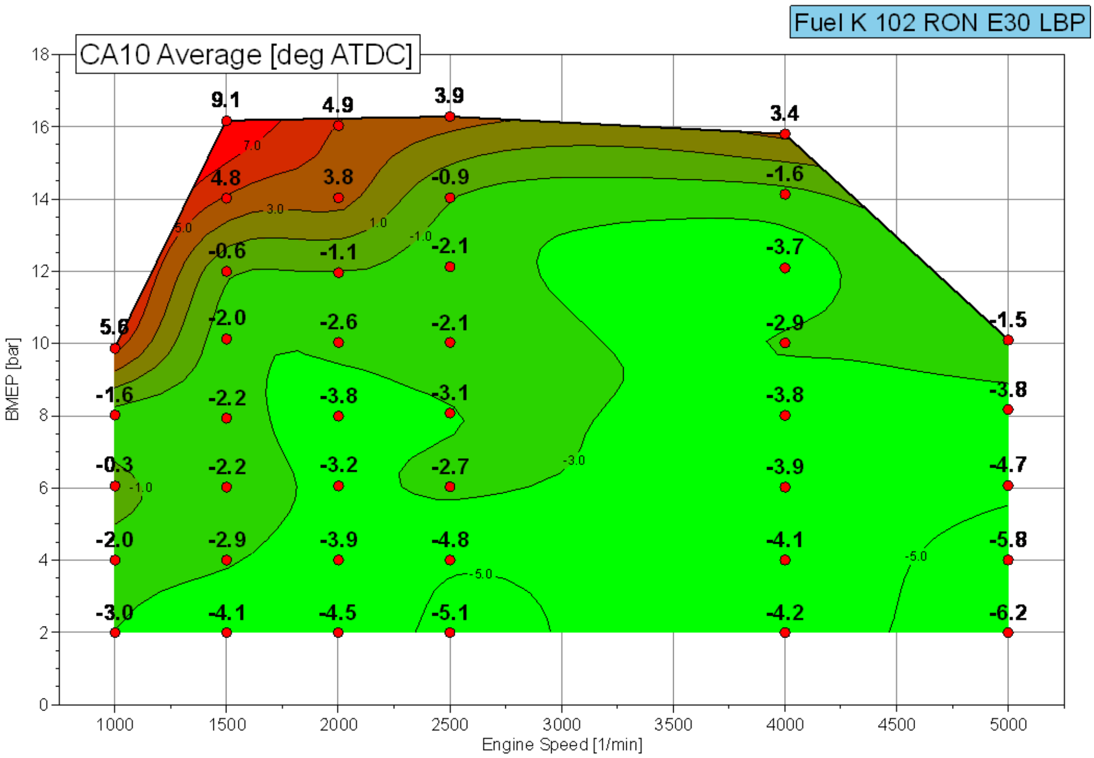

Figure 5: CA10 Average of Cylinders 1-4

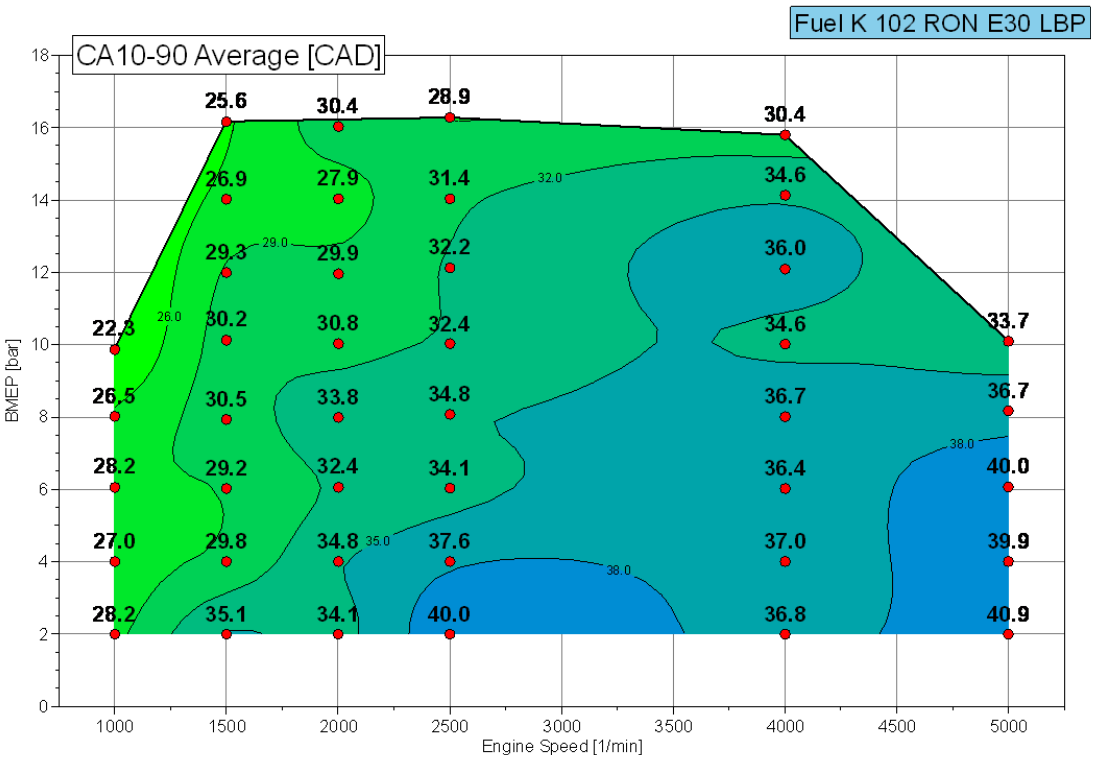

Figure 6: CA10-90 Average of Cylinders 1-4

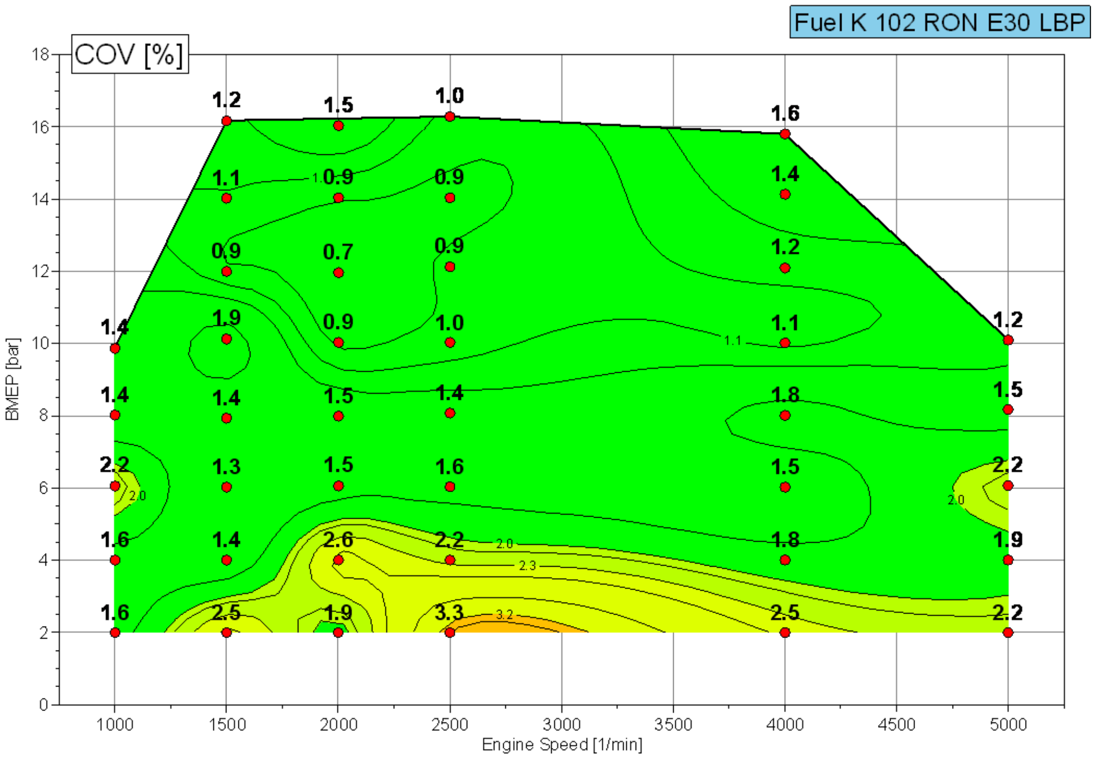

Figure 7: Coefficient of Variation Average of Cylinders 1-4

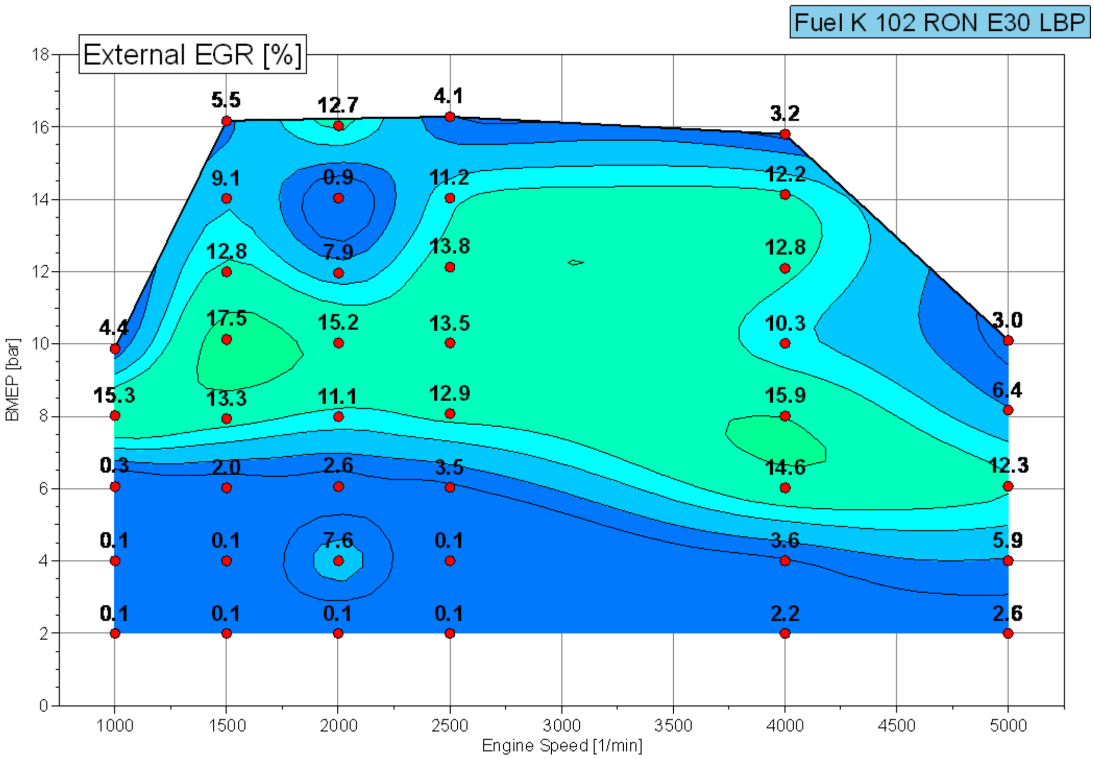

Figure 8: External EGR Percent of Intake Air

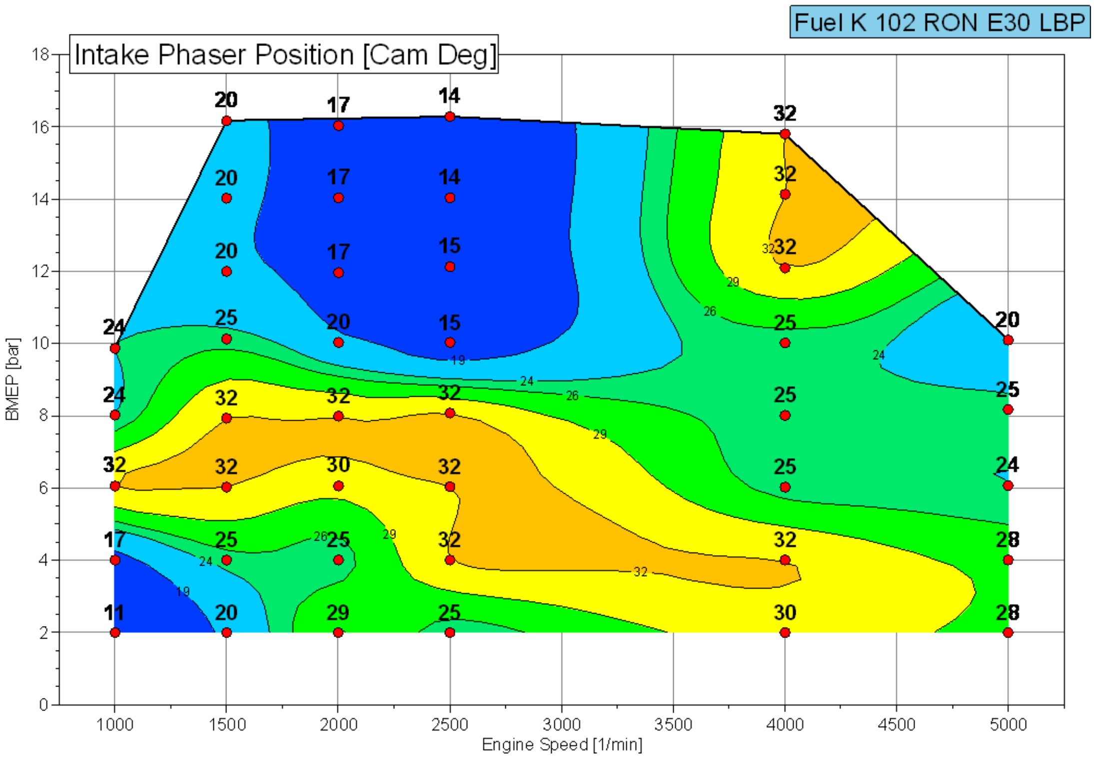

Figure 9: Intake Camshaft Position

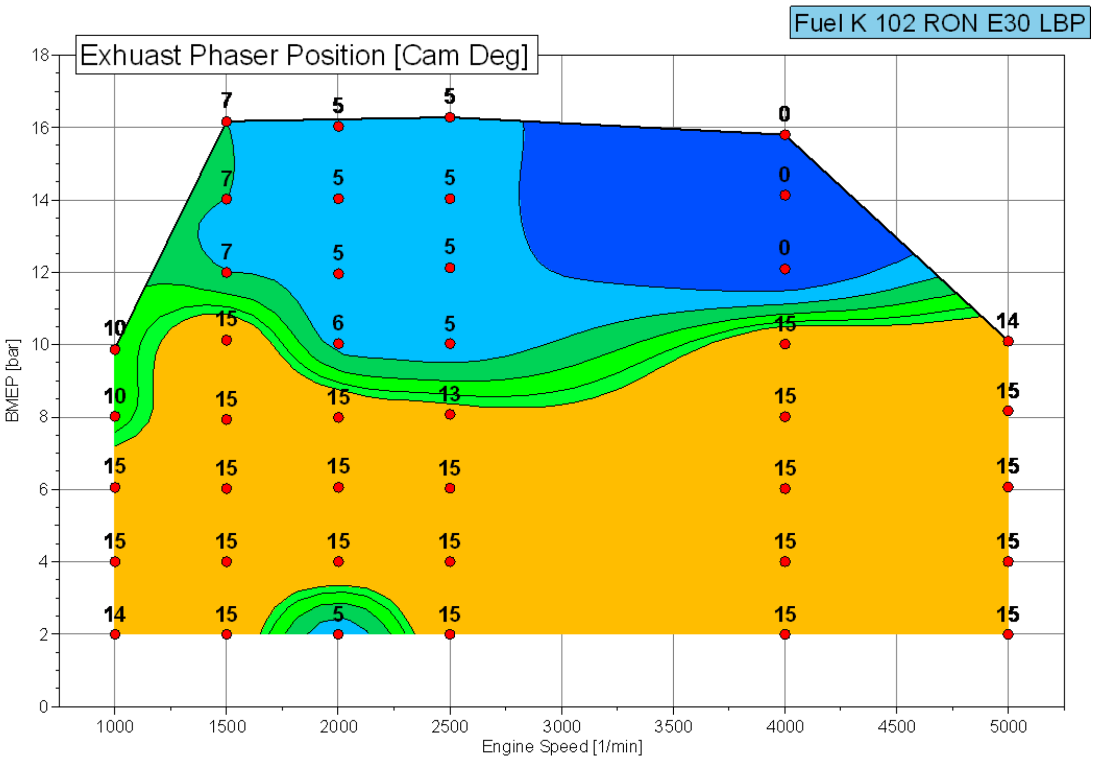

Figure 10: Exhaust Camshaft Position

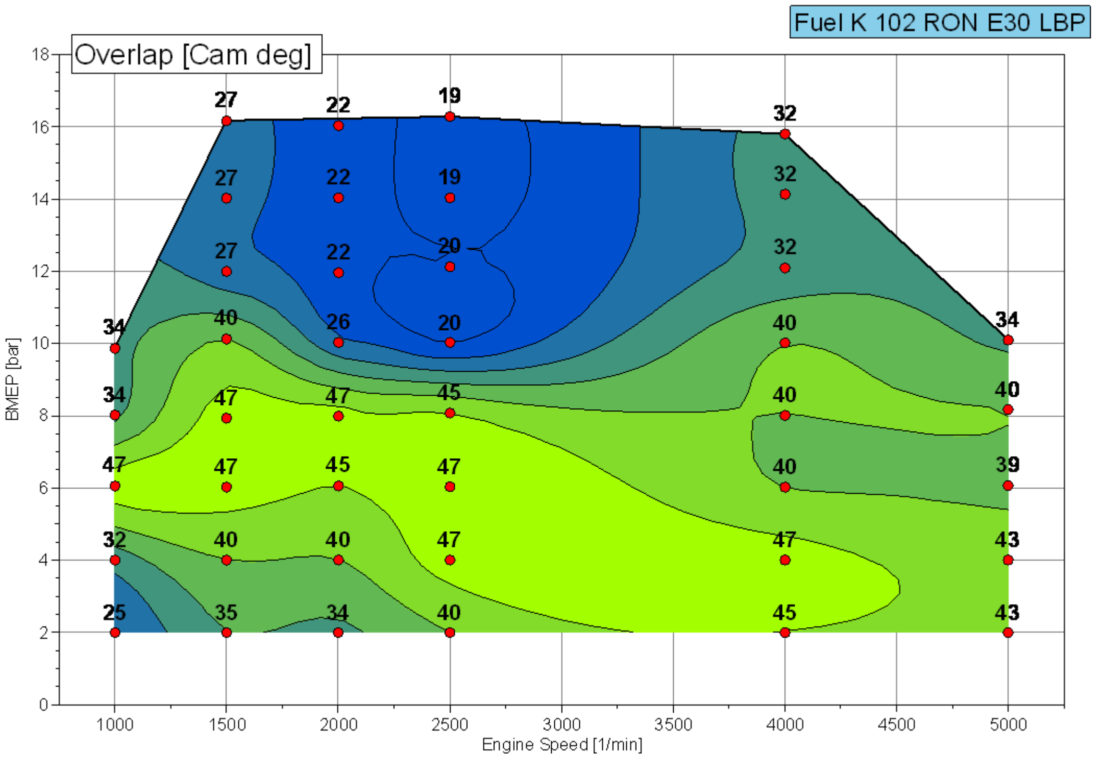

Figure 11: Camshaft Overlap

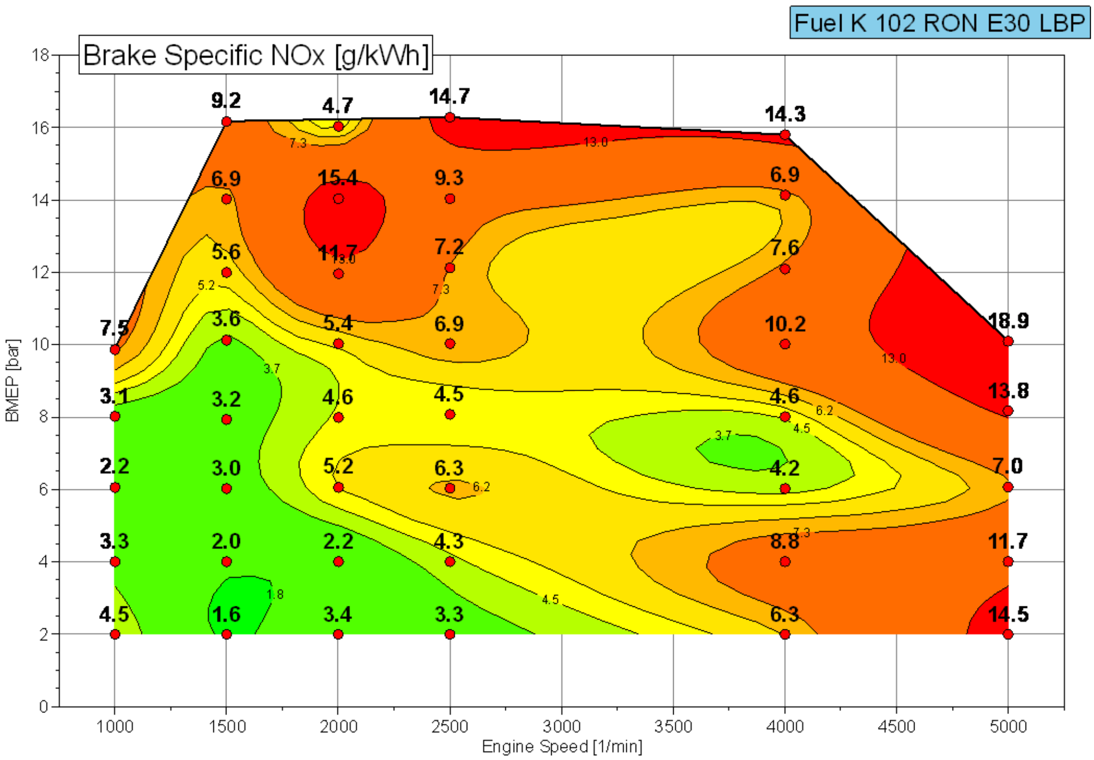

Figure 12: Brake Specific NOx Emissions

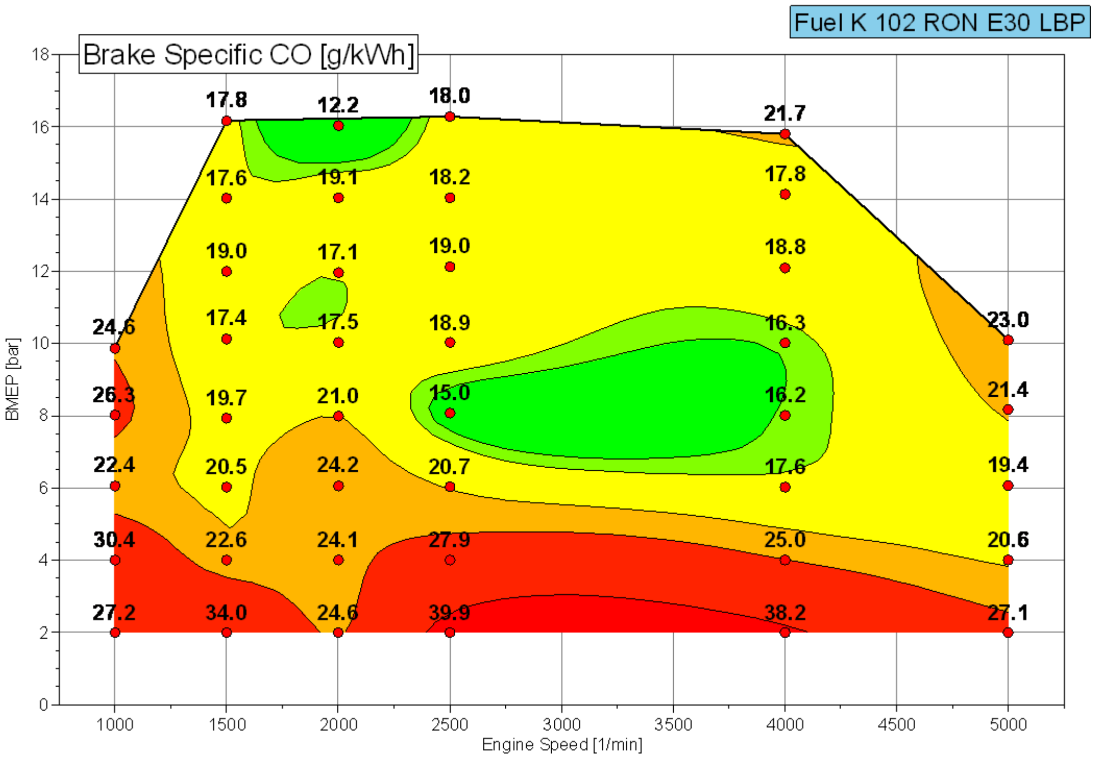

Figure 13: Brake Specific Carbon Monoxide Emissions

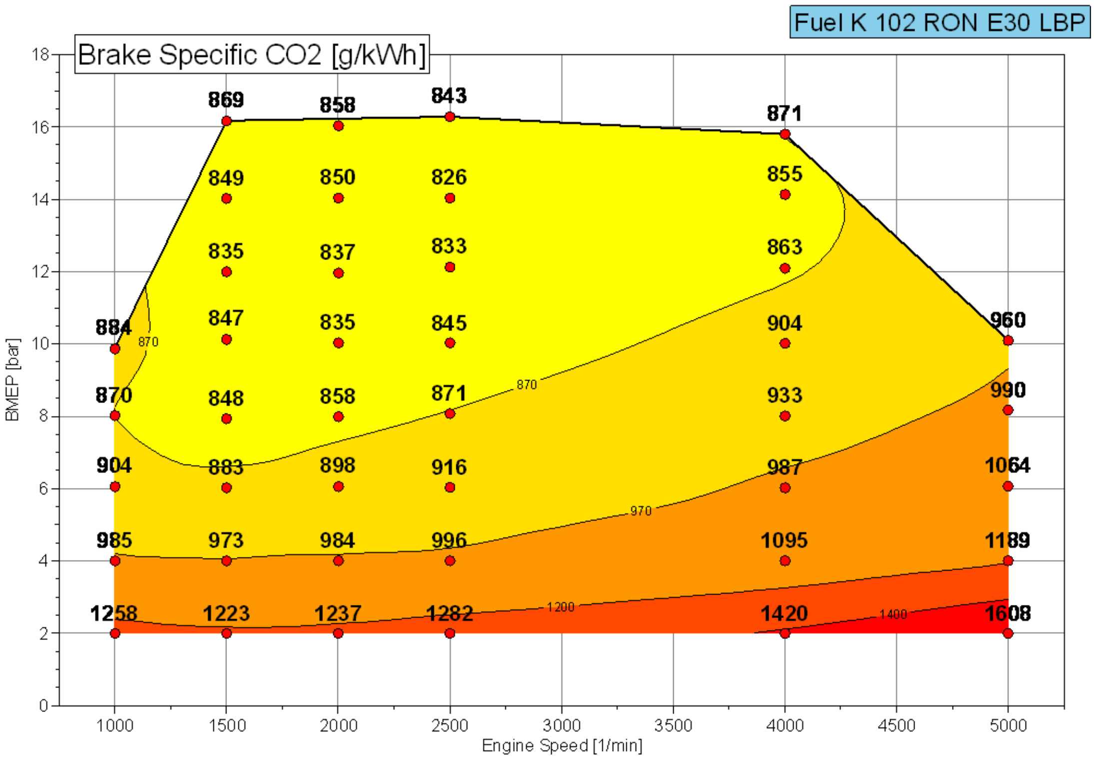

Figure 14: Brake Specific Carbon Dioxide Emissions

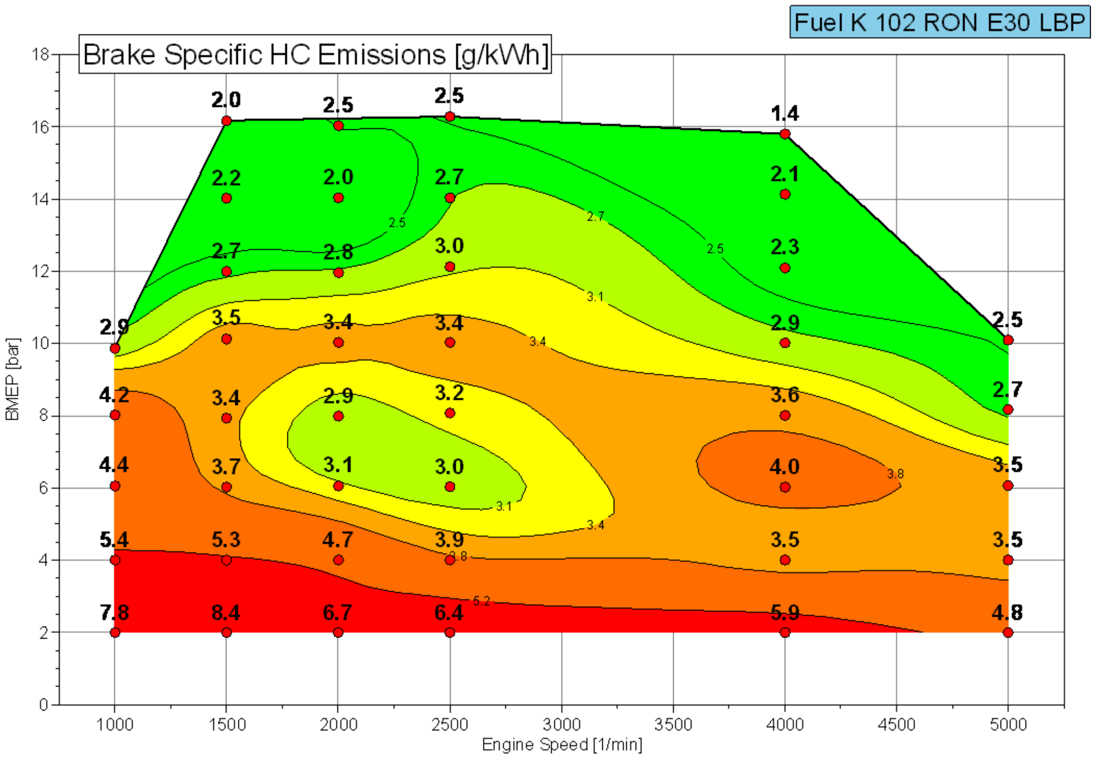

Figure 15: Brake Specific Hydrocarbon Emissions

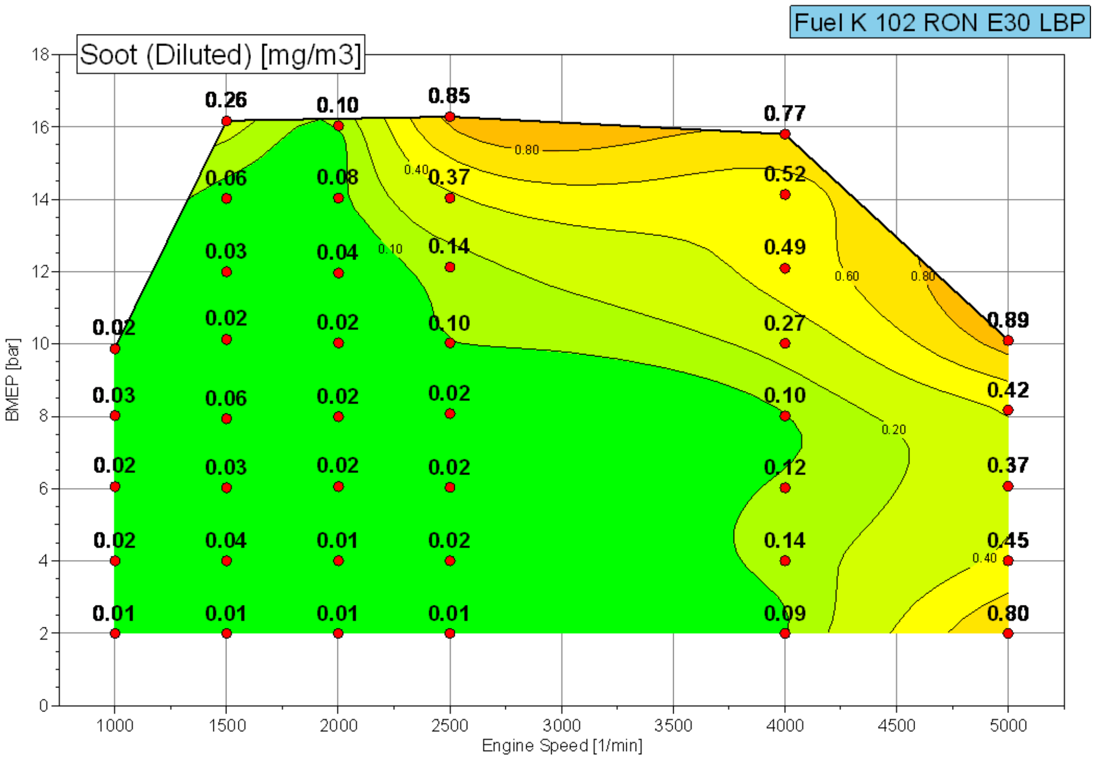

Figure 16: Particulate Soot Emissions

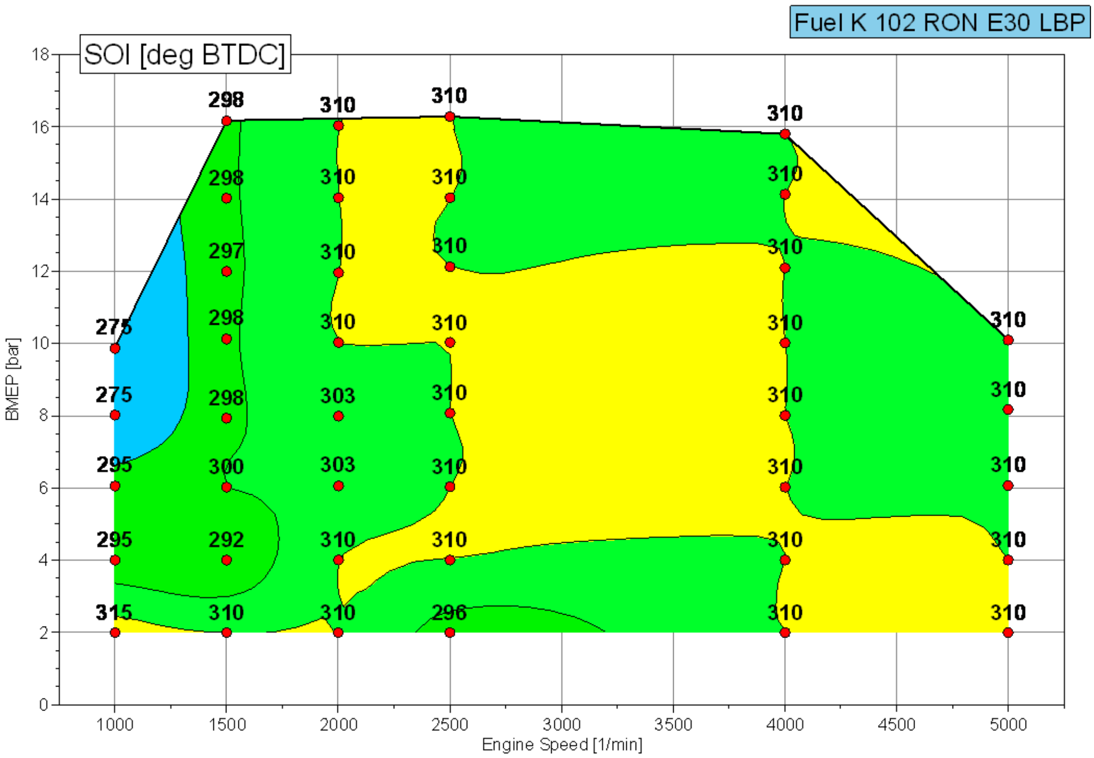

Figure 17: Start of Injection

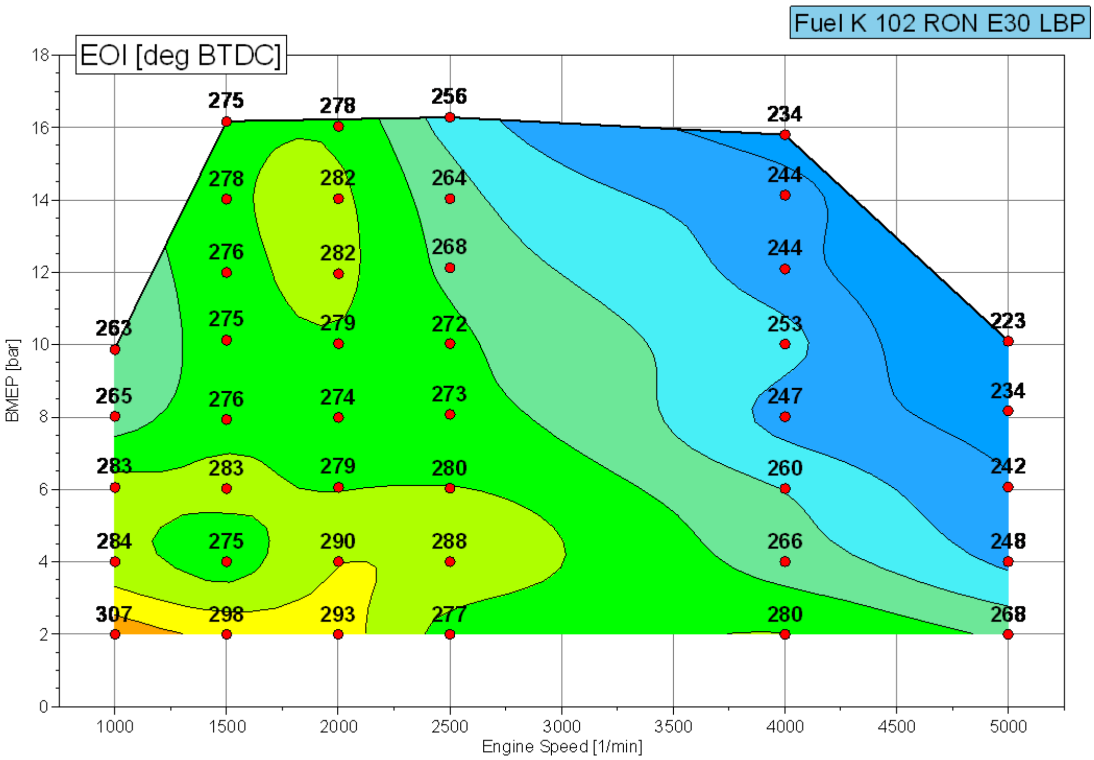

Figure 18: End of Injection

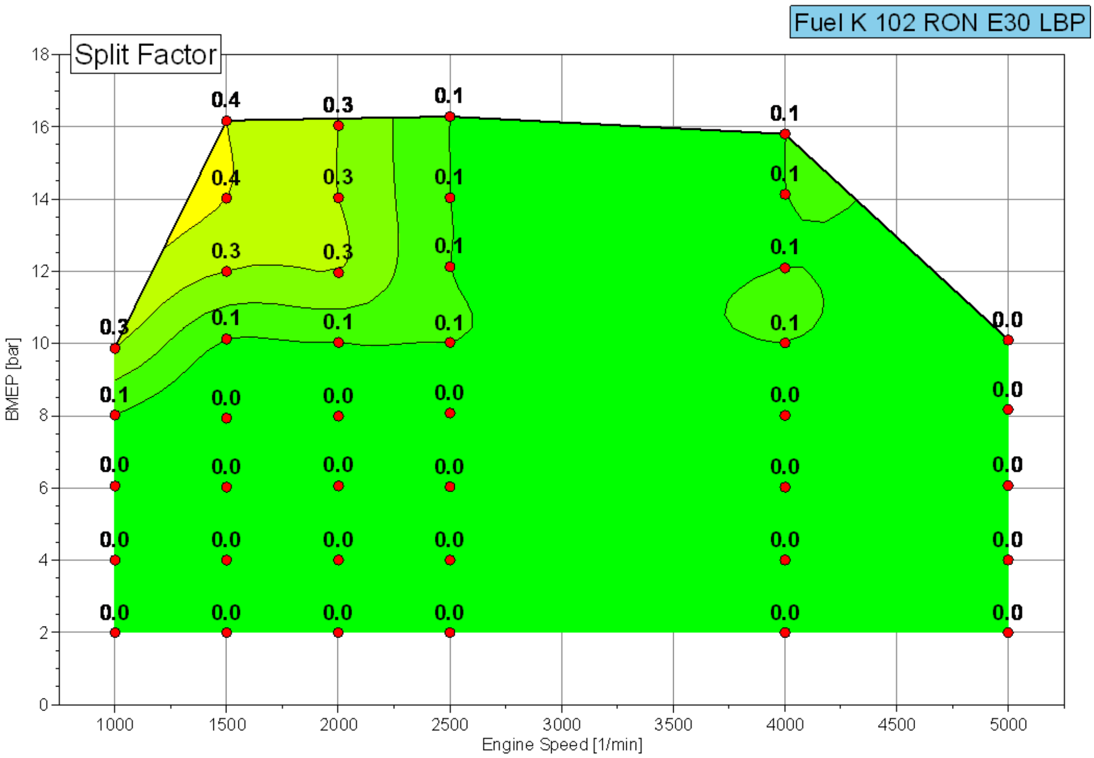

Figure 19: Injection Split Factor

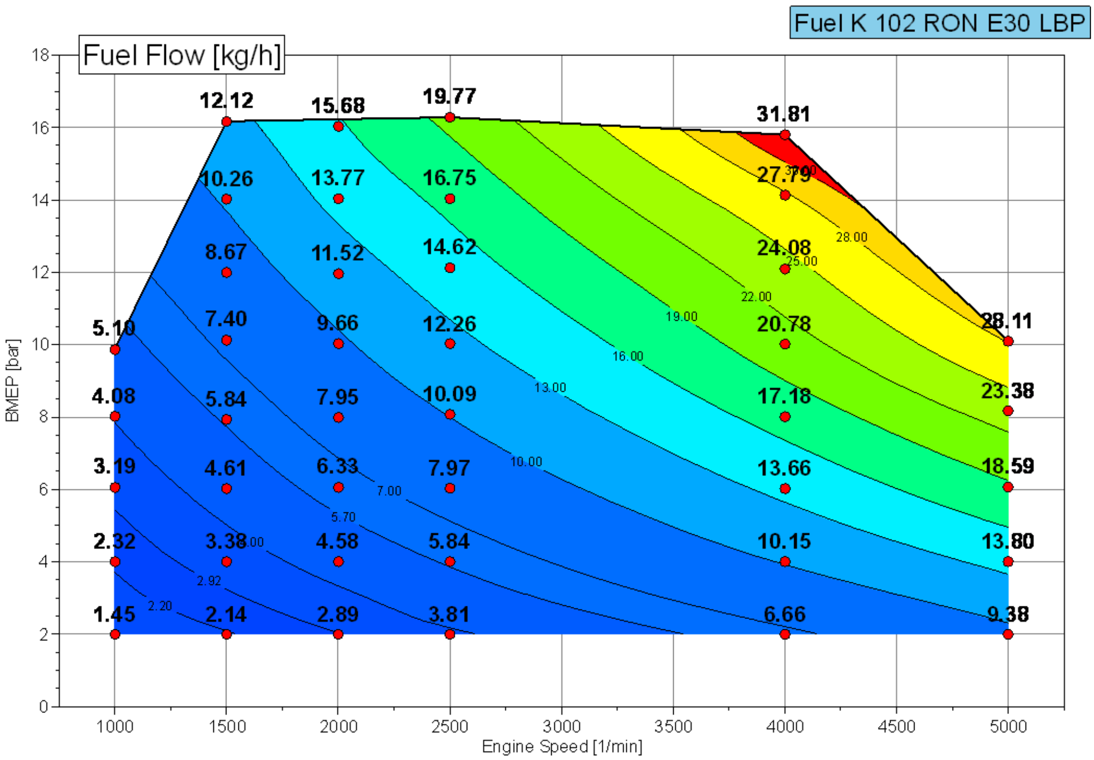

Figure 20: Fuel Flow

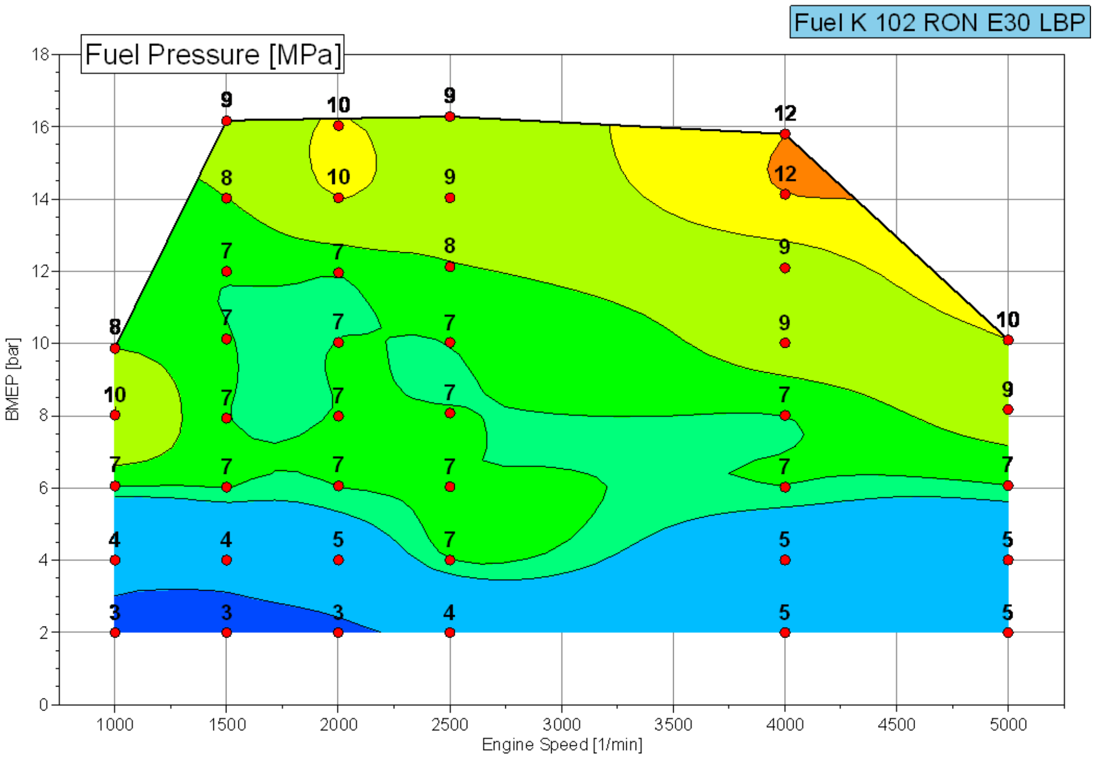

Figure 21: Fuel Rail Pressure

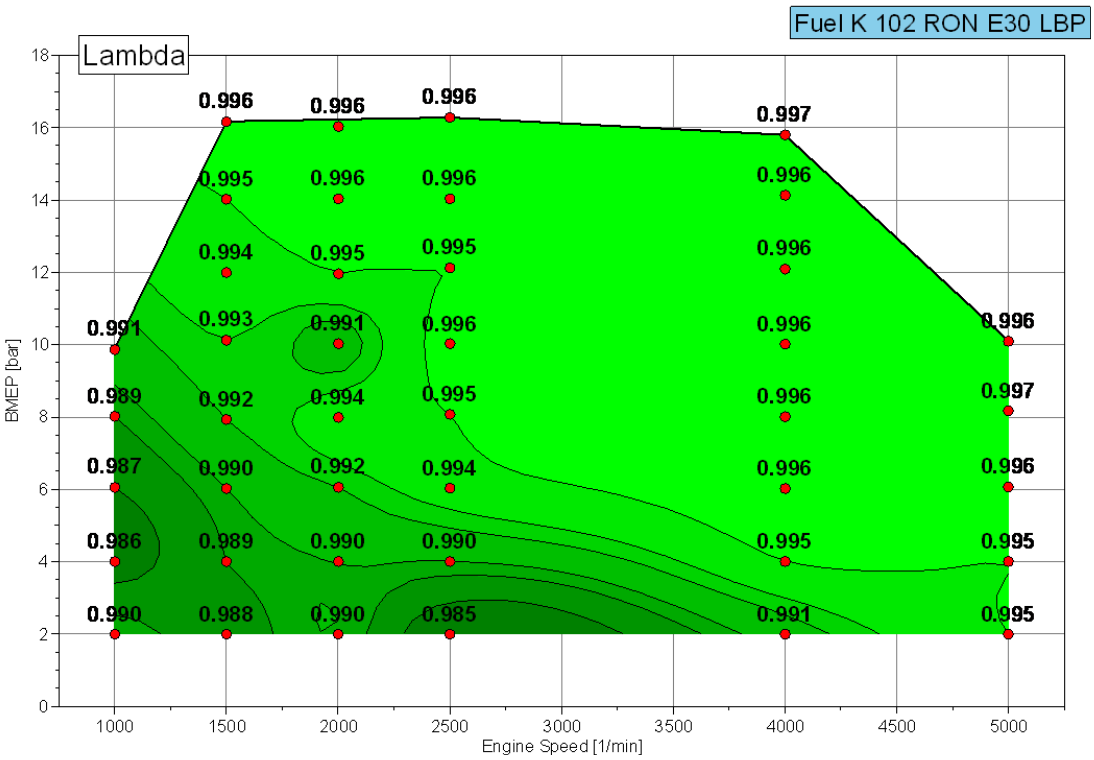

Figure 22: Lambda

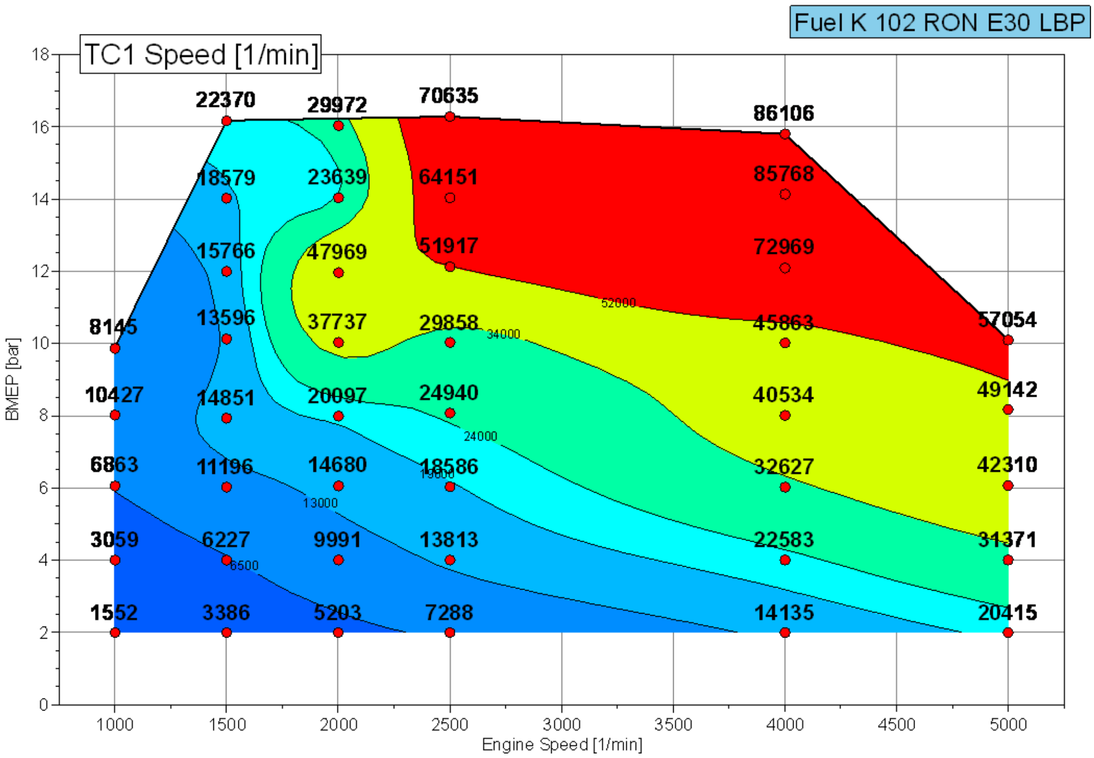

Figure 23: Low Pressure Turbocharger Speed

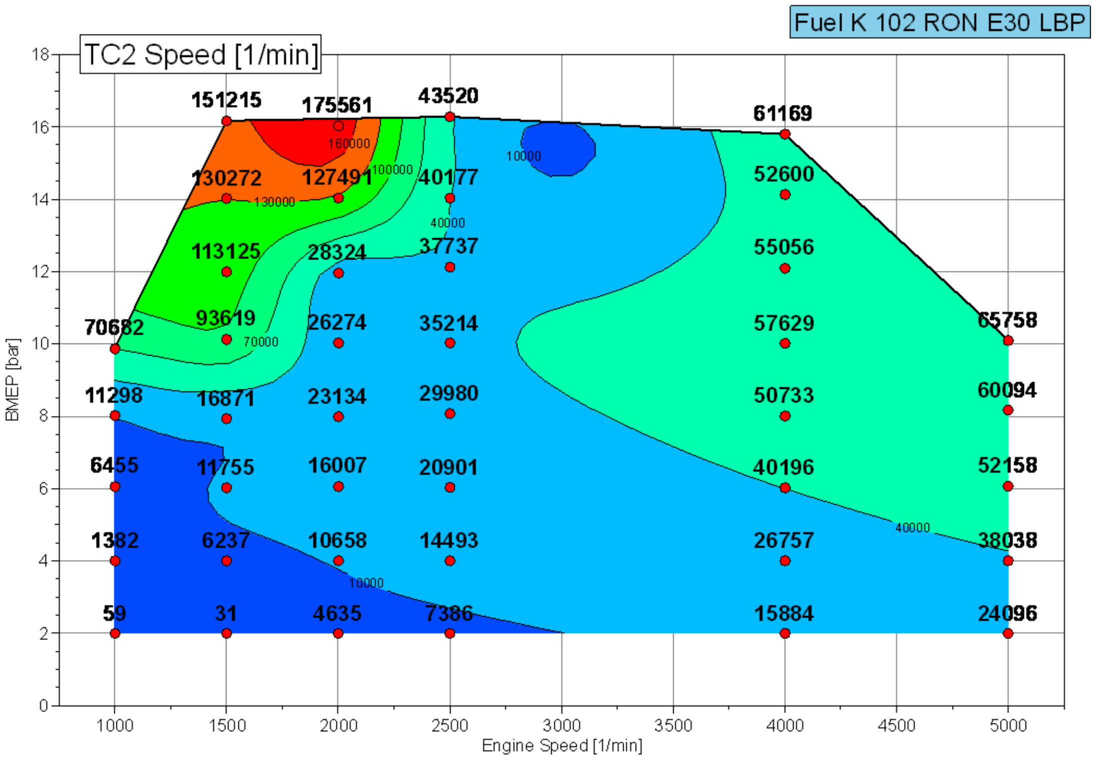

Figure 24: High Pressure Turbocharge Speed

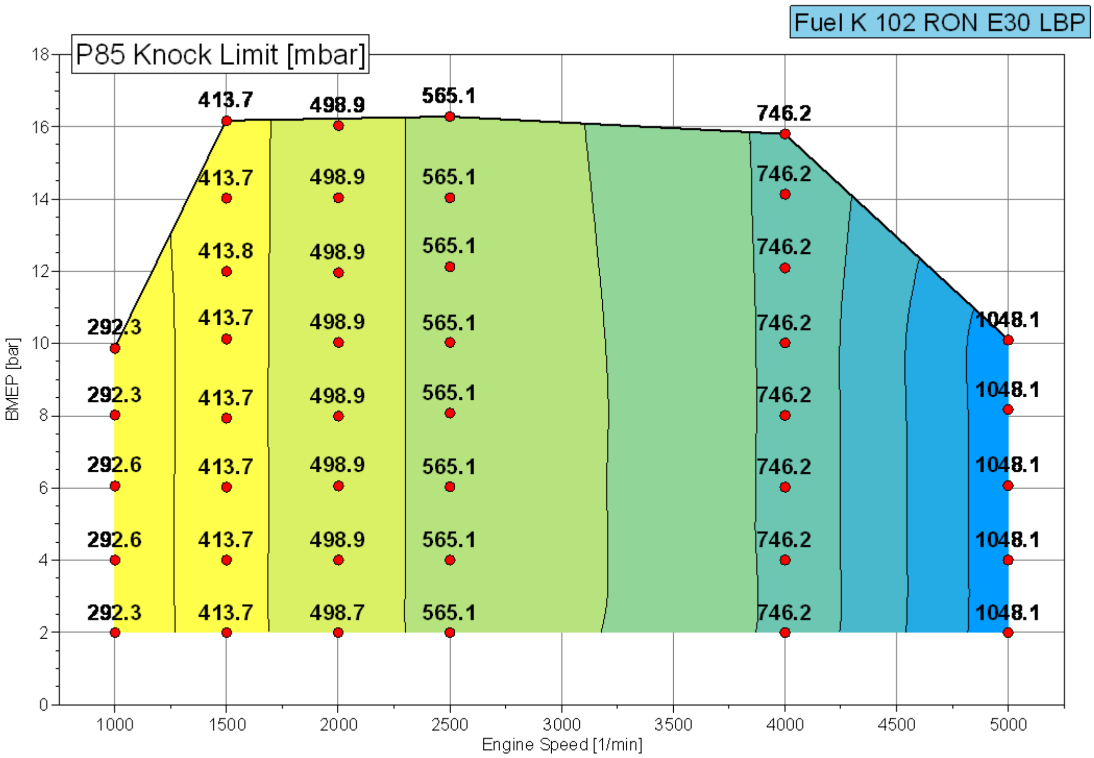

Figure 25: P85 Knock Limit

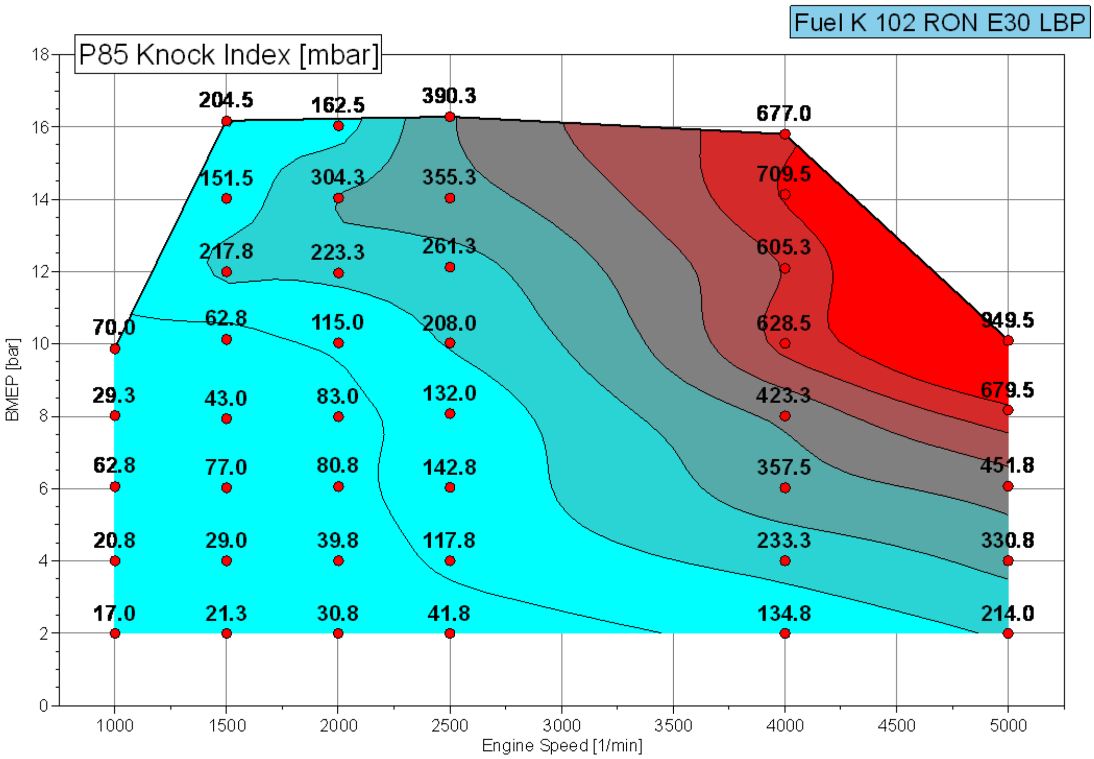

Figure 26: Averaged P85 Knock Index

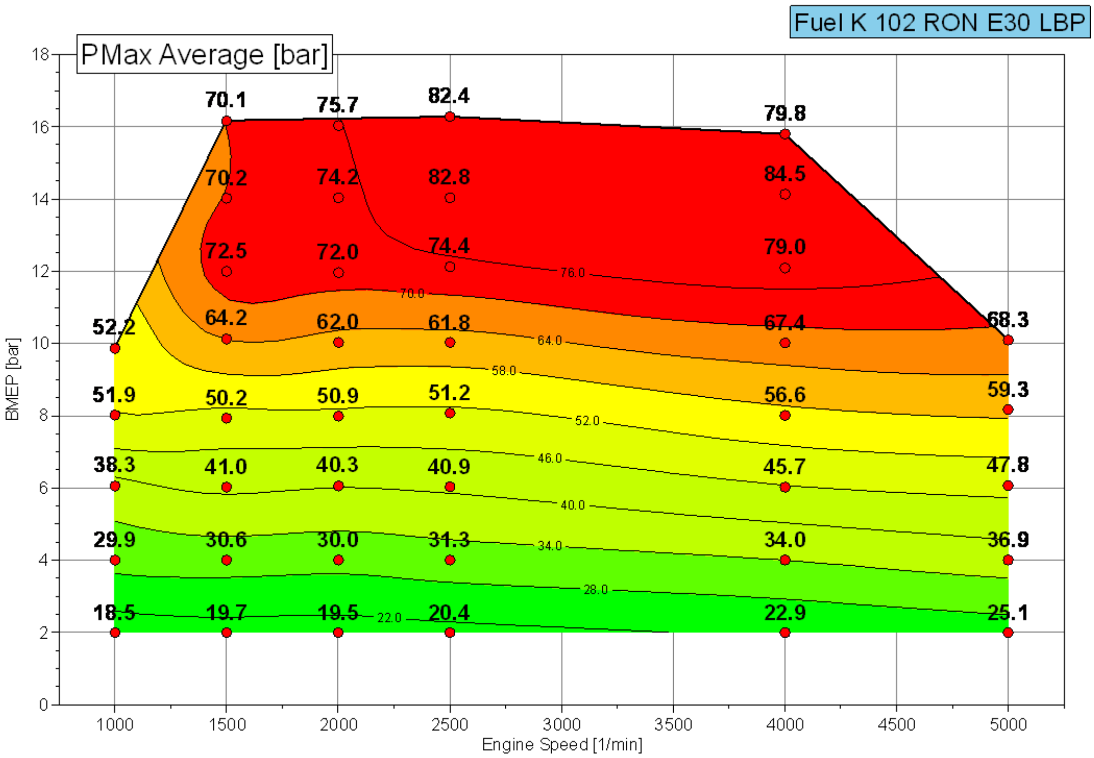

Figure 27: Averaged Max Pressure for Cylinders 1-4

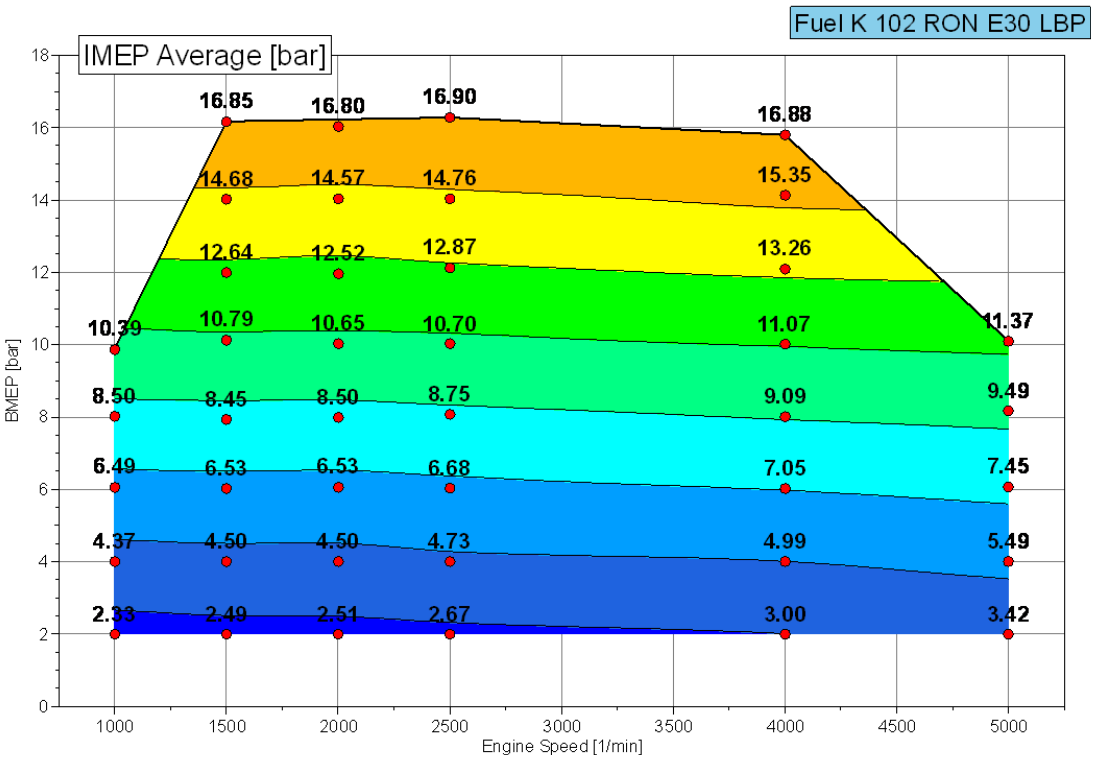

Figure 28: Indicated Mean Effective Pressure

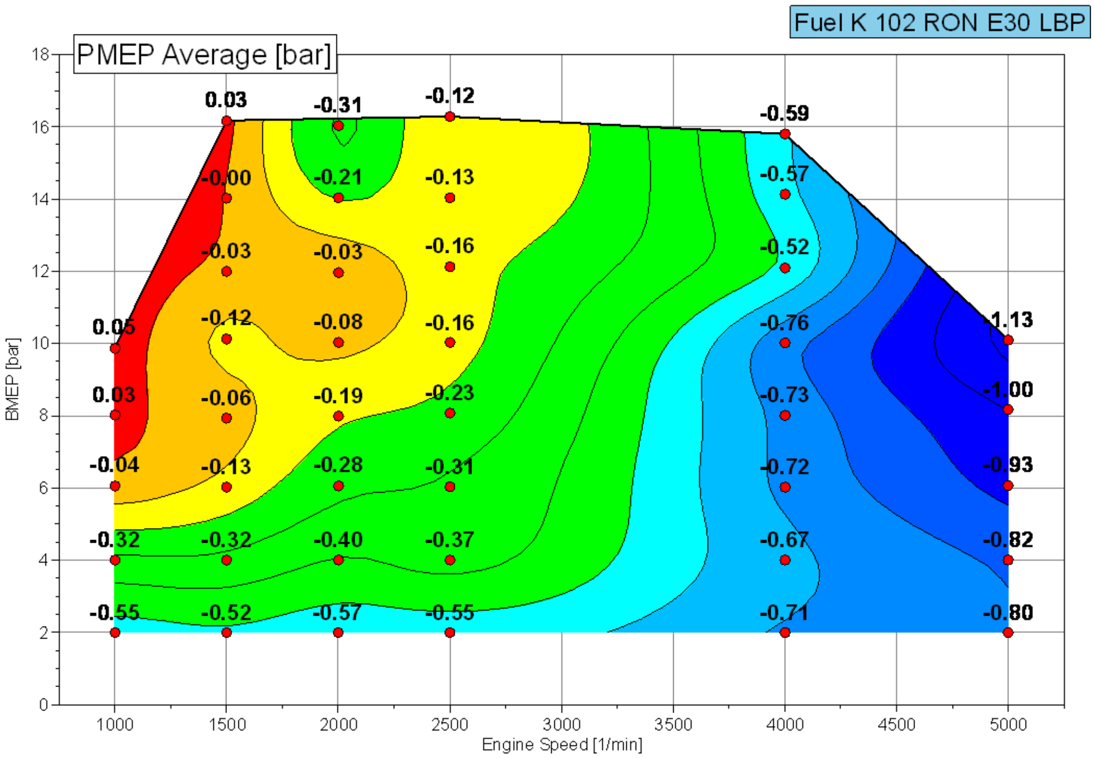

Figure 29: Pumping Mean Effective Pressure

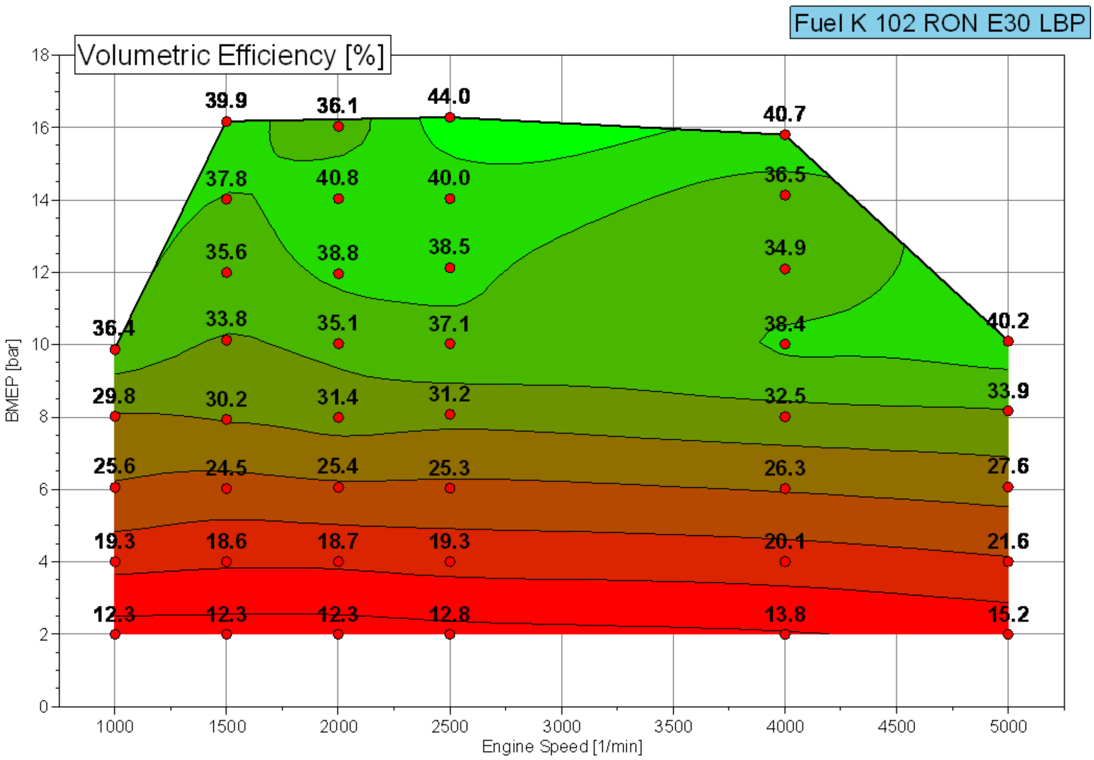

Figure 30: Calculated Volumetric Efficiency

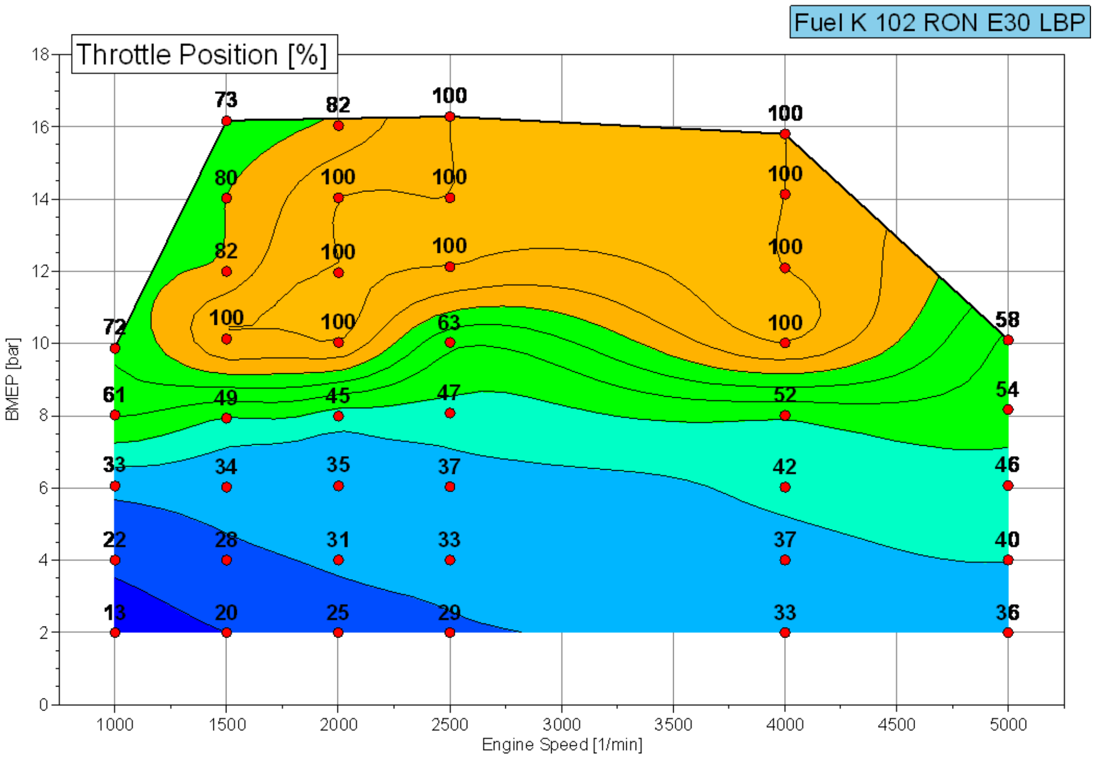

Figure 31: Throttle Position

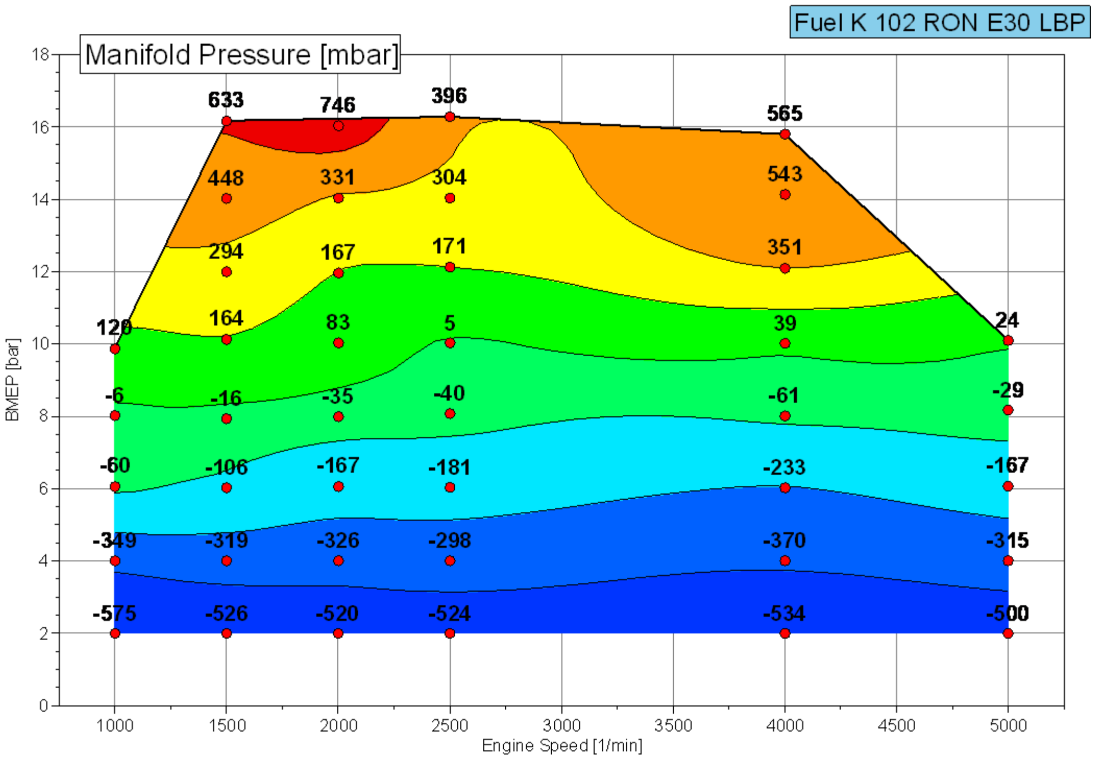

Figure 32: Intake Manifold Pressure

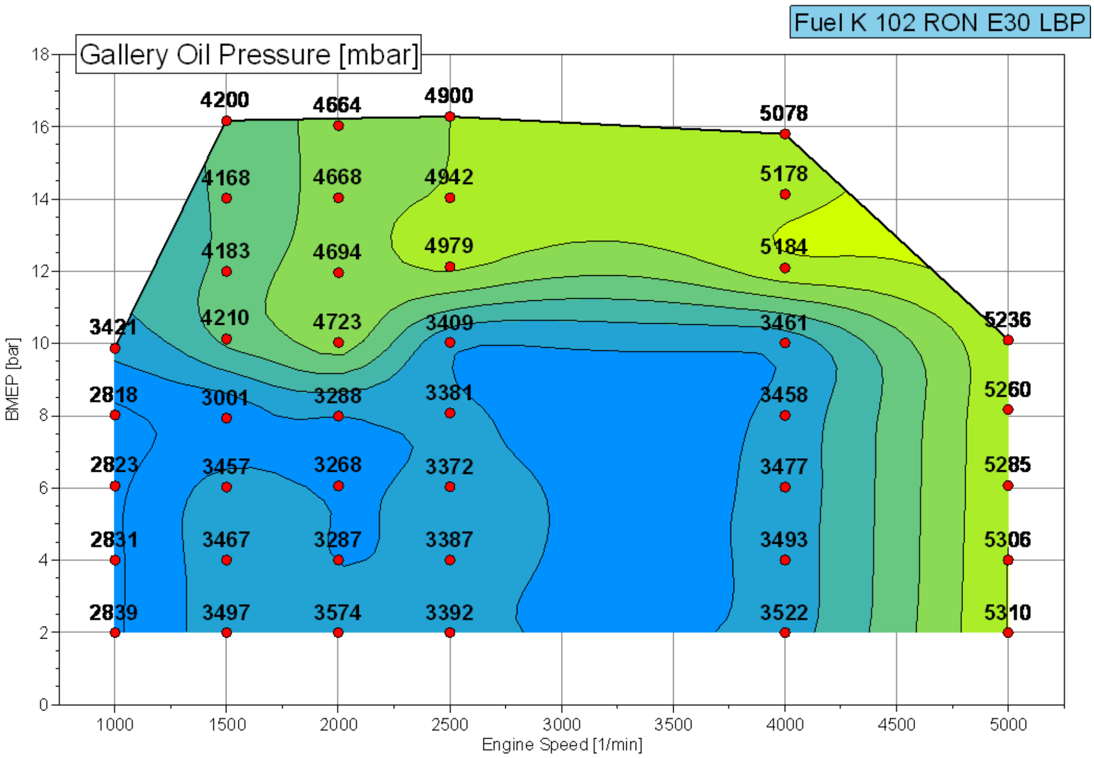

Figure 33: Gallery Oil Pressure

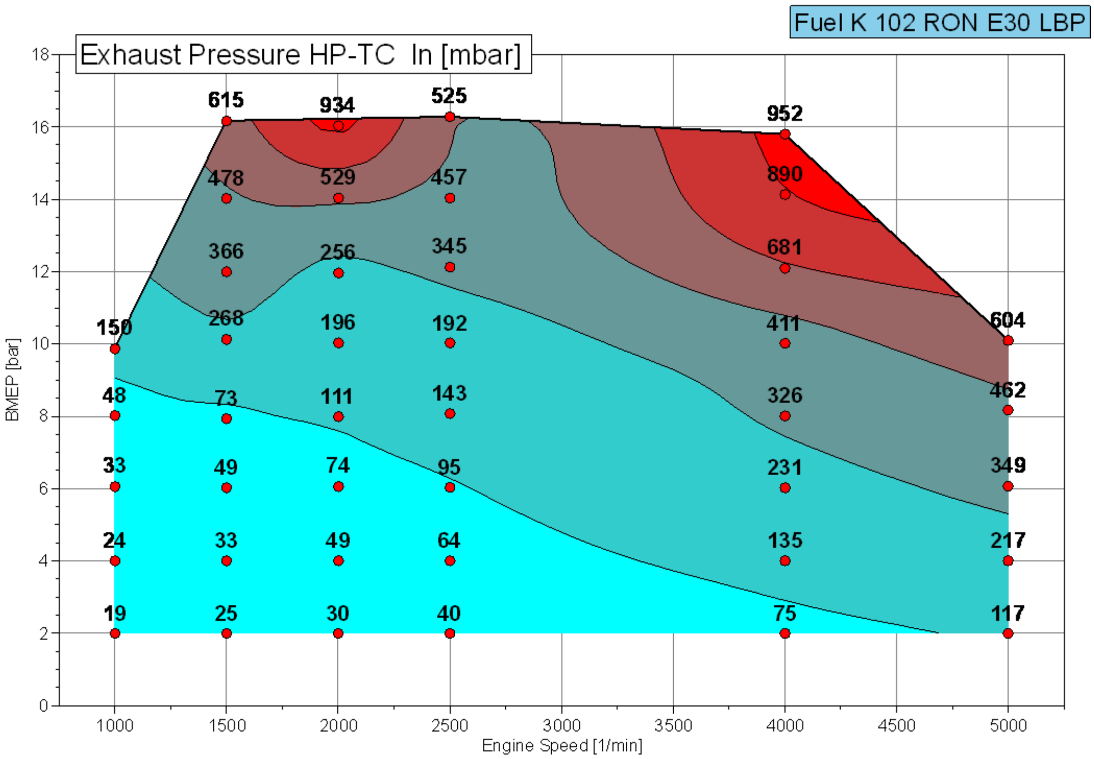

Figure 34: Exhaust Pressure High Pressure Turbocharger In

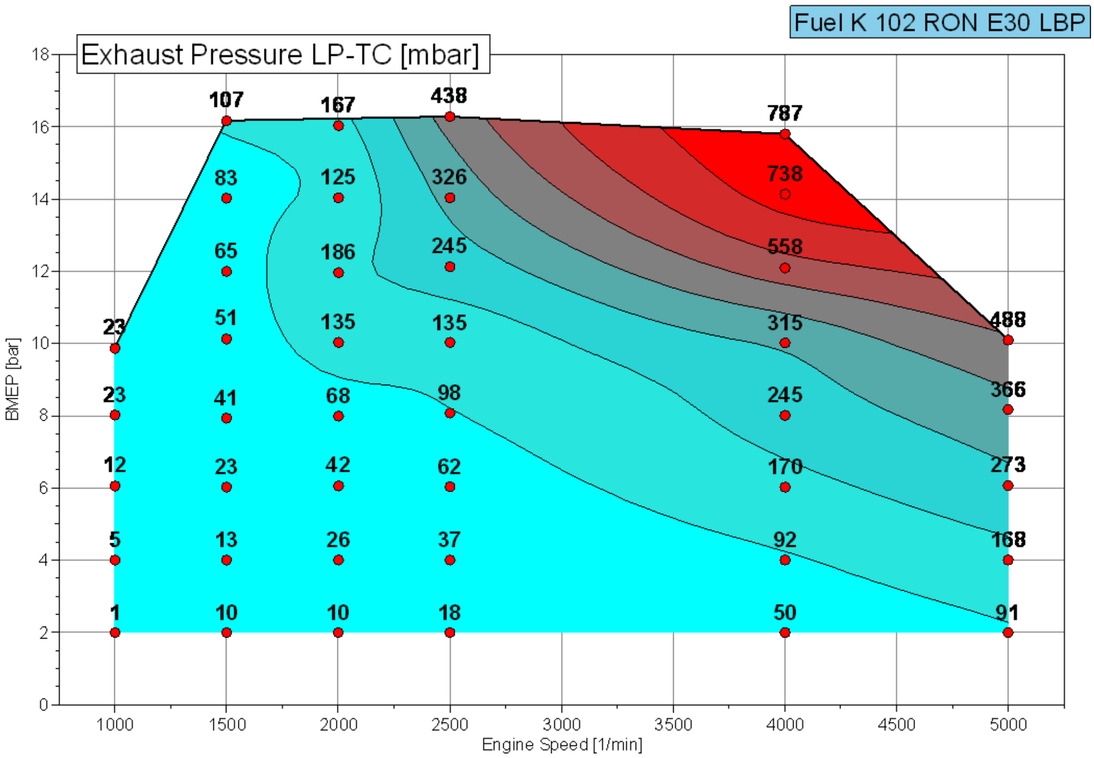

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

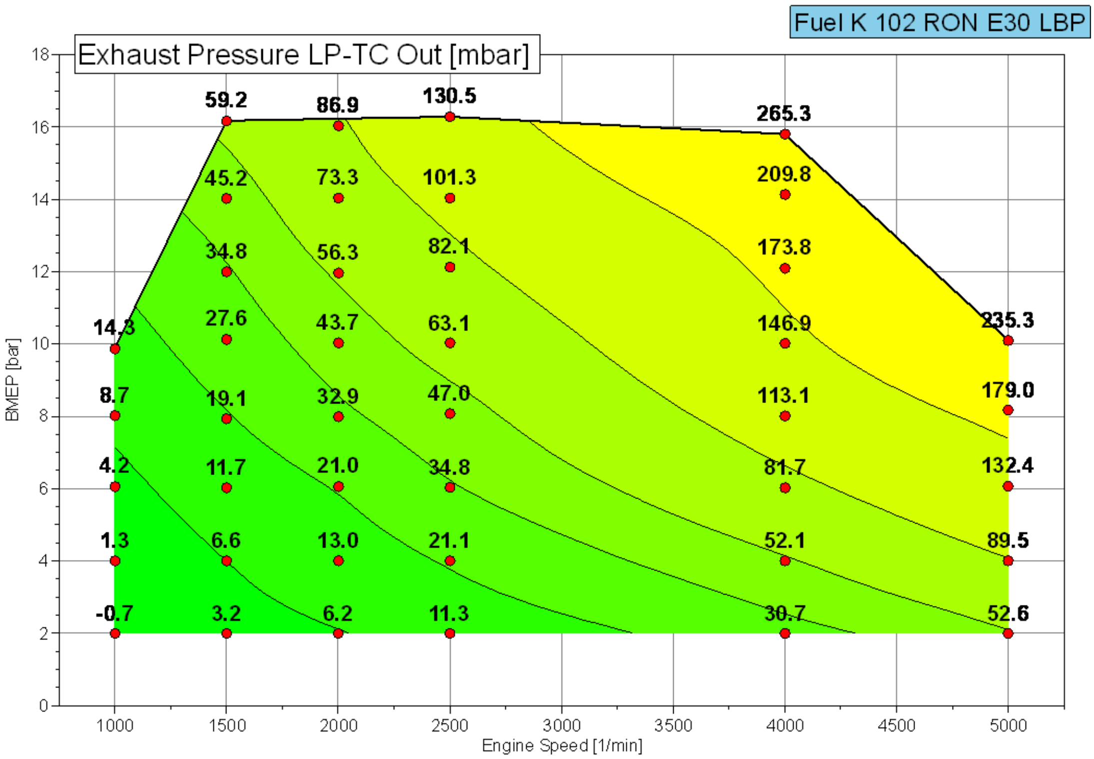

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

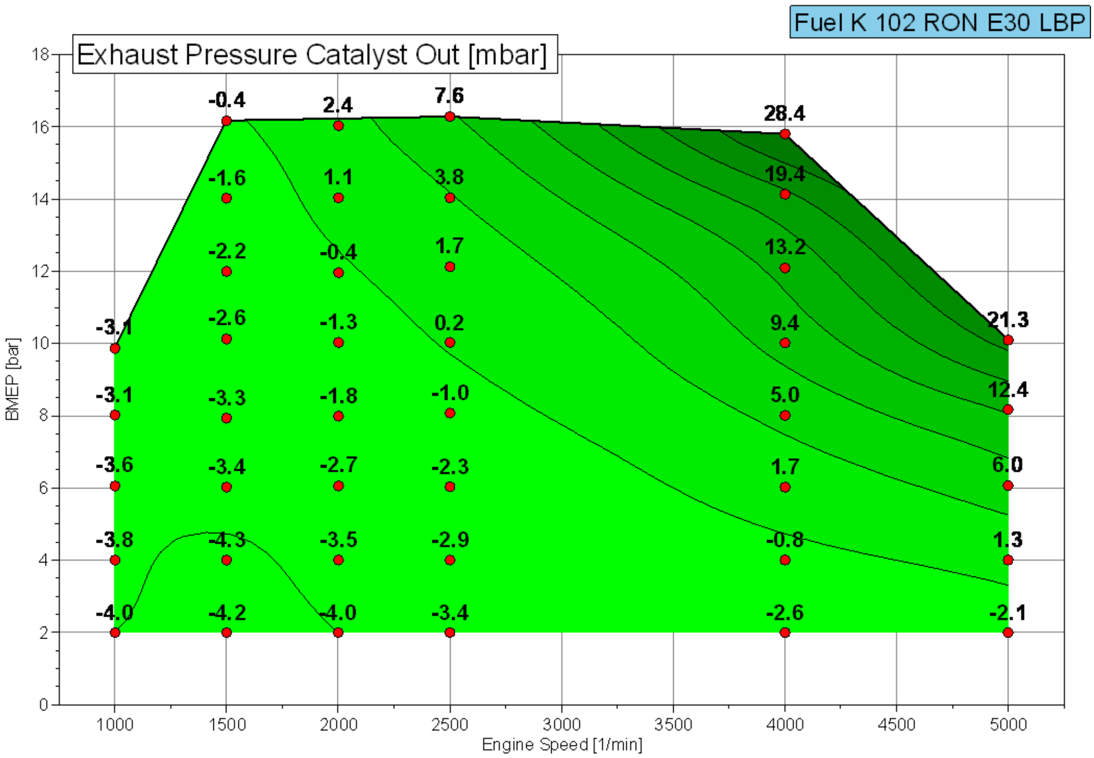

Figure 37: Exhaust Pressure Catalyst Out

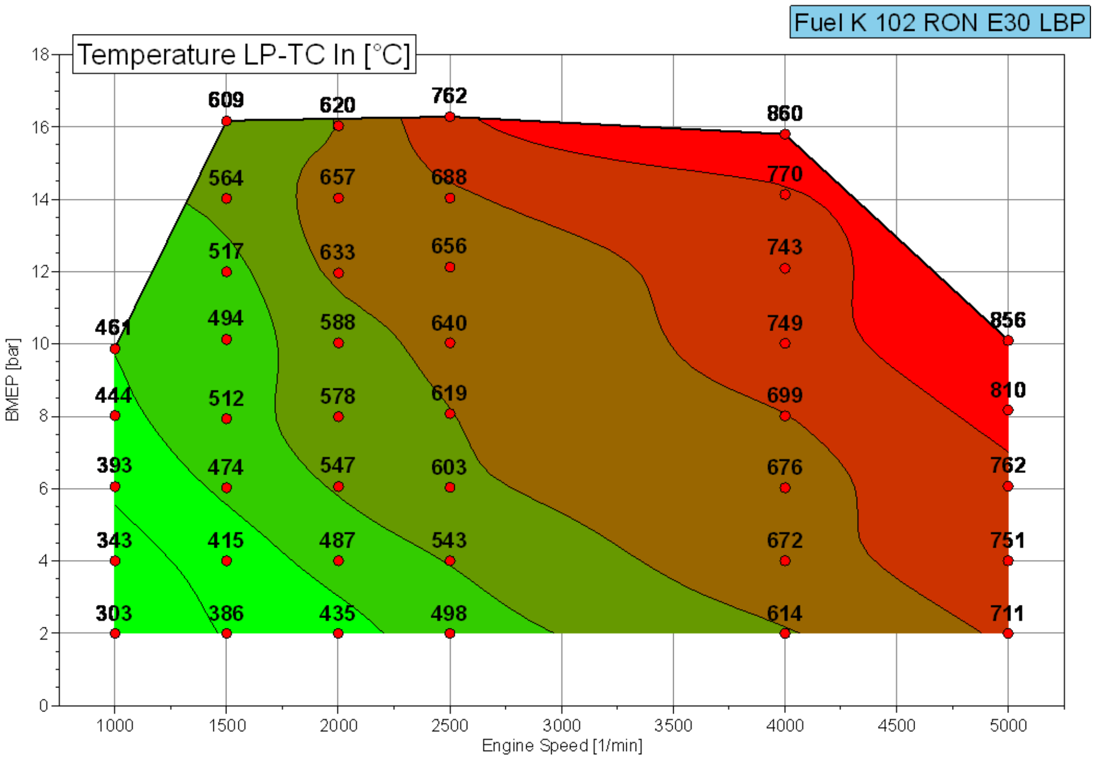

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

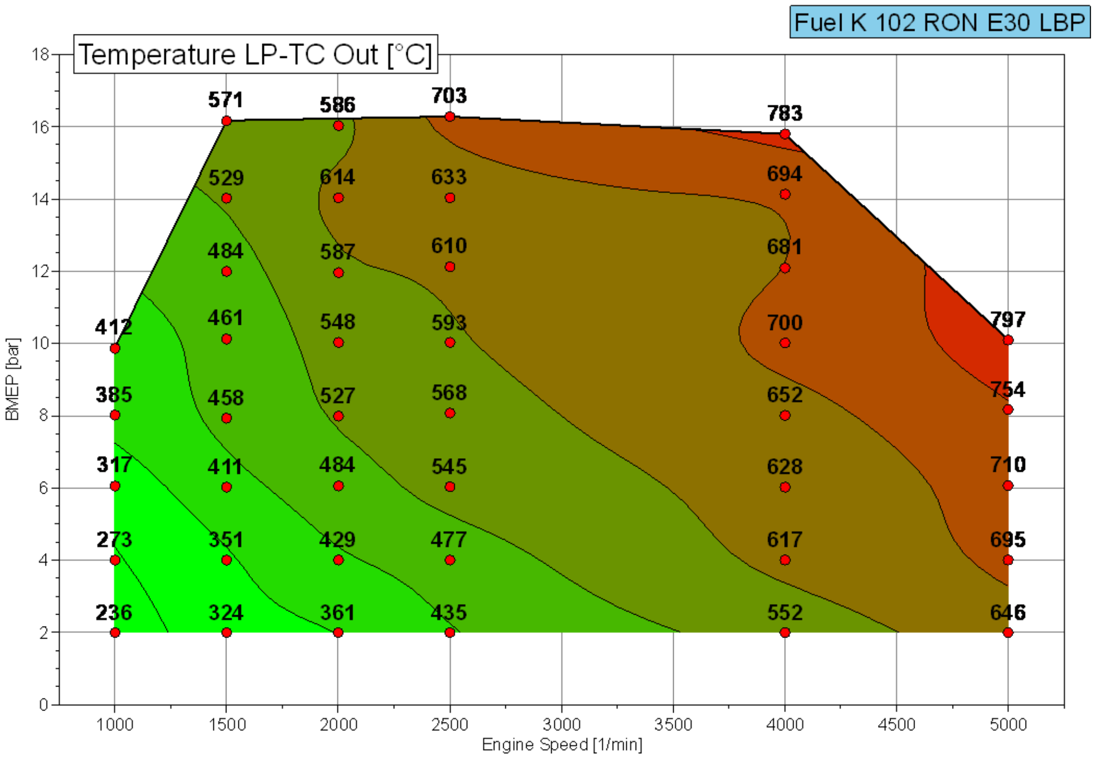

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

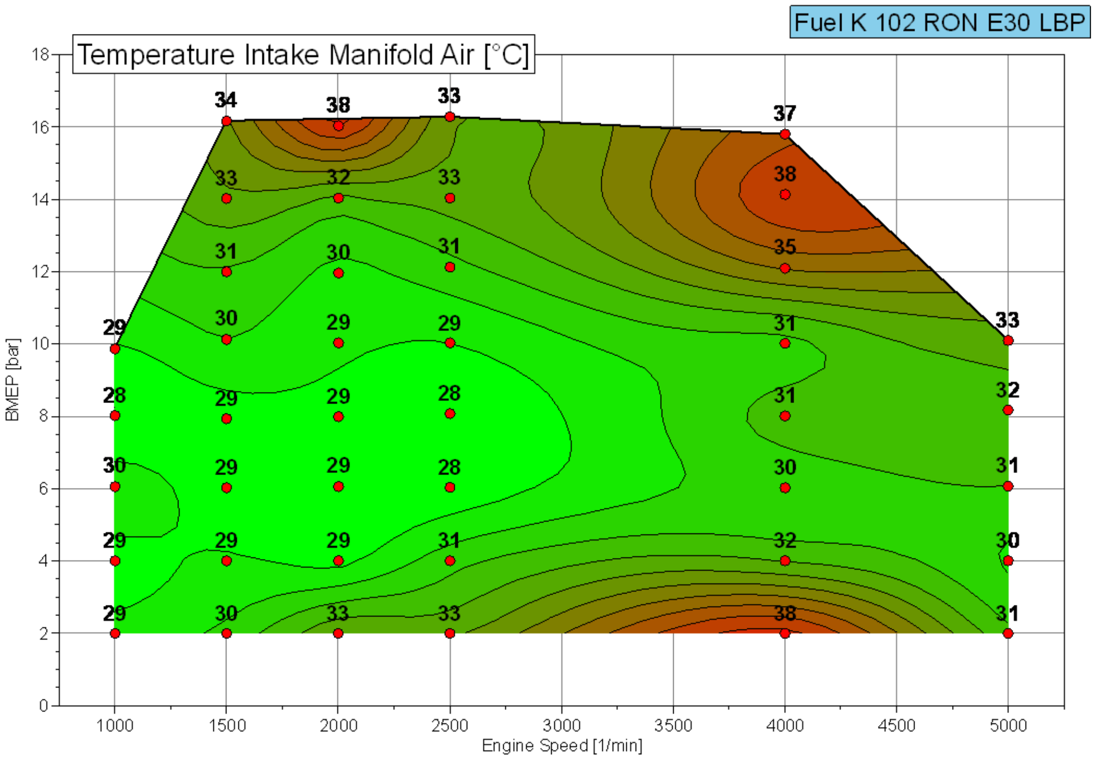

Figure 40: Intake Manifold Air Temperature

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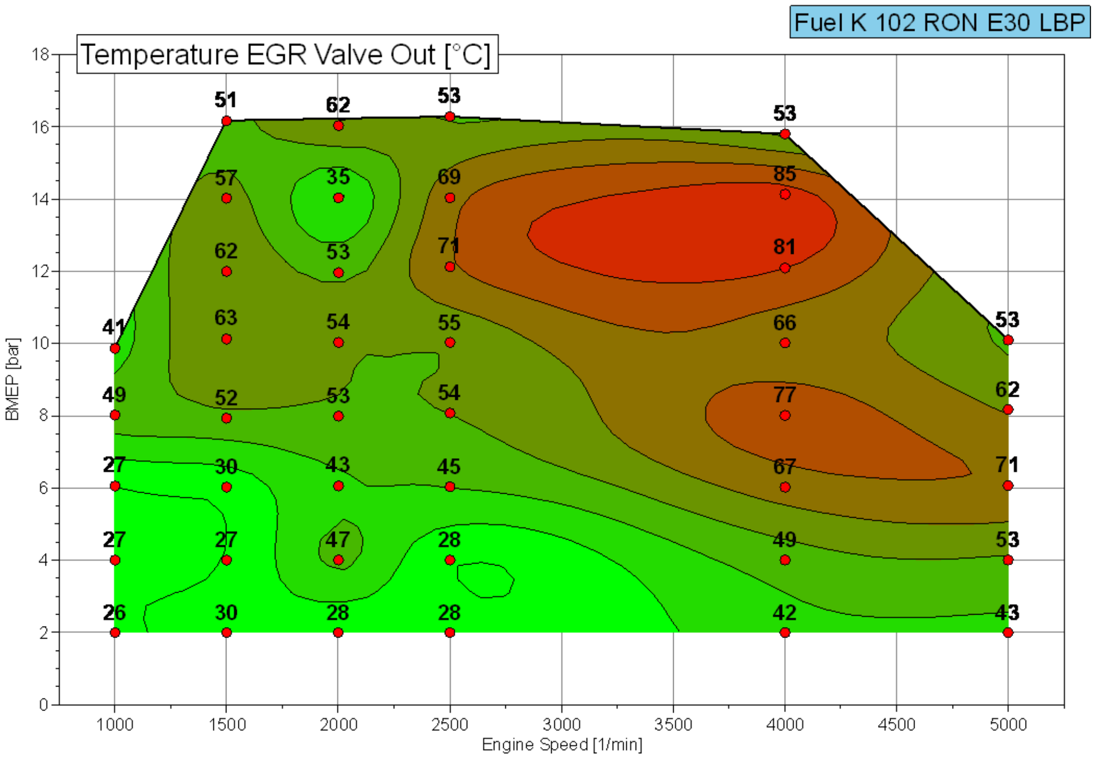

Figure 41: EGR Valve Out Temperature

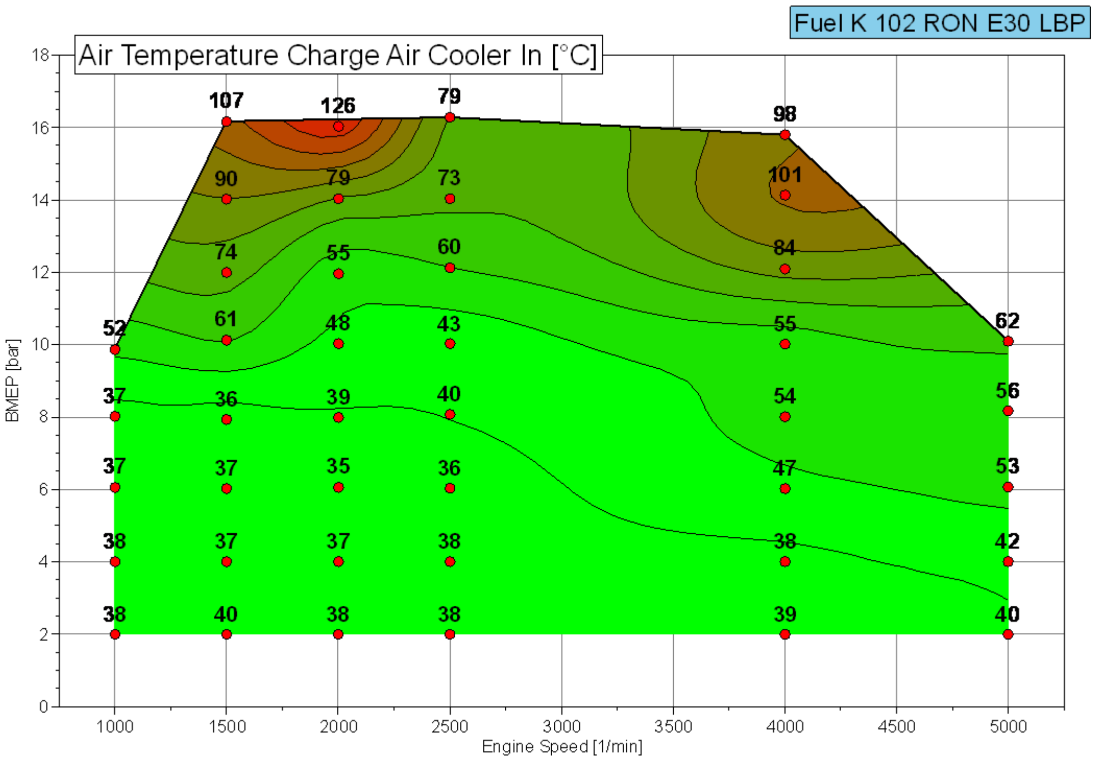

Figure 42: Charge Air Cooler Inlet Air Temperature

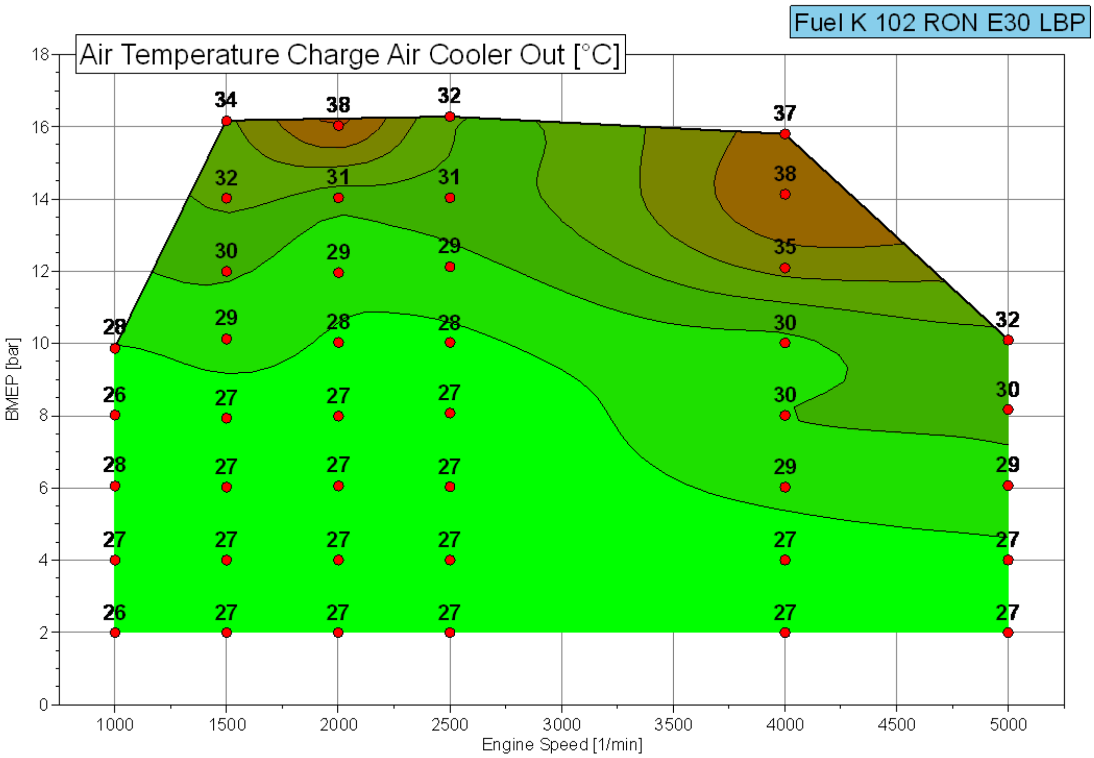

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel L Calibration Results

102 Ron 30% Ethanol High Boiling Point

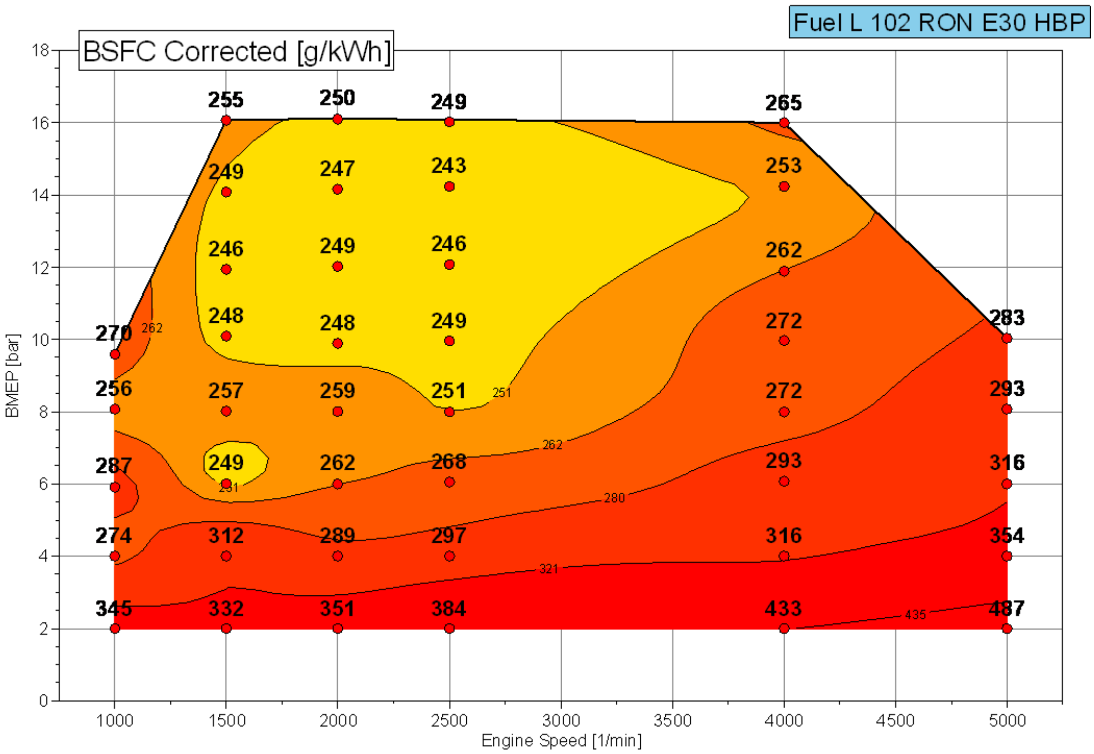

Figure 1: Brake Specific Fuel Consumption

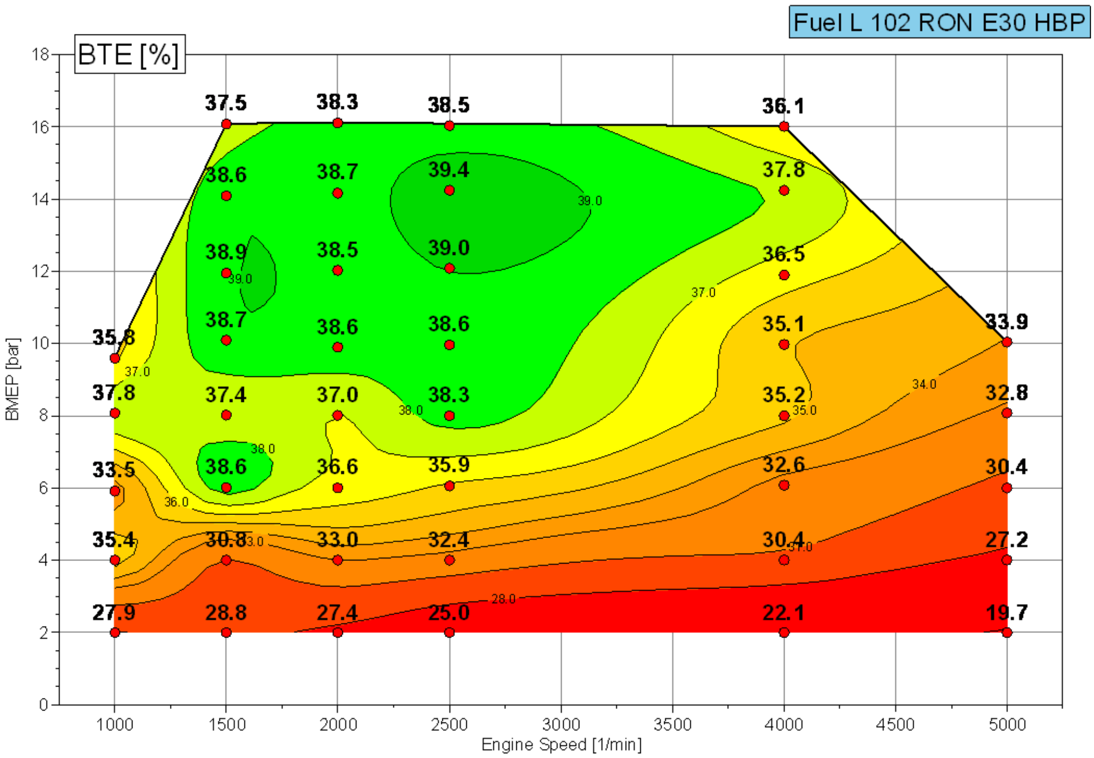

Figure 2: Brake Thermal Efficiency

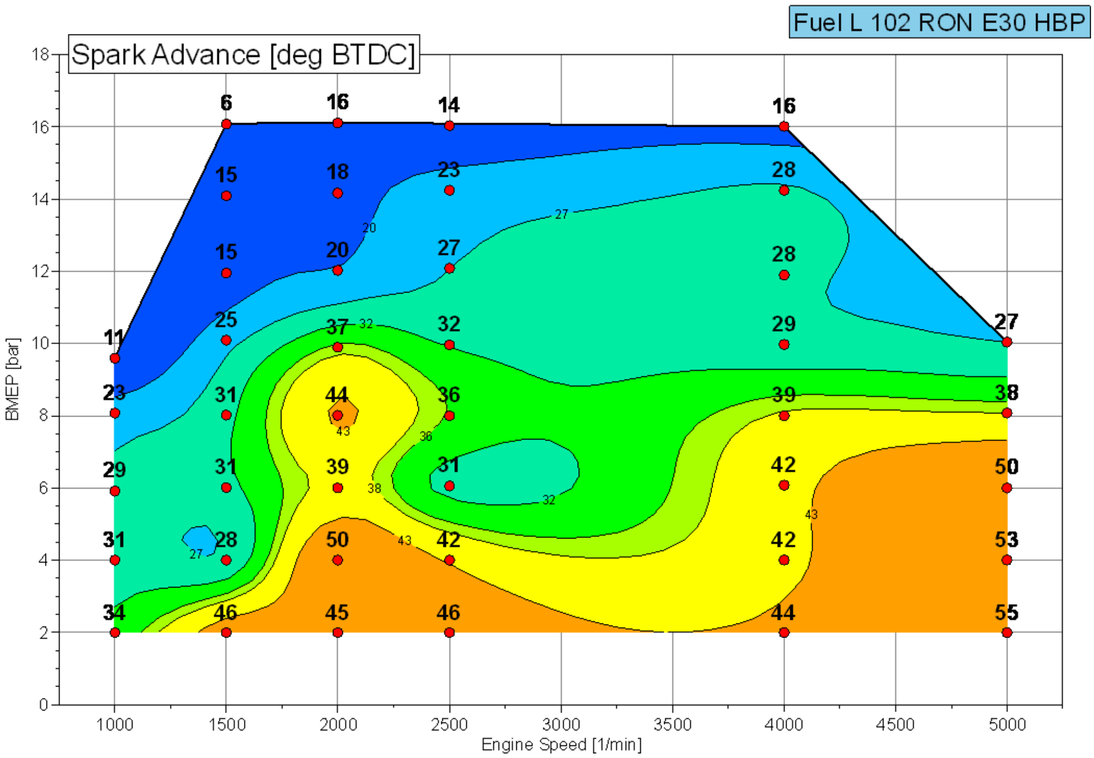

Figure 3: Spark Advance

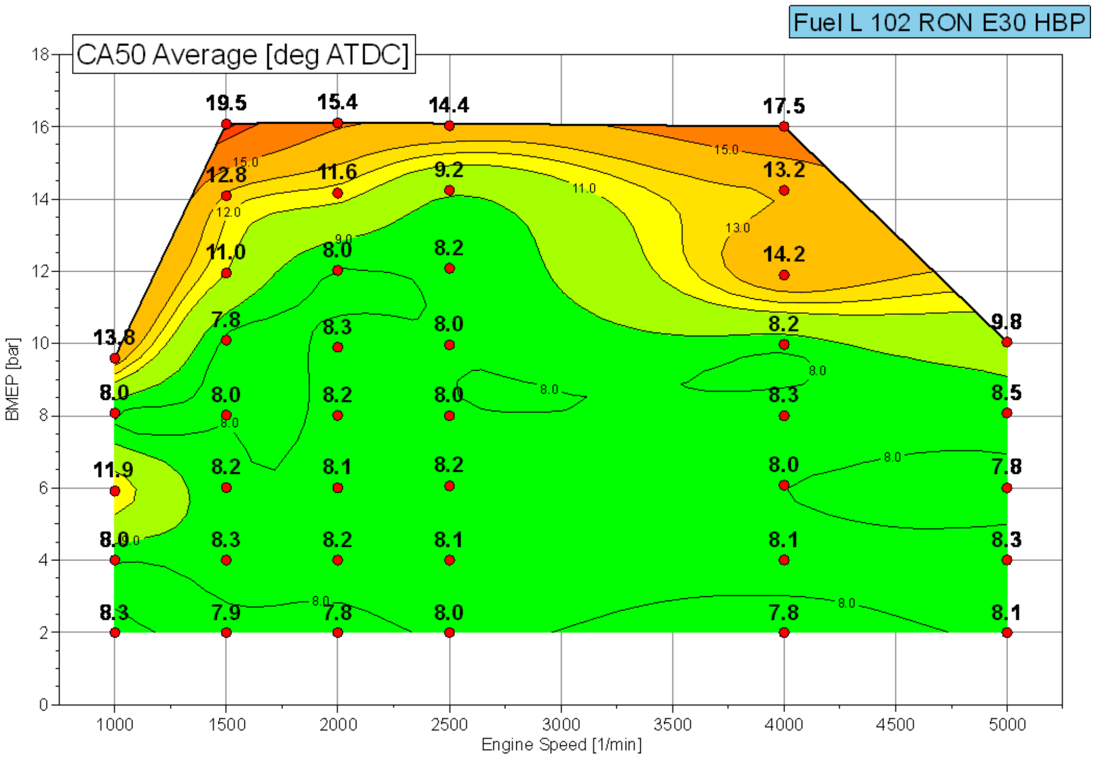

Figure 4: CA50 Average of Cylinders 1-4

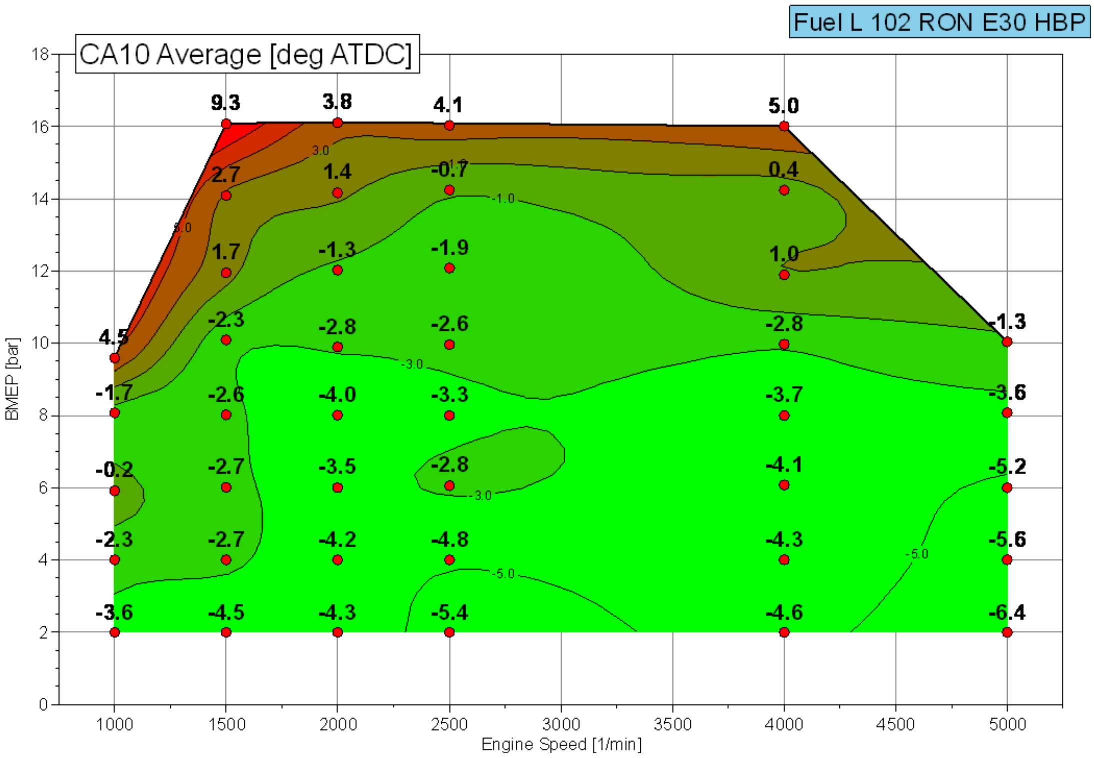

Figure 5: CA10 Average of Cylinders 1-4

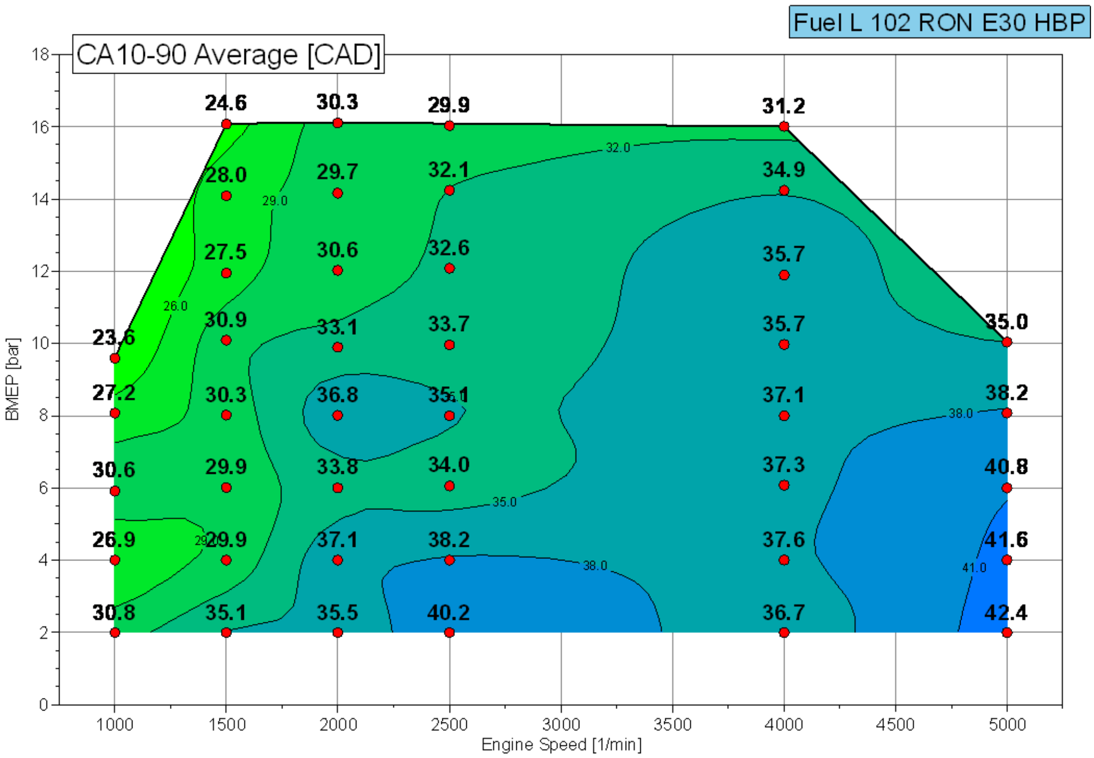

Figure 6: CA10-90 Average of Cylinders 1-4

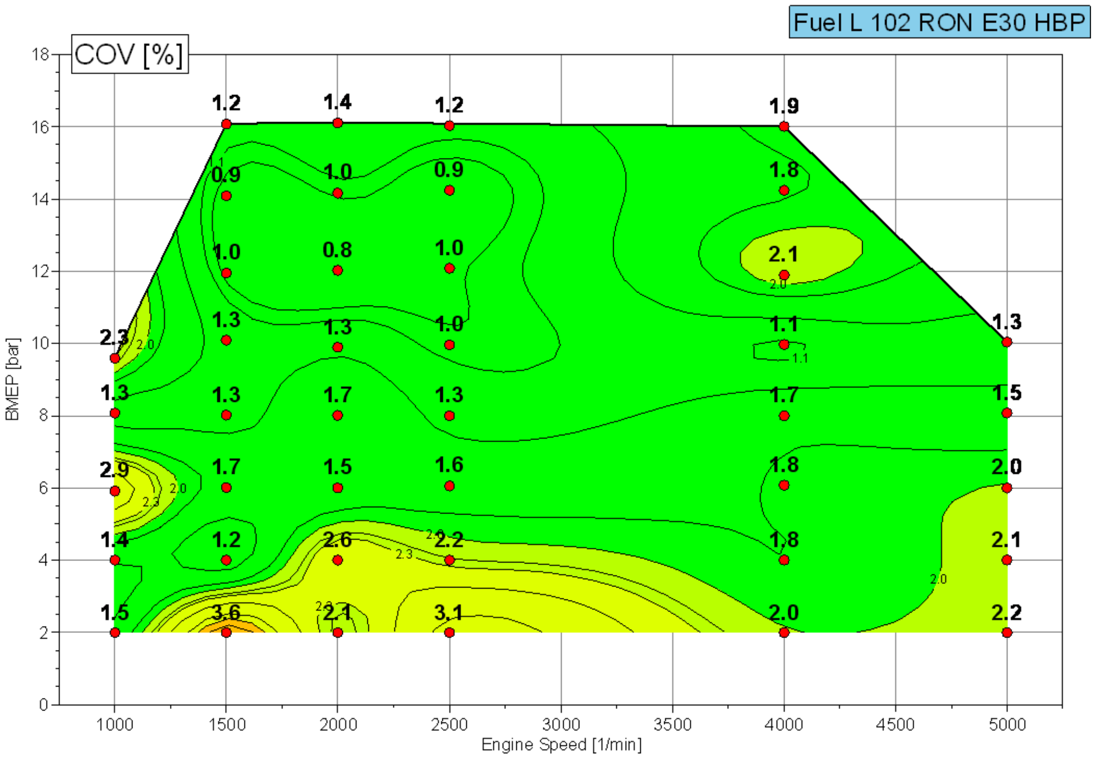

Figure 7: Coefficient of Variation Average of Cylinders 1-4

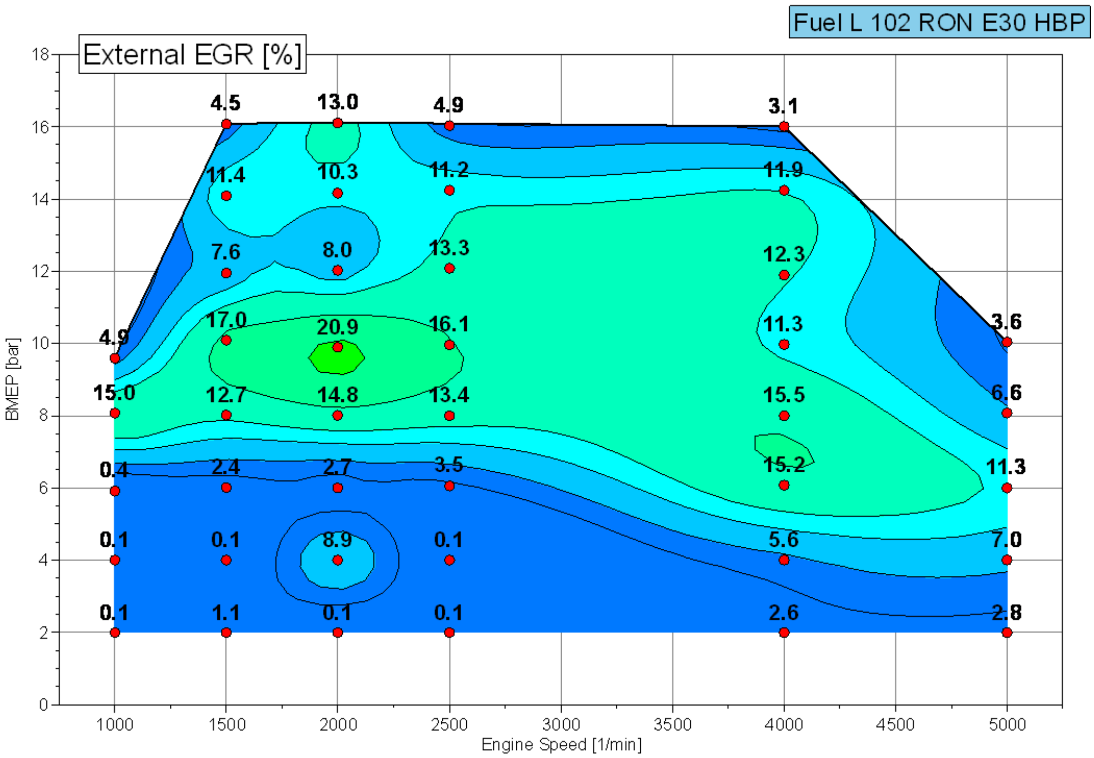

Figure 8: External EGR Percent of Intake Air

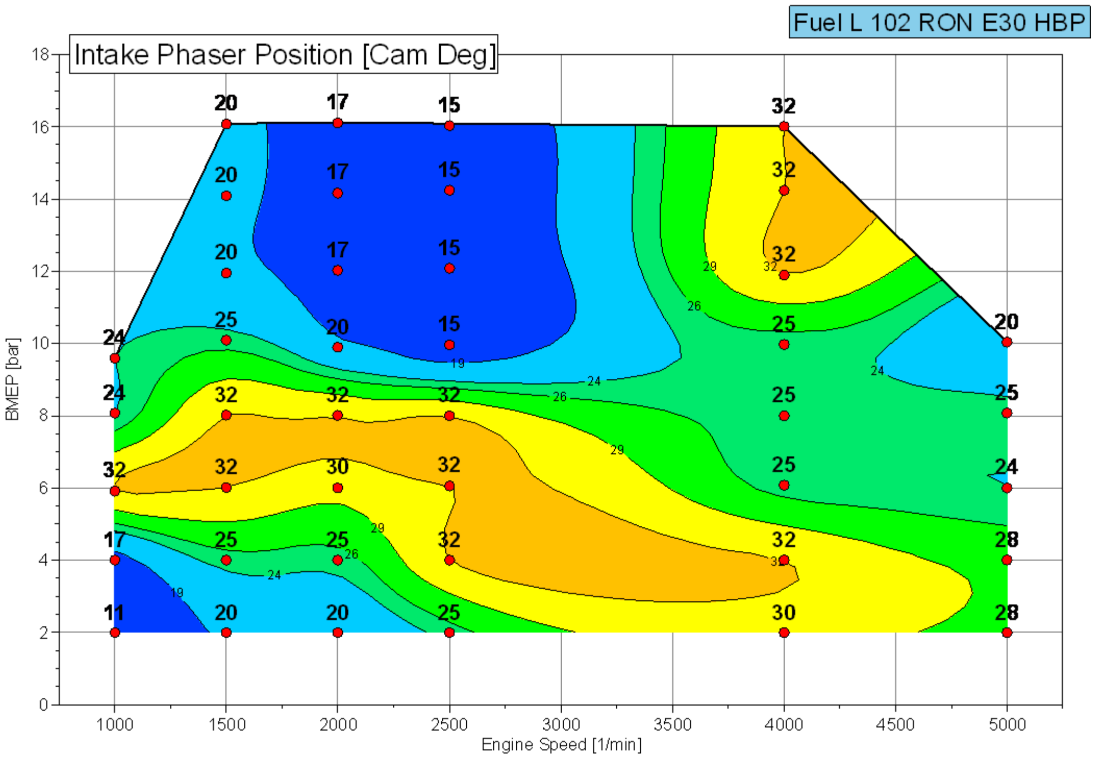

Figure 9: Intake Camshaft Position

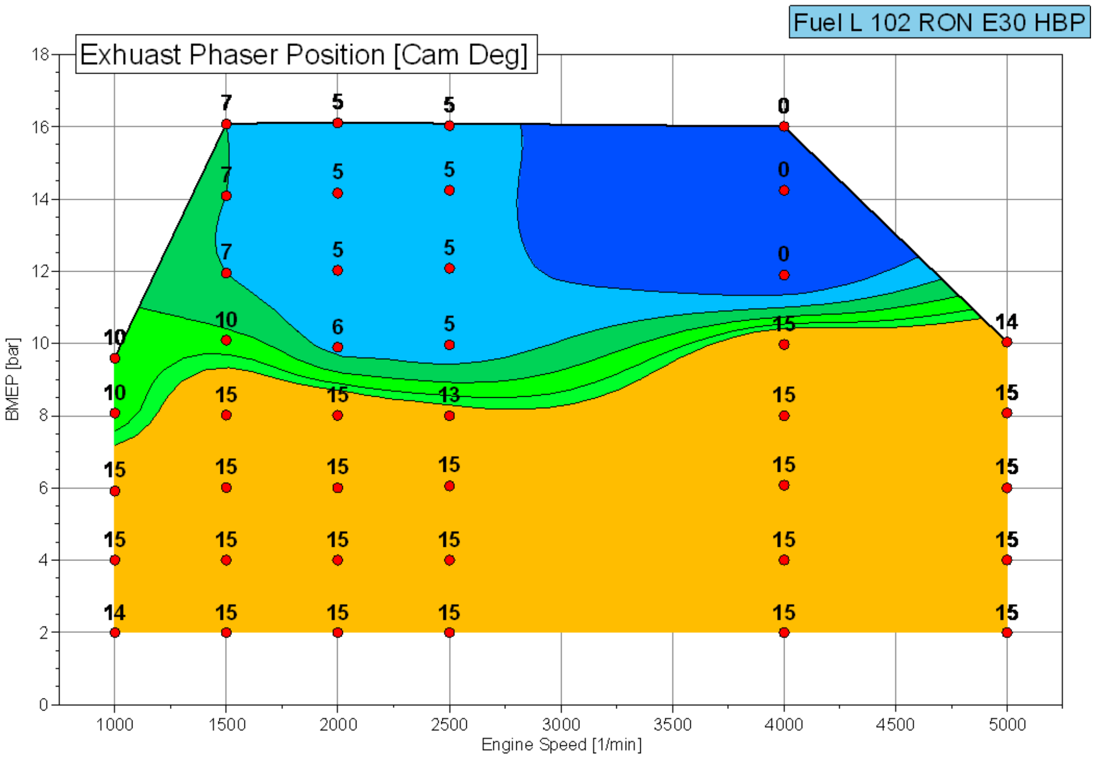

Figure 10: Exhaust Camshaft Position

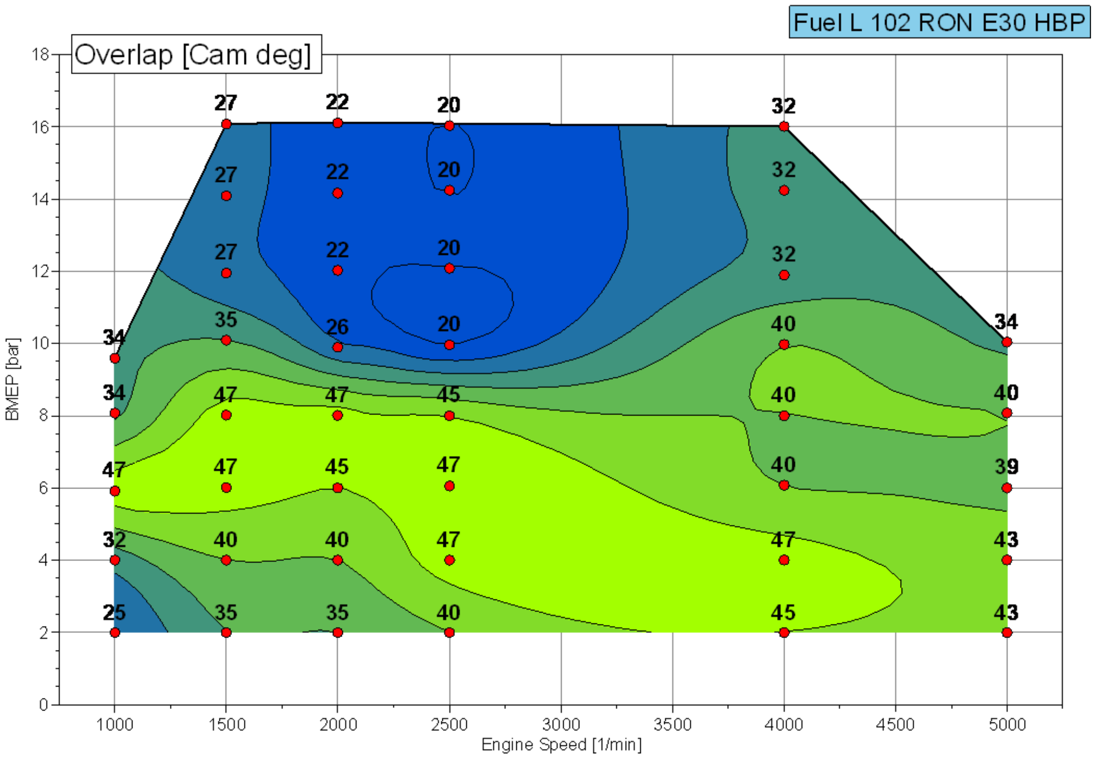

Figure 11: Camshaft Overlap

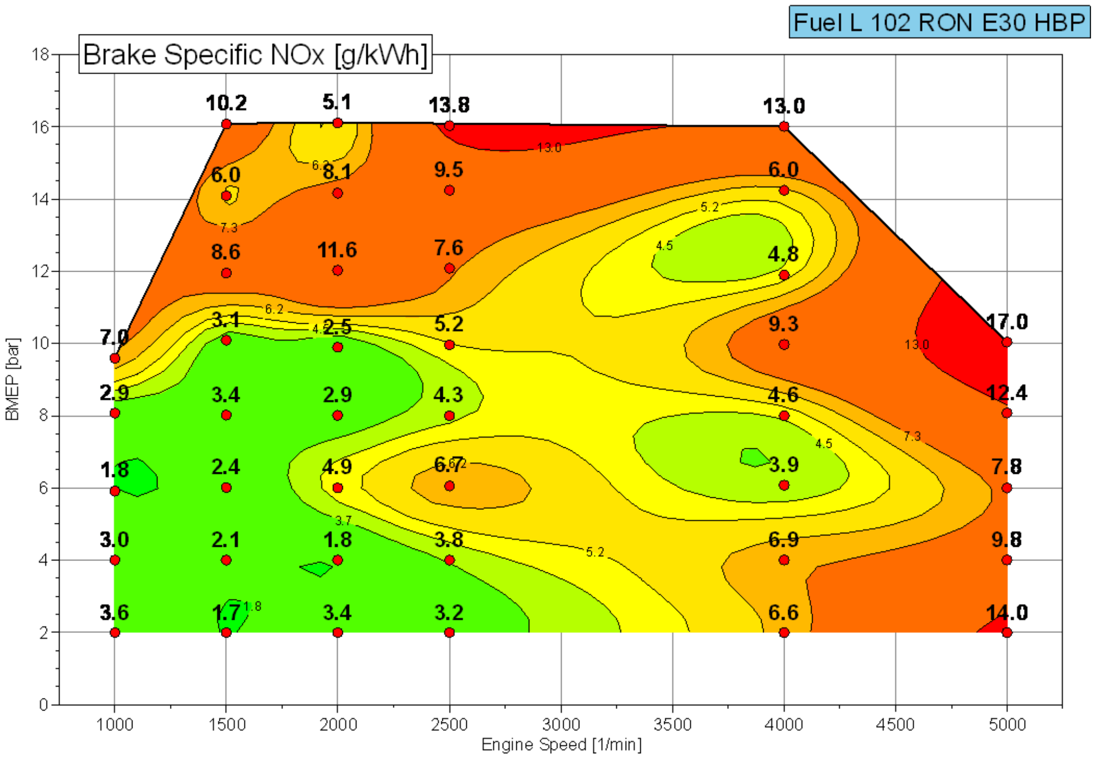

Figure 12: Brake Specific NOx Emissions

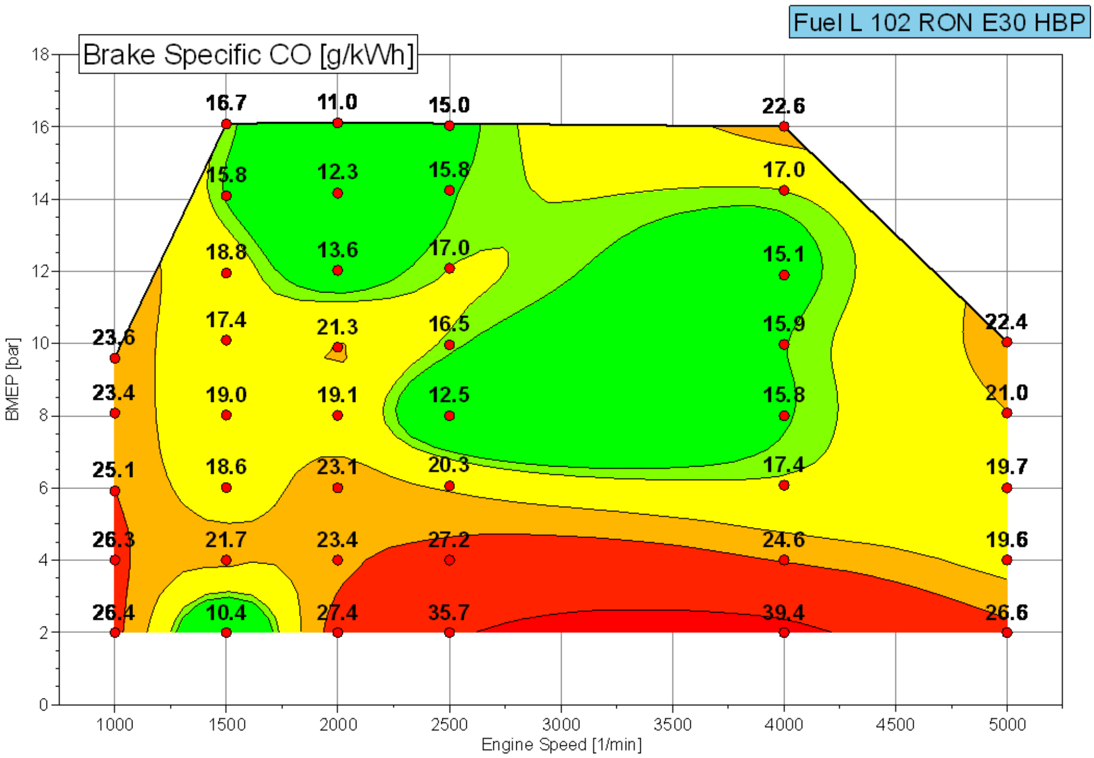

Figure 13: Brake Specific Carbon Monoxide Emissions

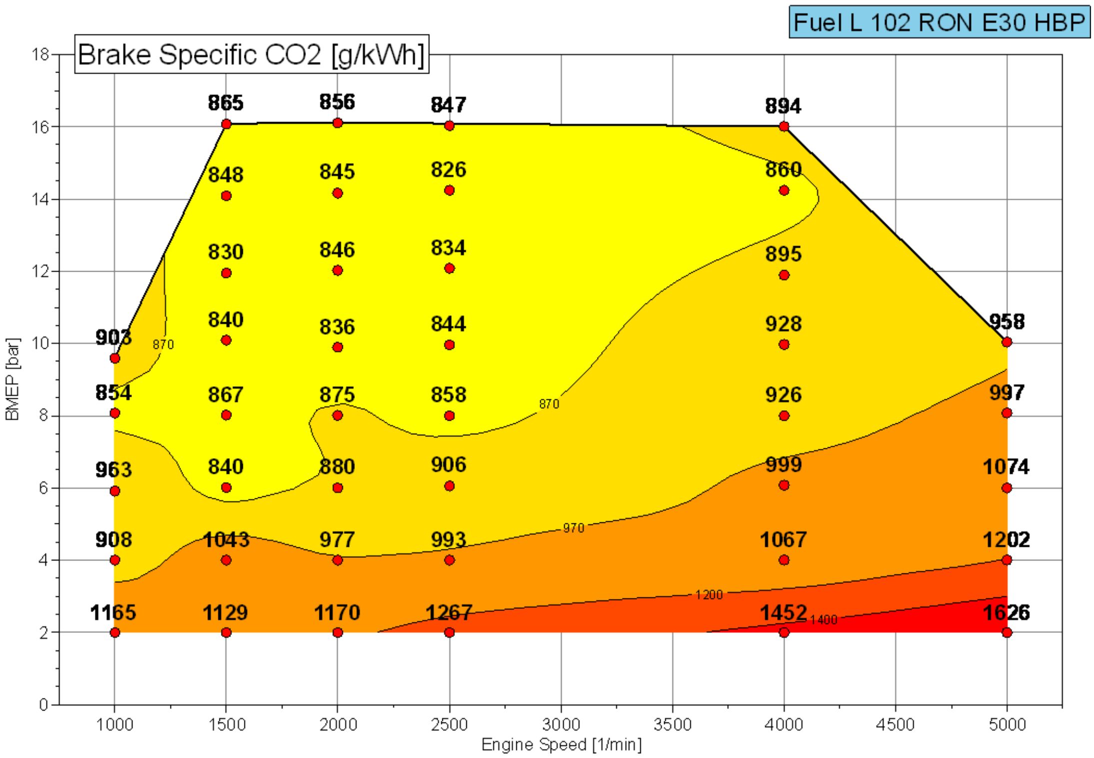

Figure 14: Brake Specific Carbon Dioxide Emissions

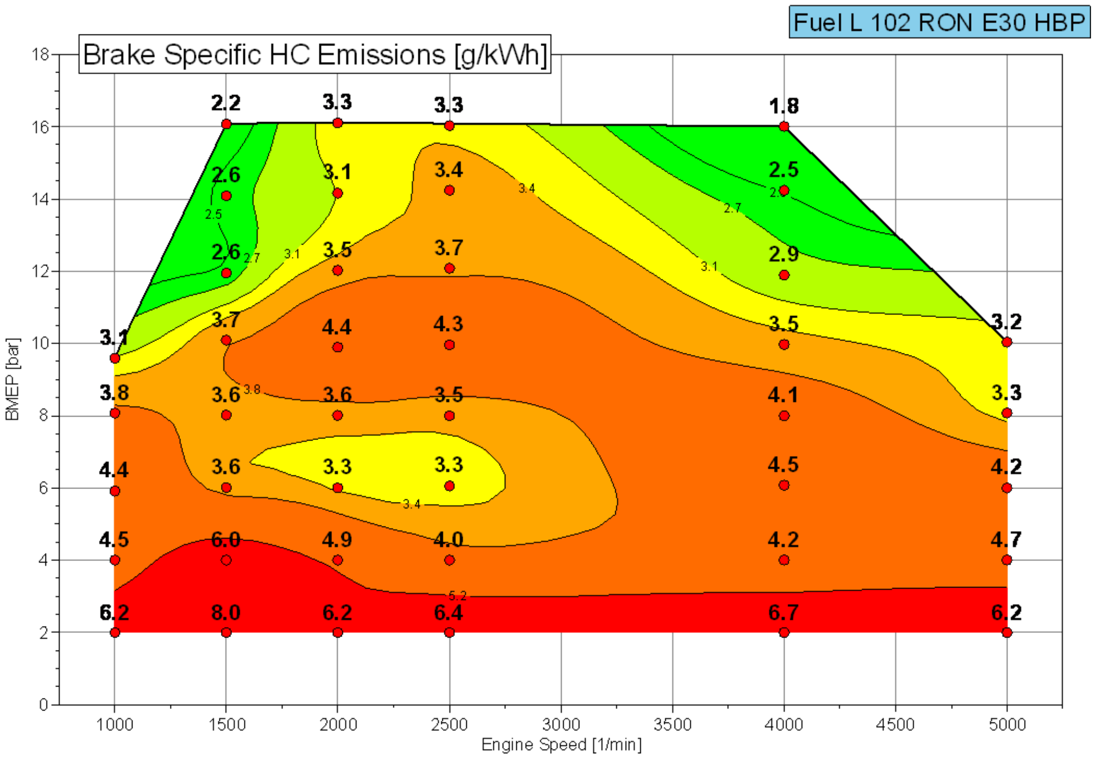

Figure 15: Brake Specific Hydrocarbon Emissions

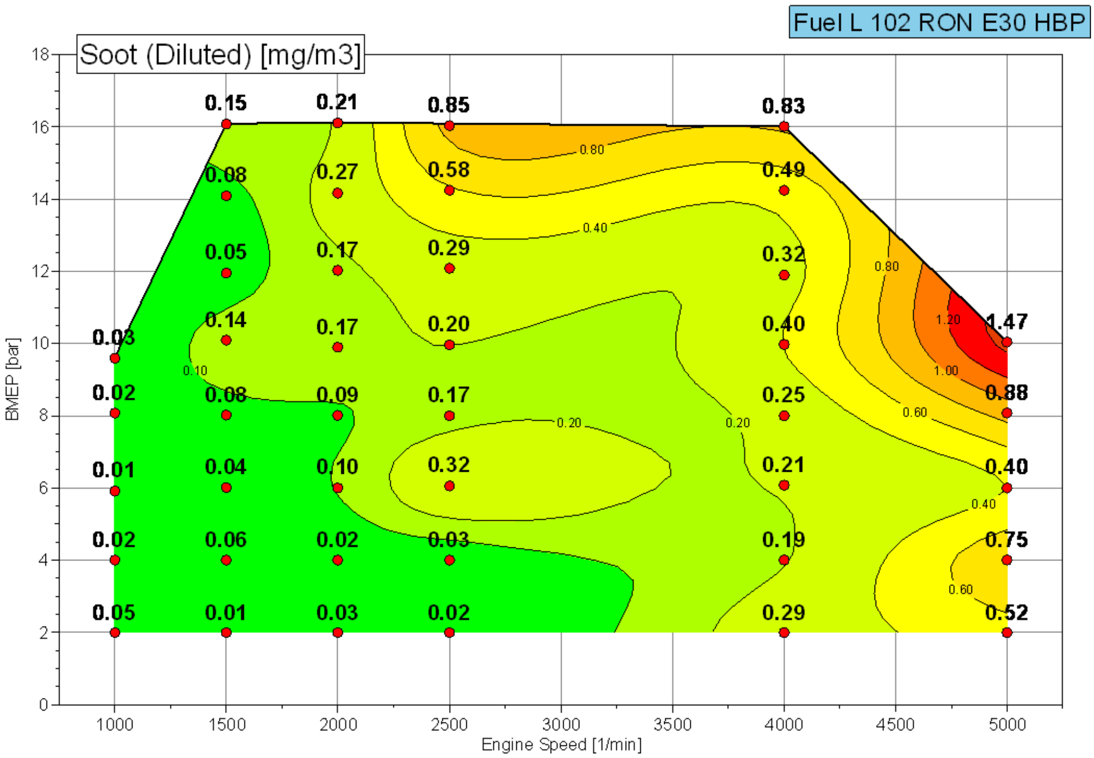

Figure 16: Particulate Soot Emissions

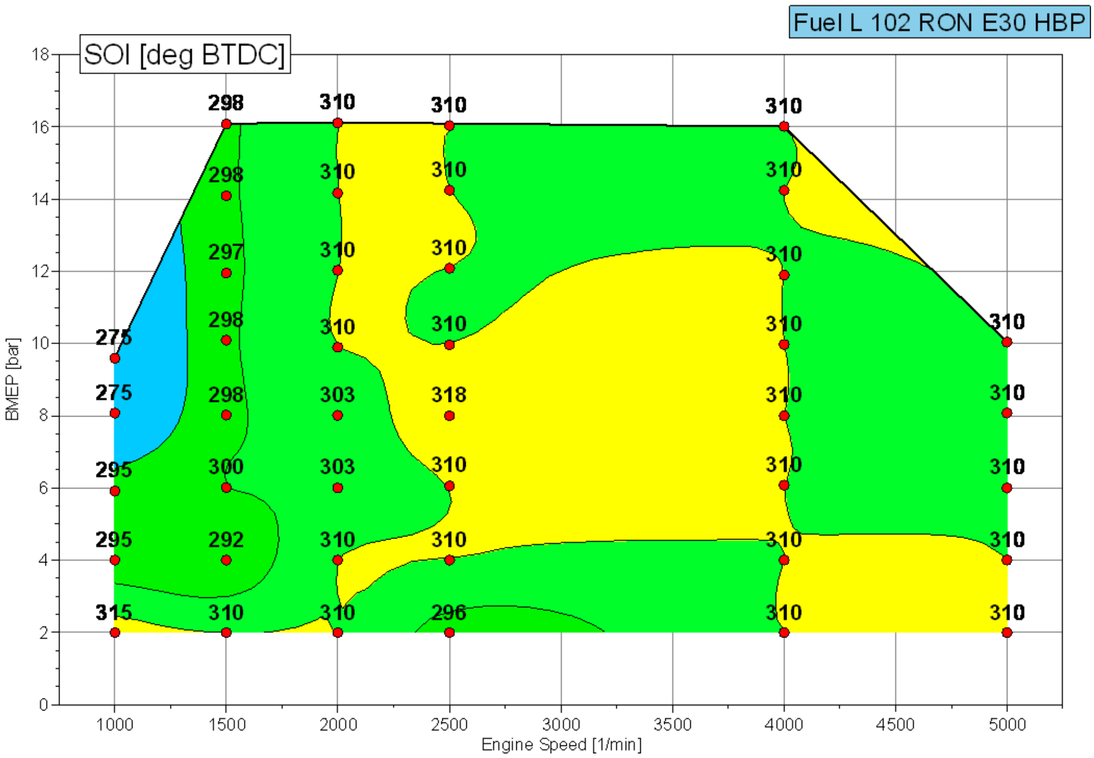

Figure 17: Start of Injection

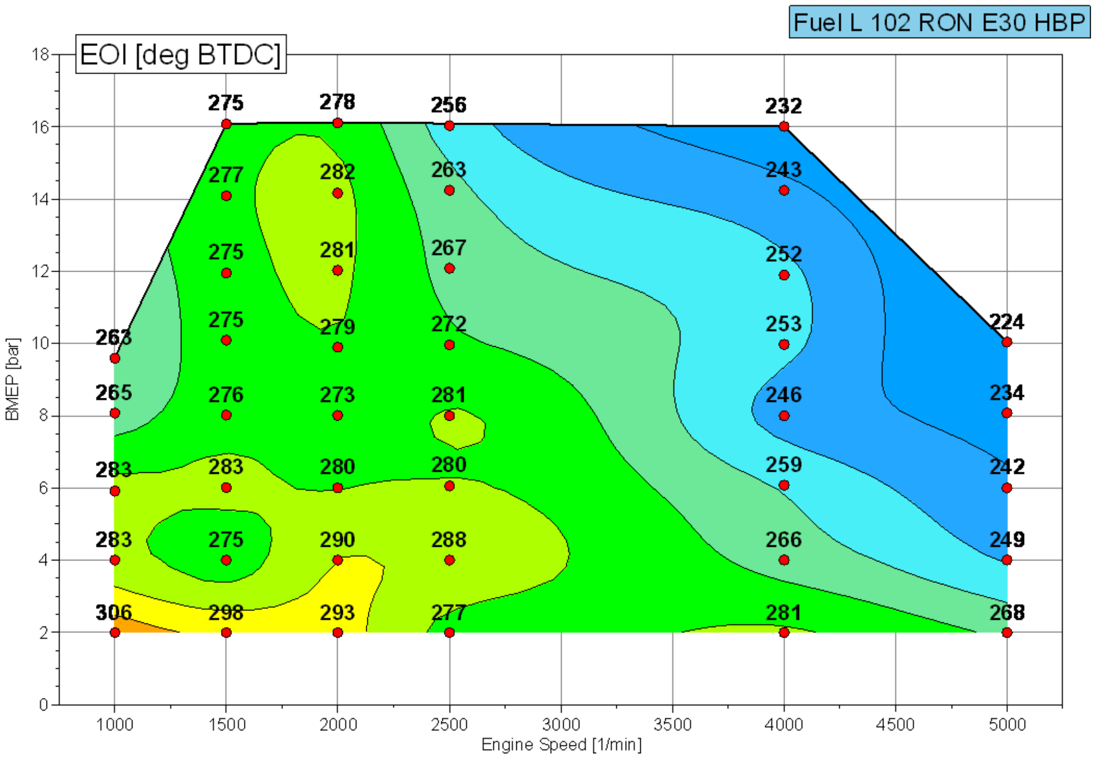

Figure 18: End of Injection

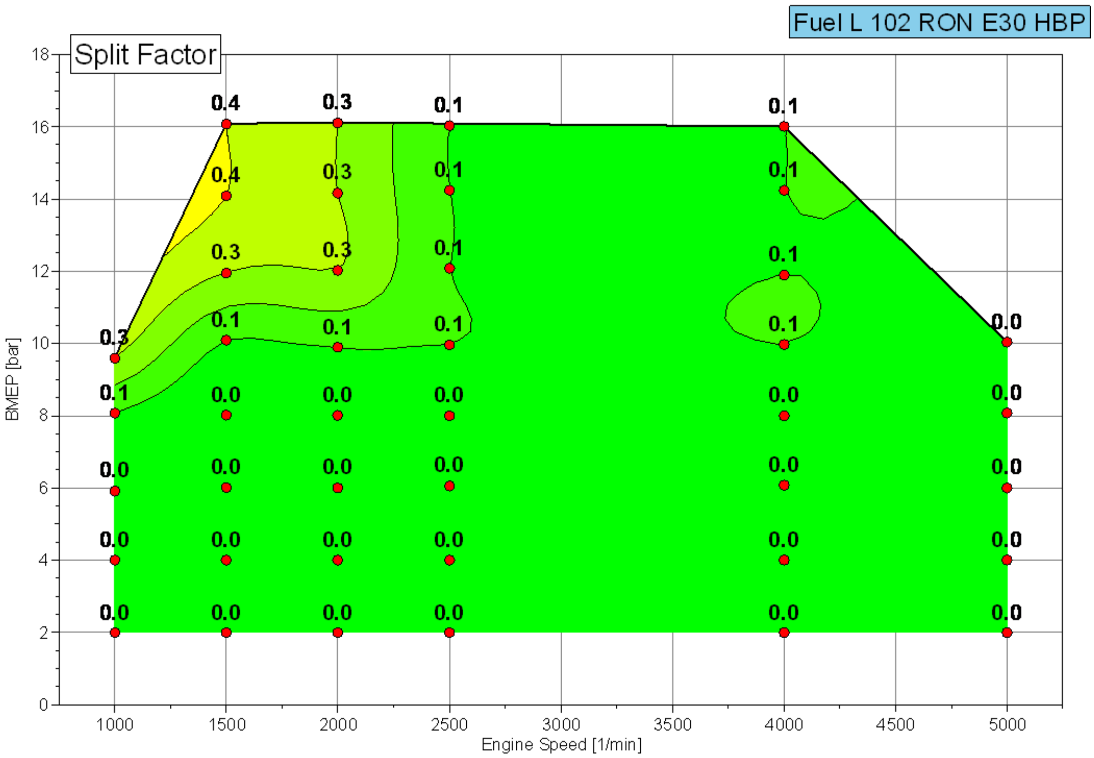

Figure 19: Injection Split Factor

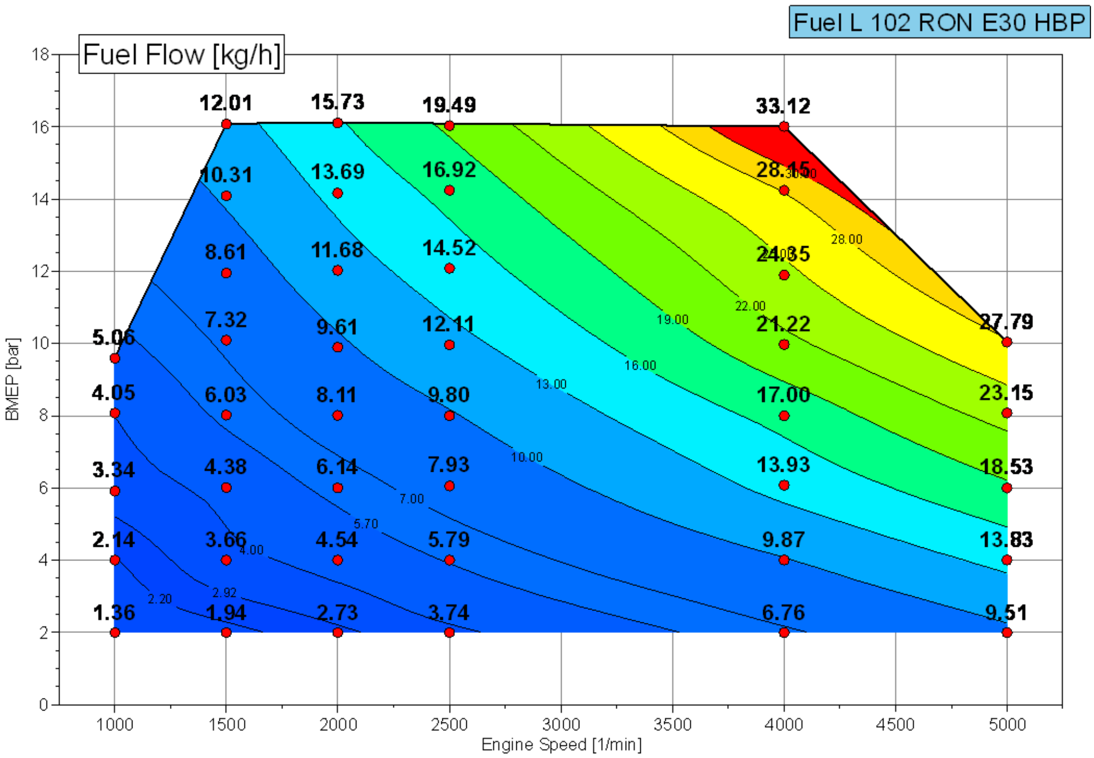

Figure 20: Fuel Flow

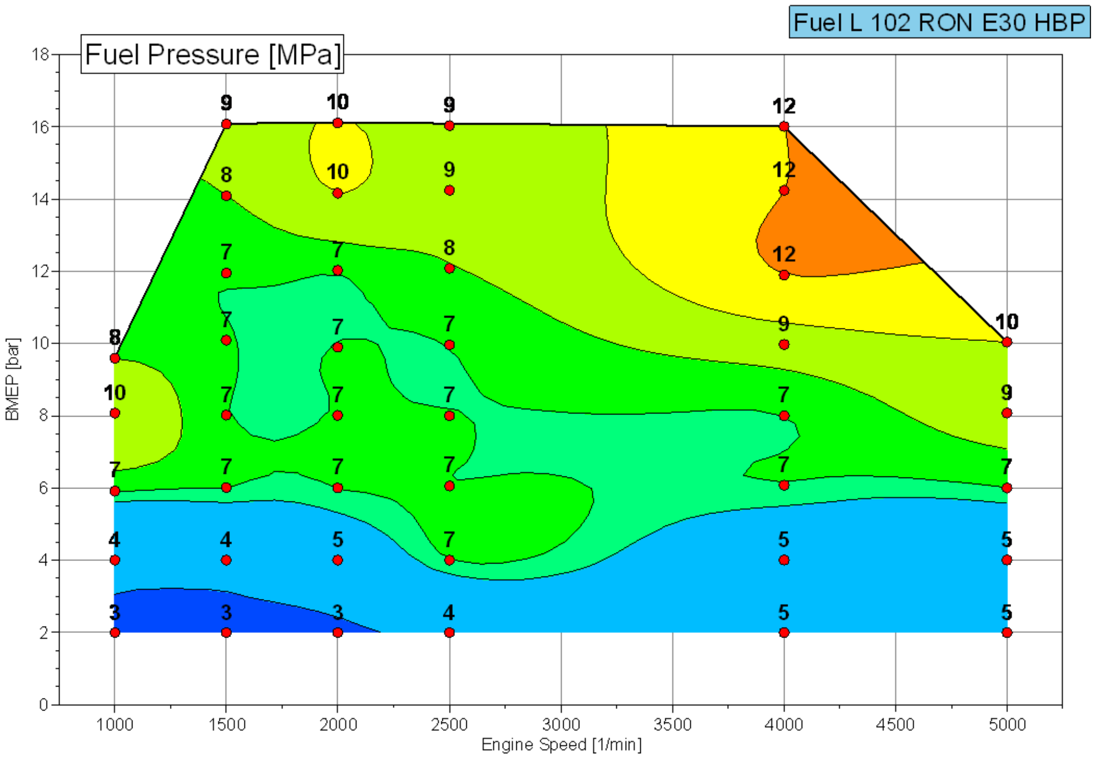

Figure 21: Fuel Rail Pressure

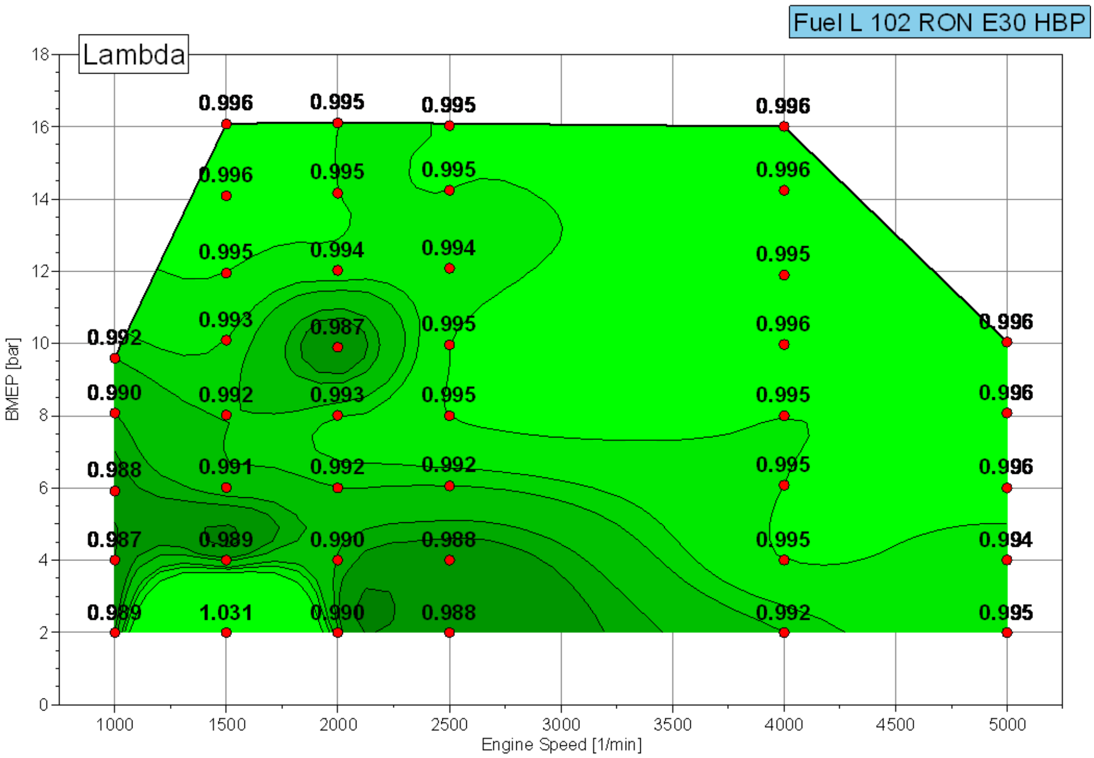

Figure 22: Lambda

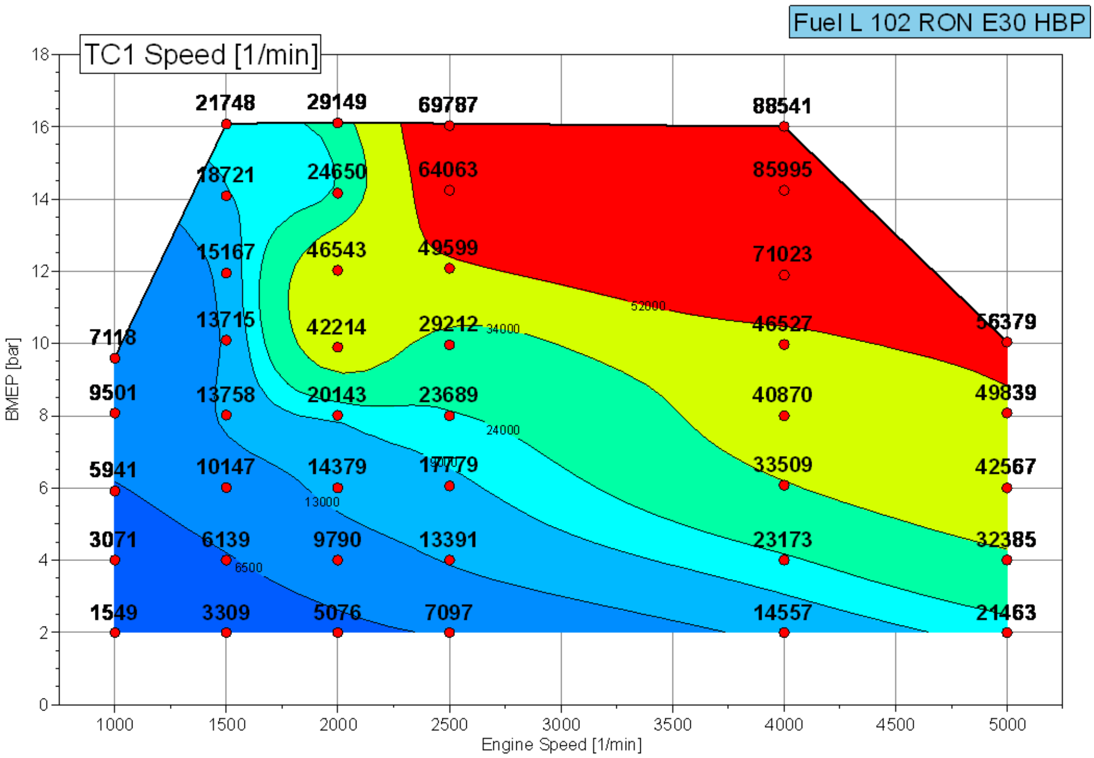

Figure 23: Low Pressure Turbocharger Speed

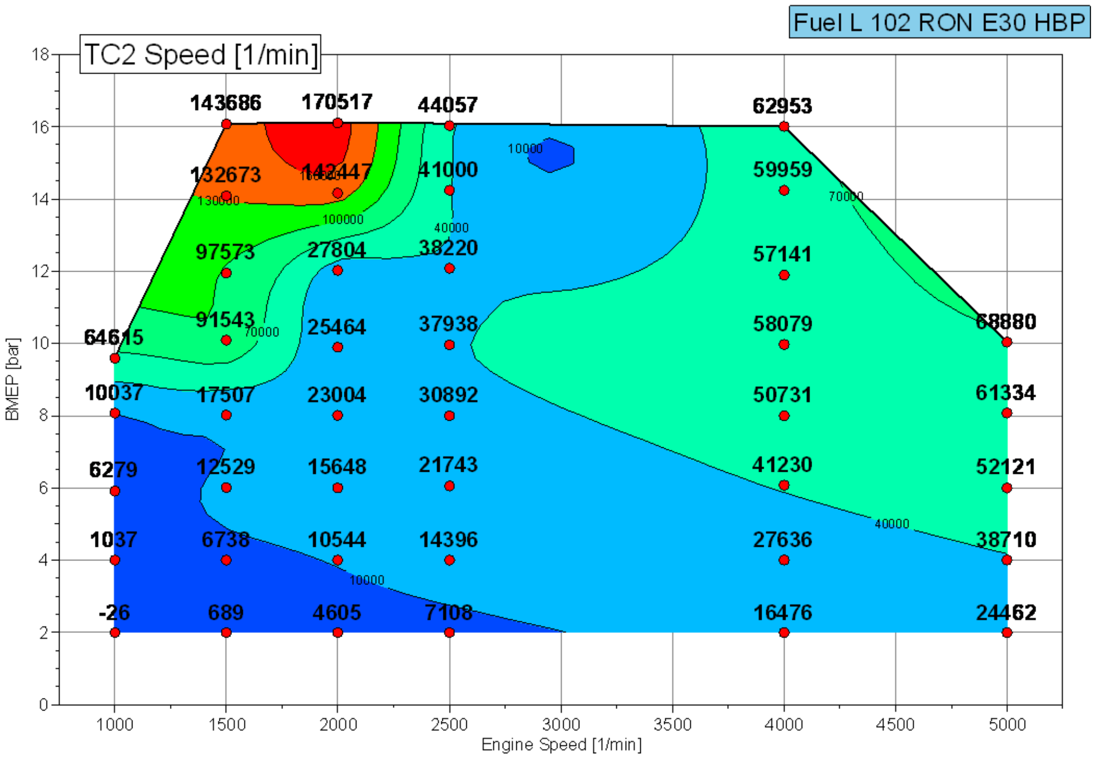

Figure 24: High Pressure Turbocharge Speed

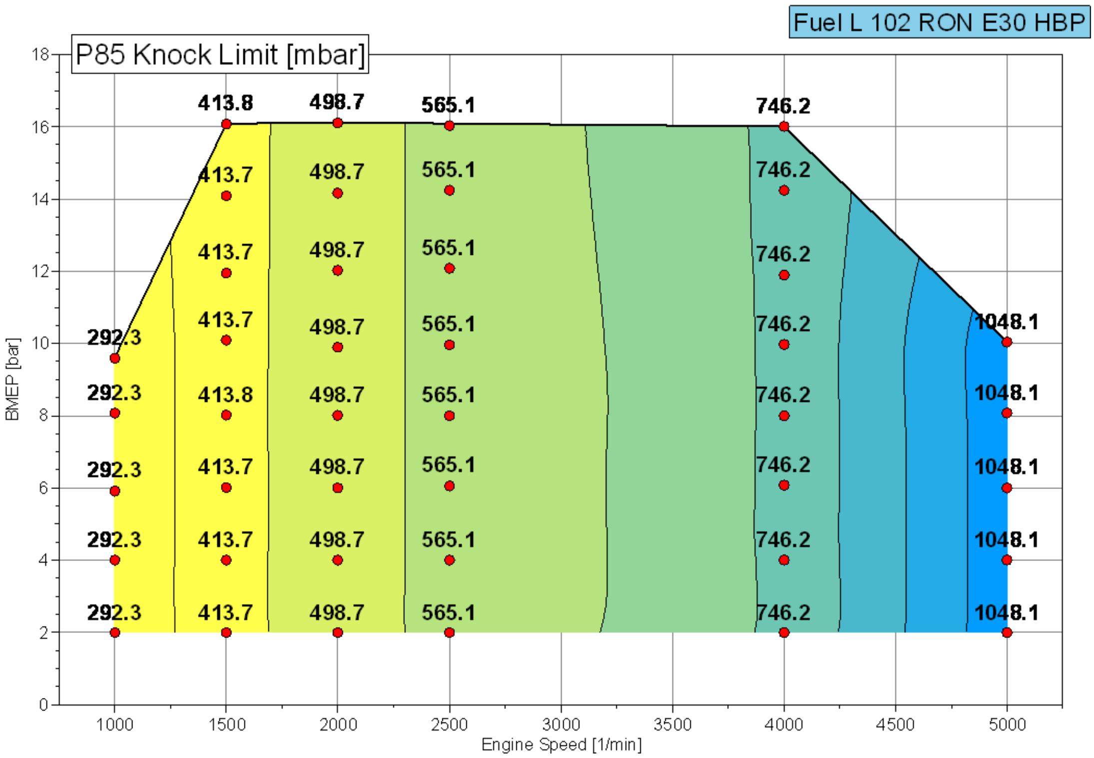

Figure 25: P85 Knock Limit

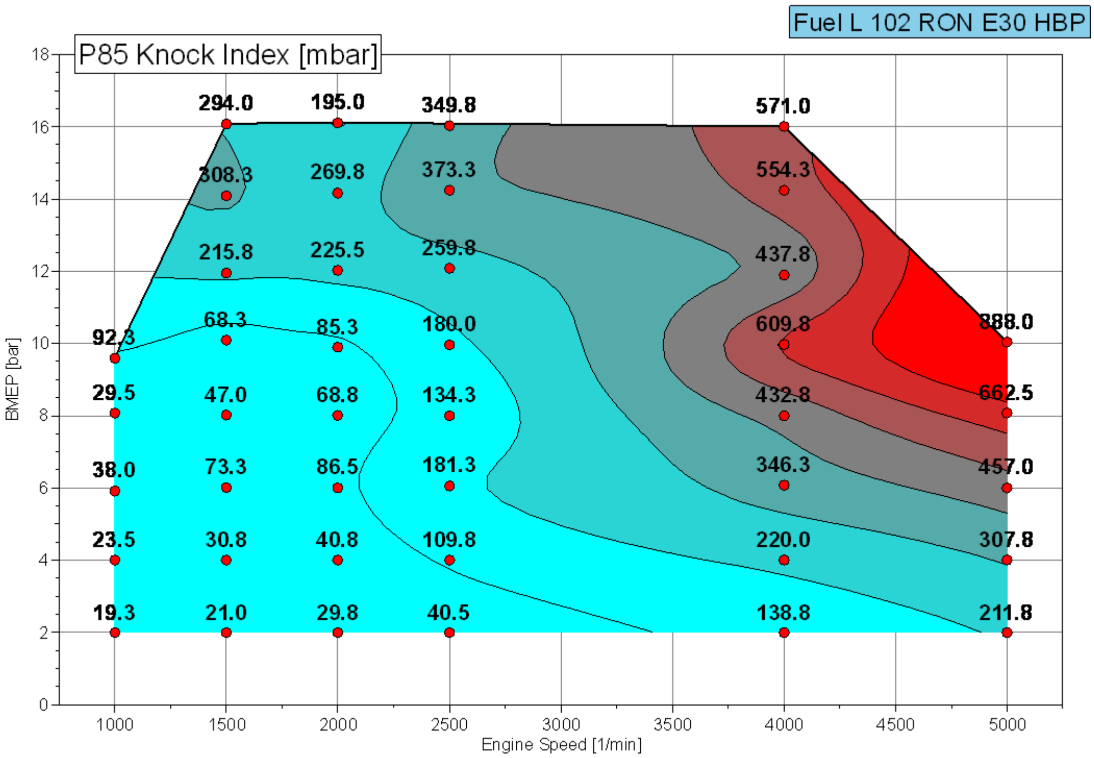

Figure 26: Averaged P85 Knock Index

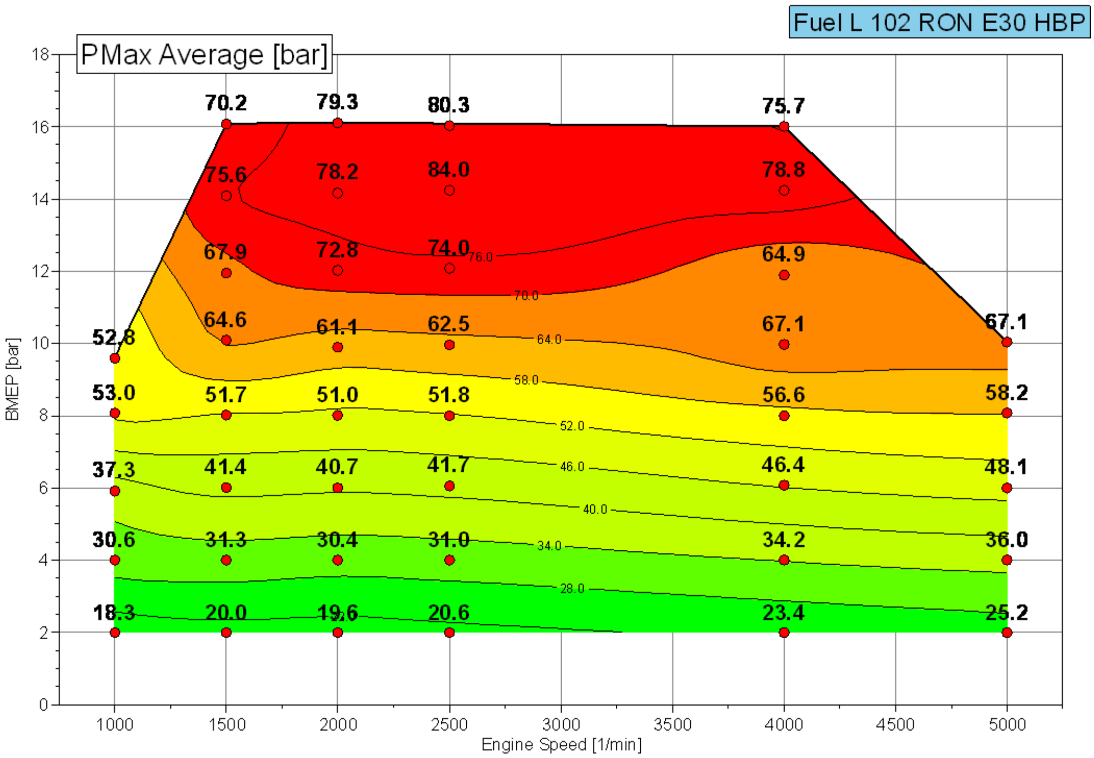

Figure 27: Averaged Max Pressure for Cylinders 1-4

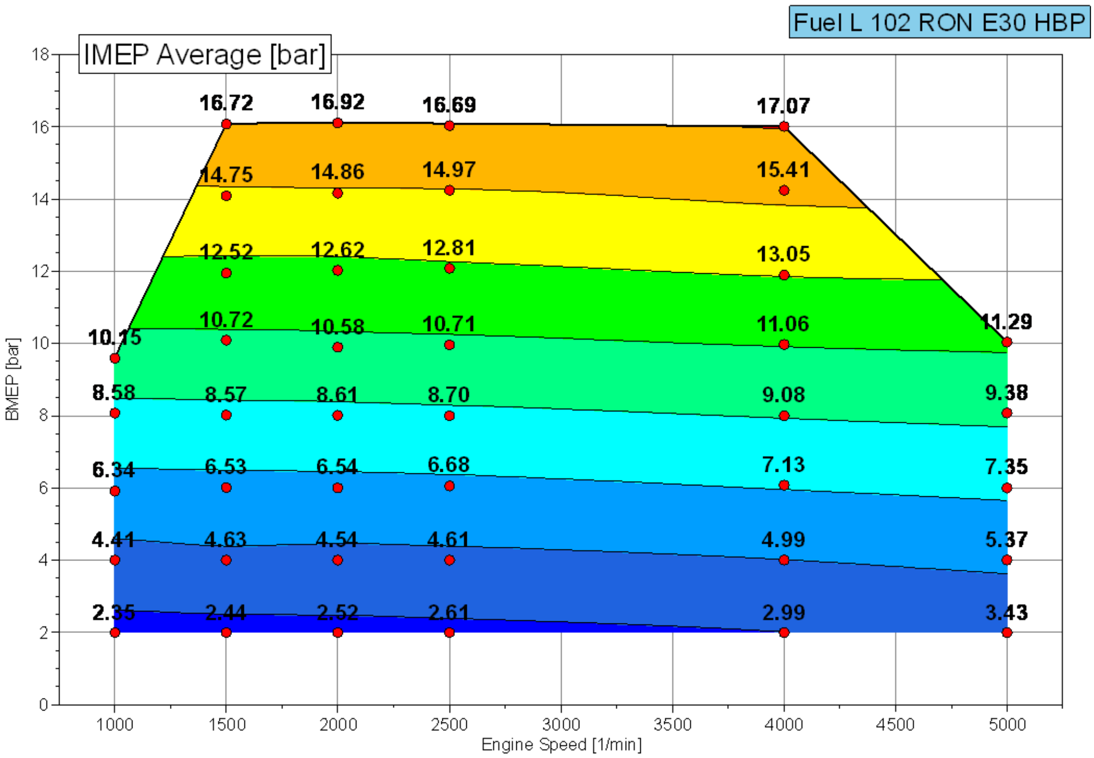

Figure 28: Indicated Mean Effective Pressure

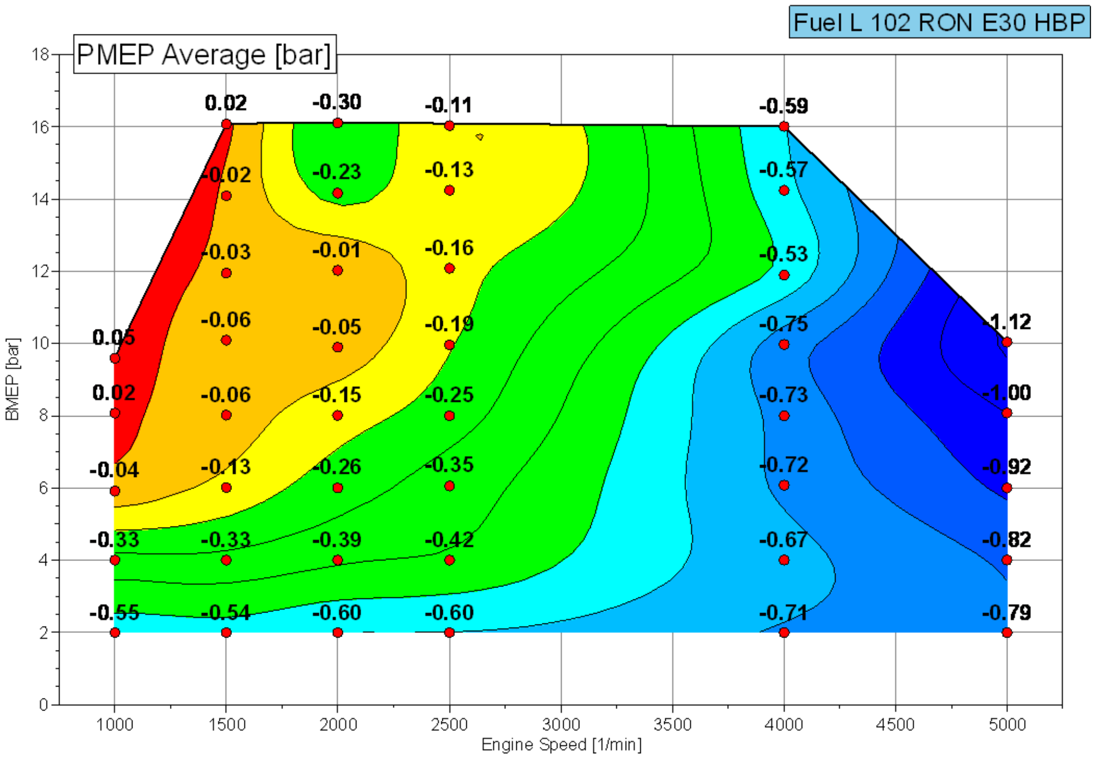

Figure 29: Pumping Mean Effective Pressure

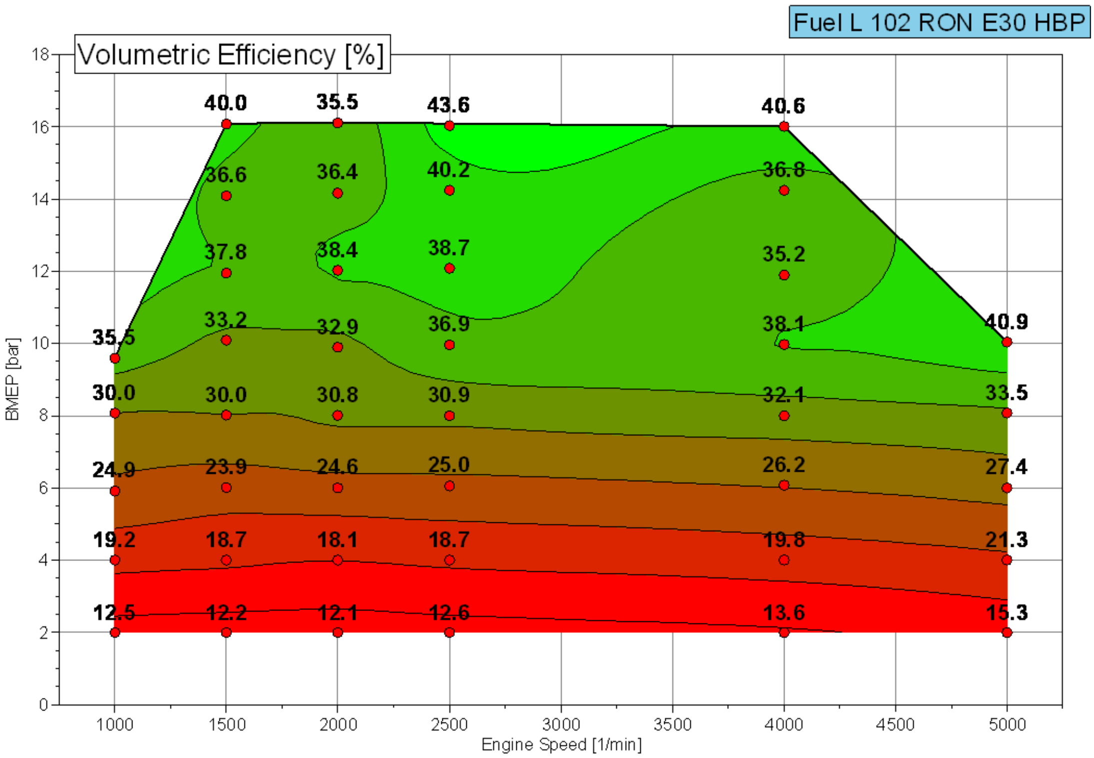

Figure 30: Calculated Volumetric Efficiency

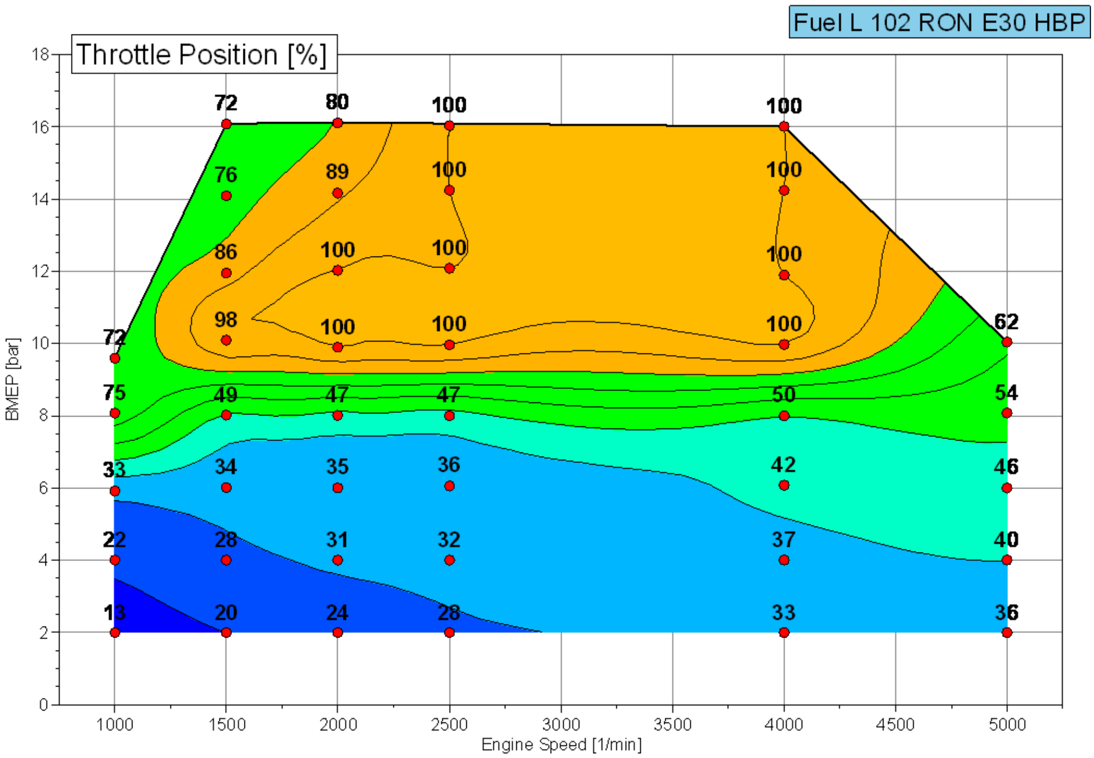

Figure 31: Throttle Position

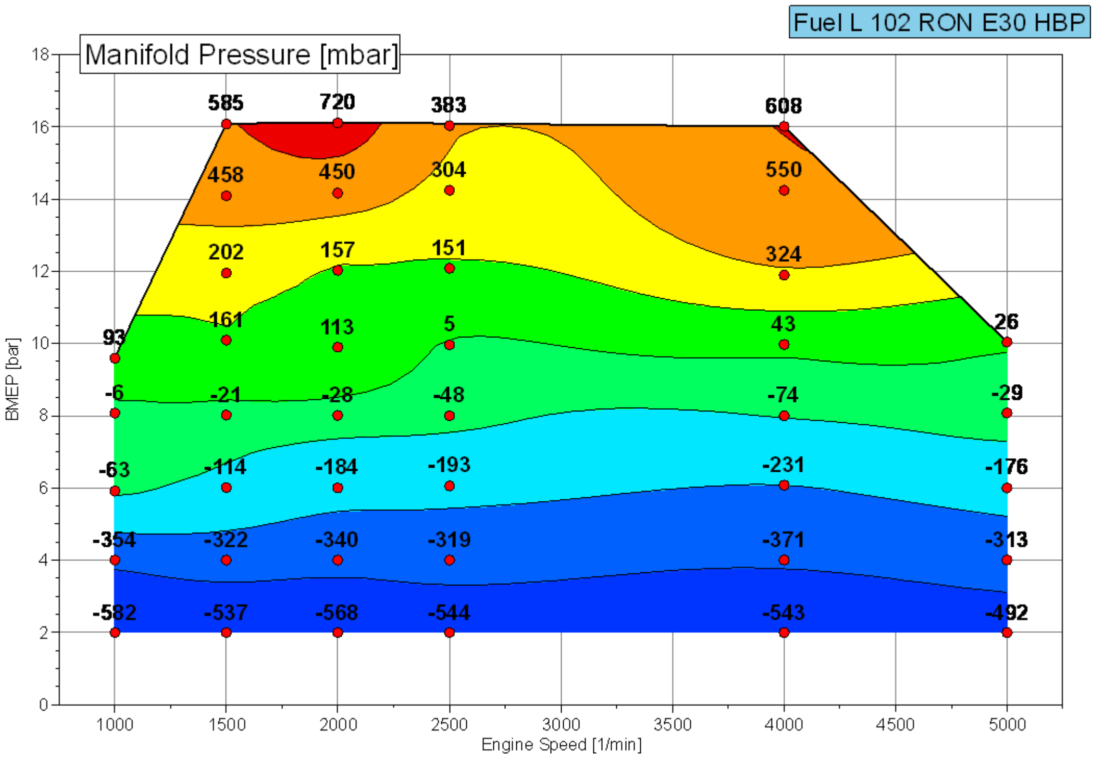

Figure 32: Intake Manifold Pressure

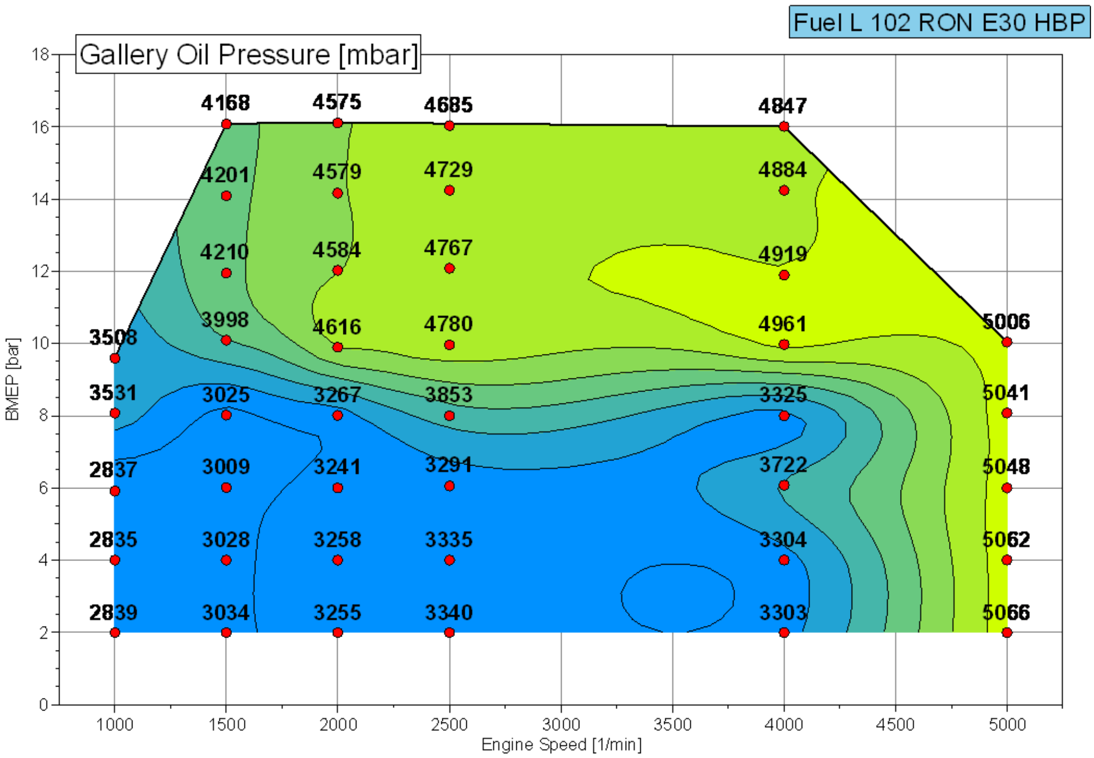

Figure 33: Gallery Oil Pressure

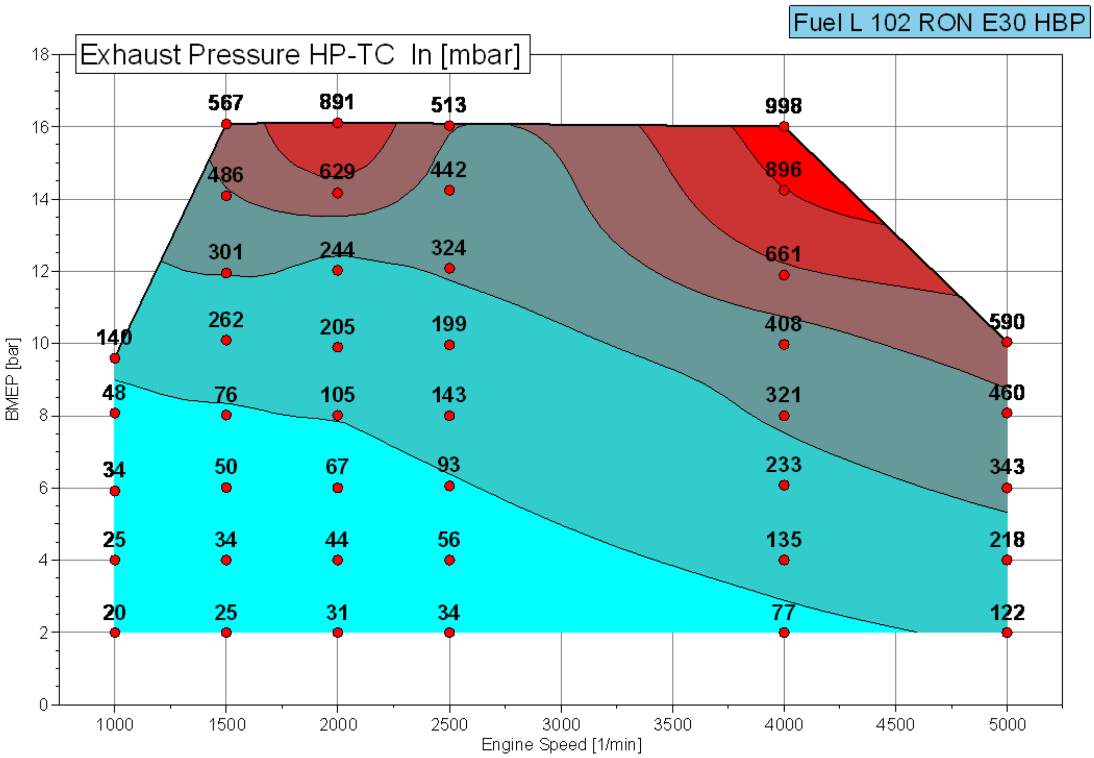

Figure 34: Exhaust Pressure High Pressure Turbocharger In

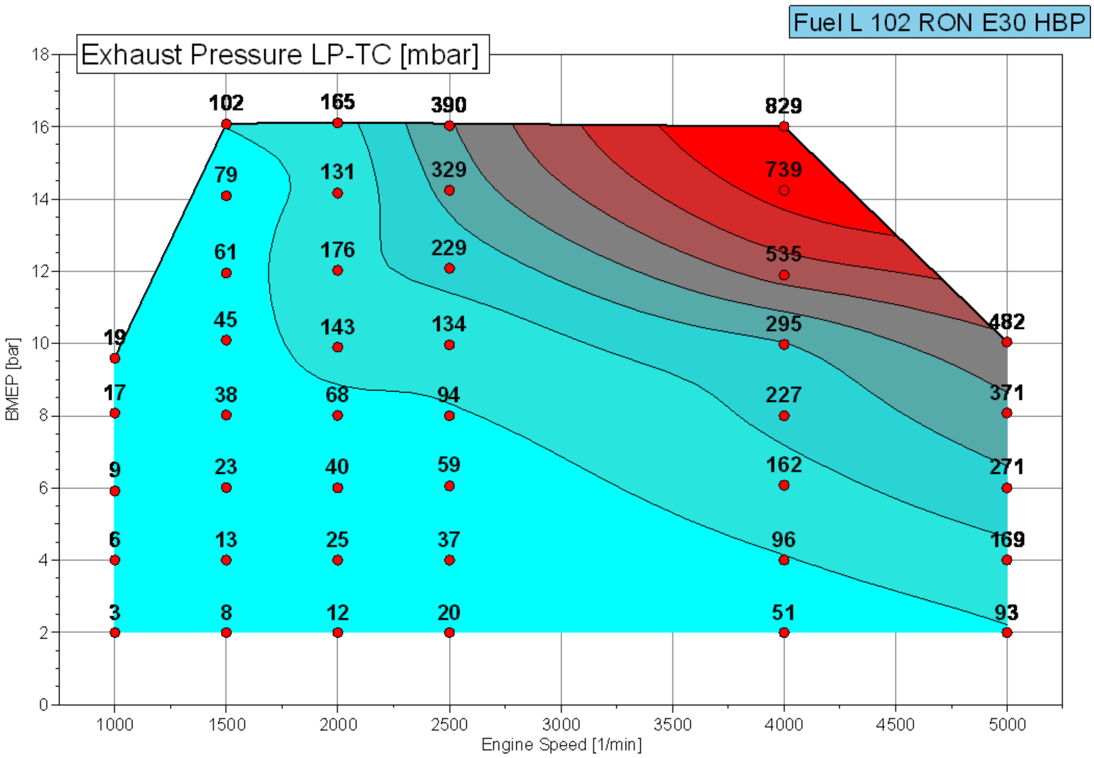

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

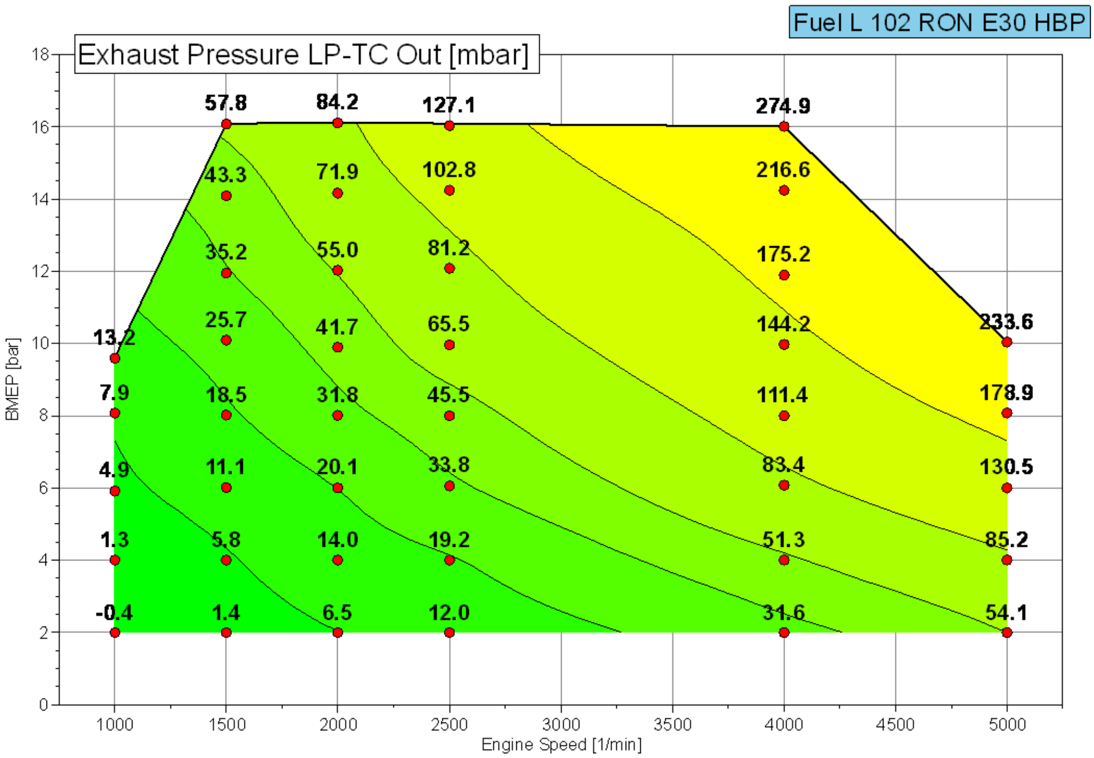

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

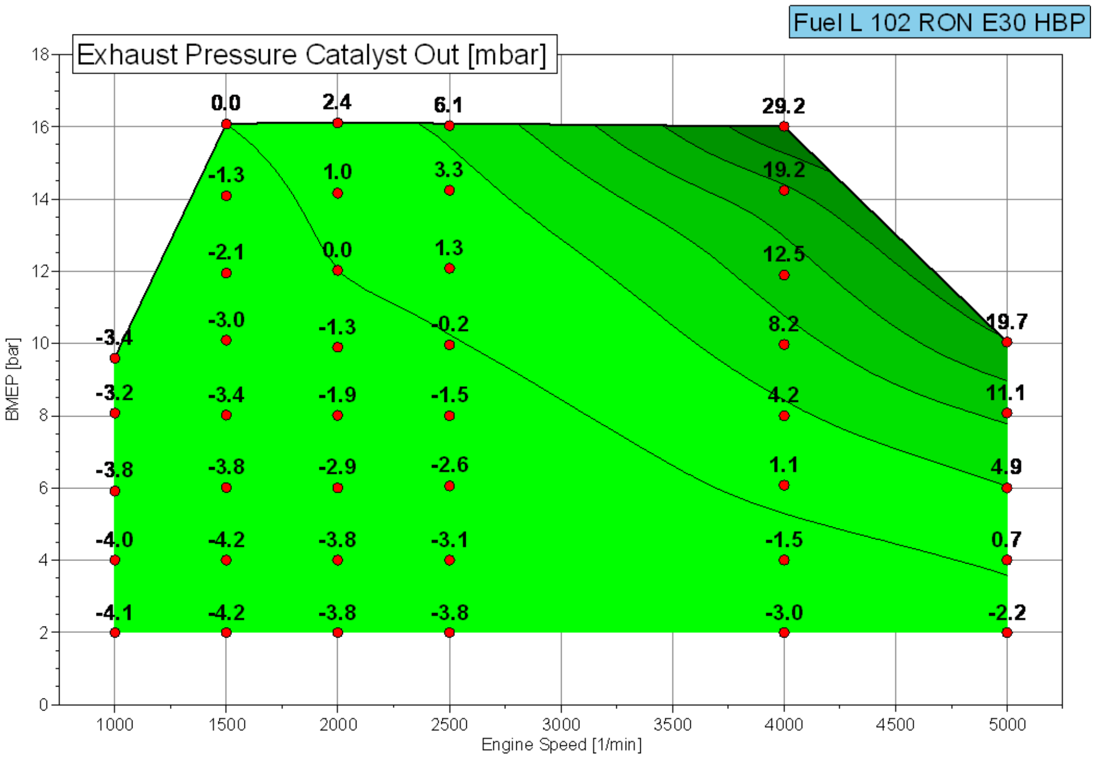

Figure 37: Exhaust Pressure Catalyst Out

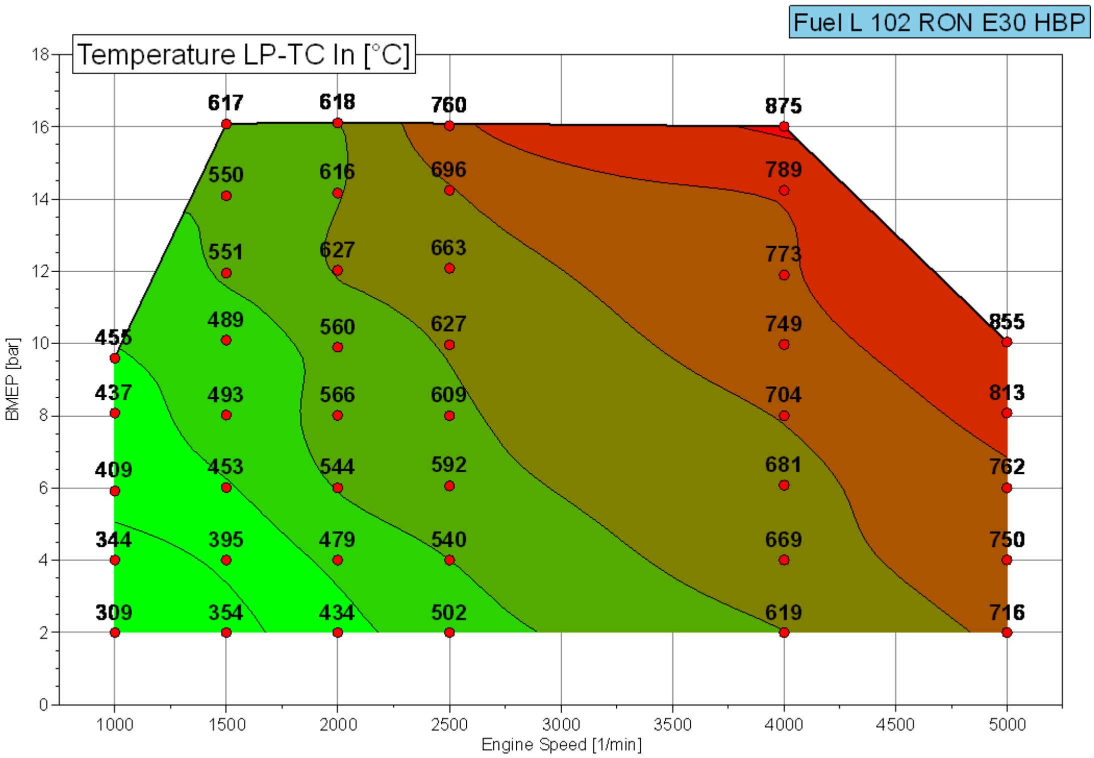

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

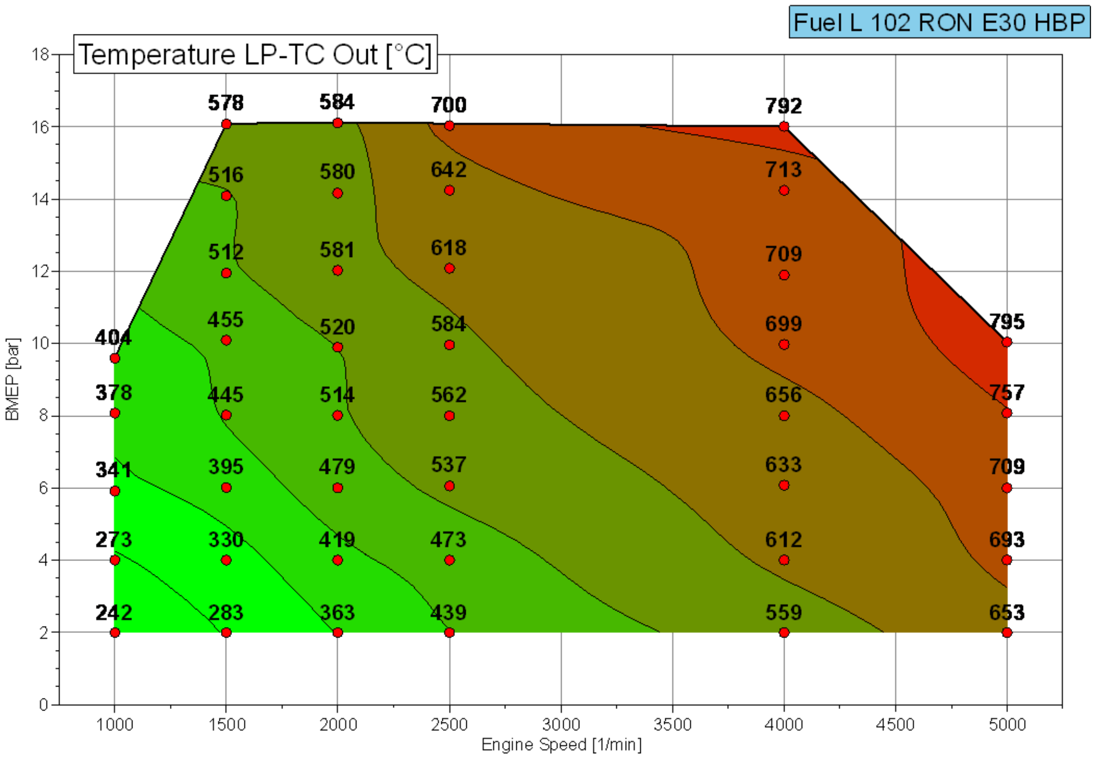

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

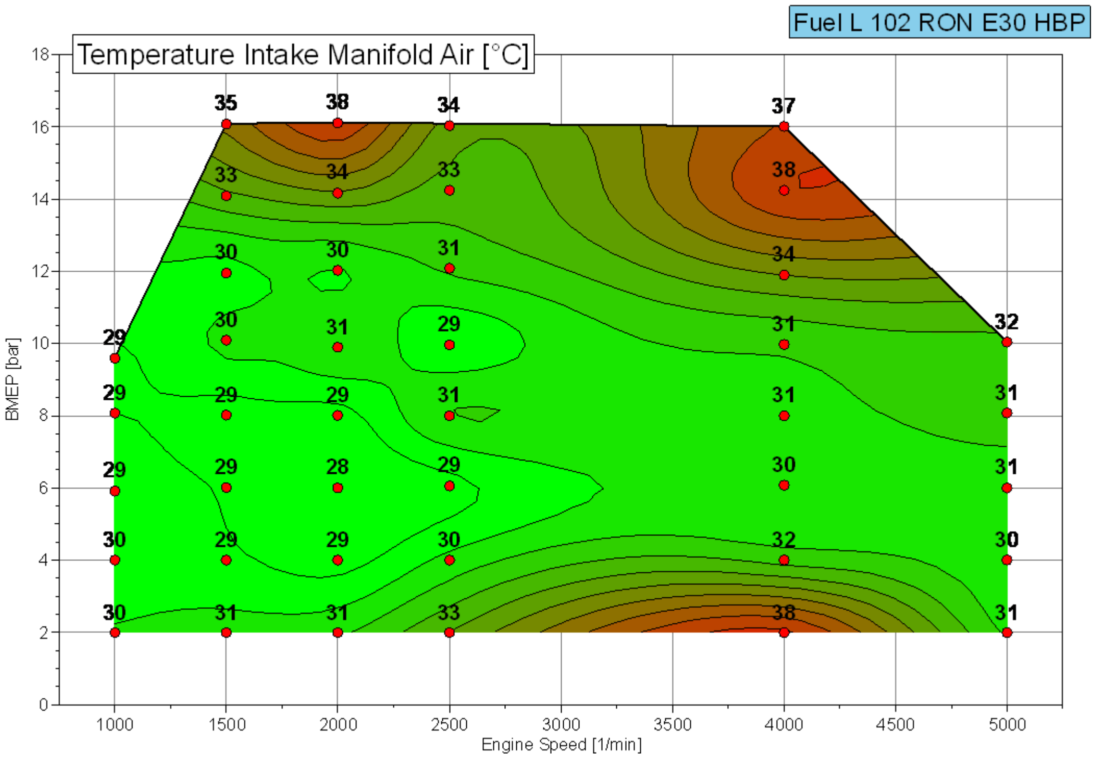

Figure 40: Intake Manifold Air Temperature

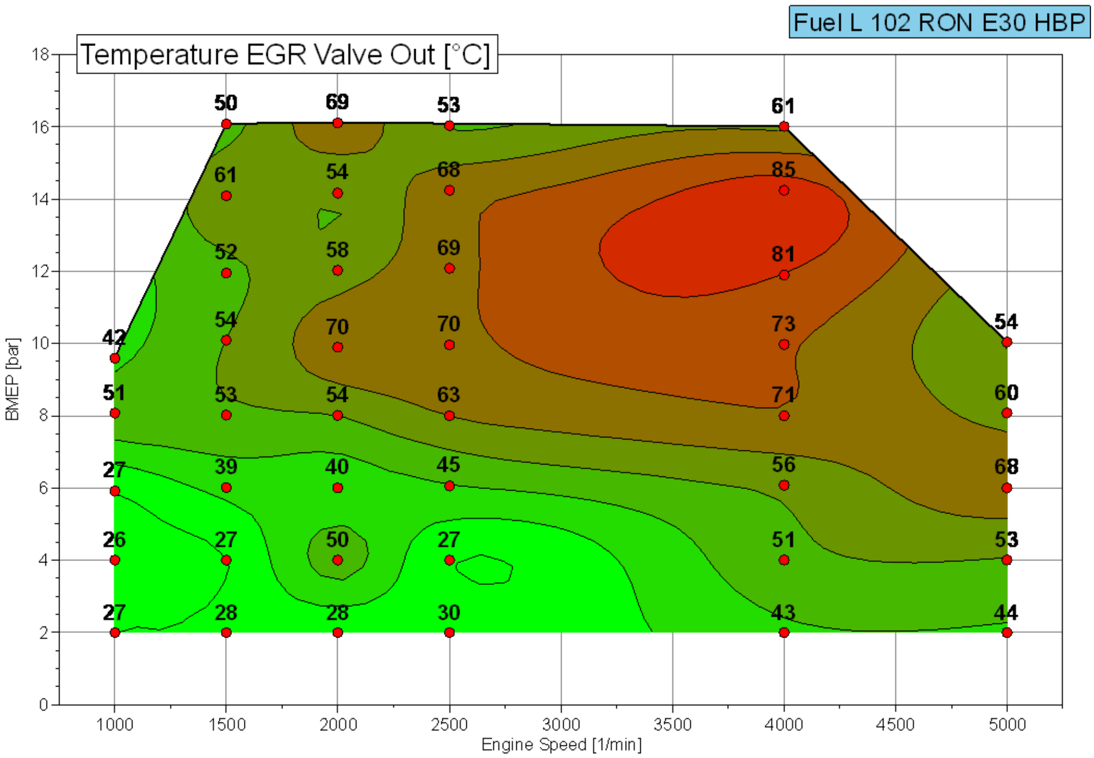

Figure 41: EGR Valve Out Temperature

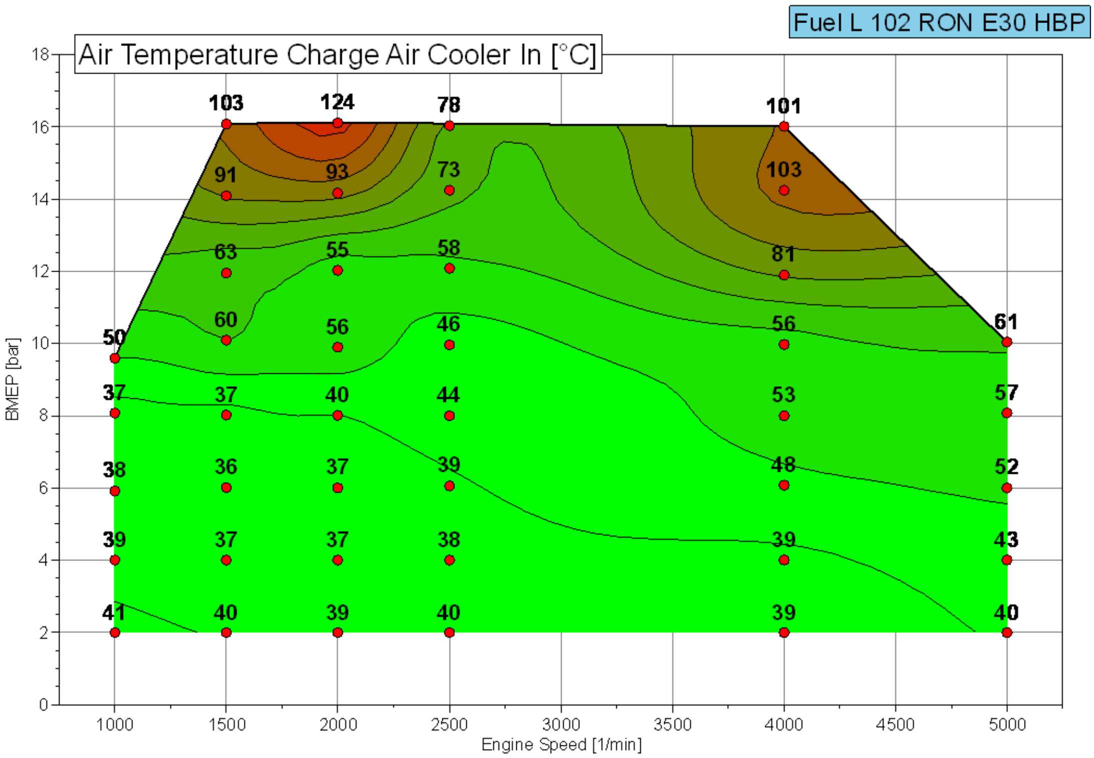

Figure 42: Charge Air Cooler Inlet Air Temperature

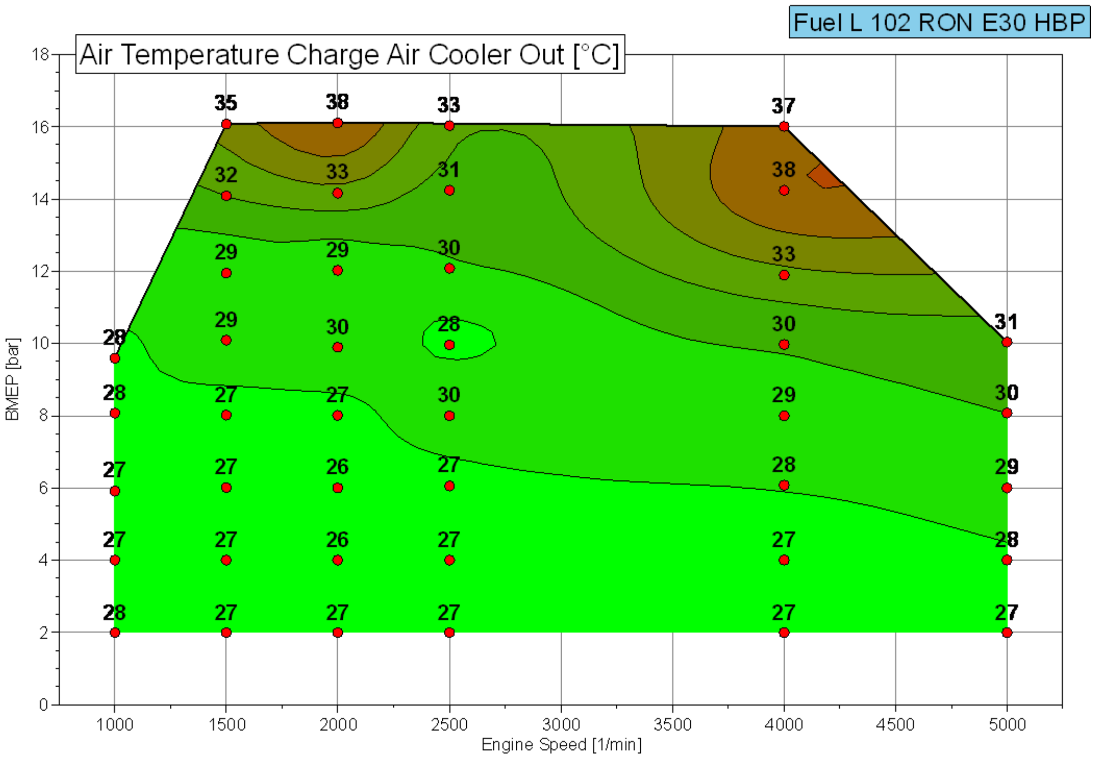

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel M Calibration Results

98 Ron 15% Ethanol High Boiling Point

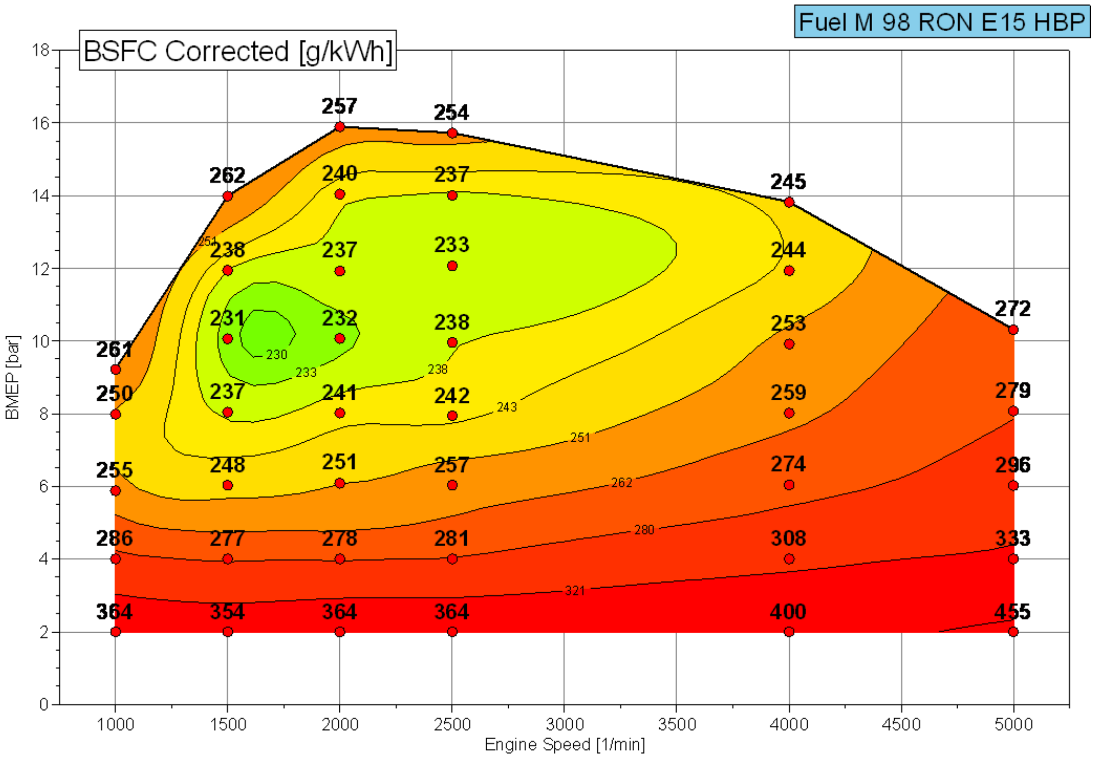

Figure 1: Brake Specific Fuel Consumption

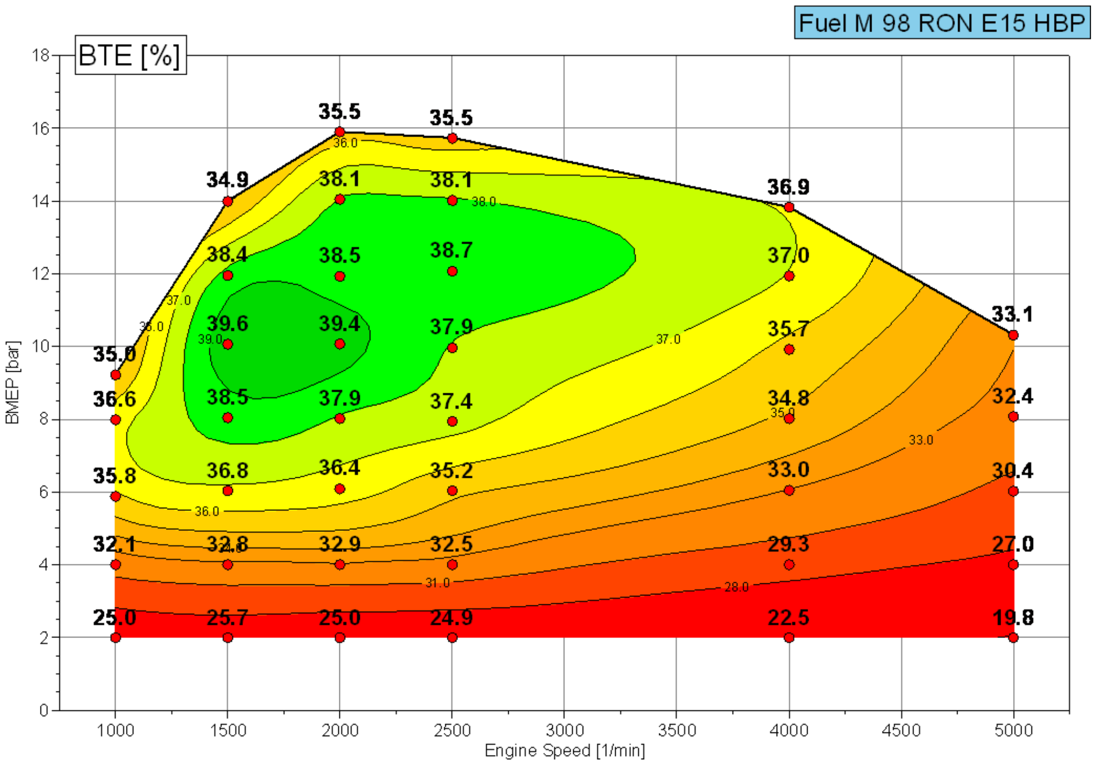

Figure 2: Brake Thermal Efficiency

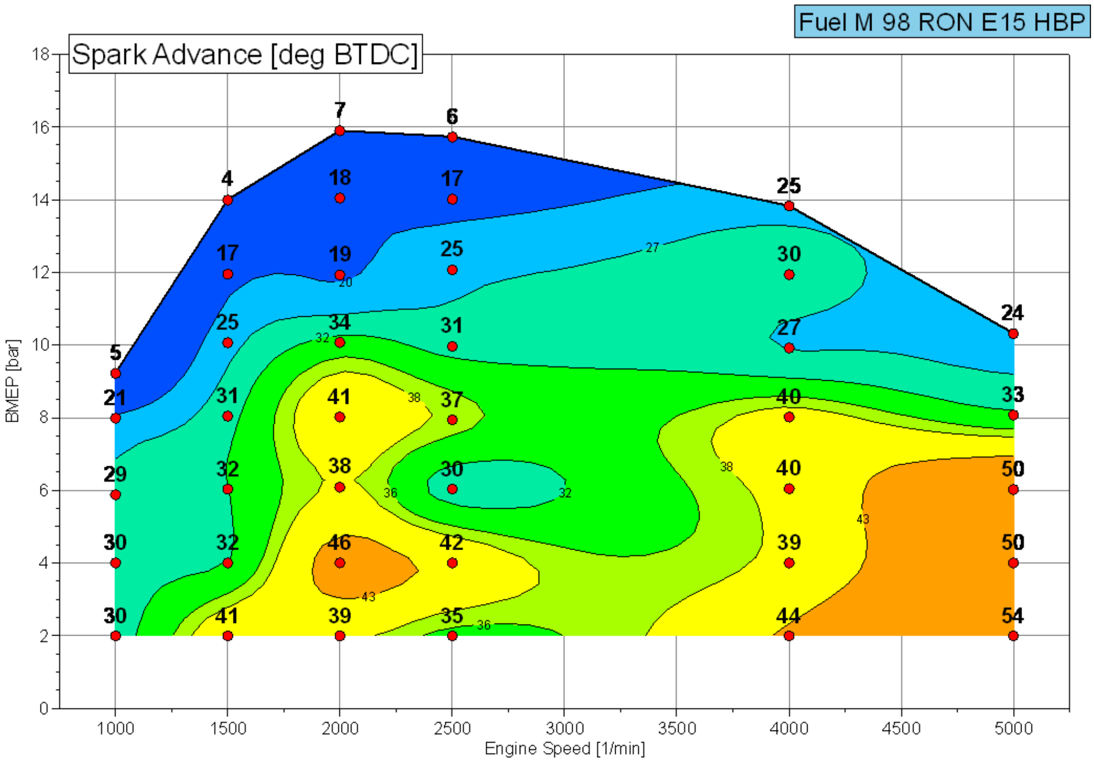

Figure 3: Spark Advance

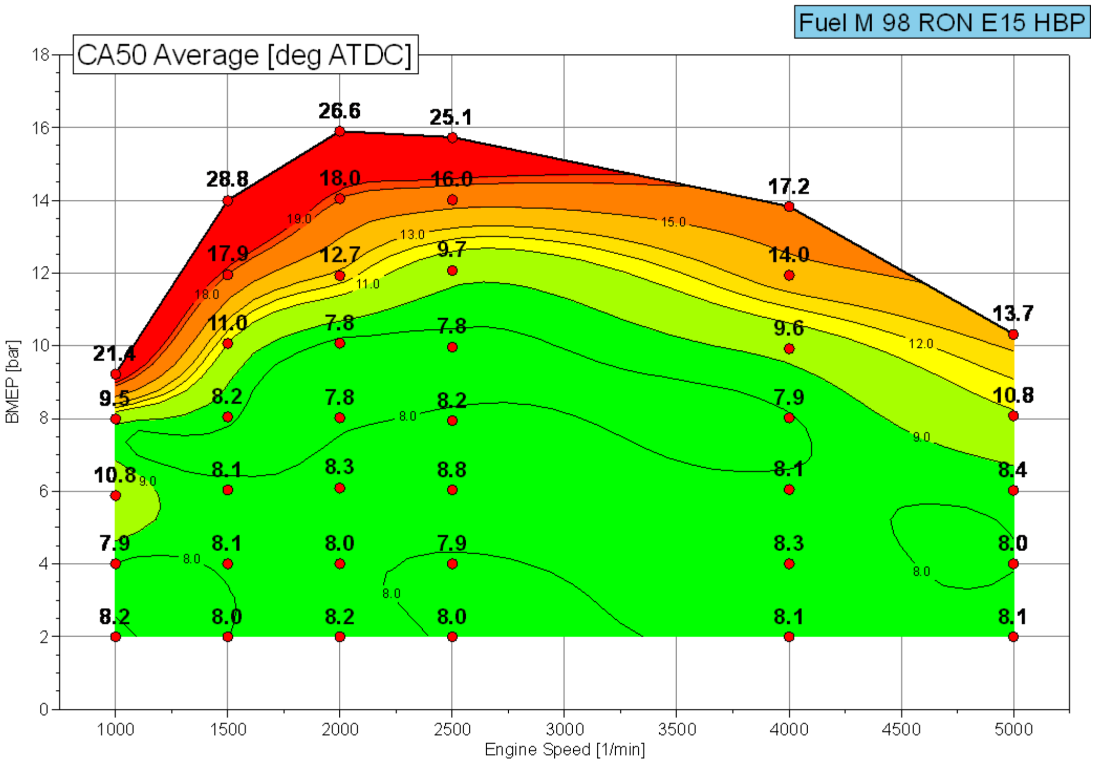

Figure 4: CA50 Average of Cylinders 1-4

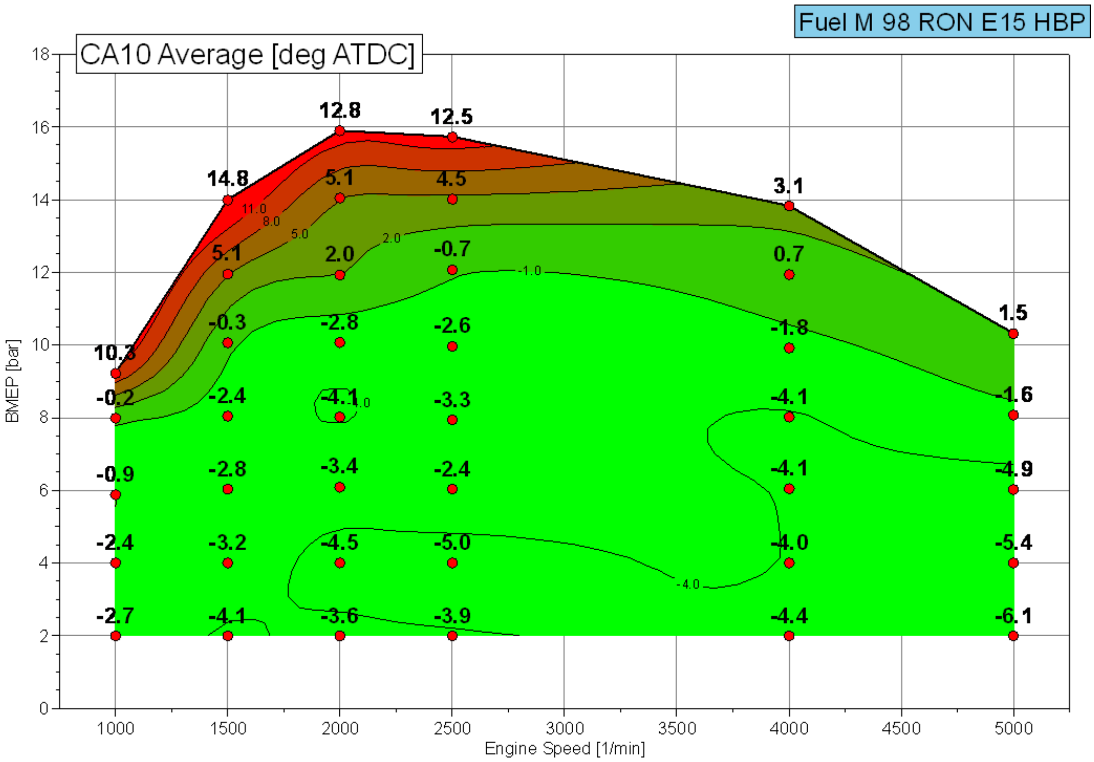

Figure 5: CA10 Average of Cylinders 1-4

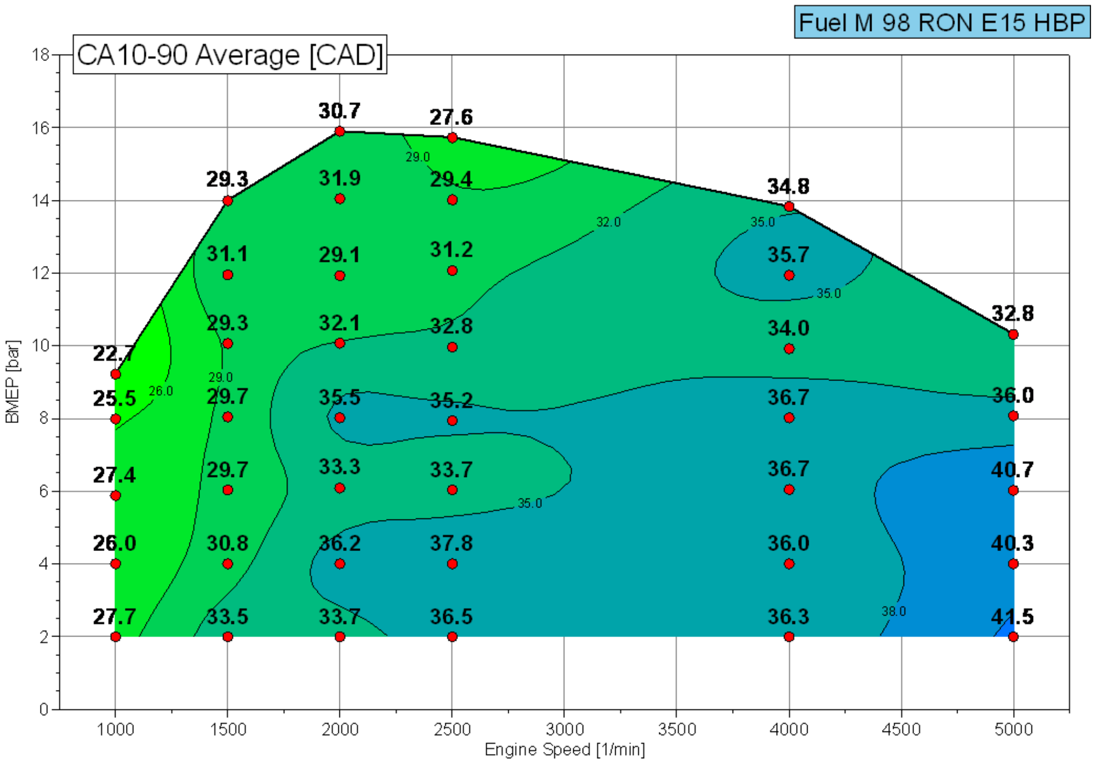

Figure 6: CA10-90 Average of Cylinders 1-4

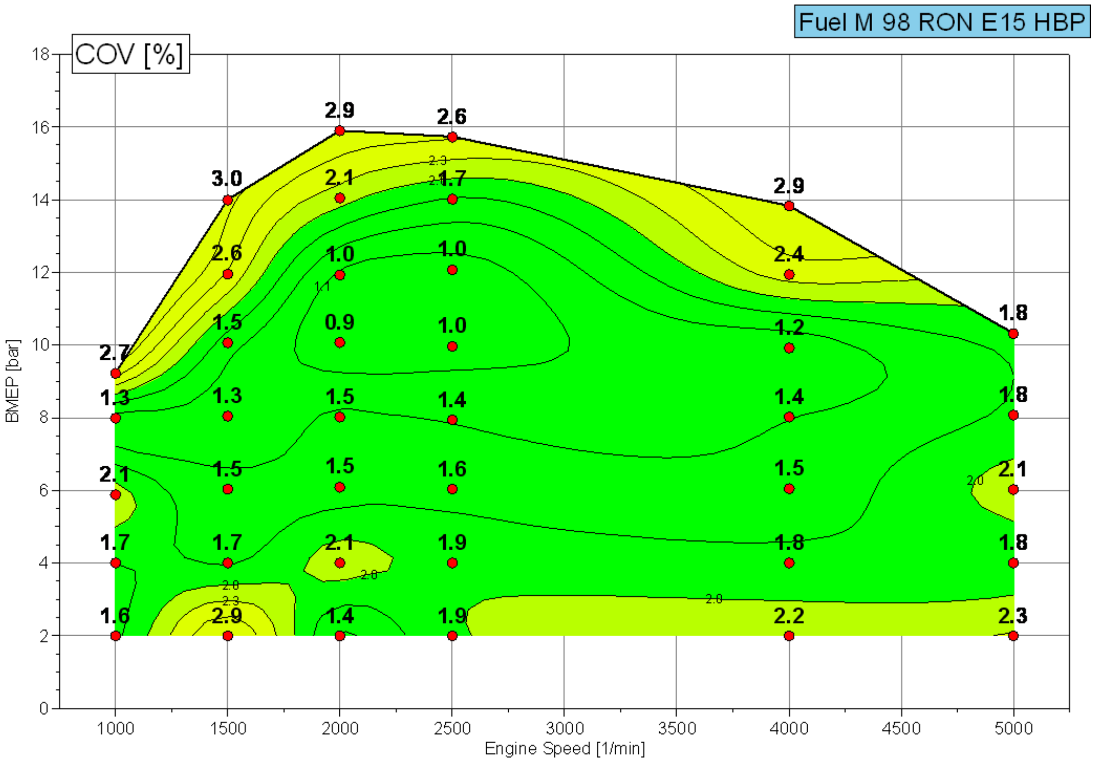

Figure 7: Coefficient of Variation Average of Cylinders 1-4

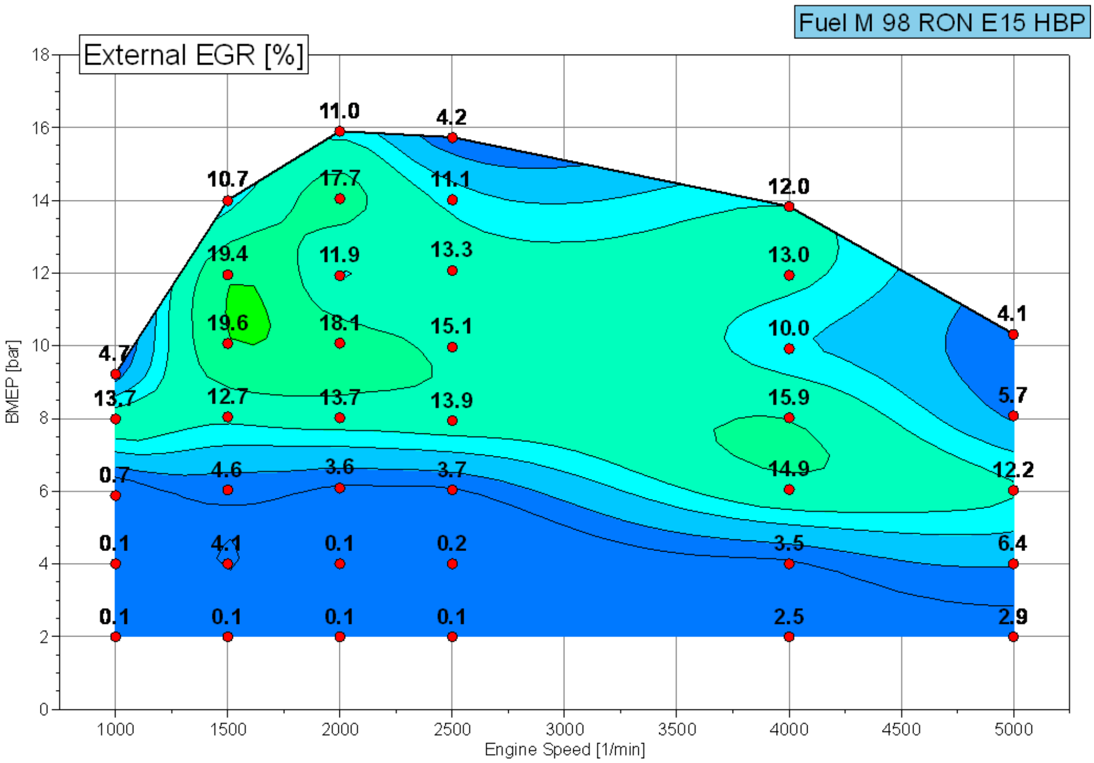

Figure 8: External EGR Percent of Intake Air

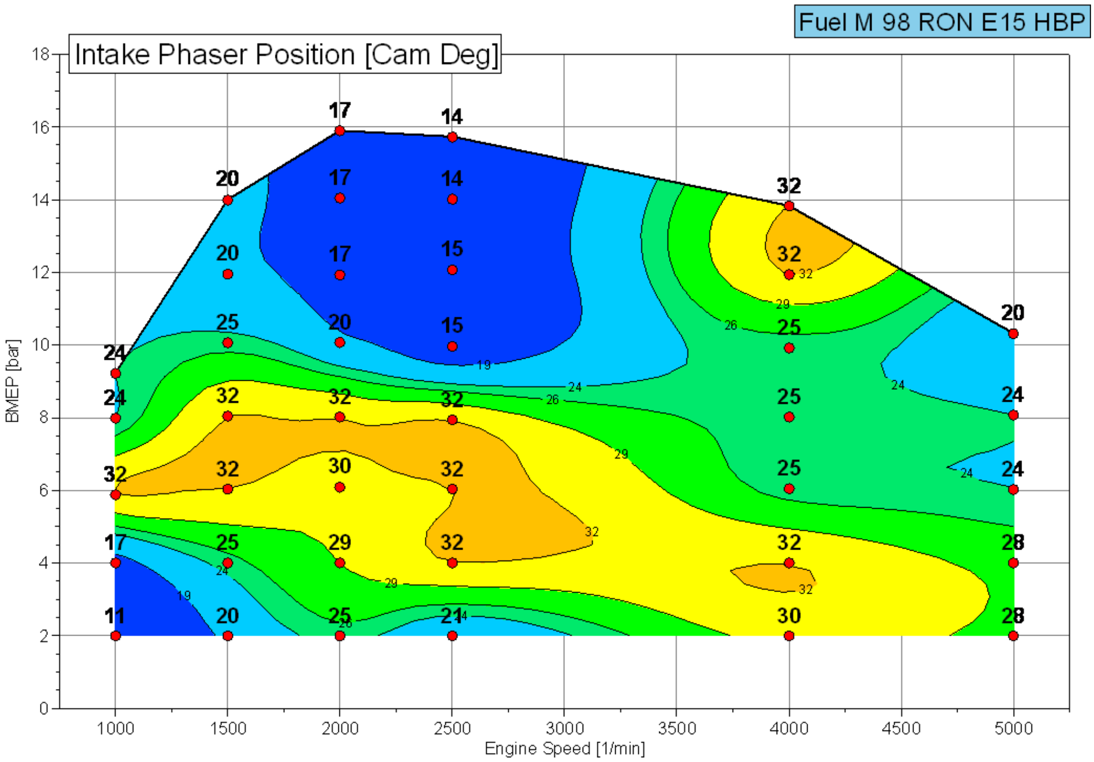

Figure 9: Intake Camshaft Phaser Position

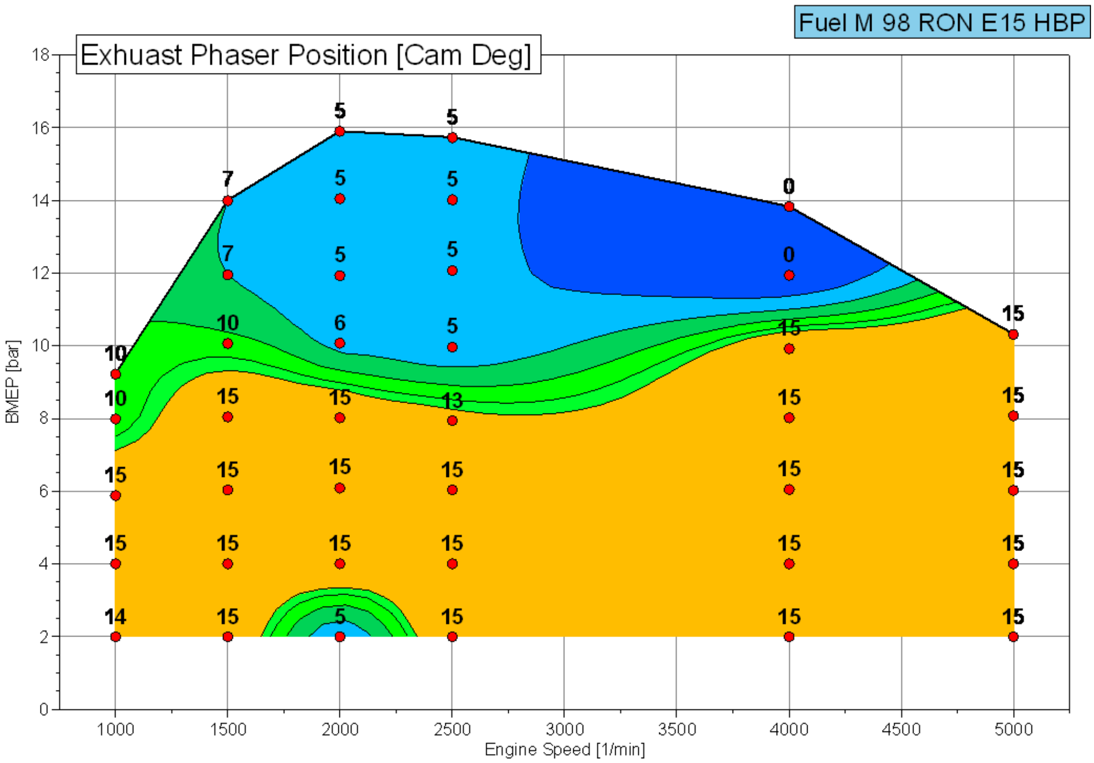

Figure 10: Exhaust Camshaft Phaser Position

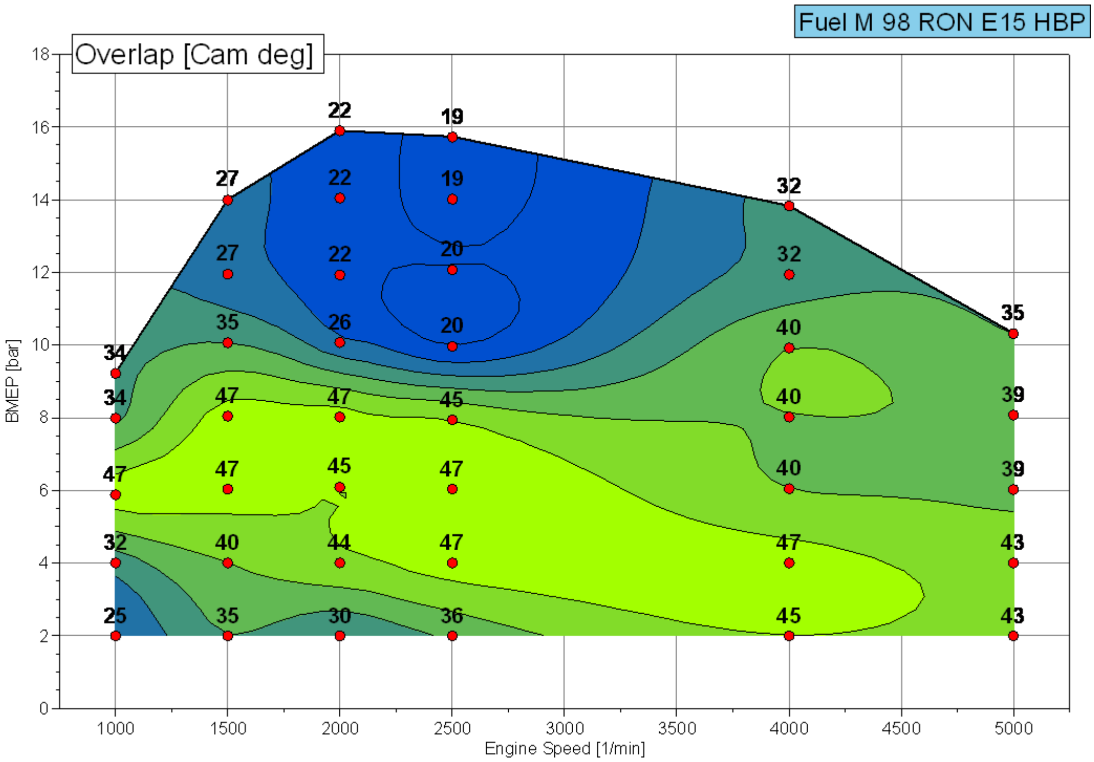

Figure 11: Camshaft Overlap

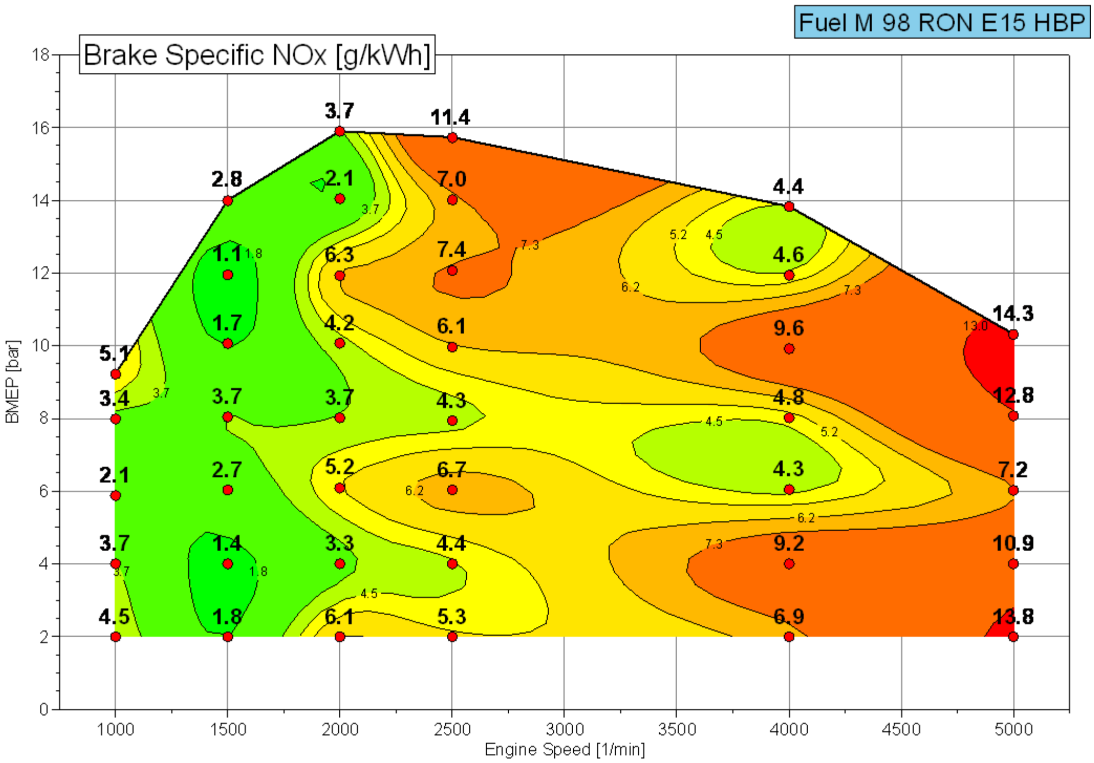

Figure 12: Brake Specific NOx Emissions

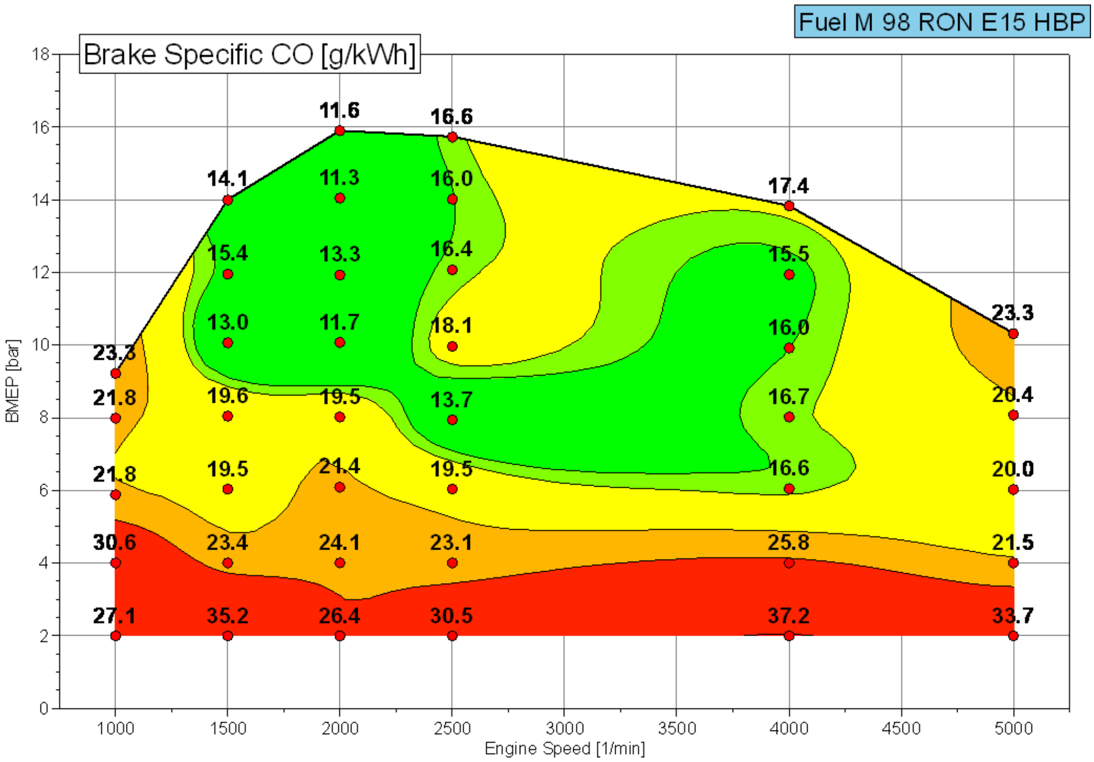

Figure 13: Brake Specific Carbon Monoxide Emissions

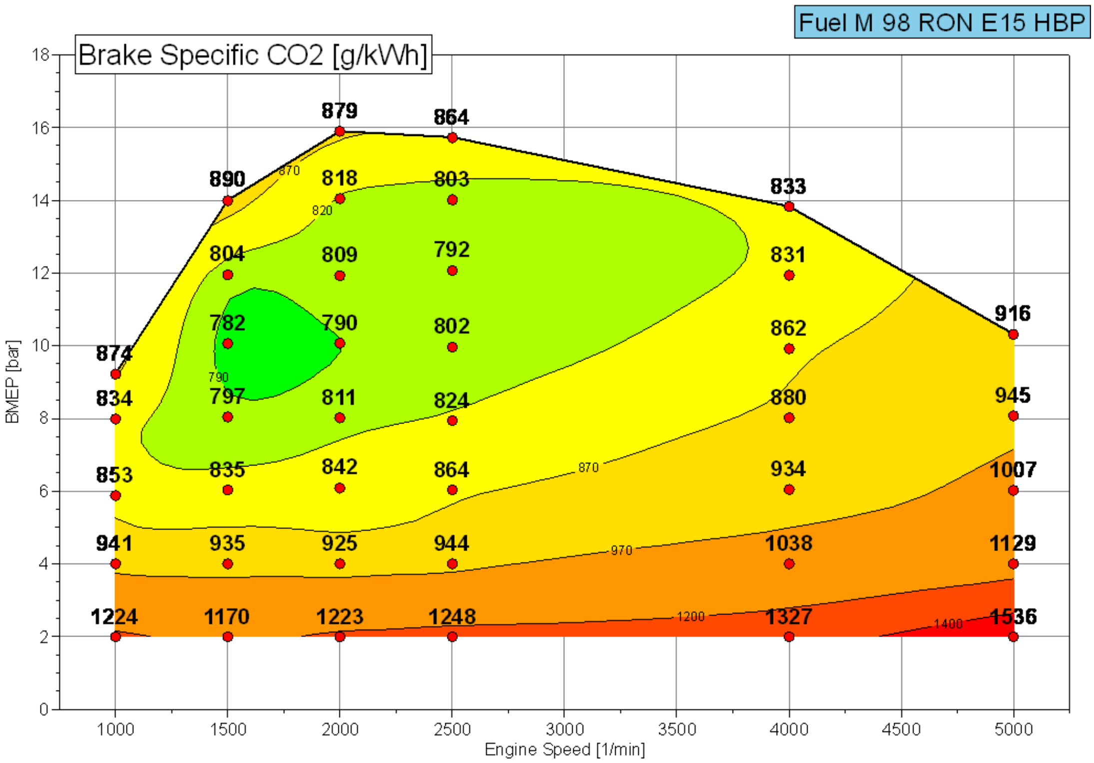

Figure 14: Brake Specific Carbon Dioxide Emissions

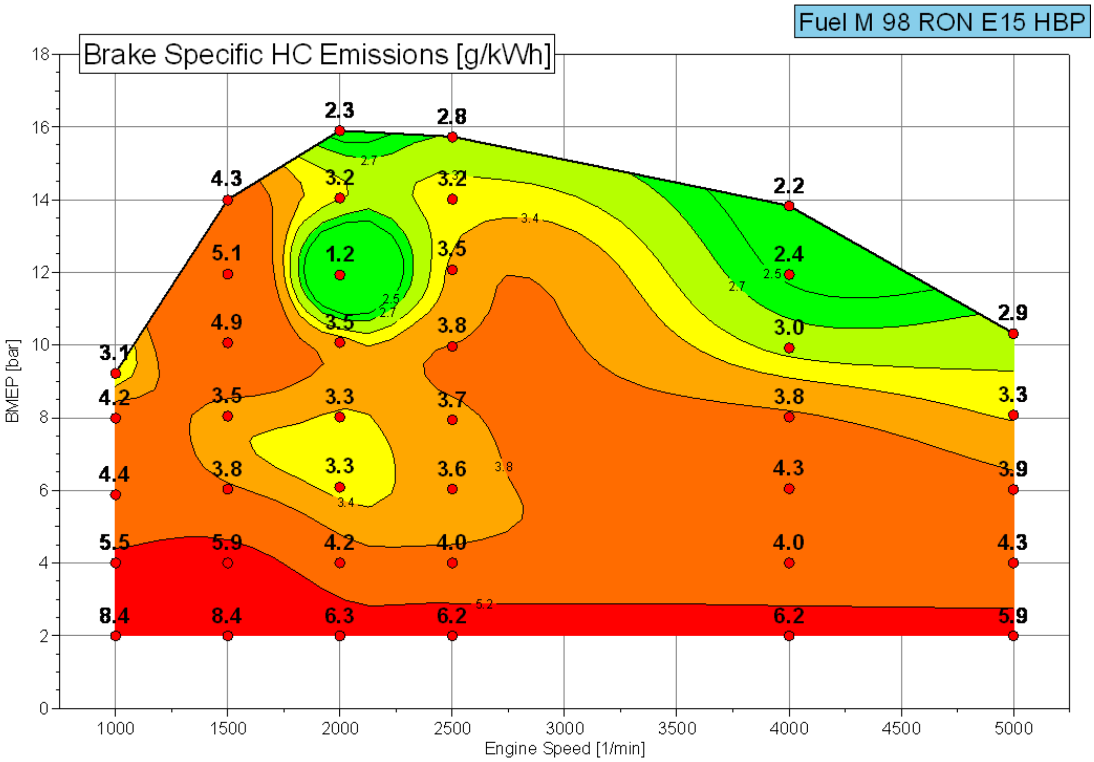

Figure 15: Brake Specific Hydrocarbon Emissions

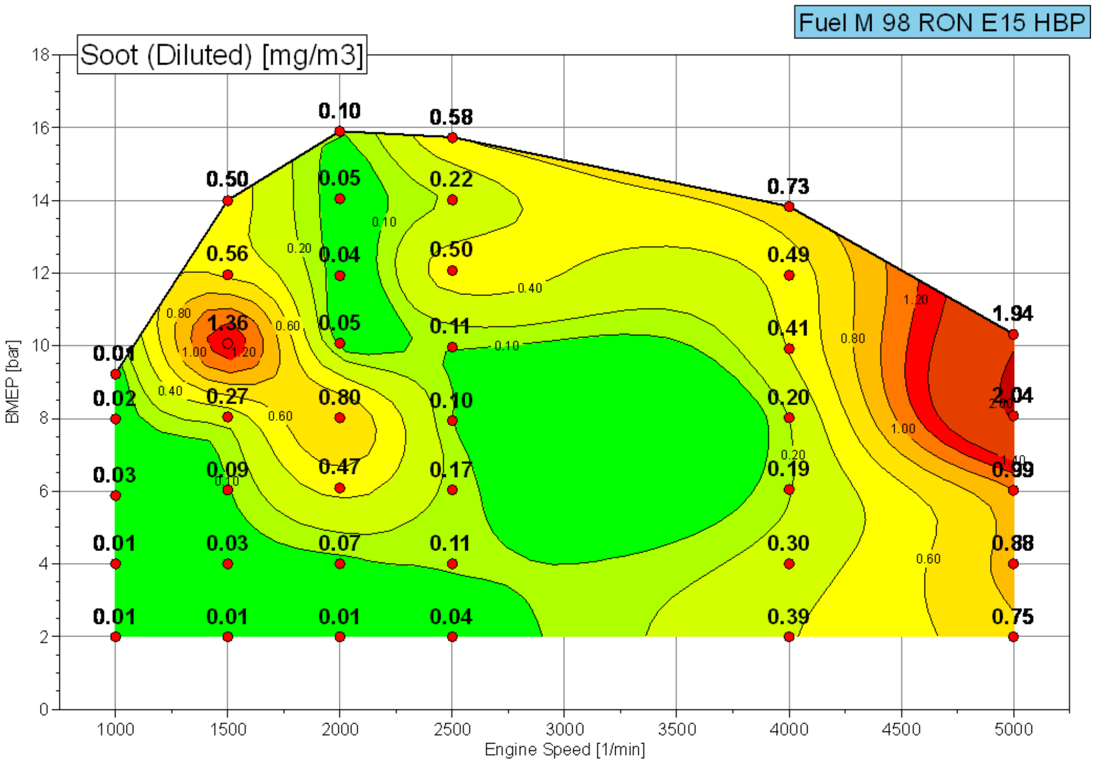

Figure 16: Particulate Soot Emissions

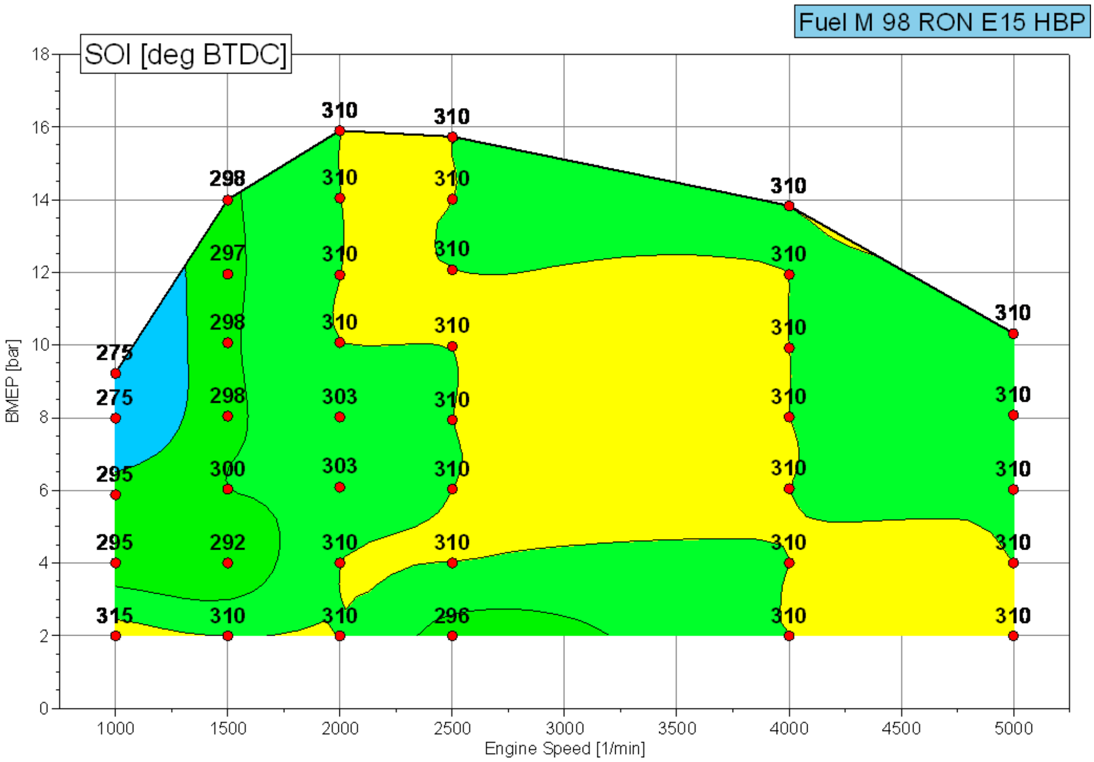

Figure 17: Start of Injection

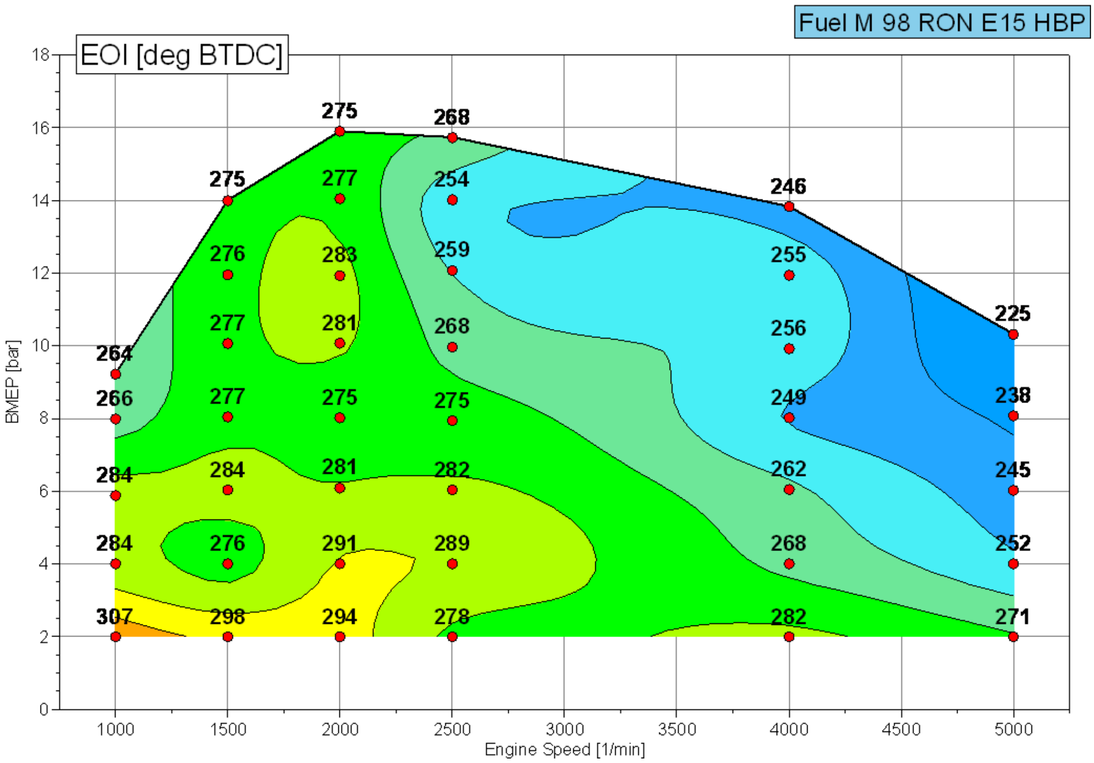

Figure 18: End of Injection

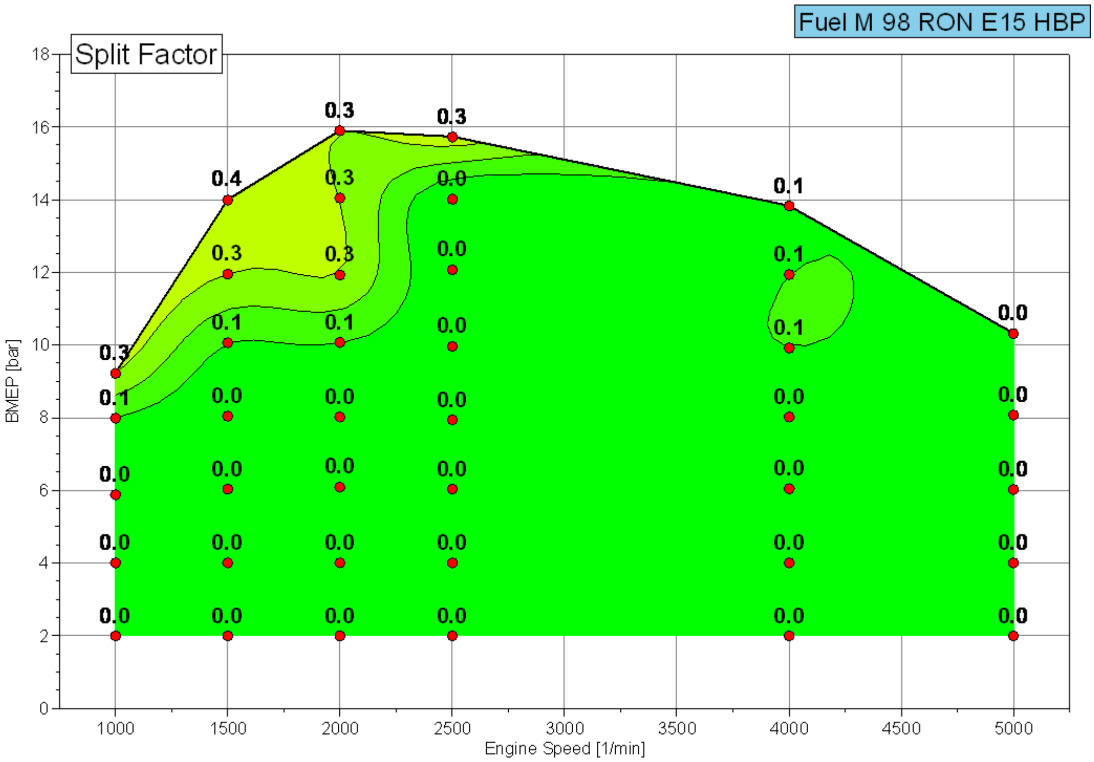

Figure 19: Injection Split Factor

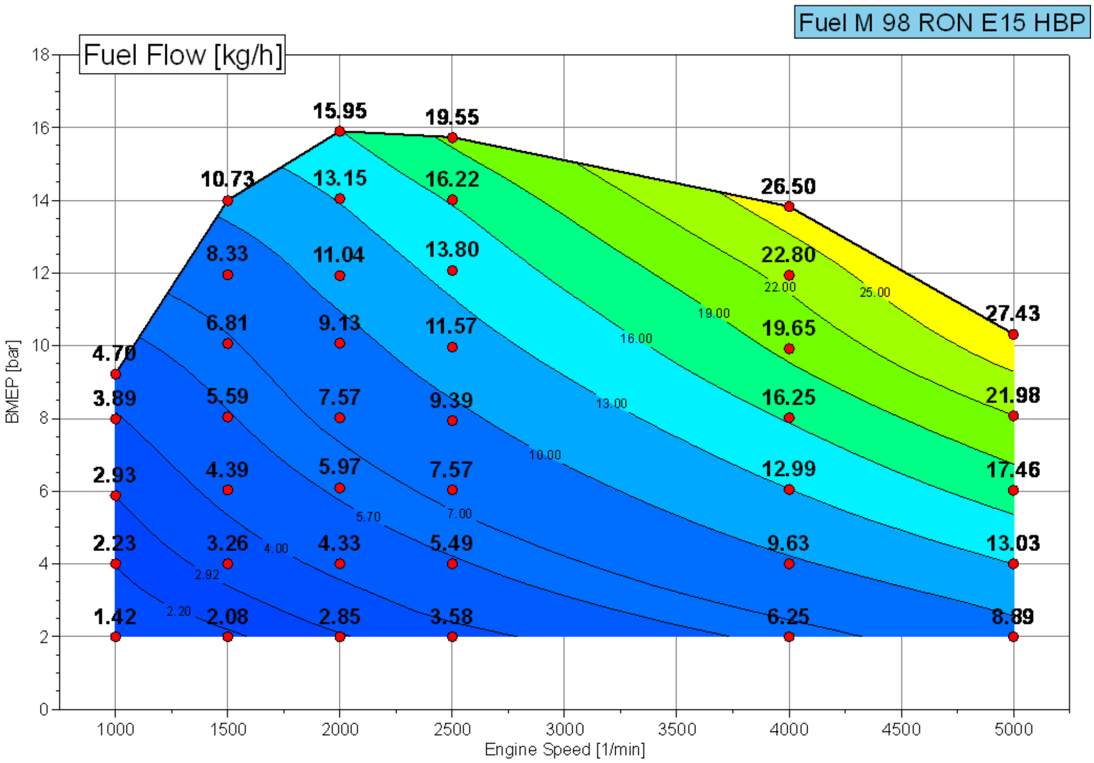

Figure 20: Fuel Flow

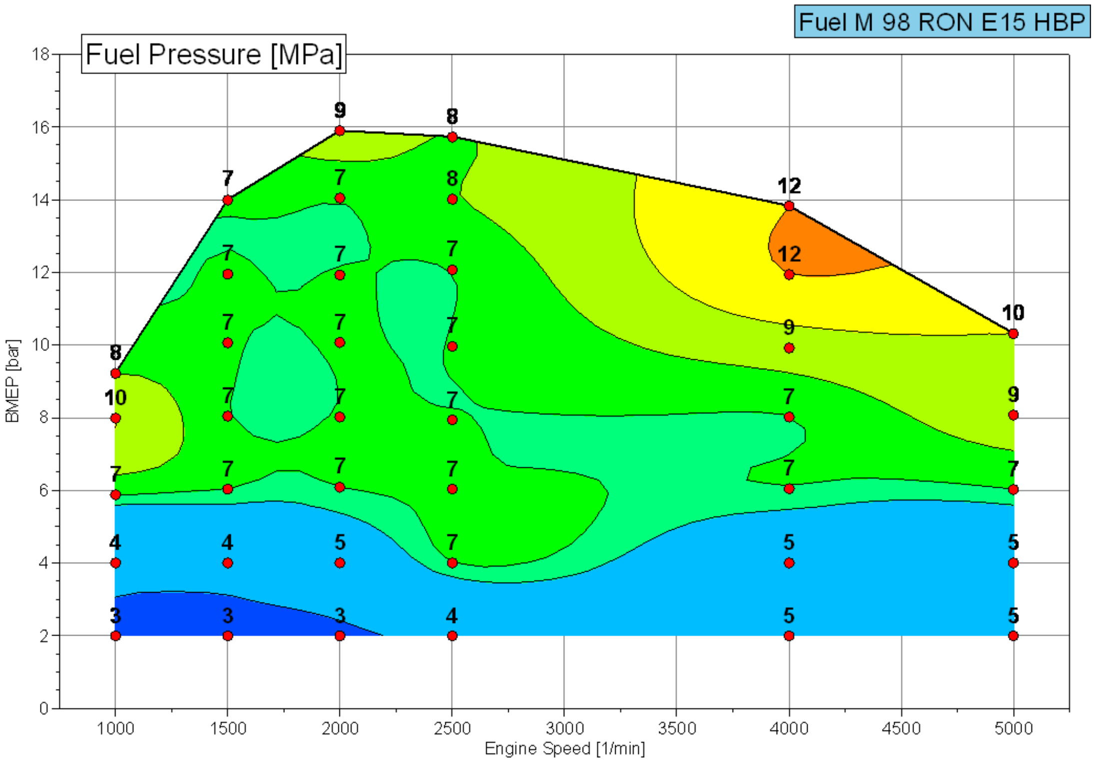

Figure 21: Fuel Rail Pressure

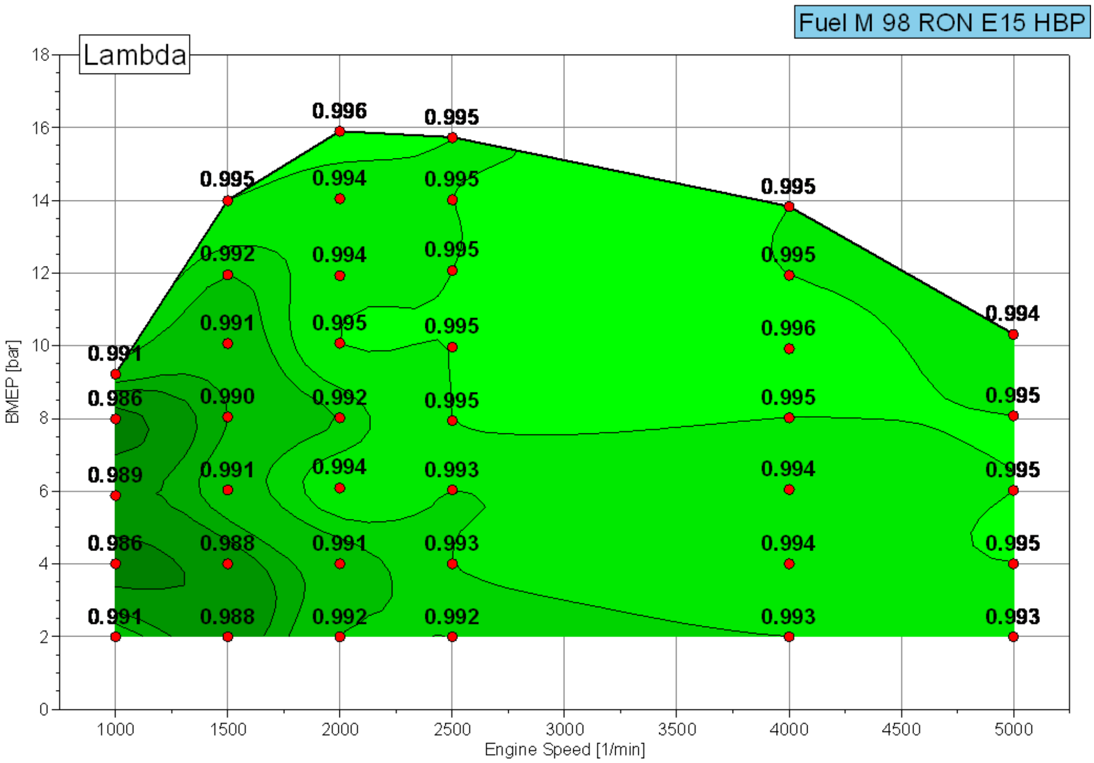

Figure 22: Lambda

automotive engineering

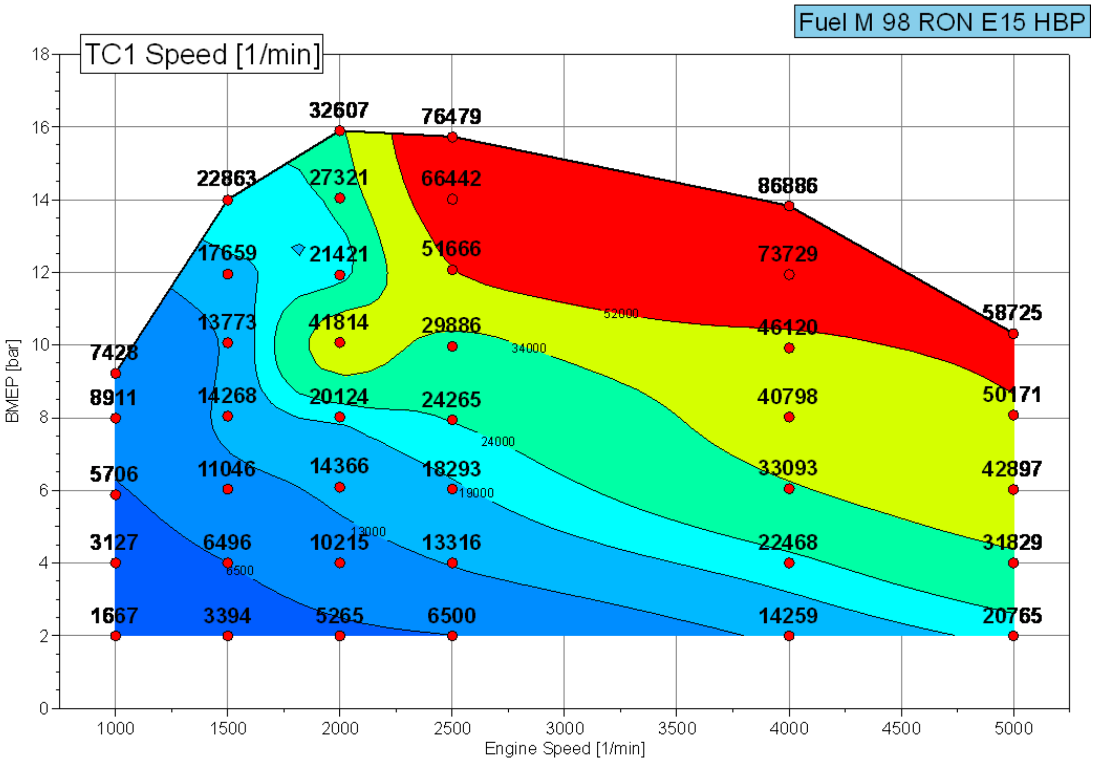

Figure 23: Low Pressure Turbocharger Speed

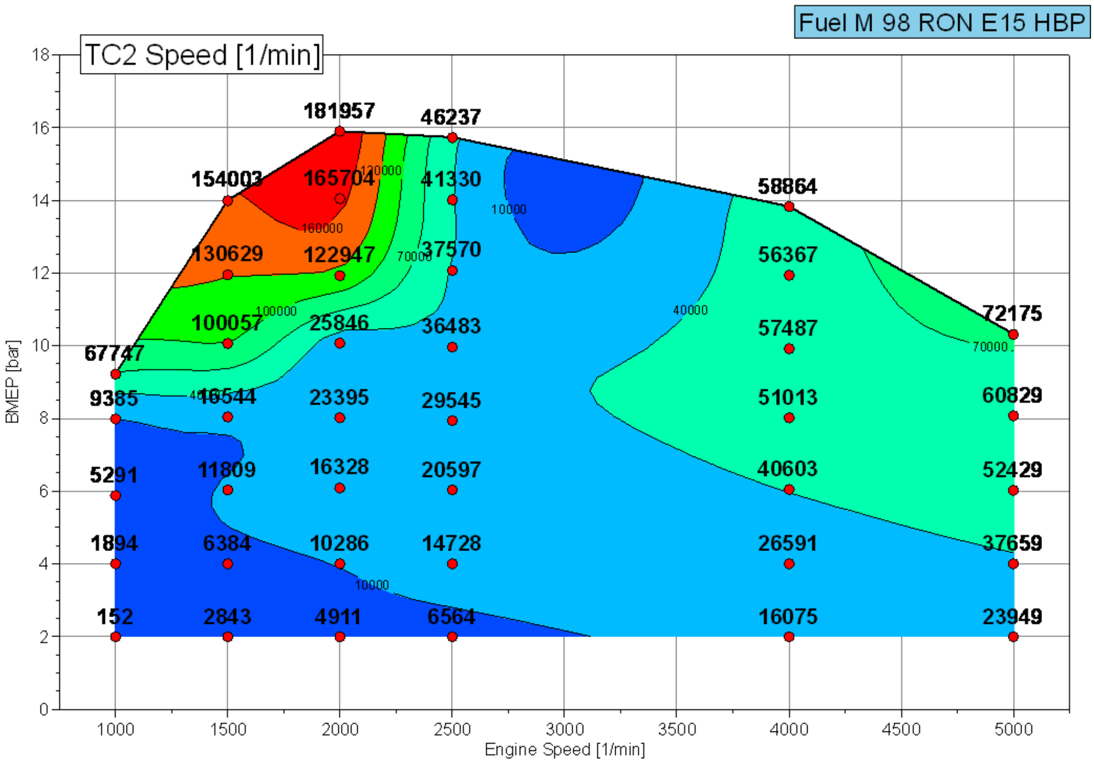

Figure 24: High Pressure Turbocharge Speed

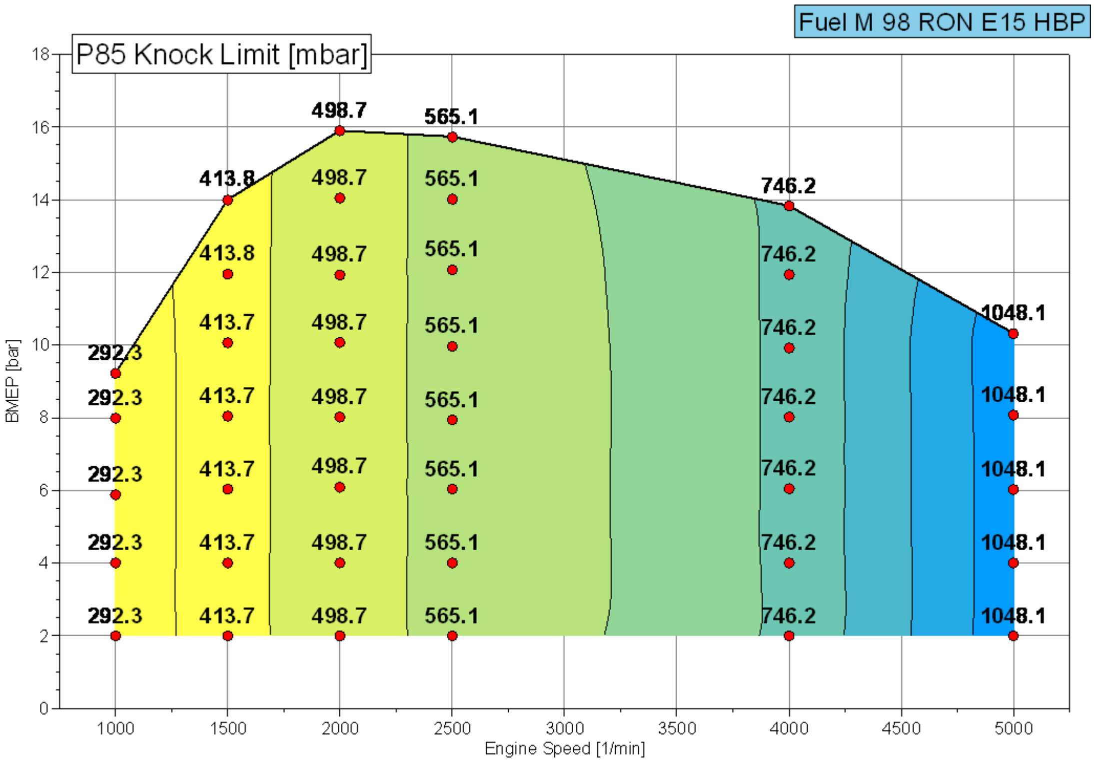

Figure 25: P85 Knock Limit

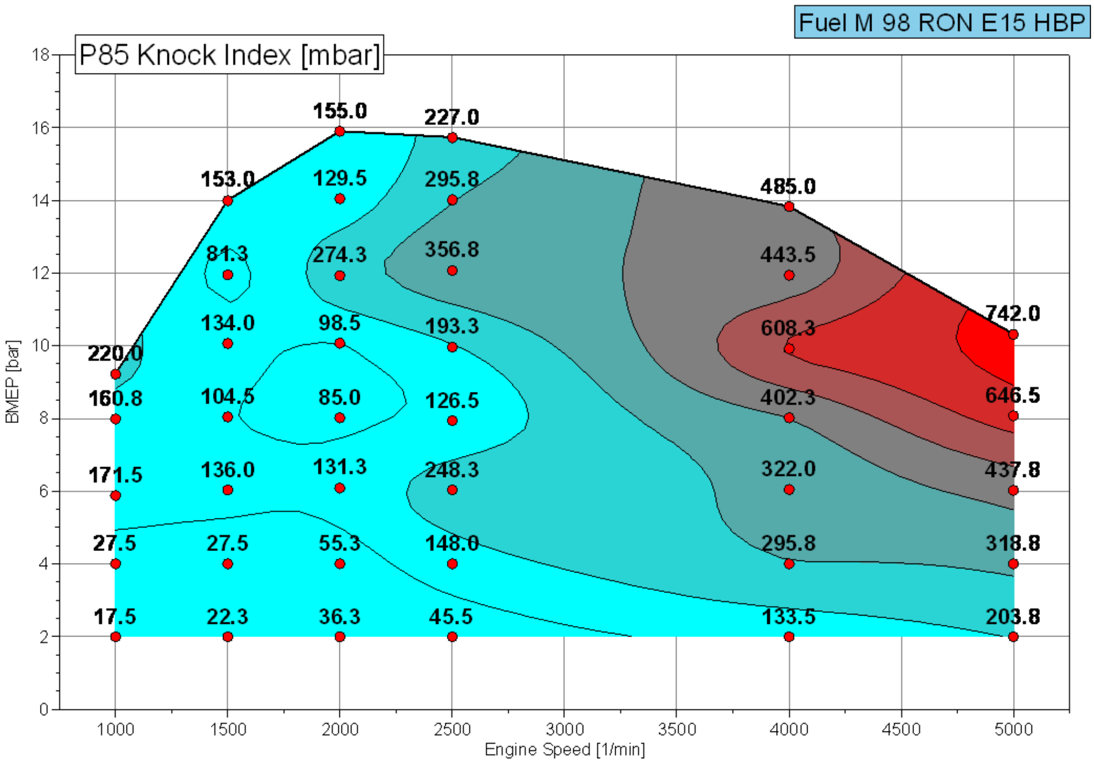

Figure 26: Averaged P85 Knock Index

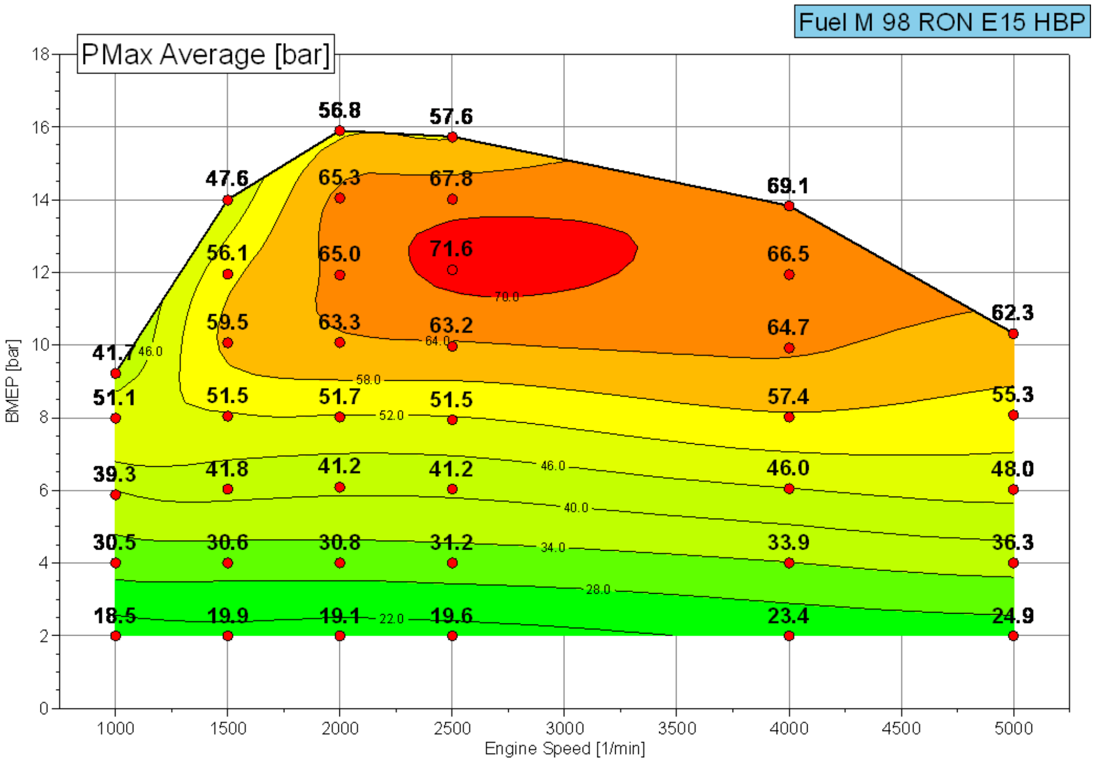

Figure 27: Averaged Max Pressure for Cylinders 1-4

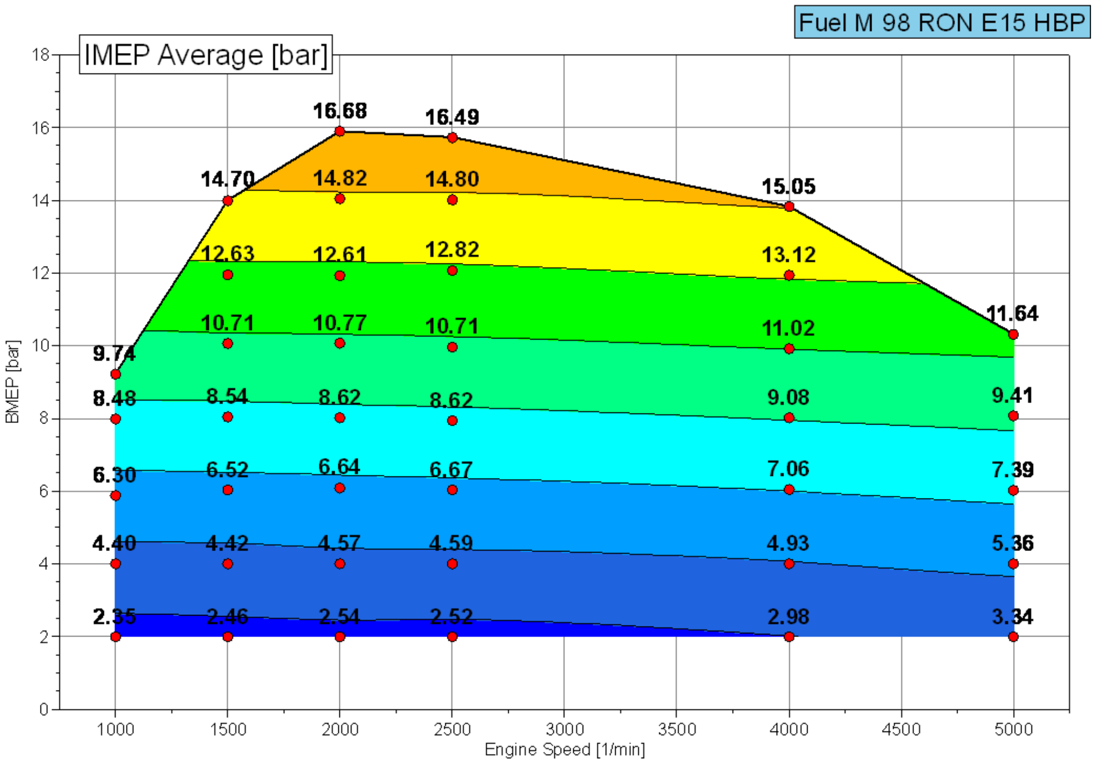

Figure 28: Indicated Mean Effective Pressure

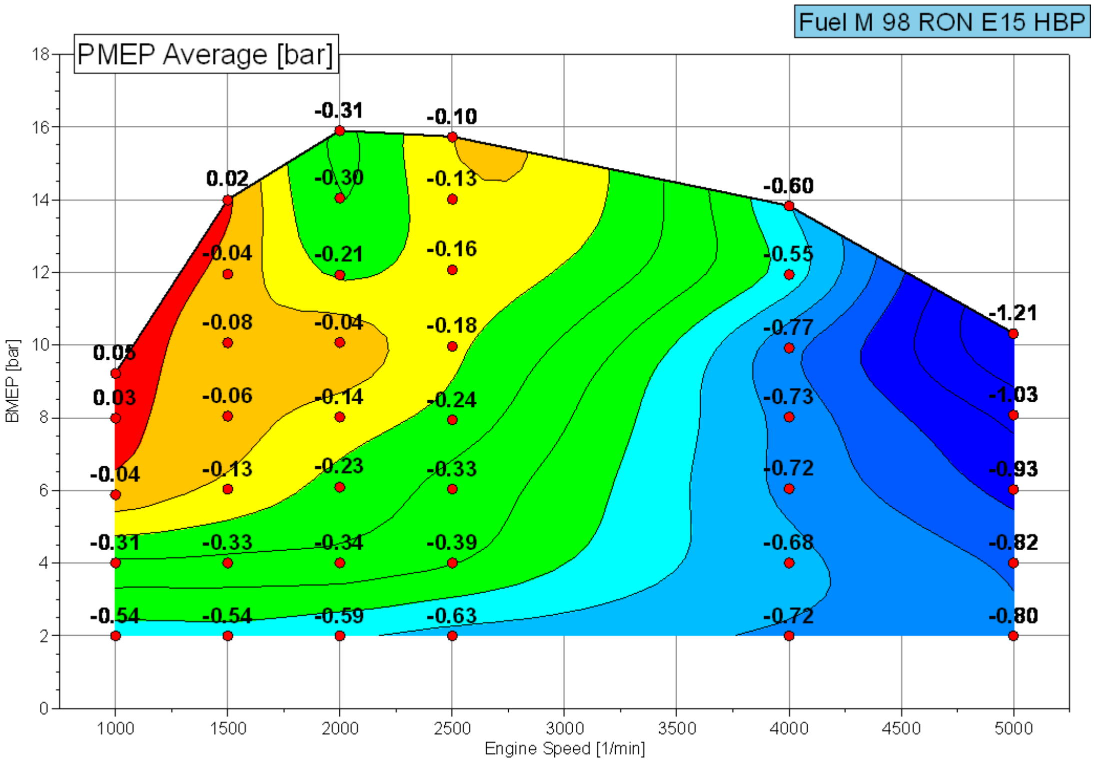

Figure 29: Pumping Mean Effective Pressure

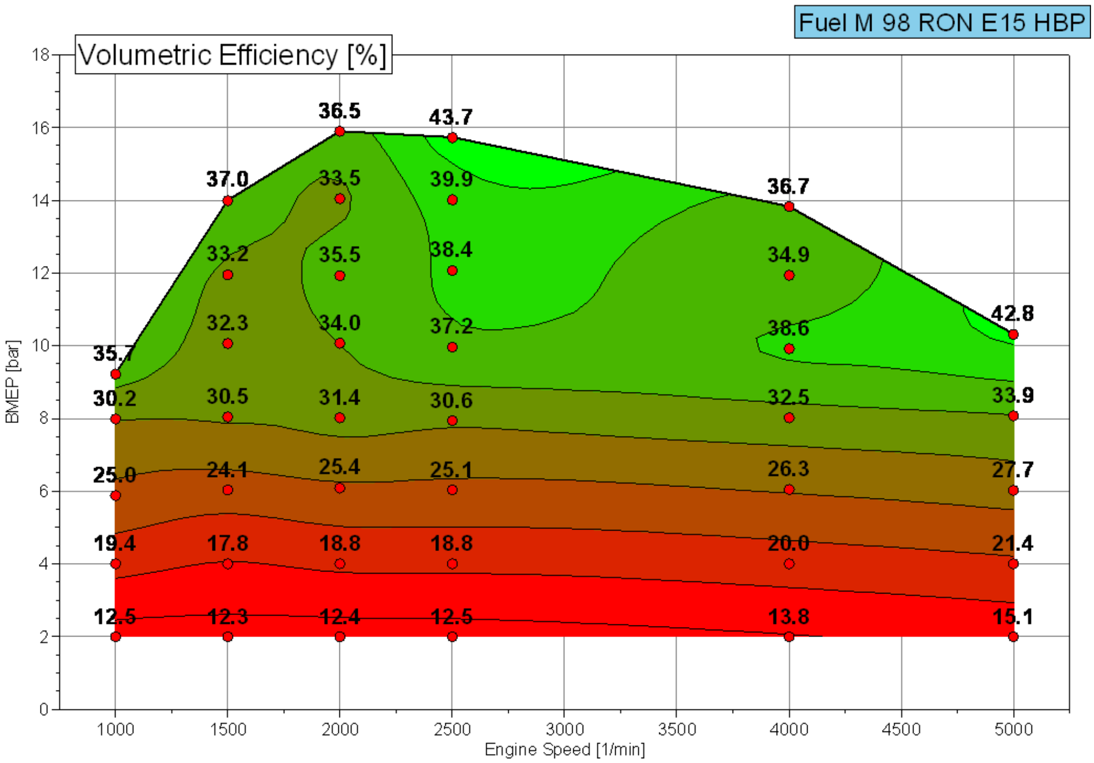

Figure 30: Calculated Volumetric Efficiency

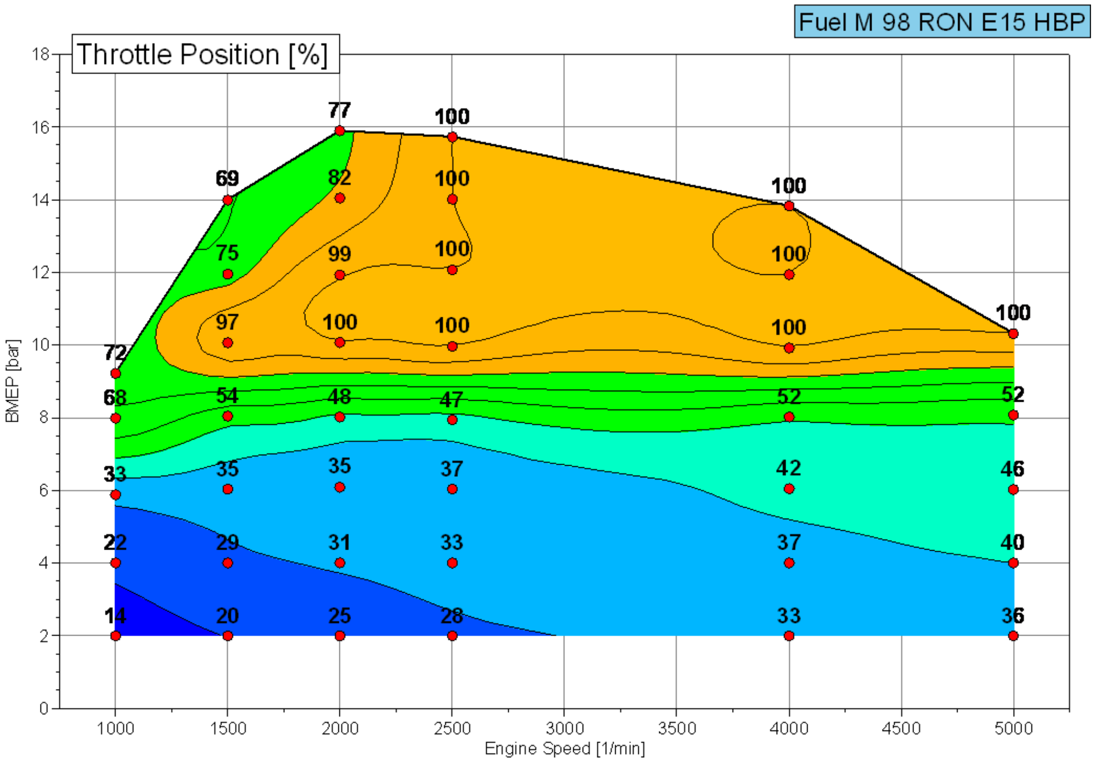

Figure 31: Throttle Position

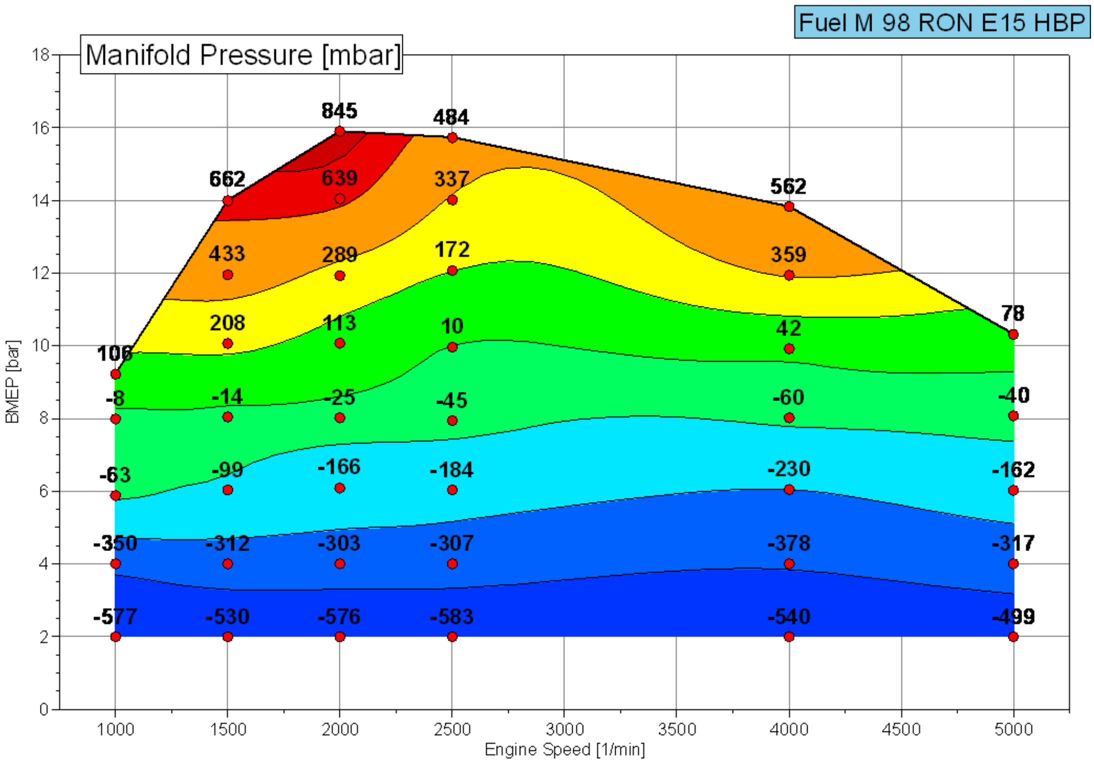

Figure 32: Intake Manifold Pressure

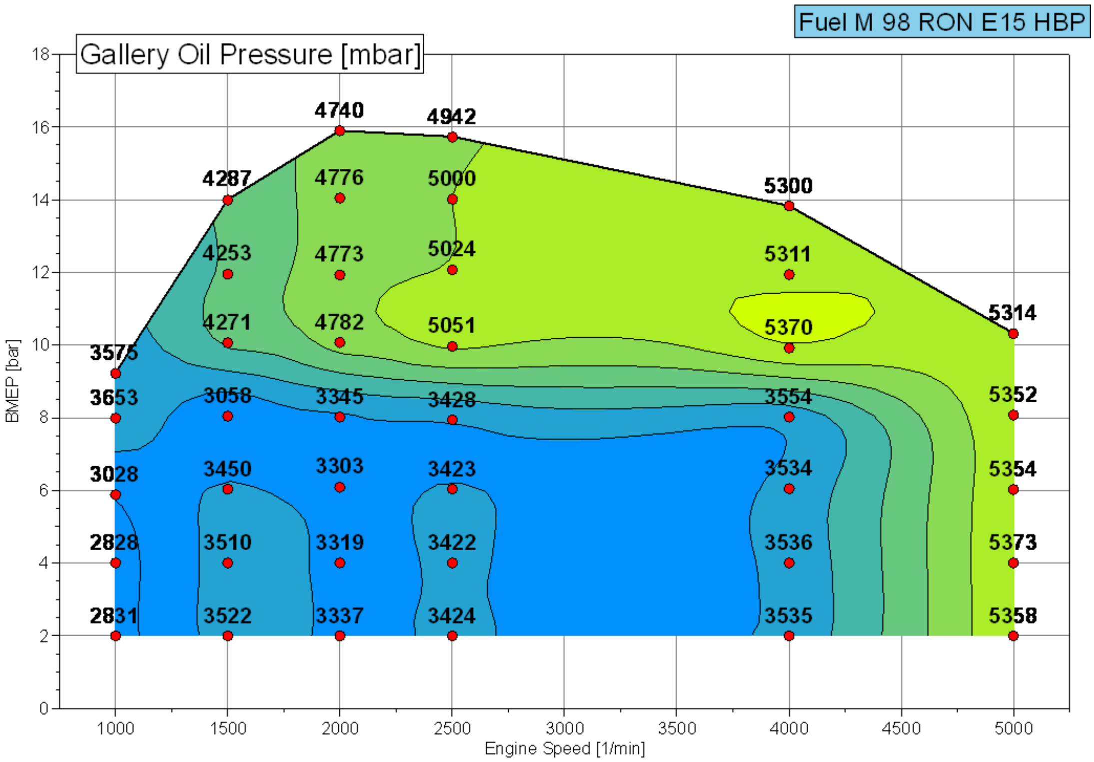

Figure 33: Gallery Oil Pressure

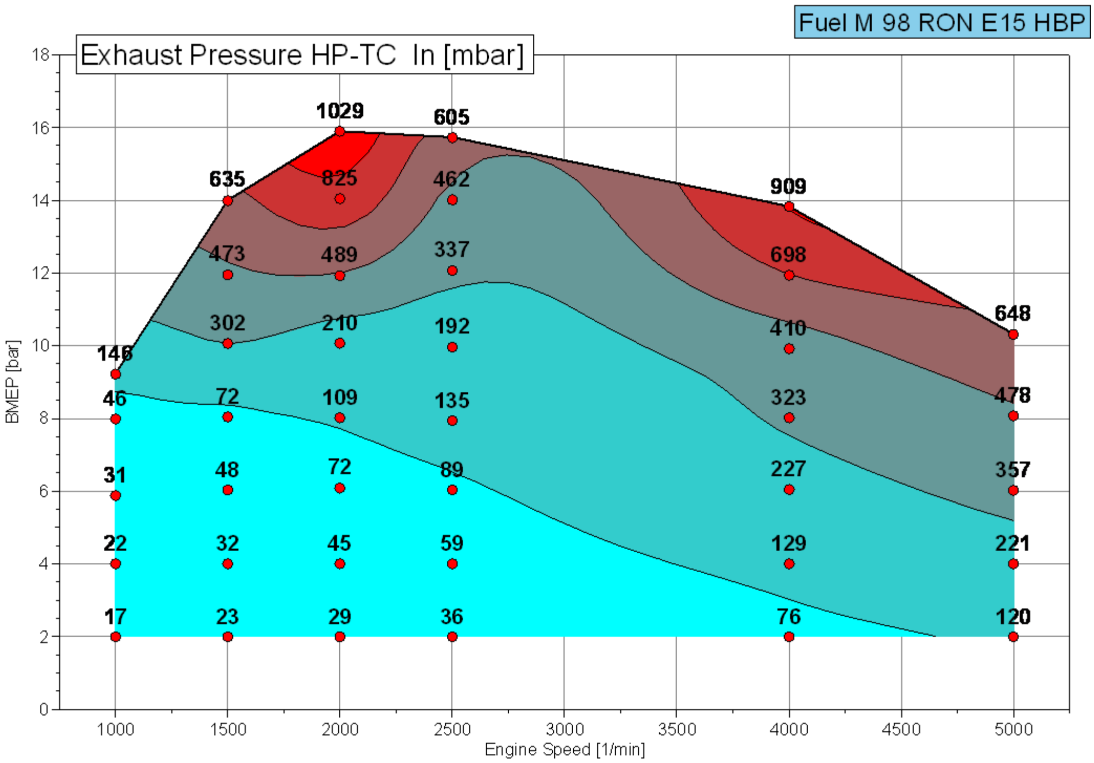

Figure 34: Exhaust Pressure High Pressure Turbocharger In

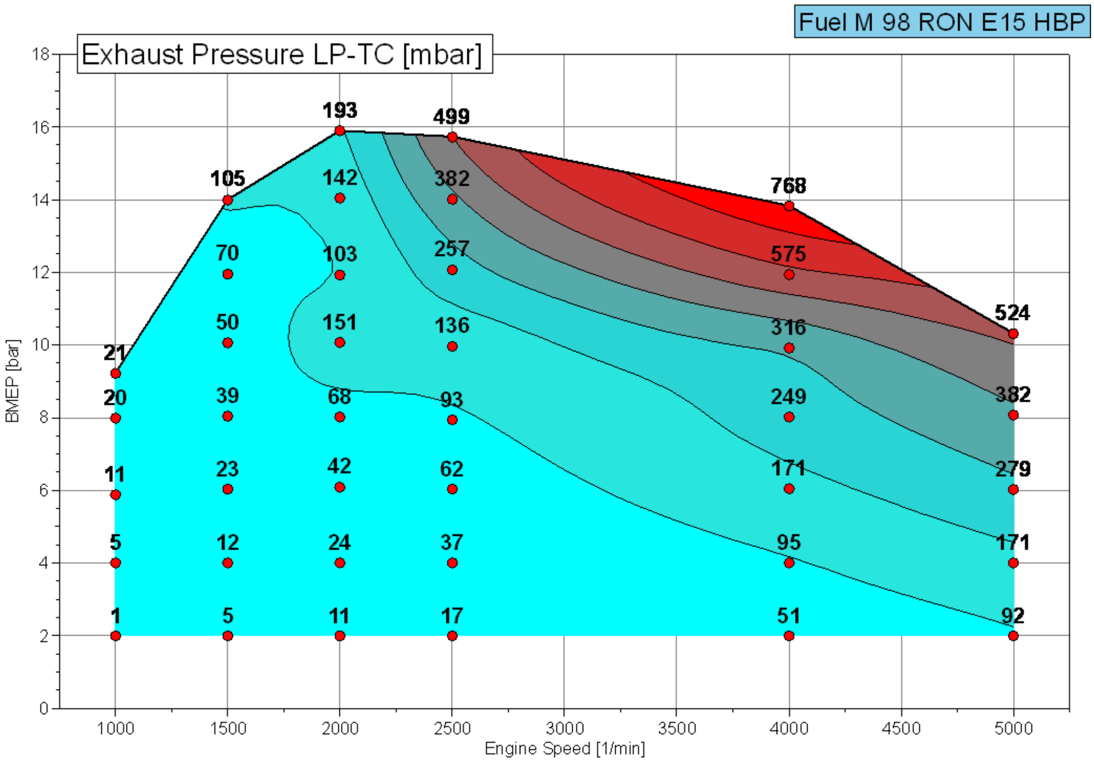

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

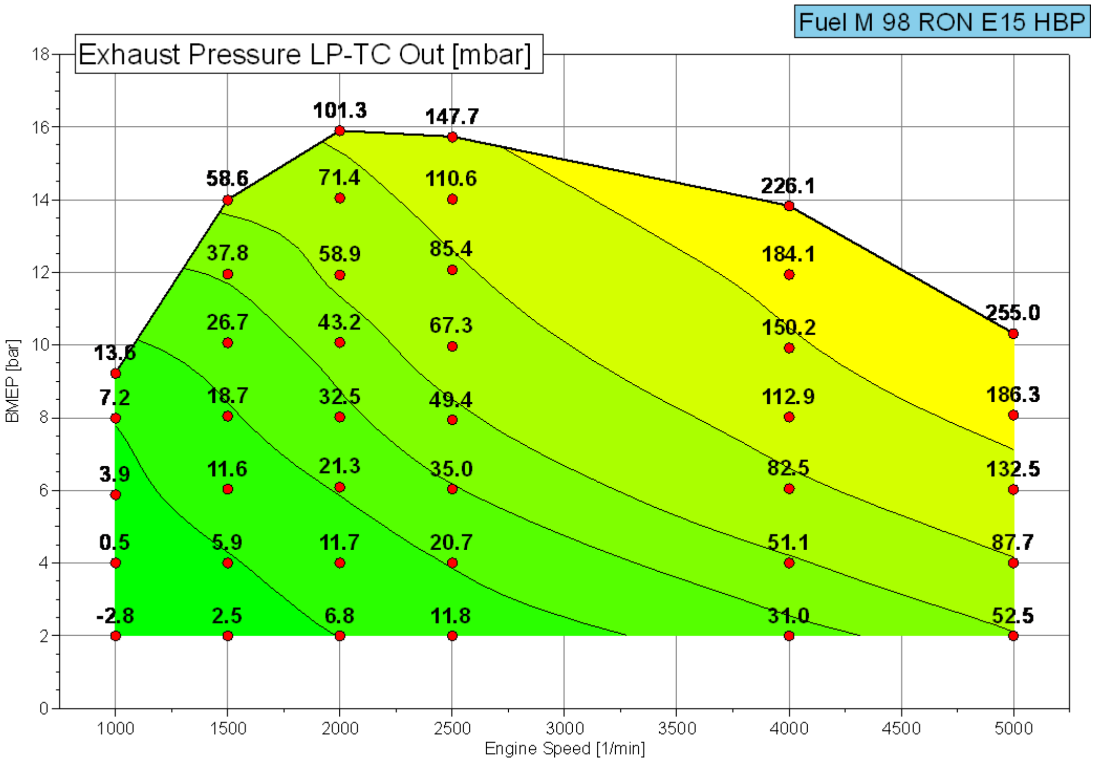

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

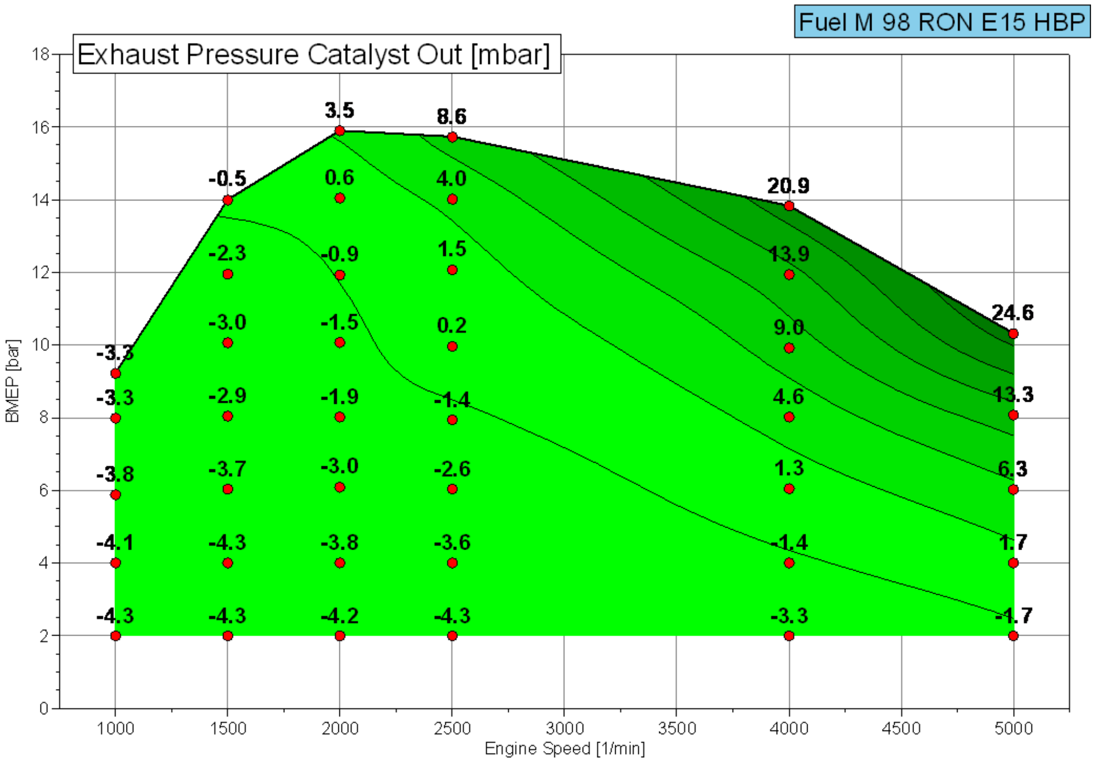

Figure 37: Exhaust Pressure Catalyst Out

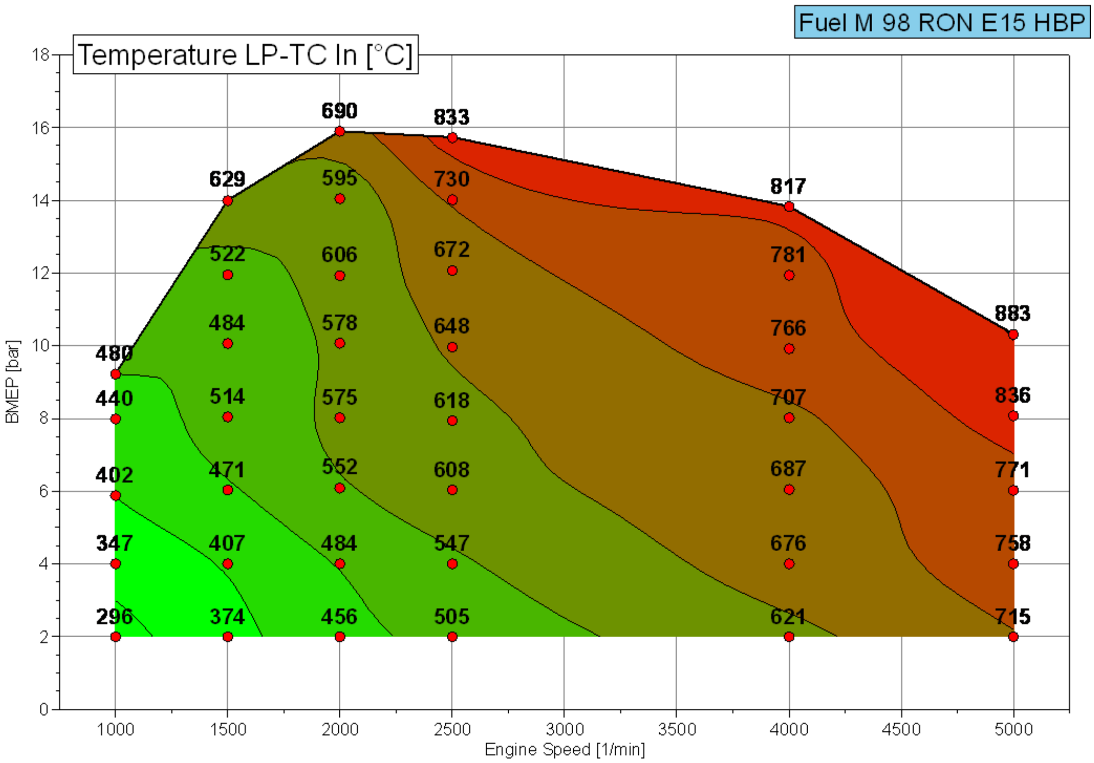

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

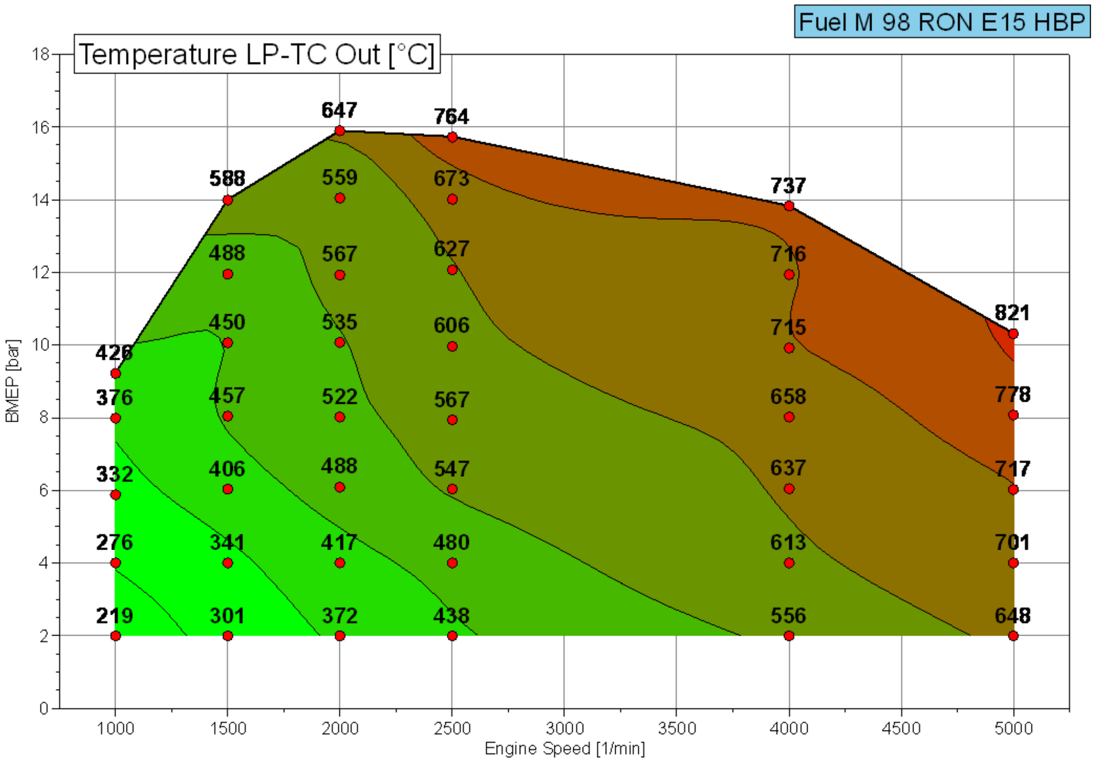

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

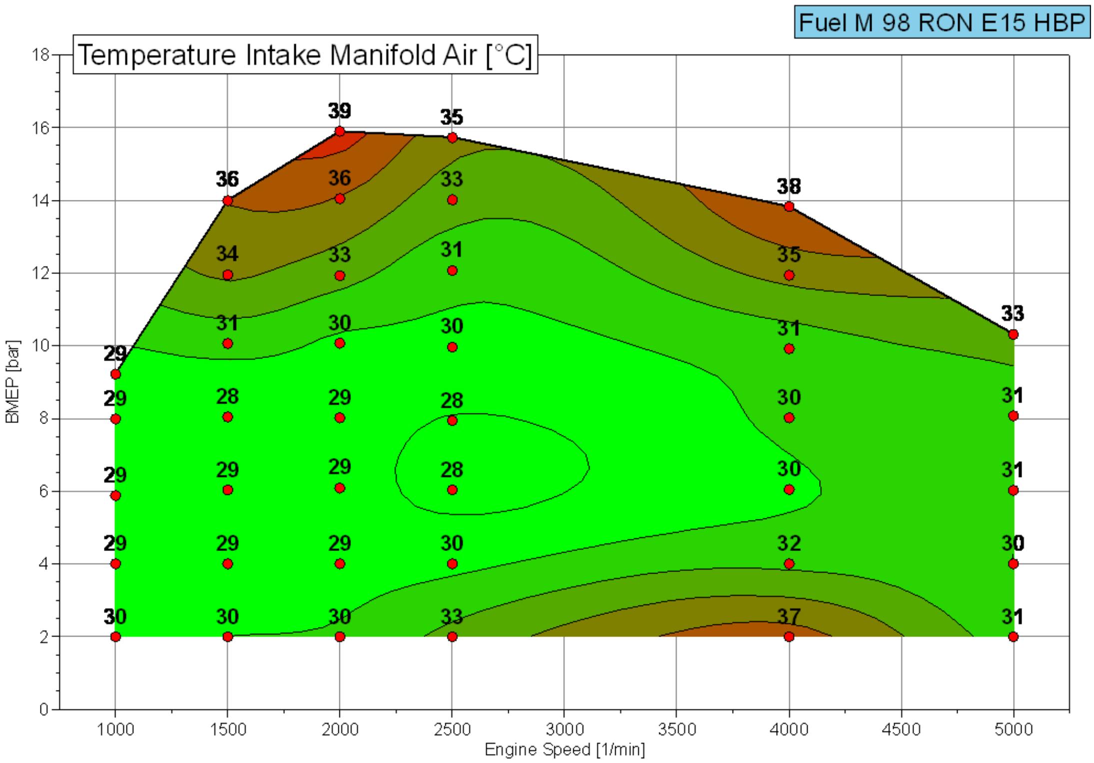

Figure 40: Intake Manifold Air Temperature

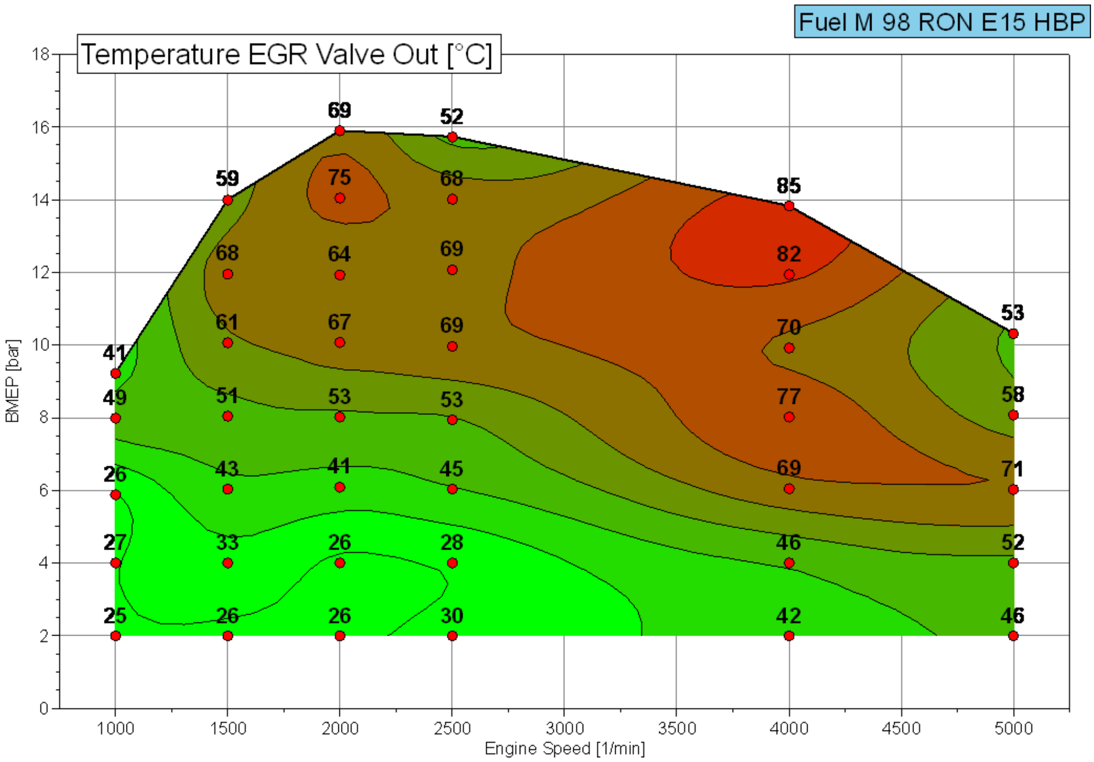

Figure 41: EGR Valve Out Temperature

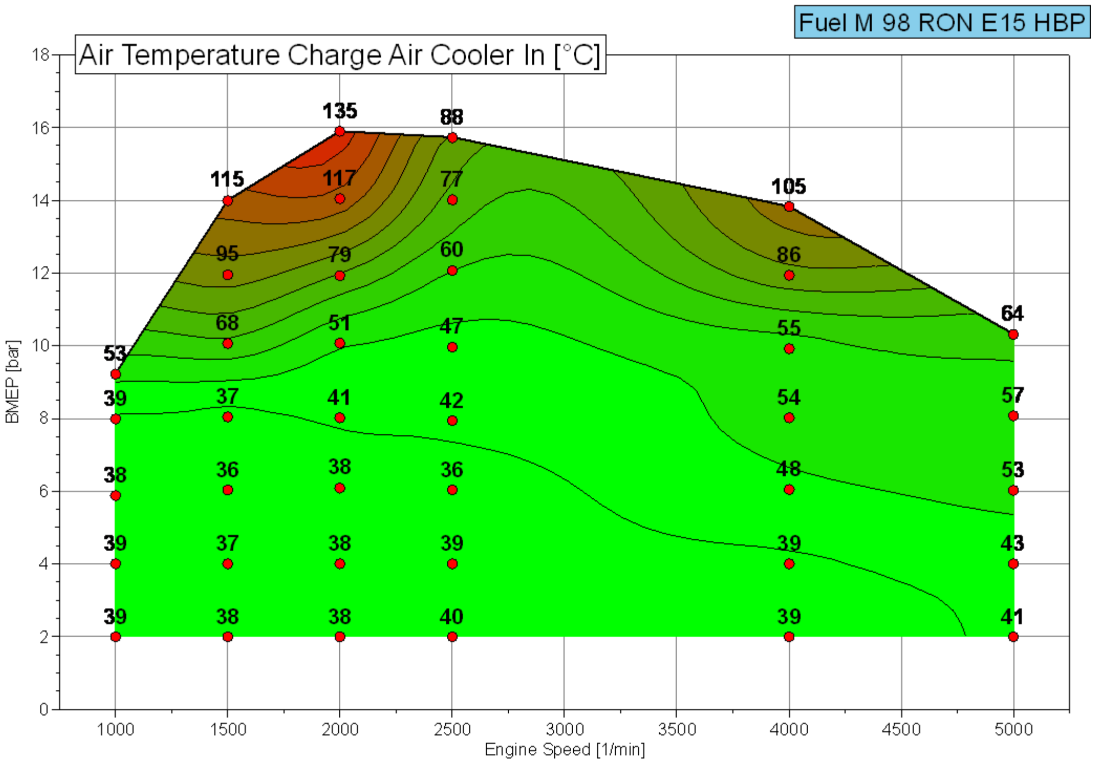

Figure 42: Charge Air Cooler Inlet Air Temperature

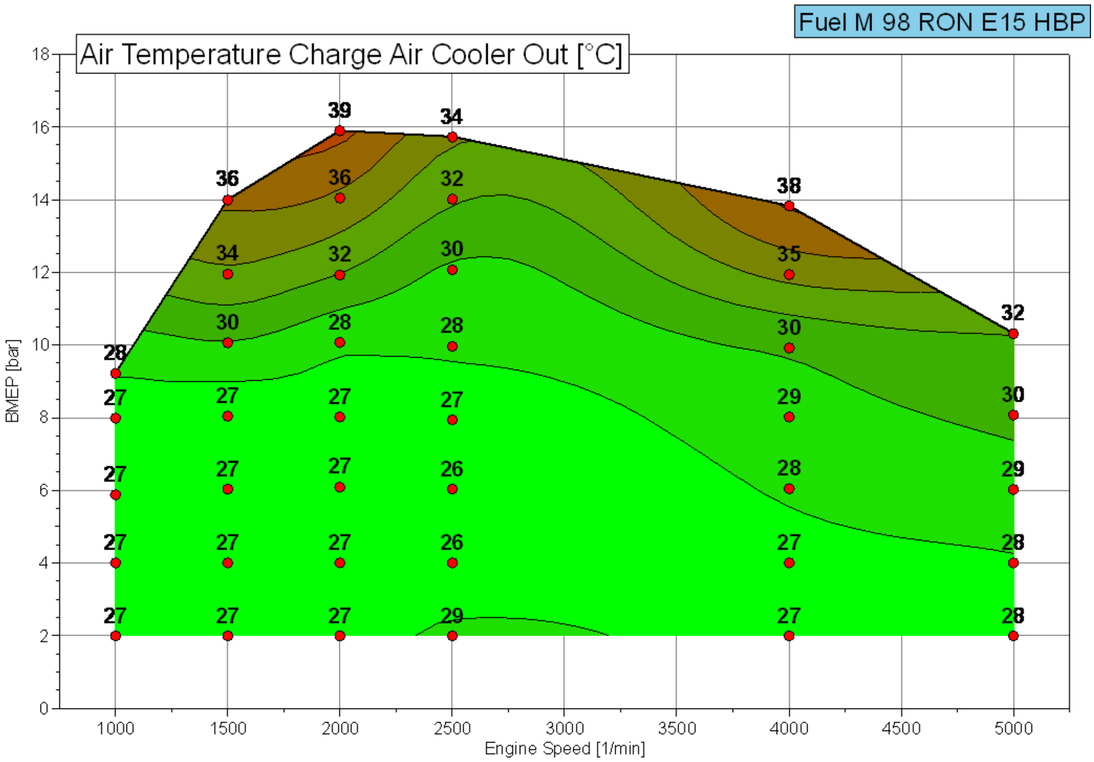

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel O Calibration Results

98 Ron 30% Ethanol Medium Boiling Point

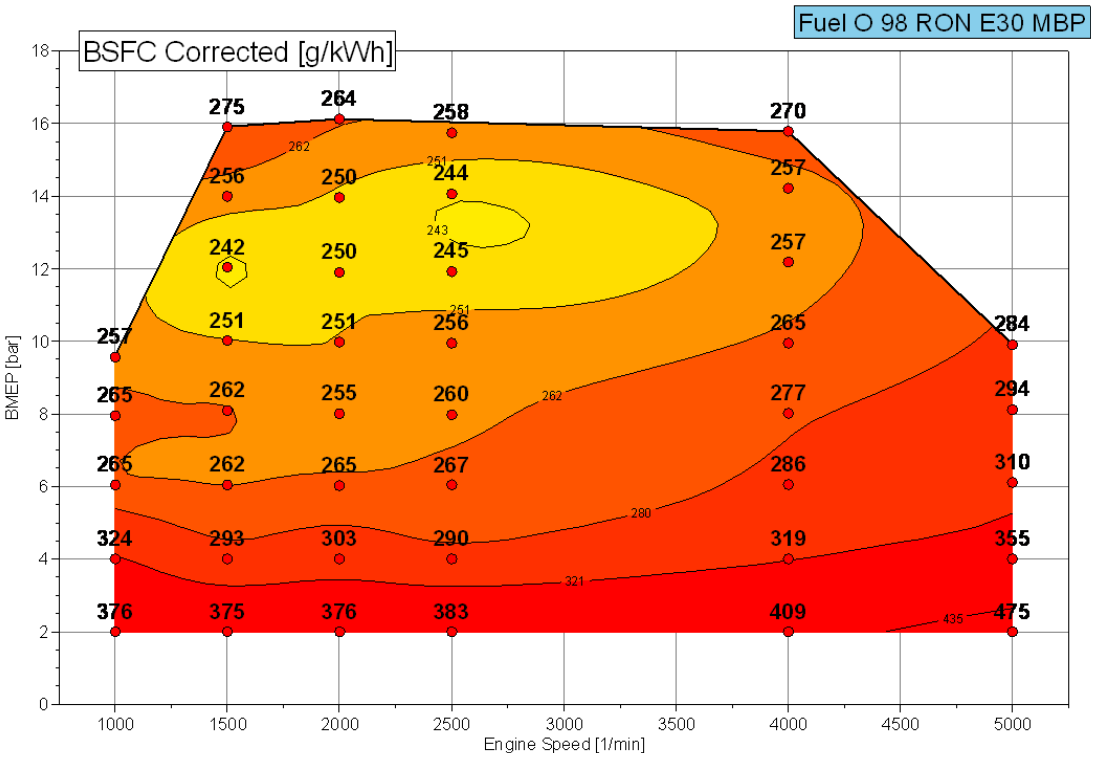

Figure 1: Brake Specific Fuel Consumption

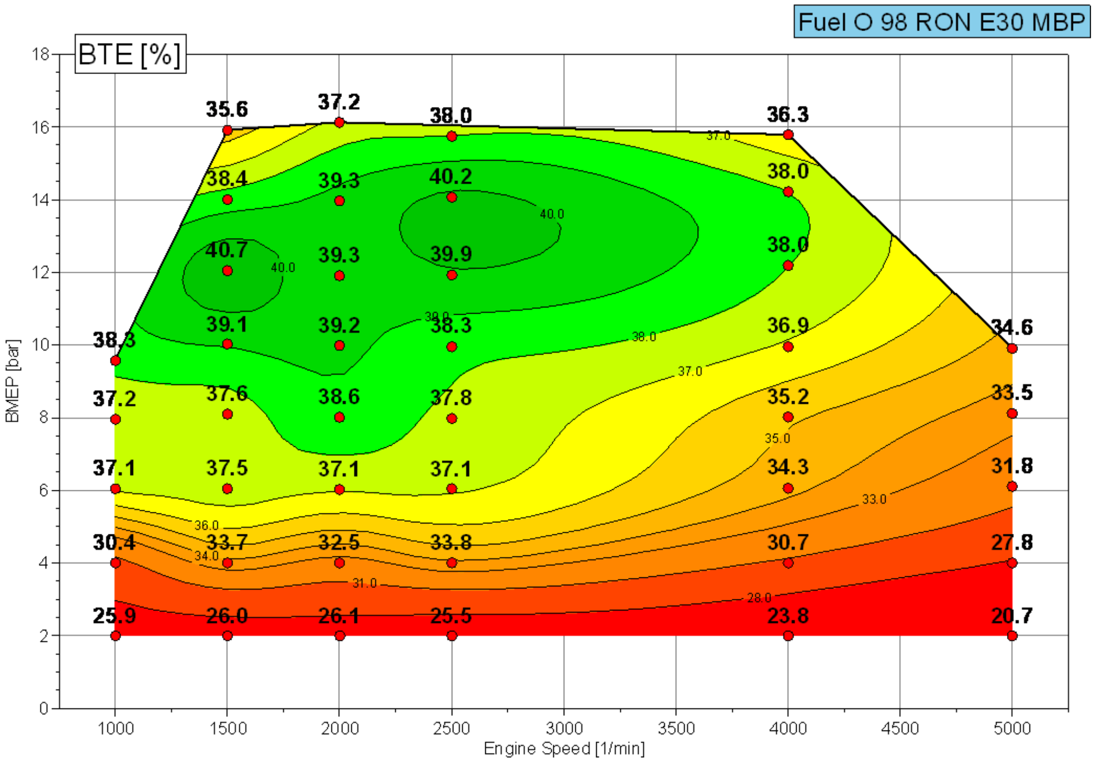

Figure 2: Brake Thermal Efficiency

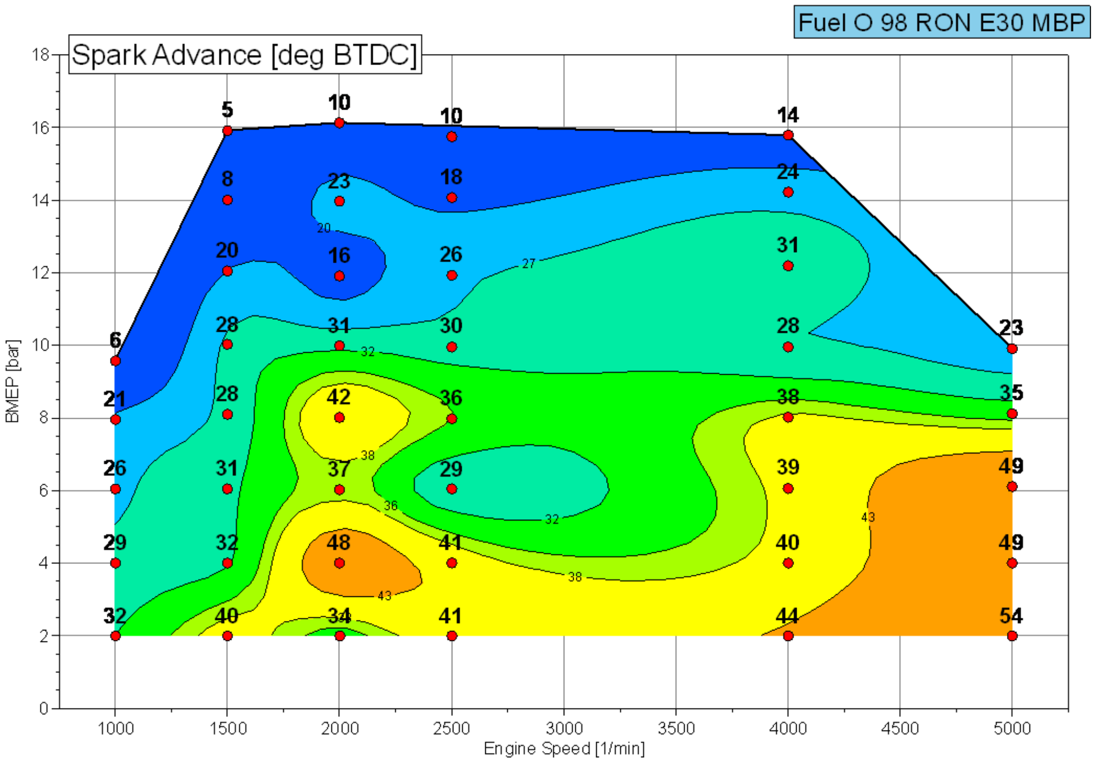

Figure 3: Spark Advance

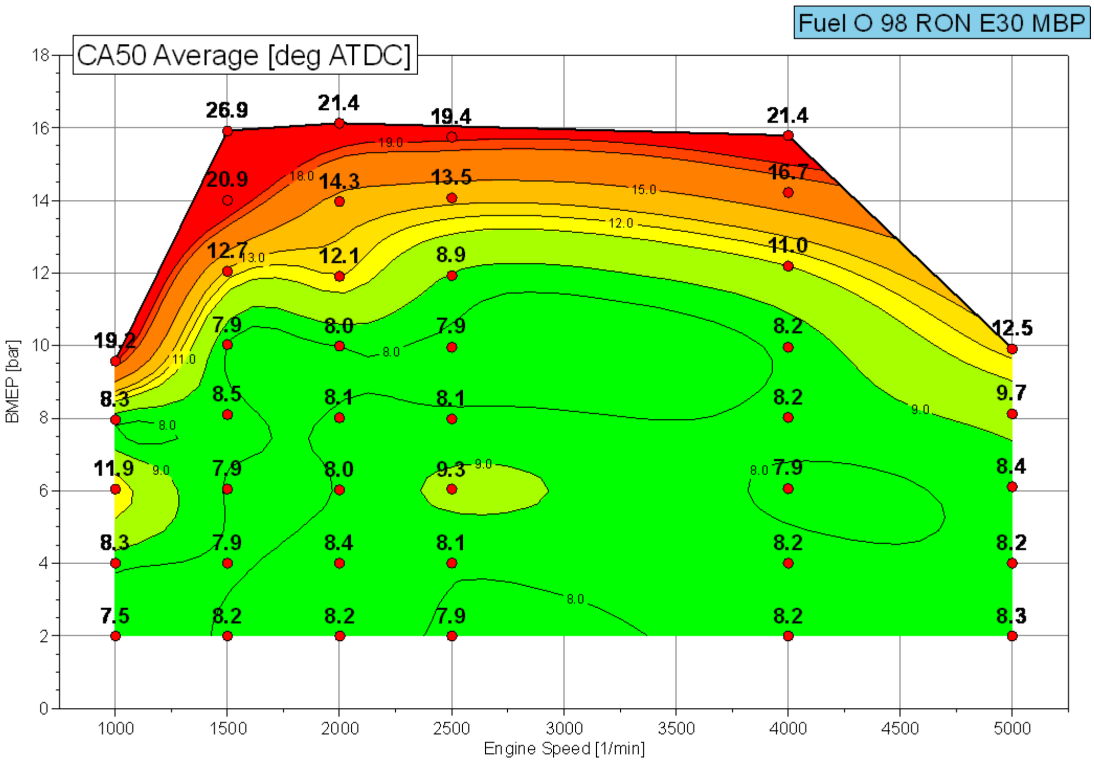

Figure 4: CA50 Average of Cylinders 1-4

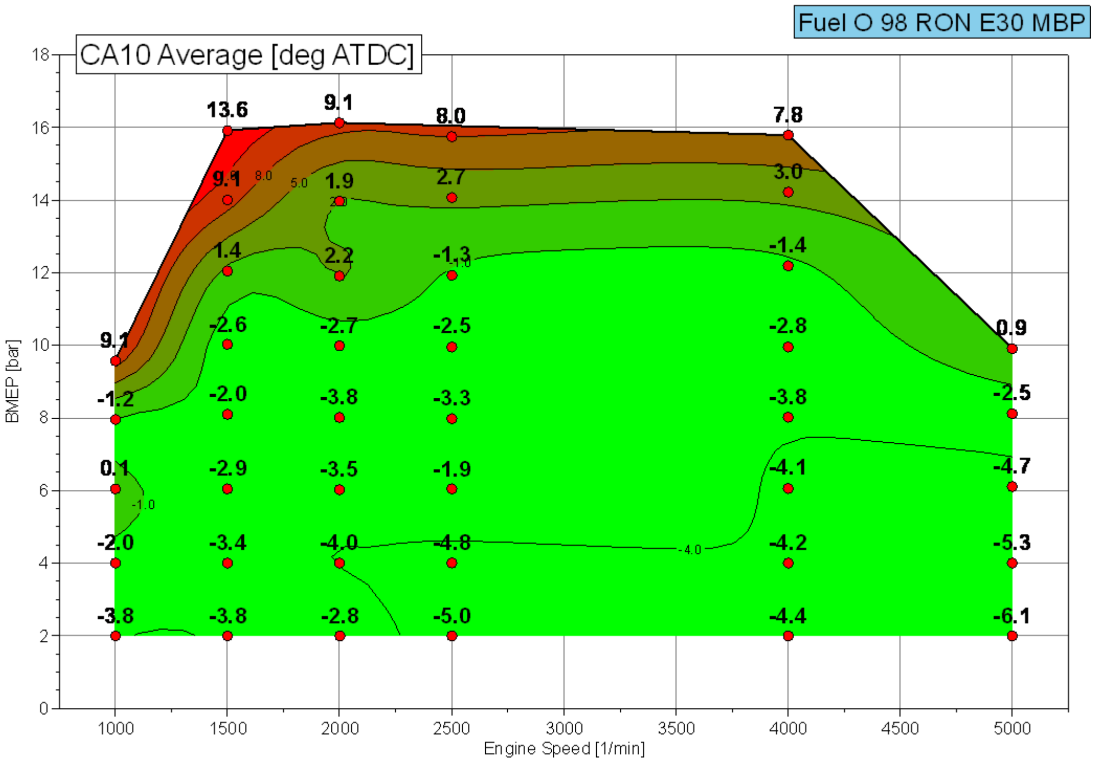

Figure 5: CA10 Average of Cylinders 1-4

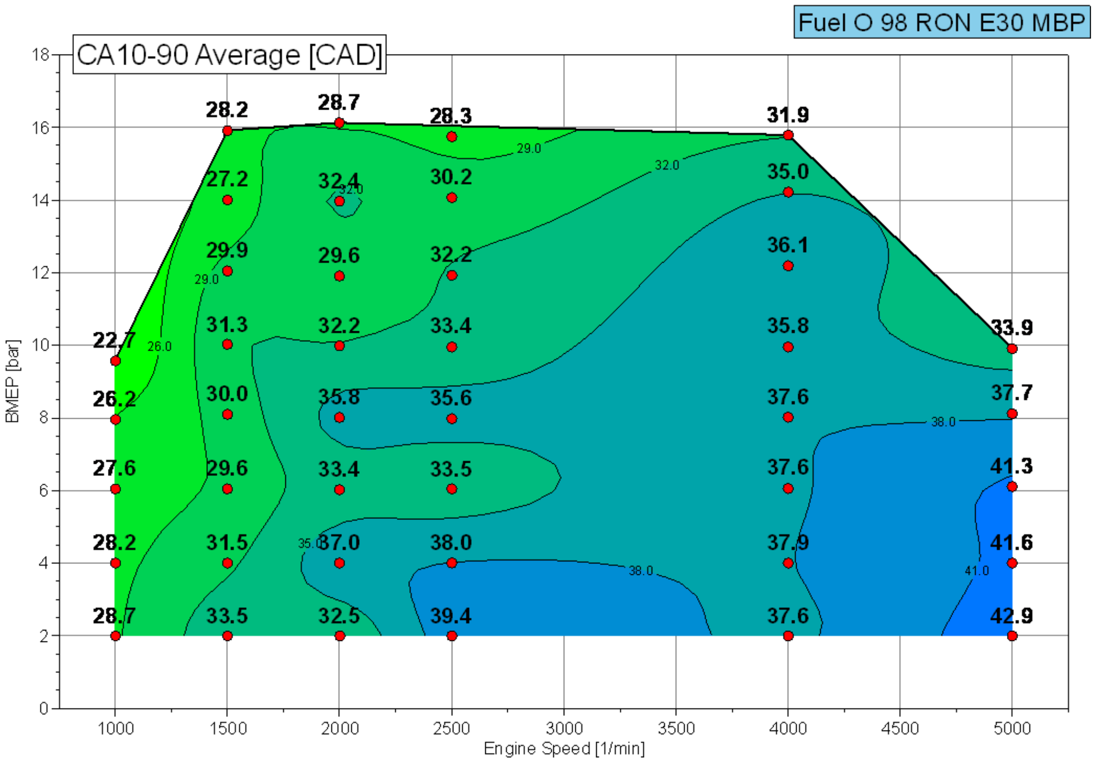

Figure 6: CA10-90 Average of Cylinders 1-4

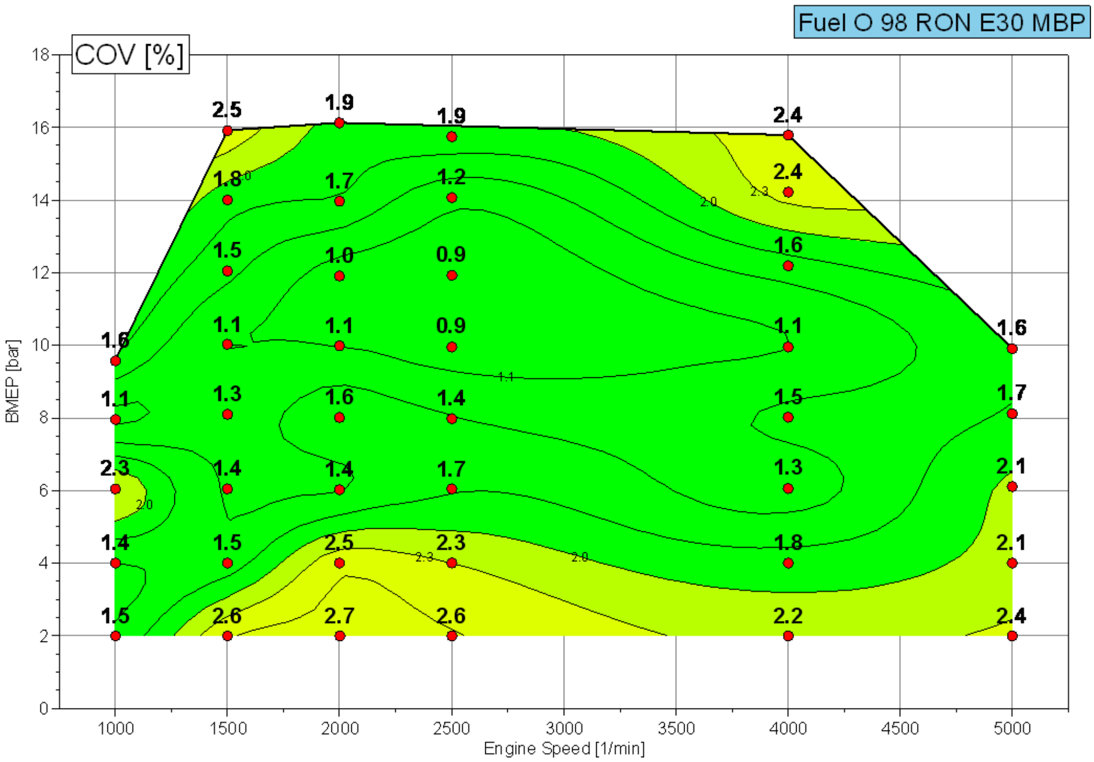

Figure 7: Coefficient of Variation Average of Cylinders 1-4

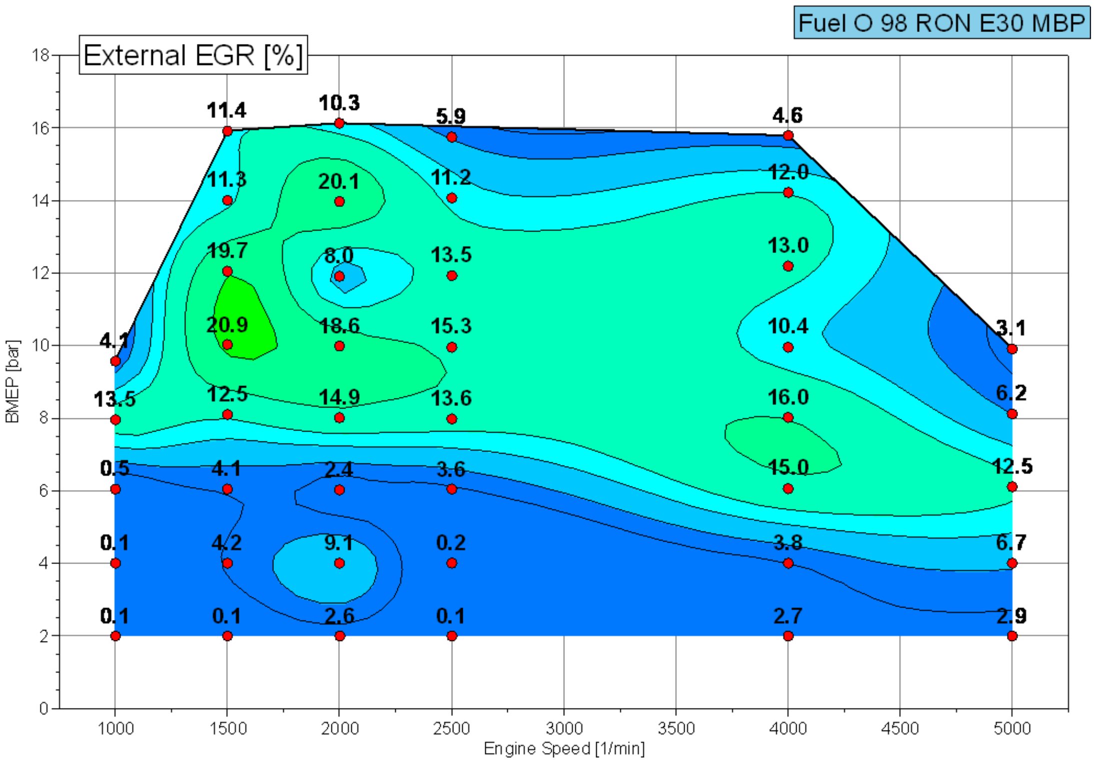

Figure 8: External EGR Percent of Intake Air

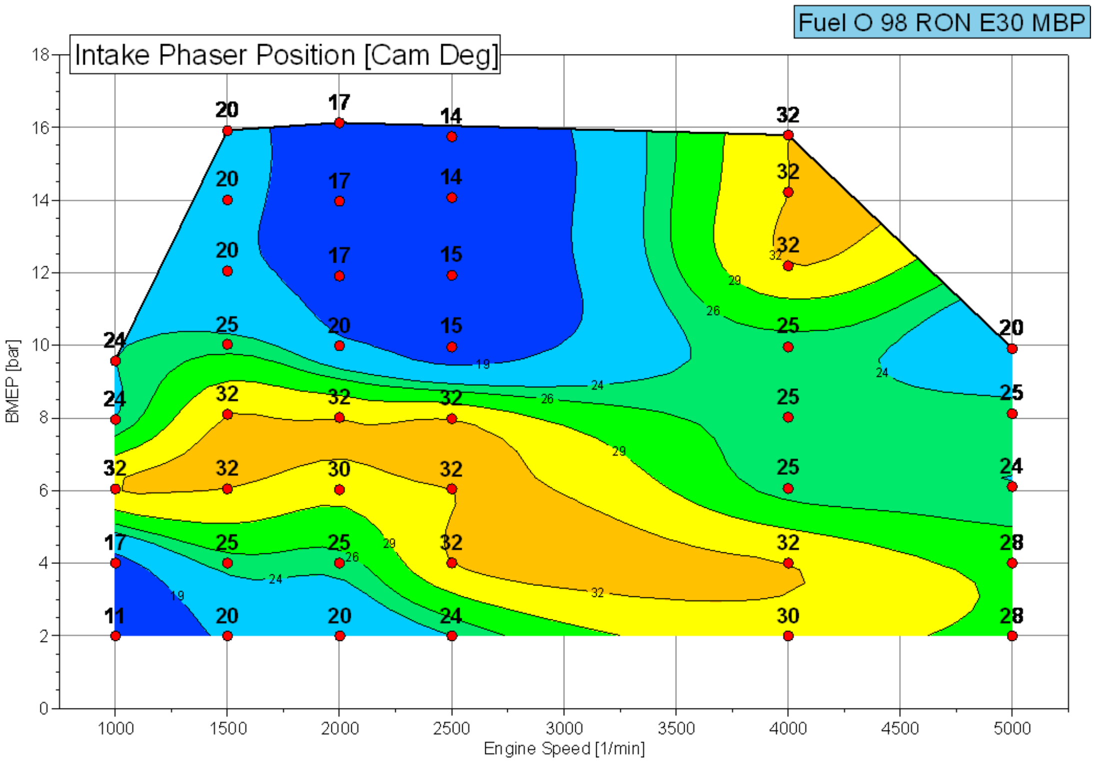

Figure 9: Intake Camshaft Phaser Position

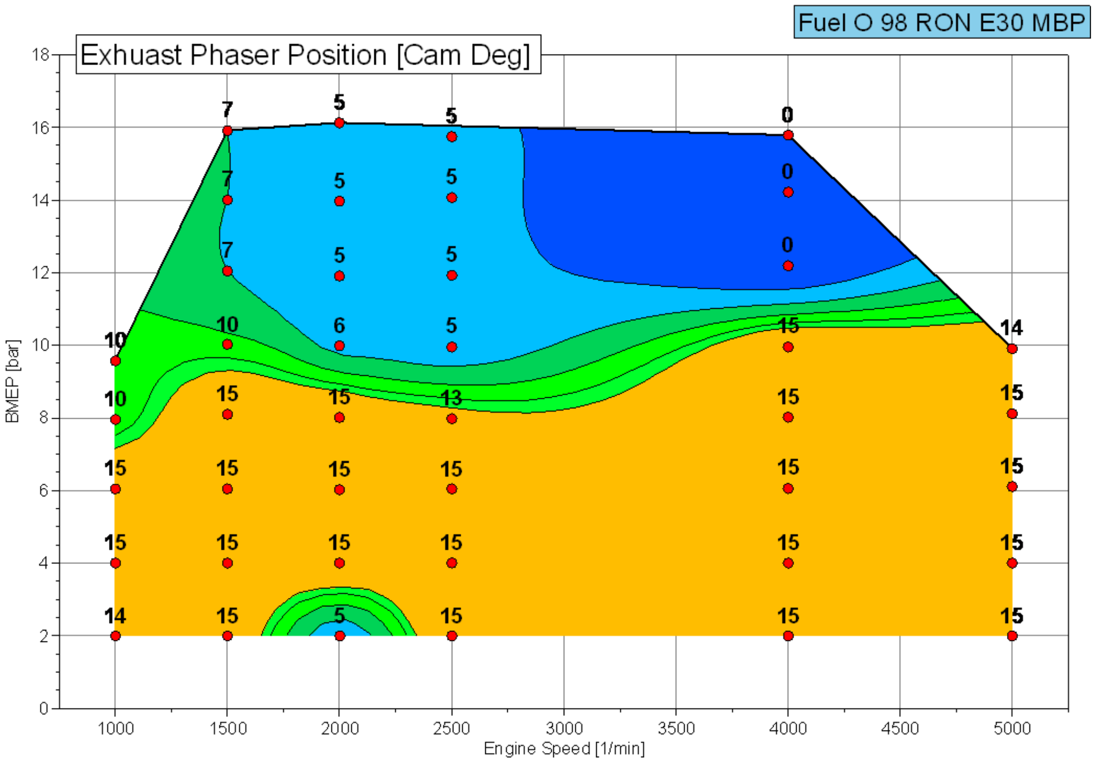

Figure 10: Exhaust Camshaft Phaser Position

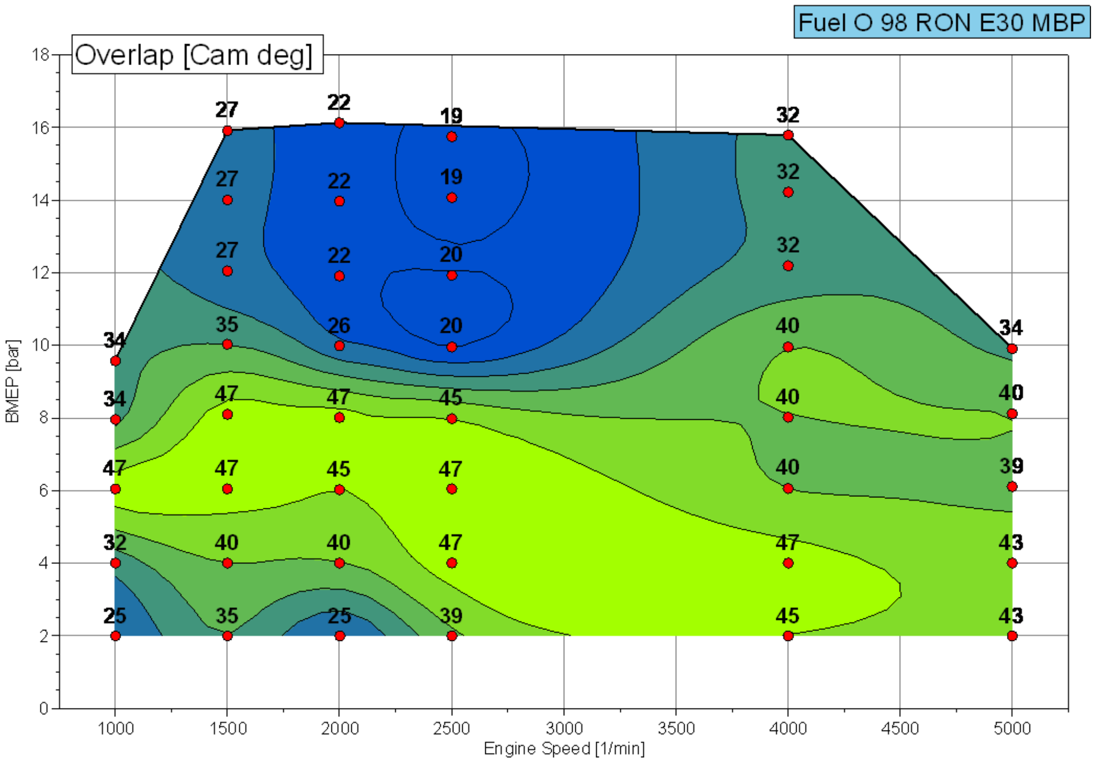

Figure 11: Camshaft Overlap

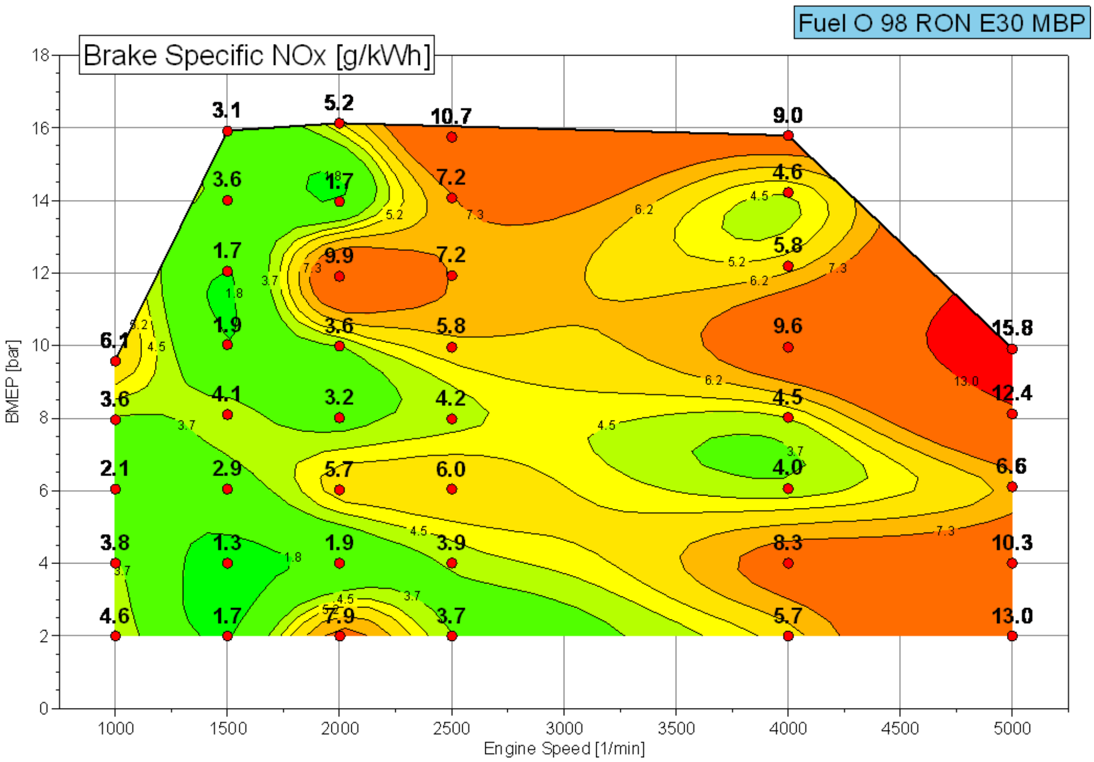

Figure 12: Brake Specific NOx Emissions

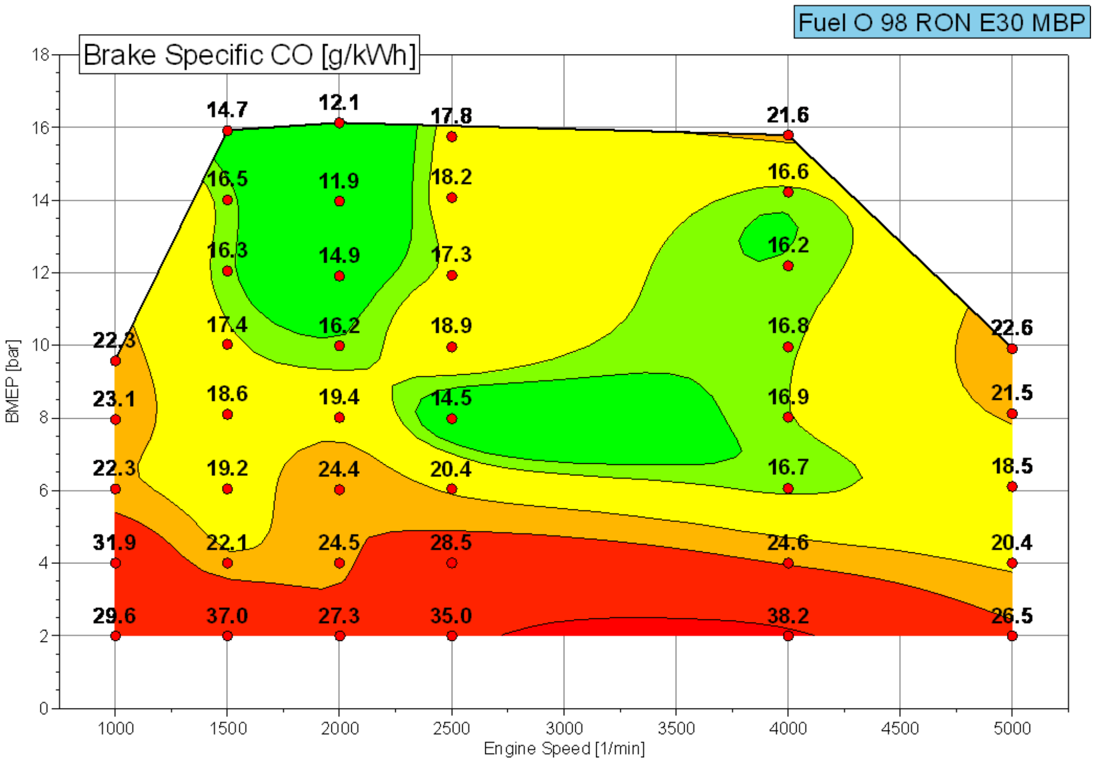

Figure 13: Brake Specific Carbon Monoxide Emissions

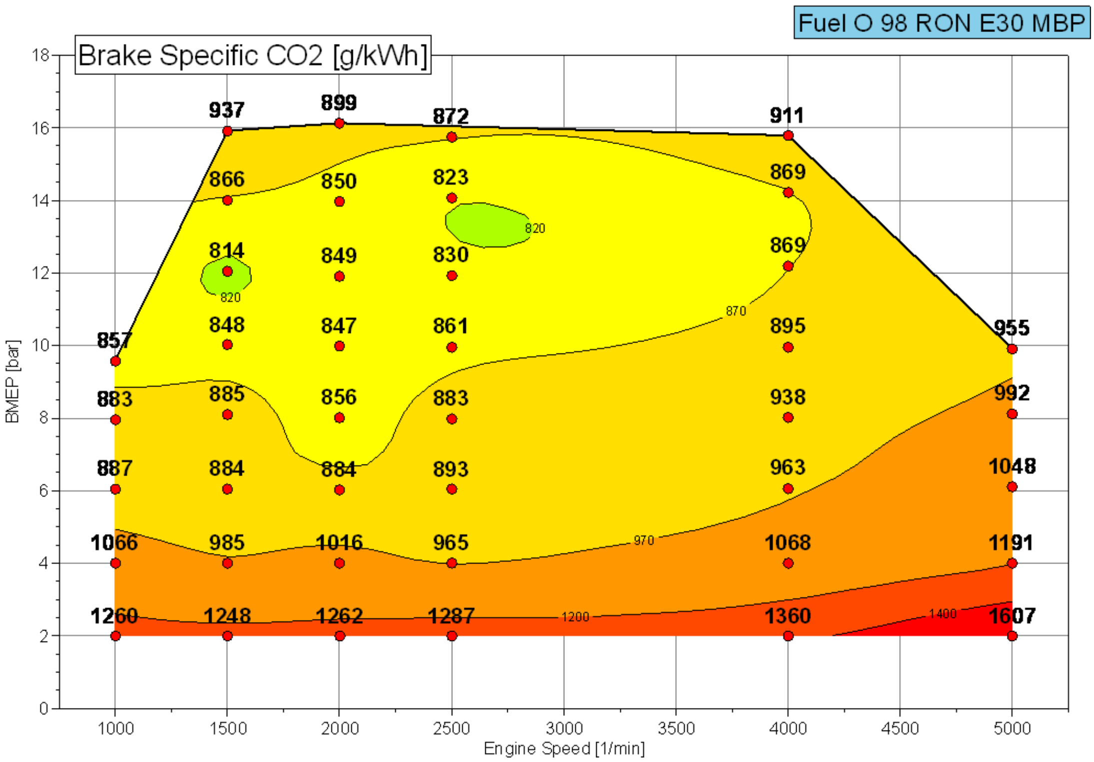

Figure 14: Brake Specific Carbon Dioxide Emissions

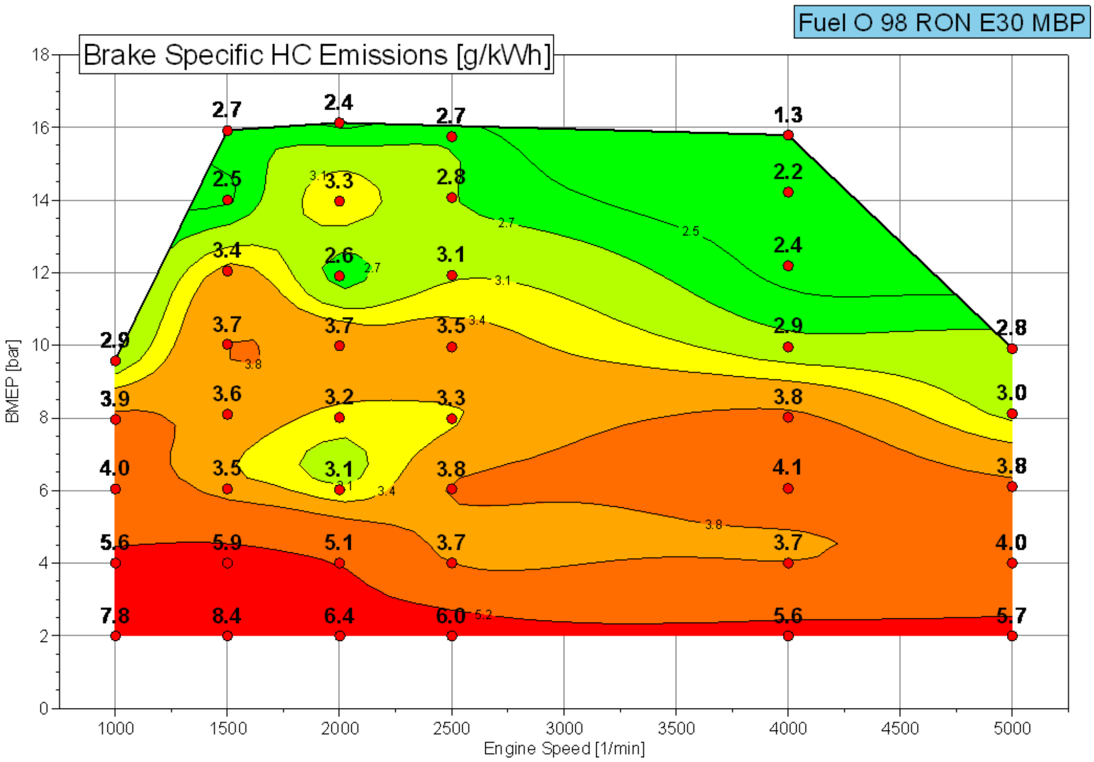

Figure 15: Brake Specific Hydrocarbon Emissions

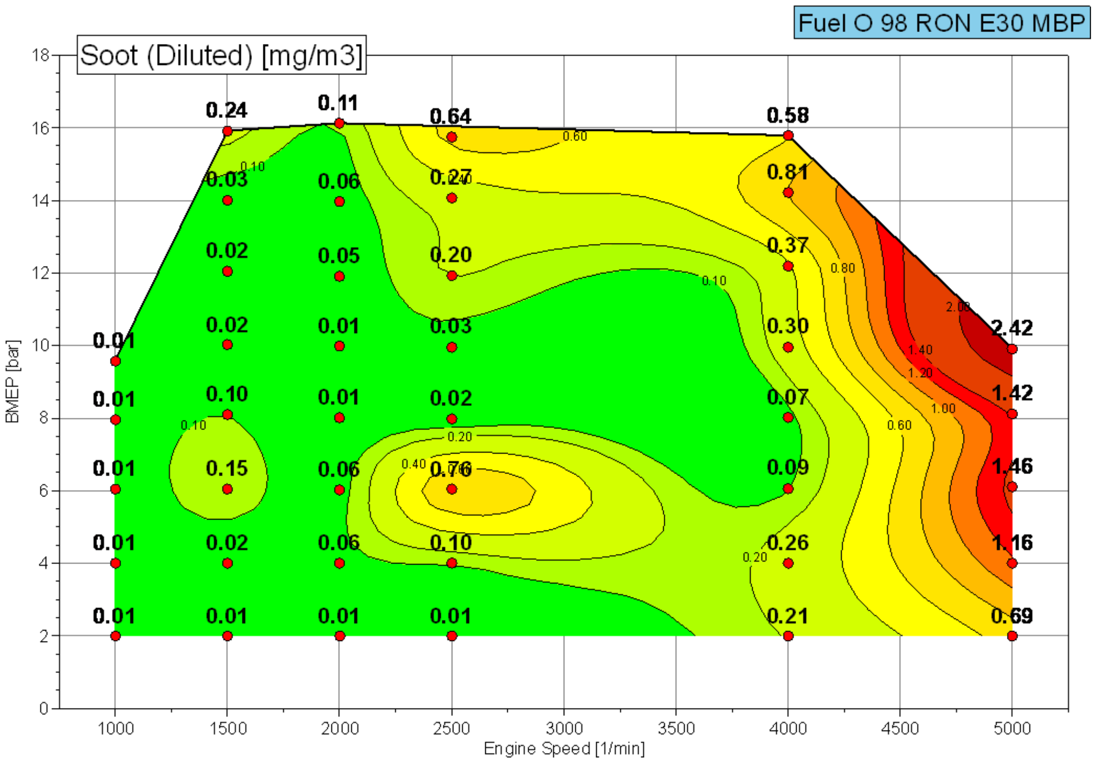

Figure 16: Particulate Soot Emissions

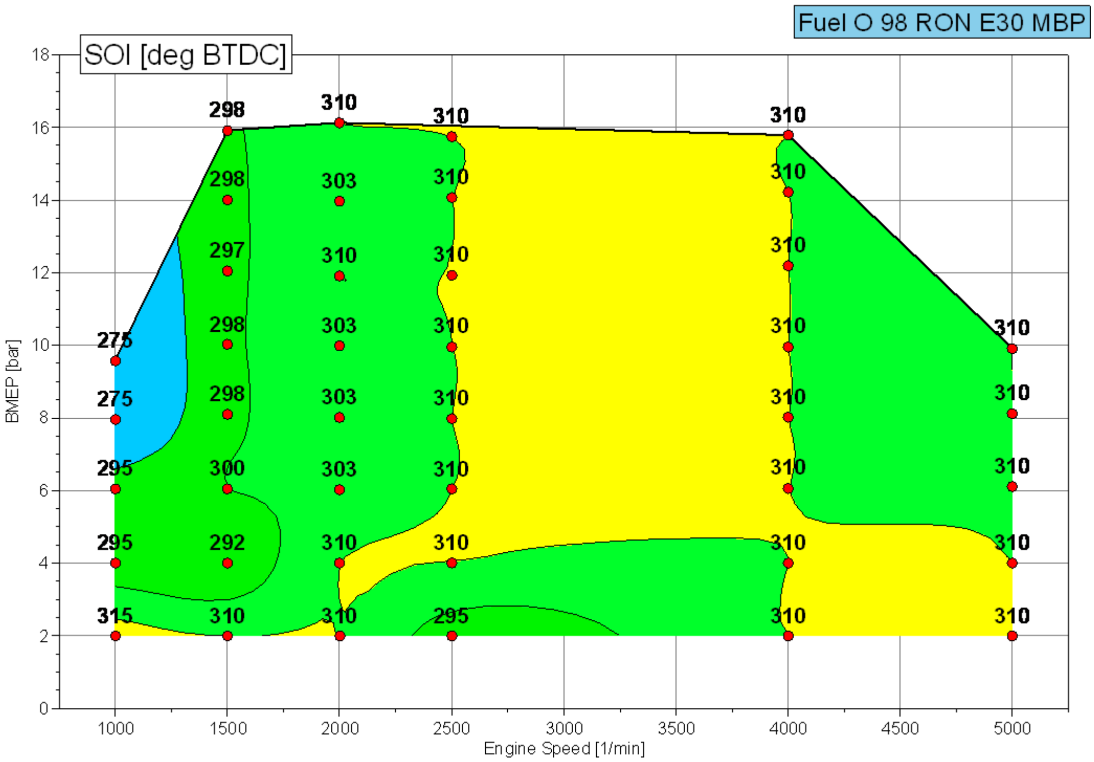

Figure 17: Start of Injection

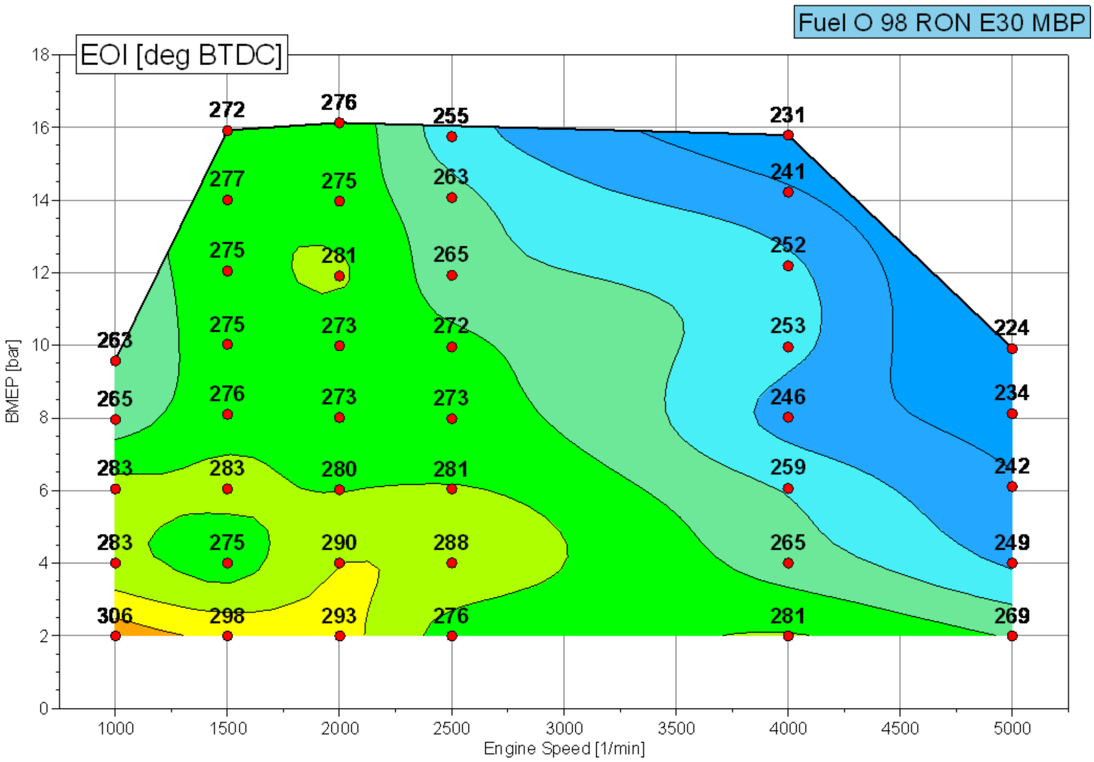

Figure 18: End of Injection

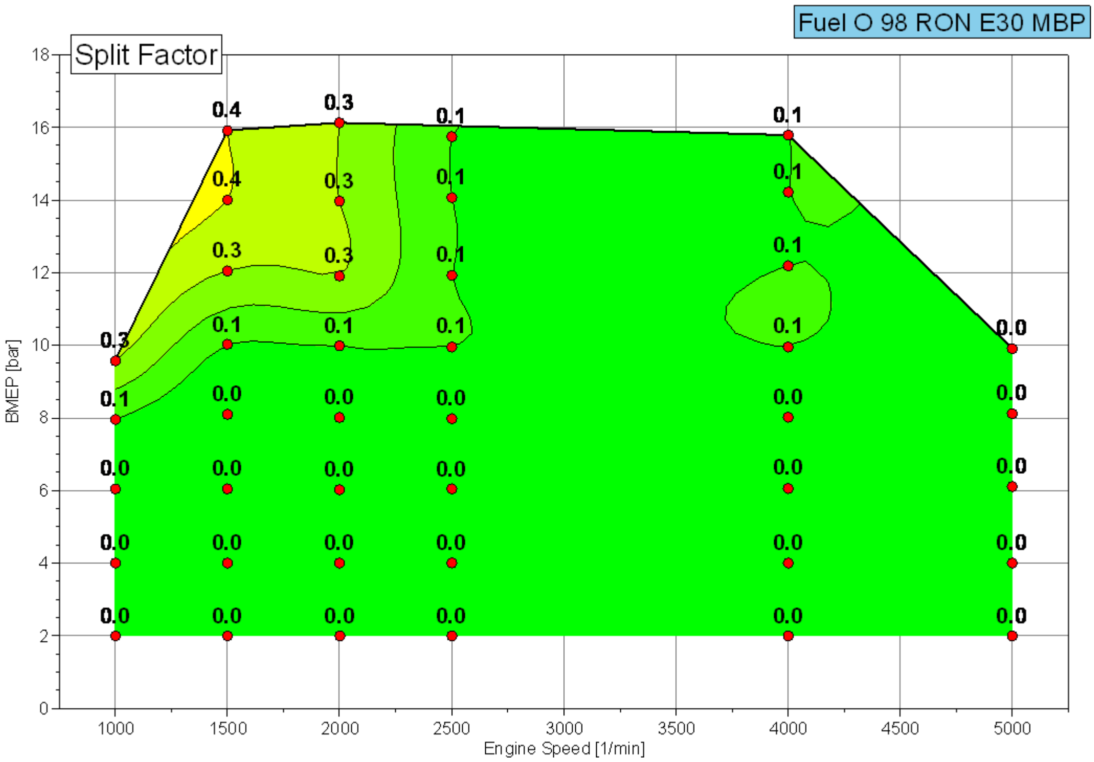

Figure 19: Injection Split Factor

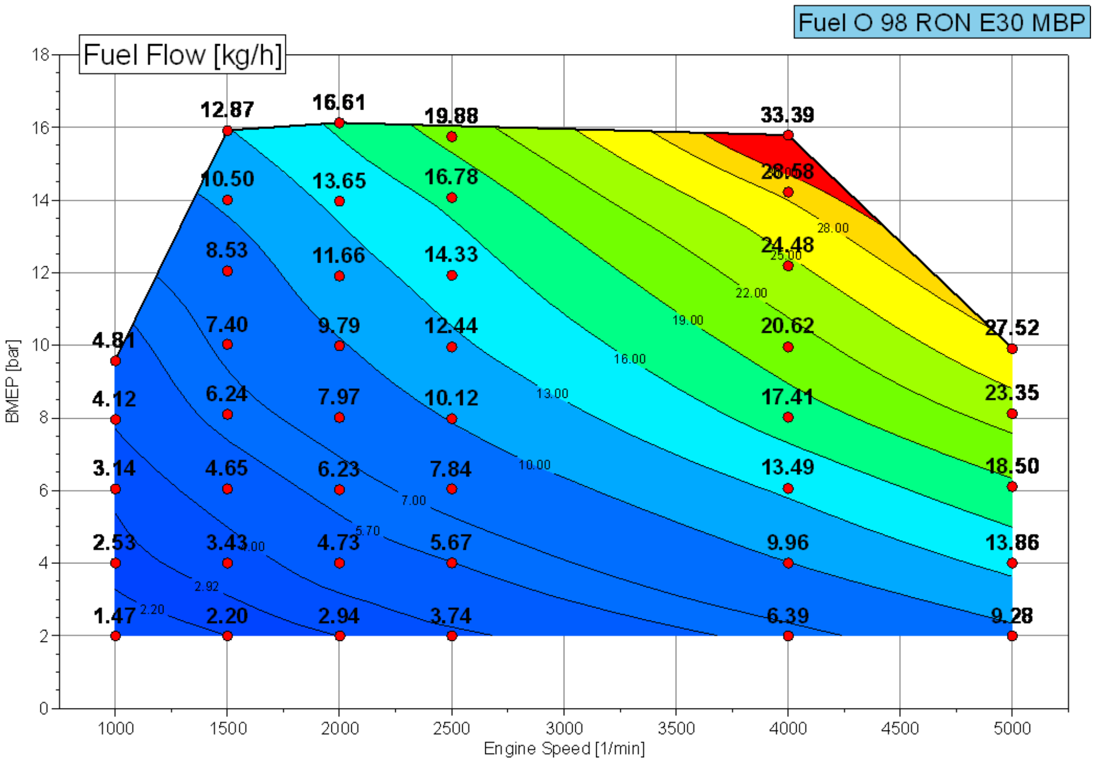

Figure 20: Fuel Flow

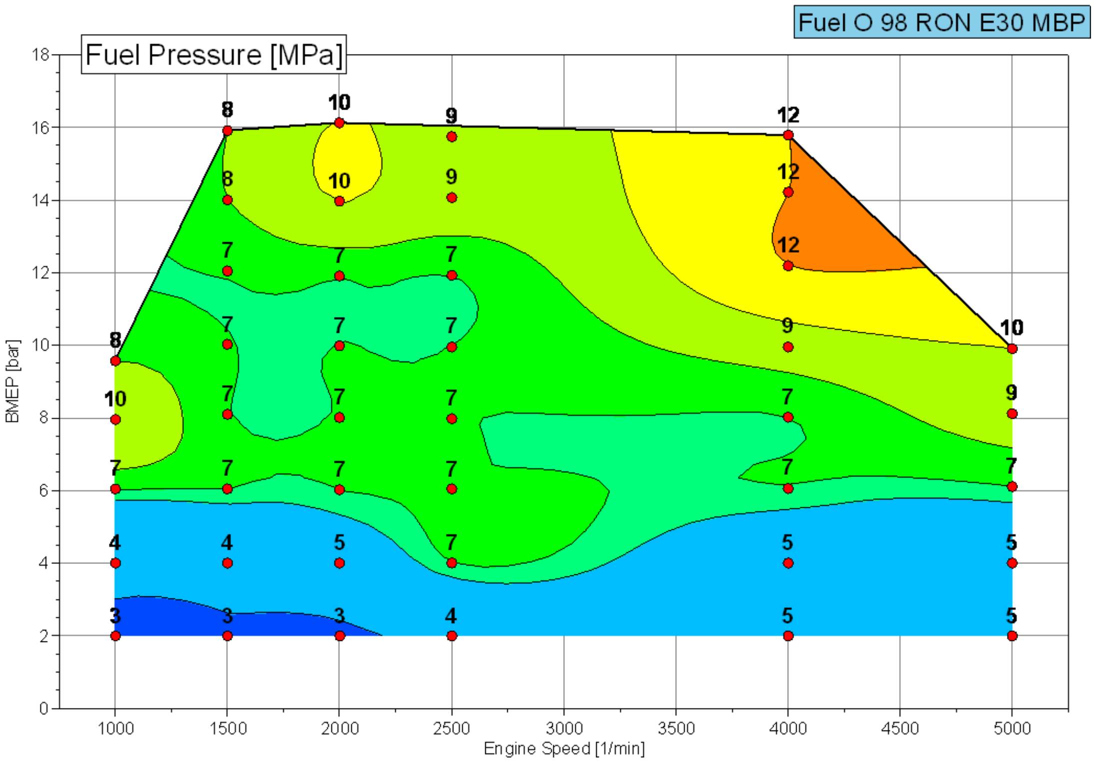

Figure 21: Fuel Rail Pressure

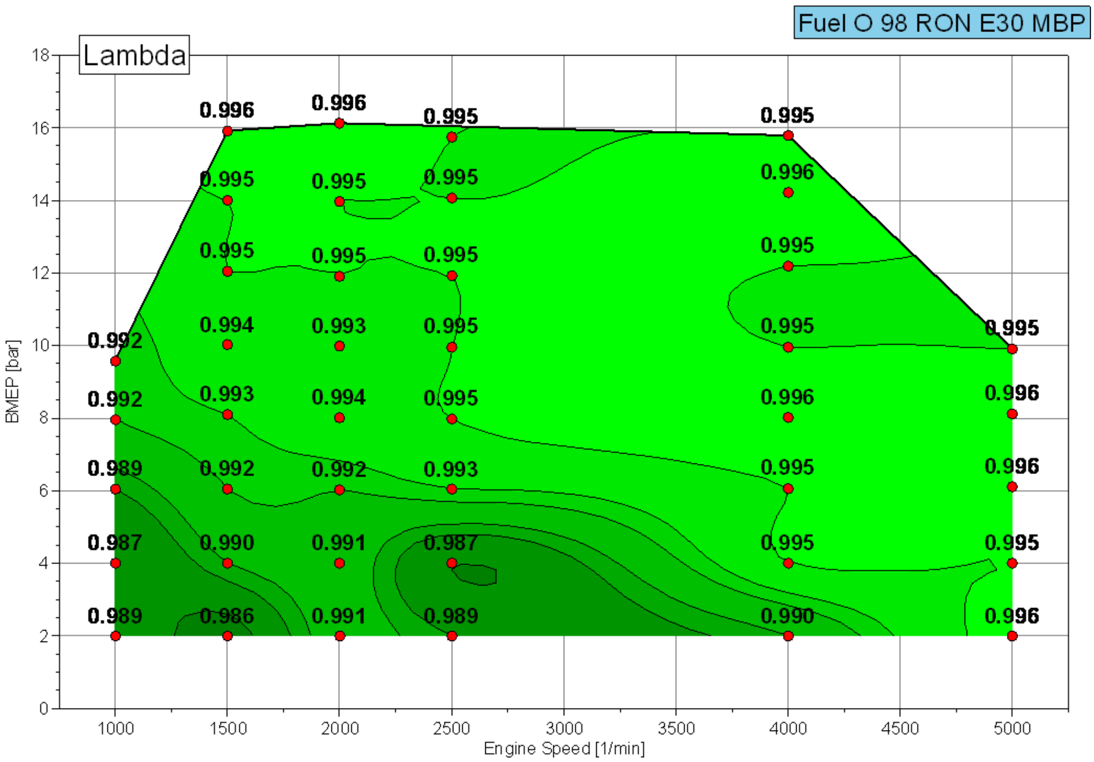

Figure 22: Lambda

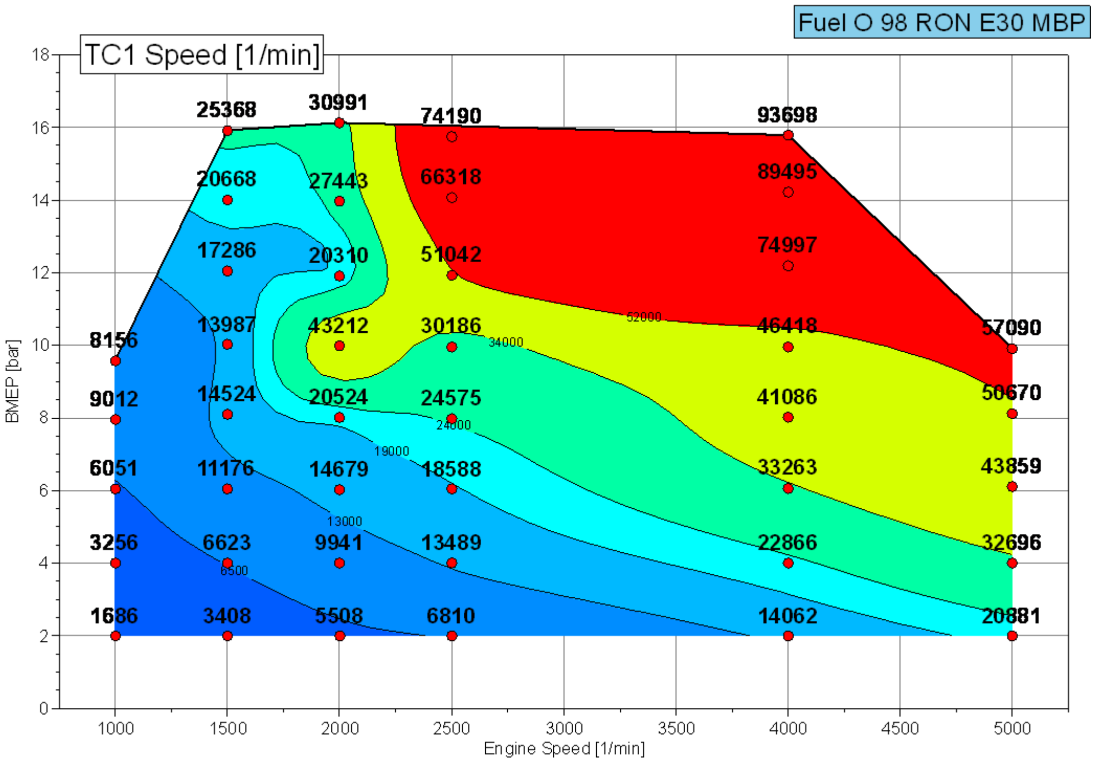

Figure 23: Low Pressure Turbocharger Speed

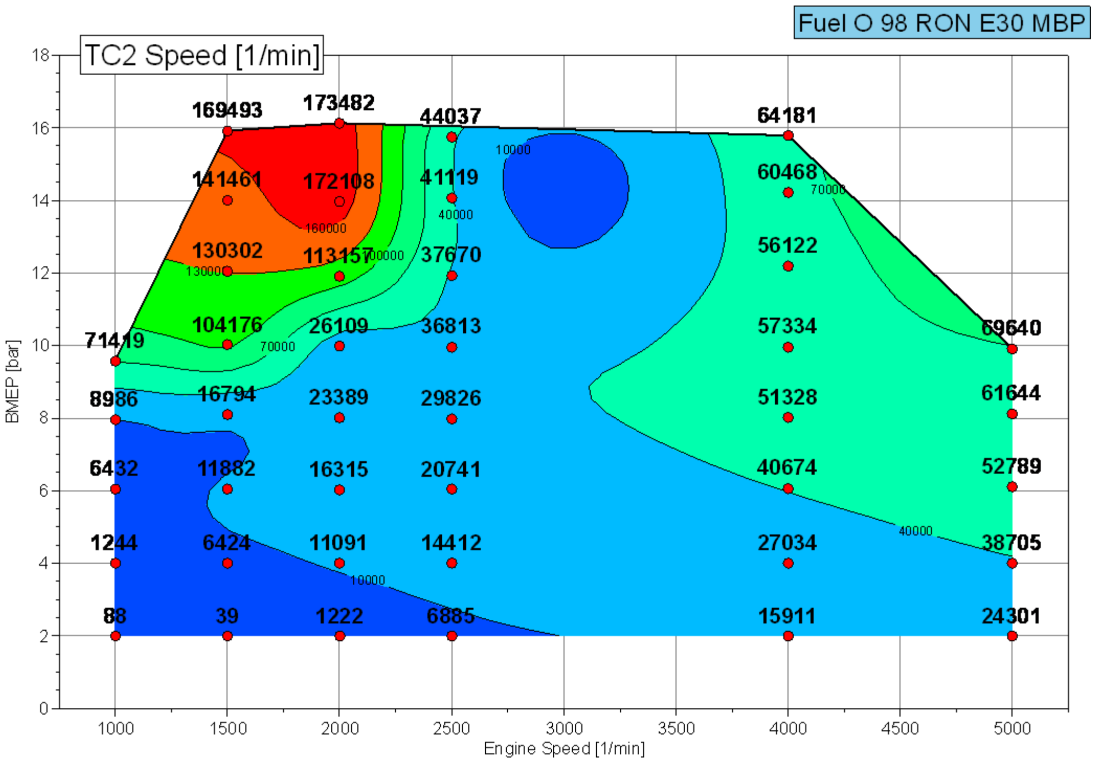

Figure 24: High Pressure Turbocharge Speed

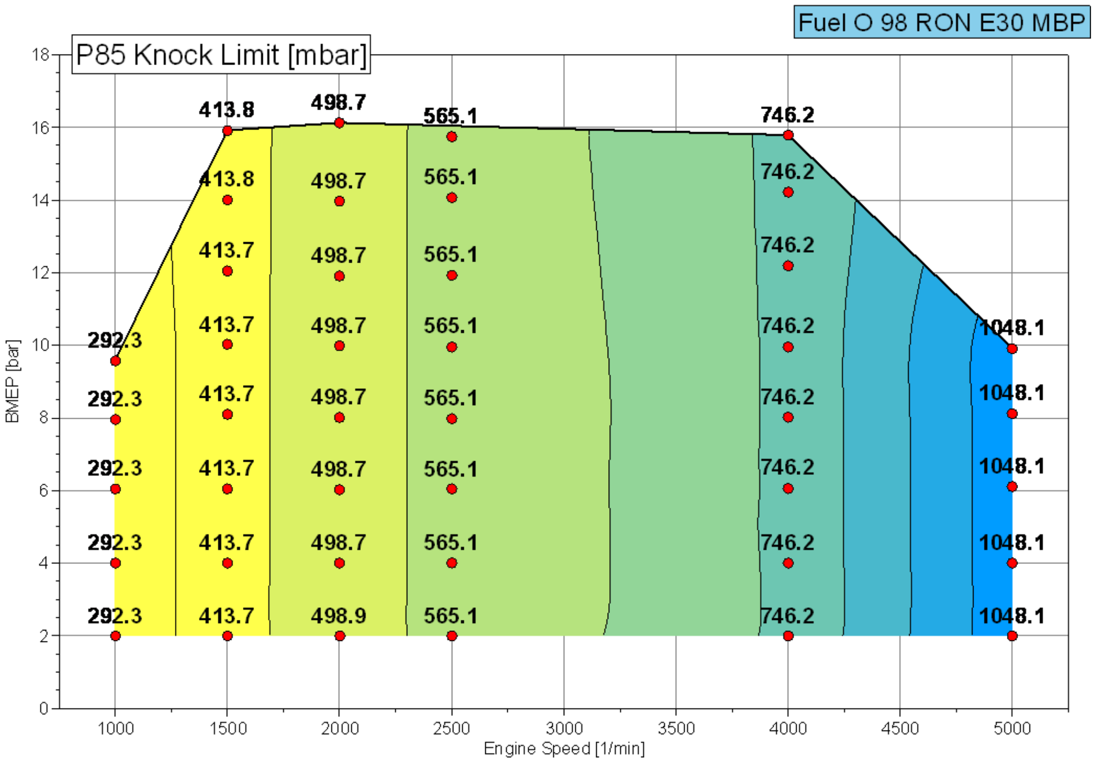

Figure 25: P85 Knock Limit

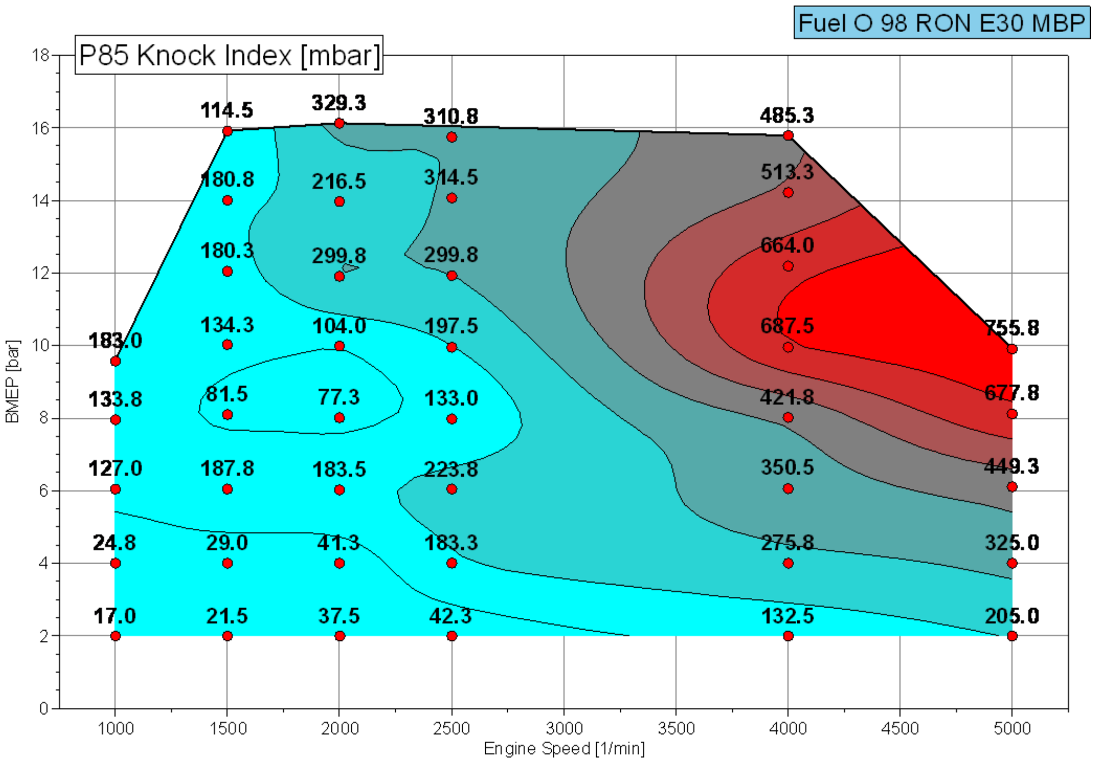

Figure 26: Averaged P85 Knock Index

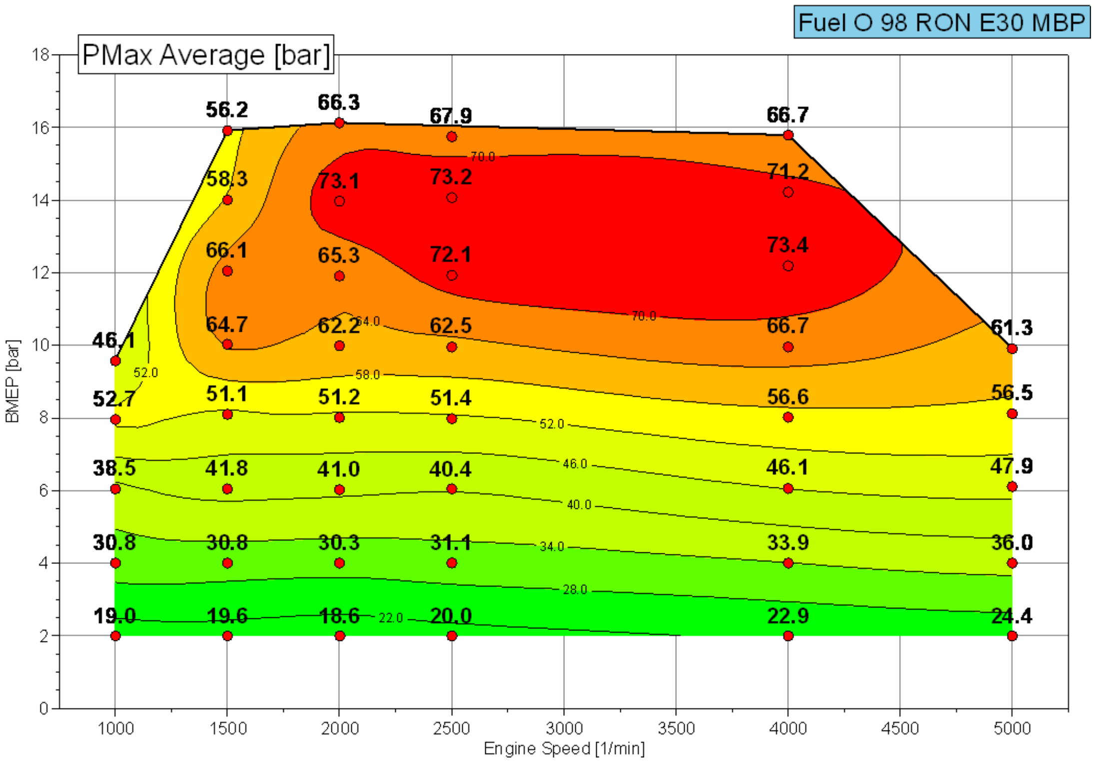

Figure 27: Averaged Max Pressure for Cylinders 1-4

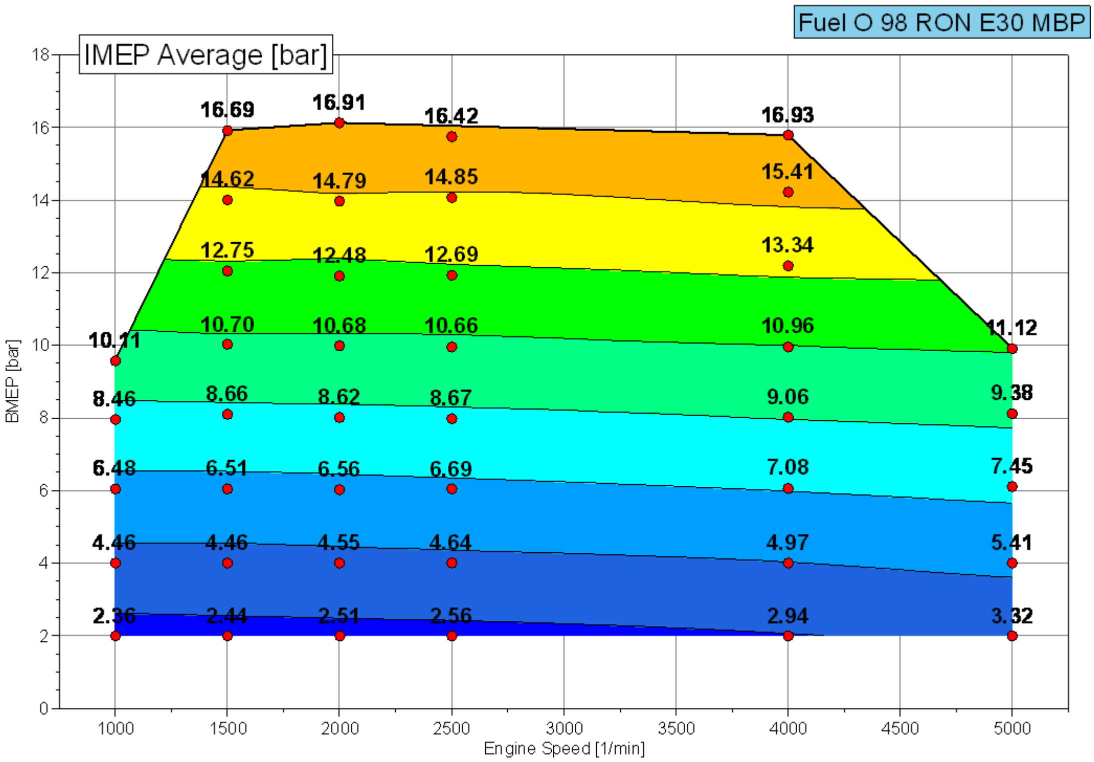

Figure 28: Indicated Mean Effective Pressure

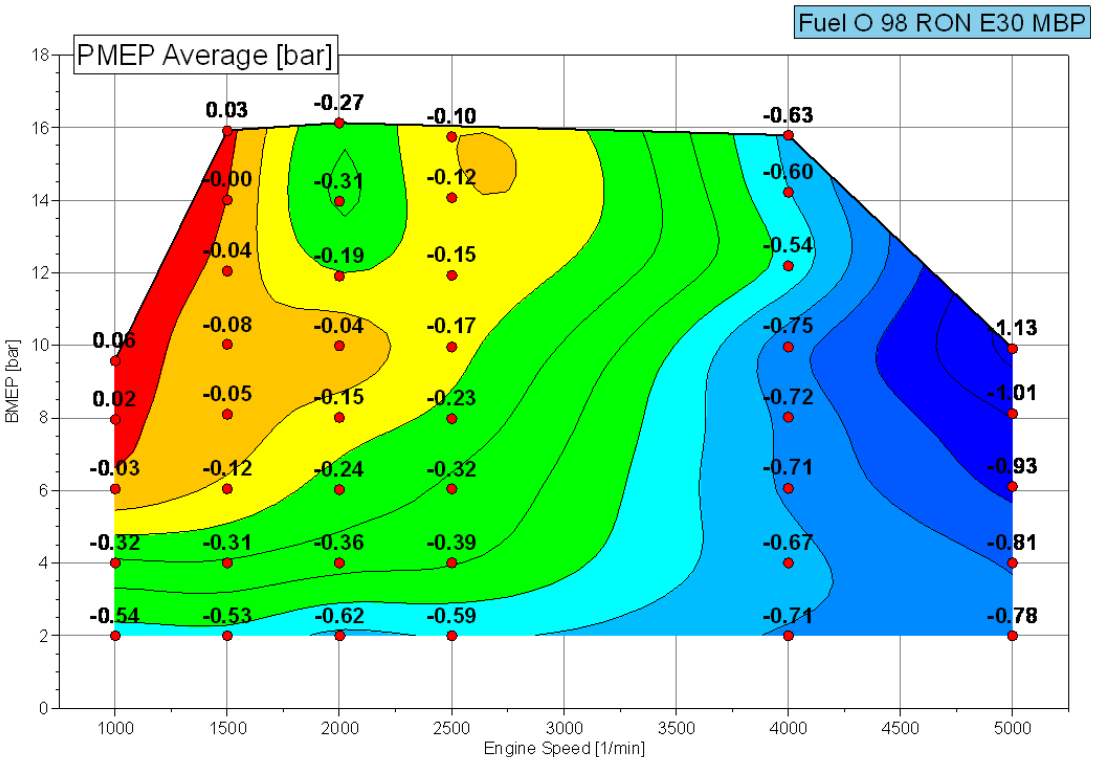

Figure 29: Pumping Mean Effective Pressure

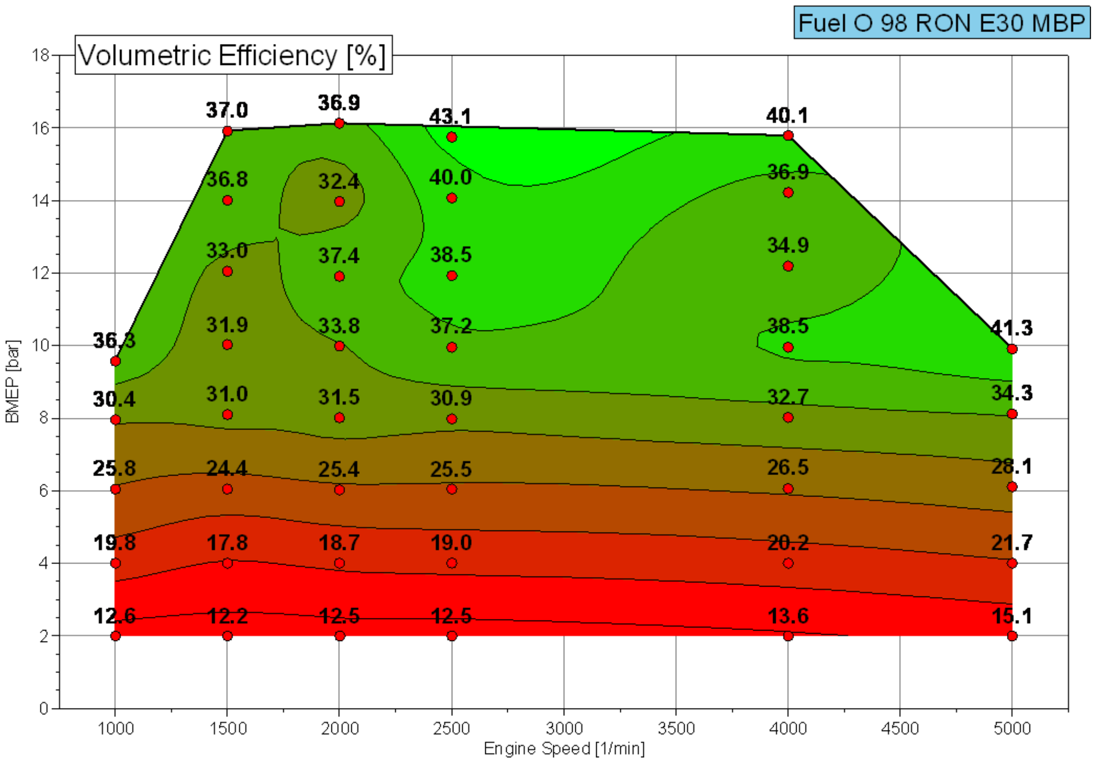

Figure 30: Calculated Volumetric Efficiency

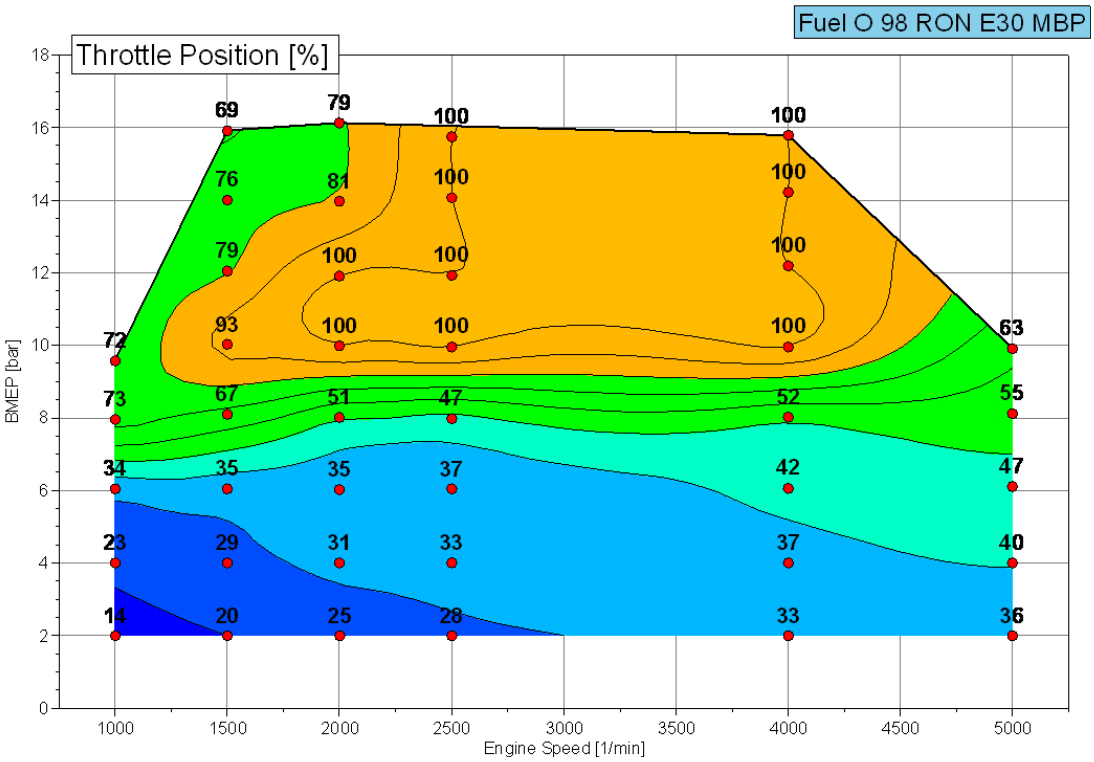

Figure 31: Throttle Position

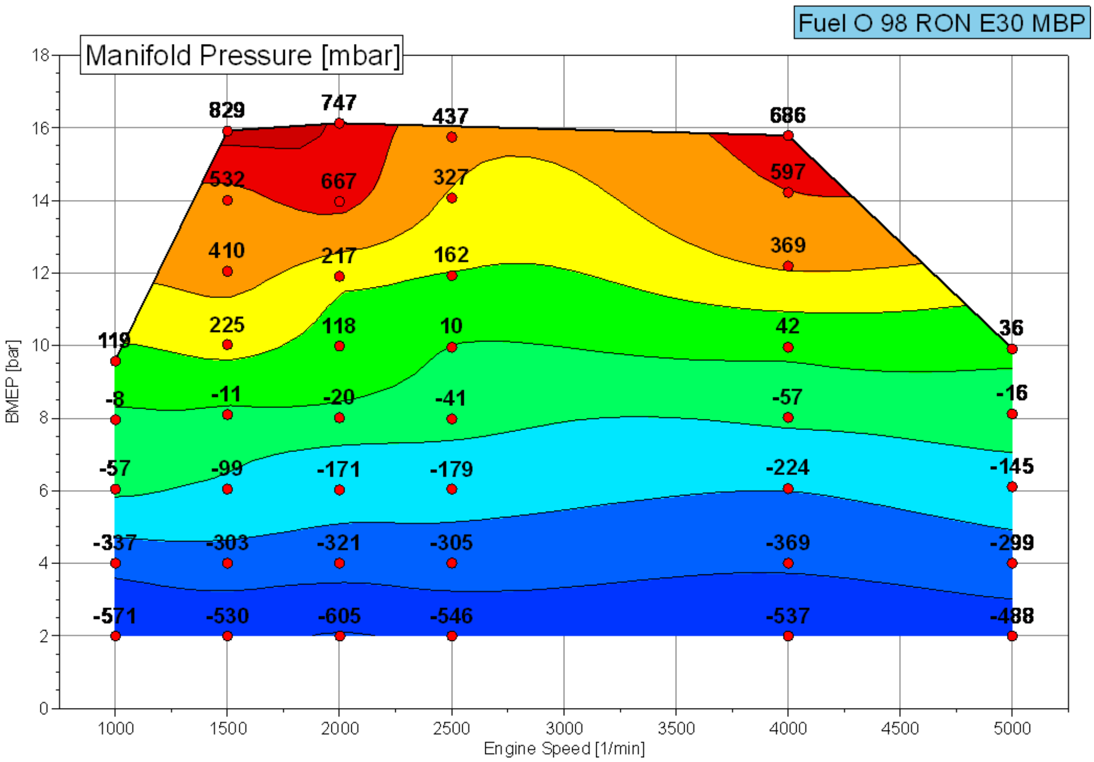

Figure 32: Intake Manifold Pressure

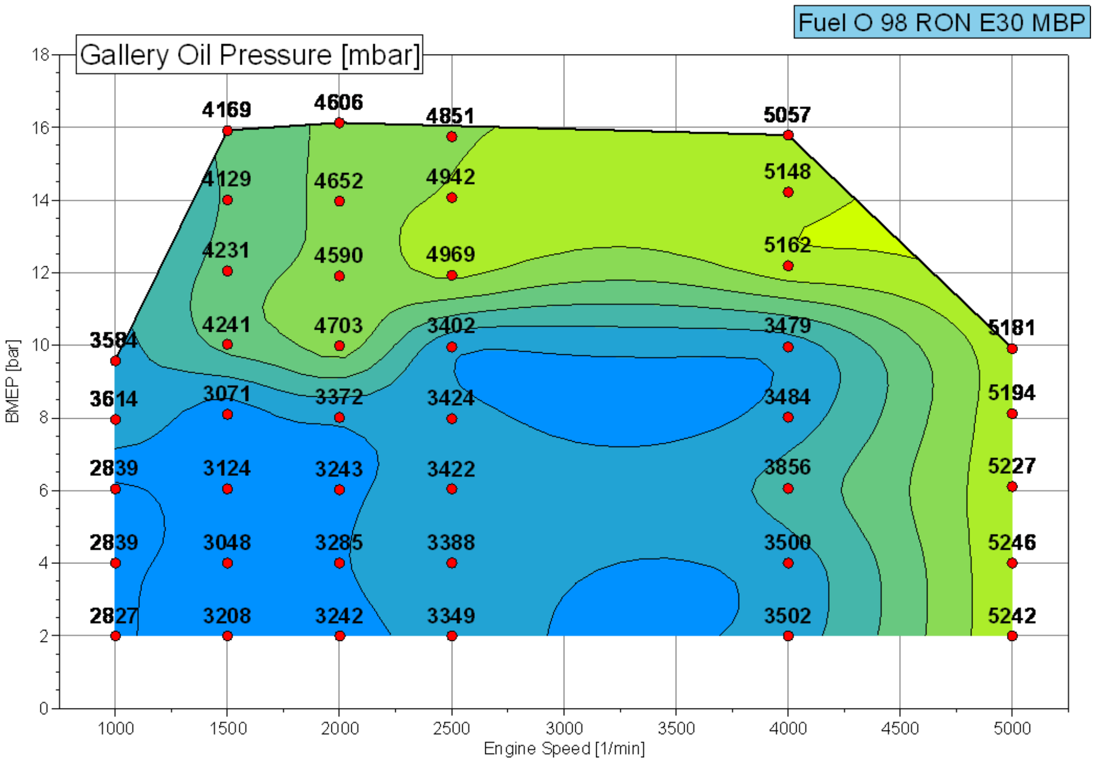

Figure 33: Gallery Oil Pressure

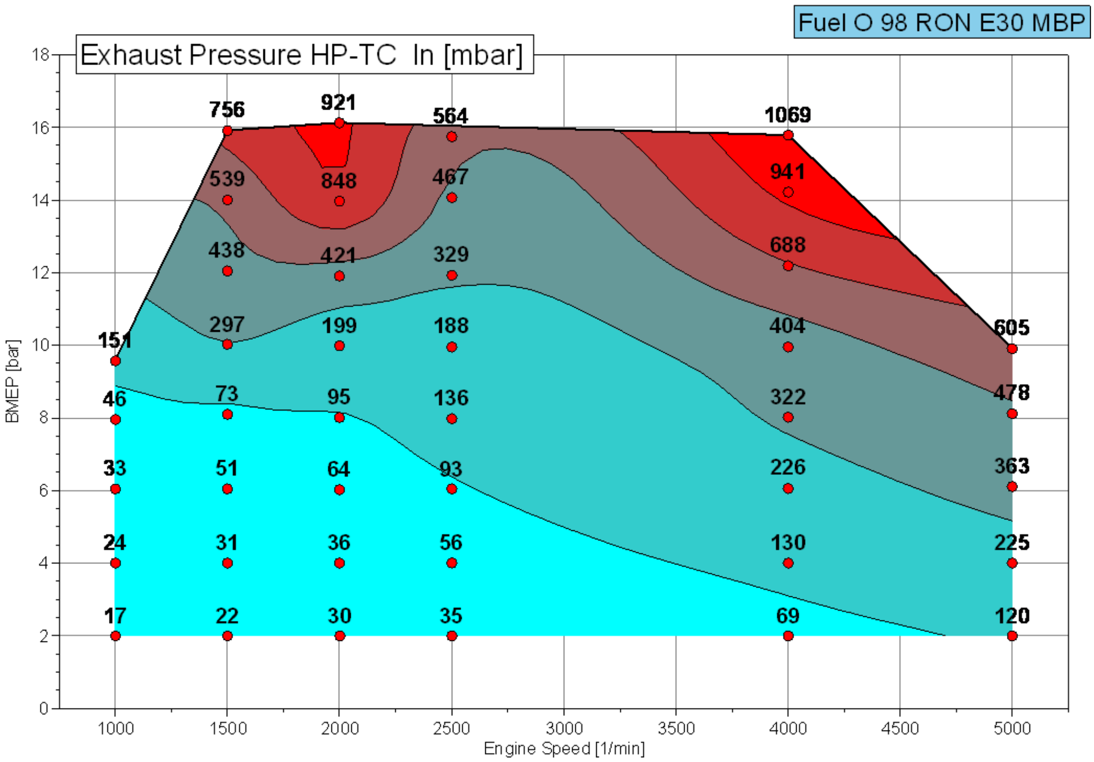

Figure 34: Exhaust Pressure High Pressure Turbocharger In

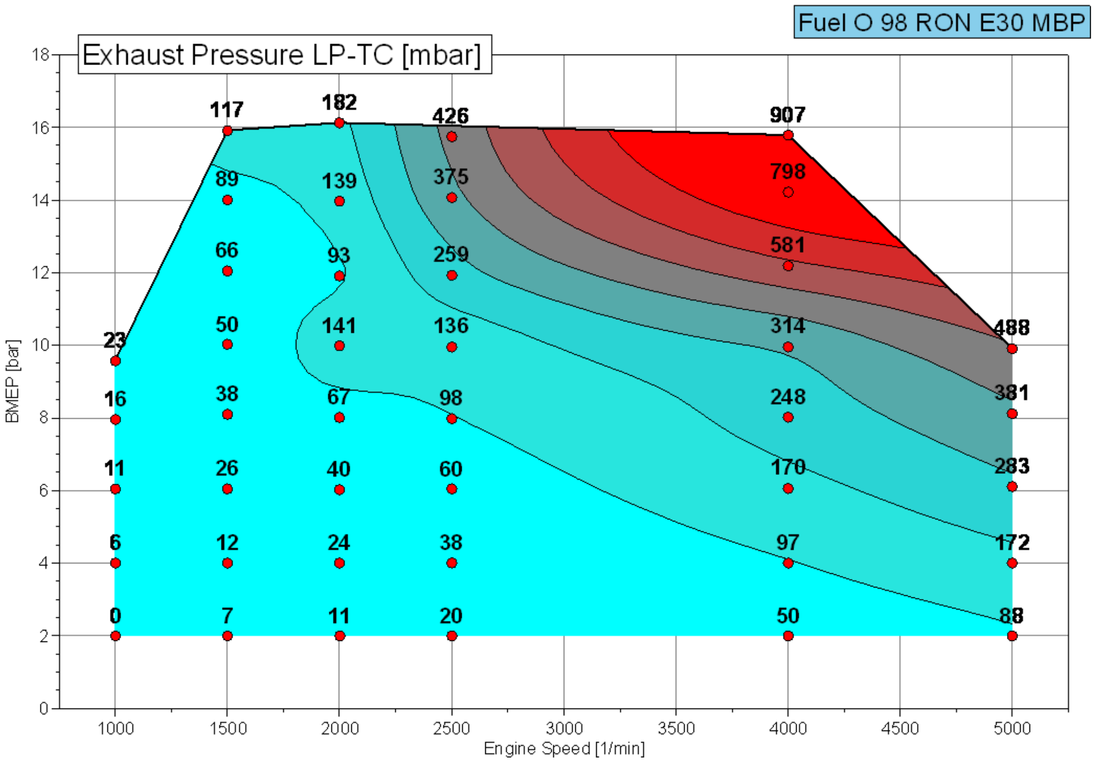

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

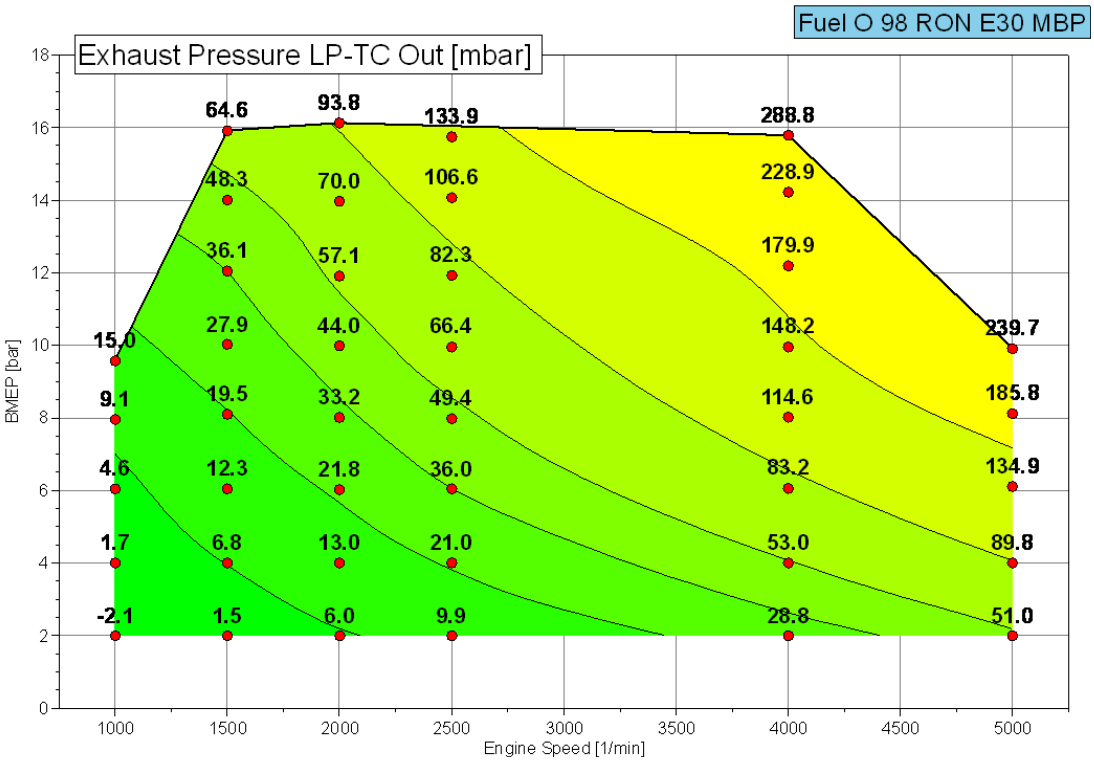

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

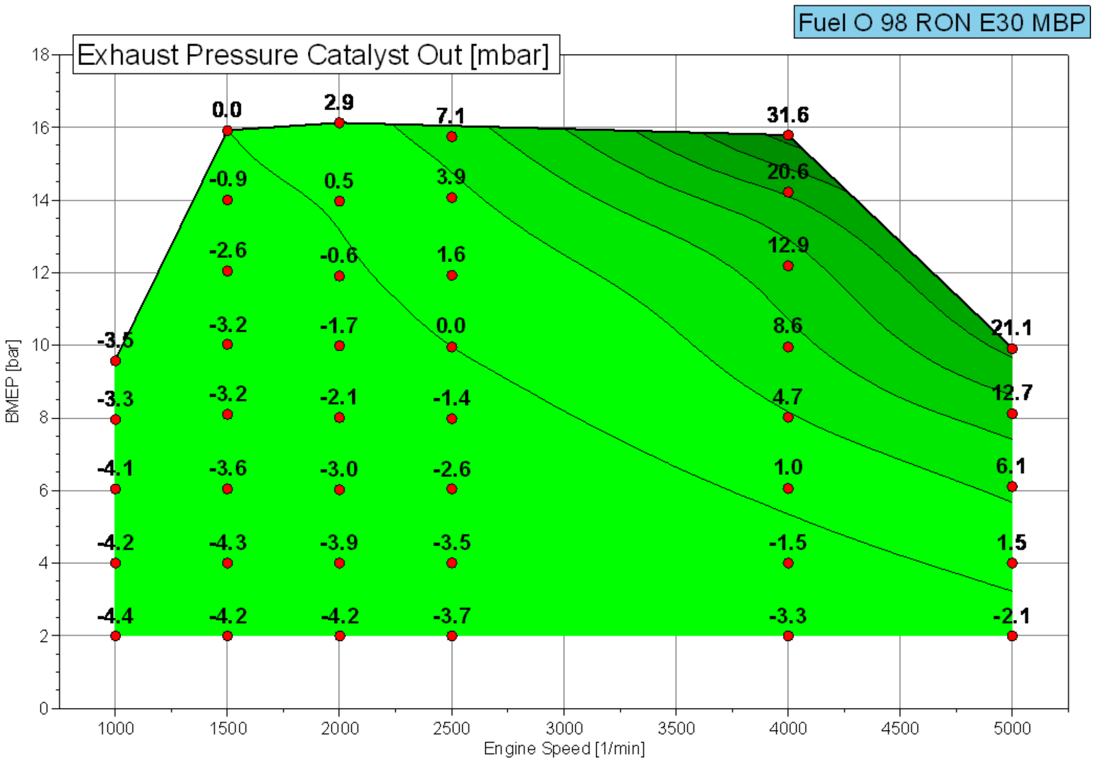

Figure 37: Exhaust Pressure Catalyst Out

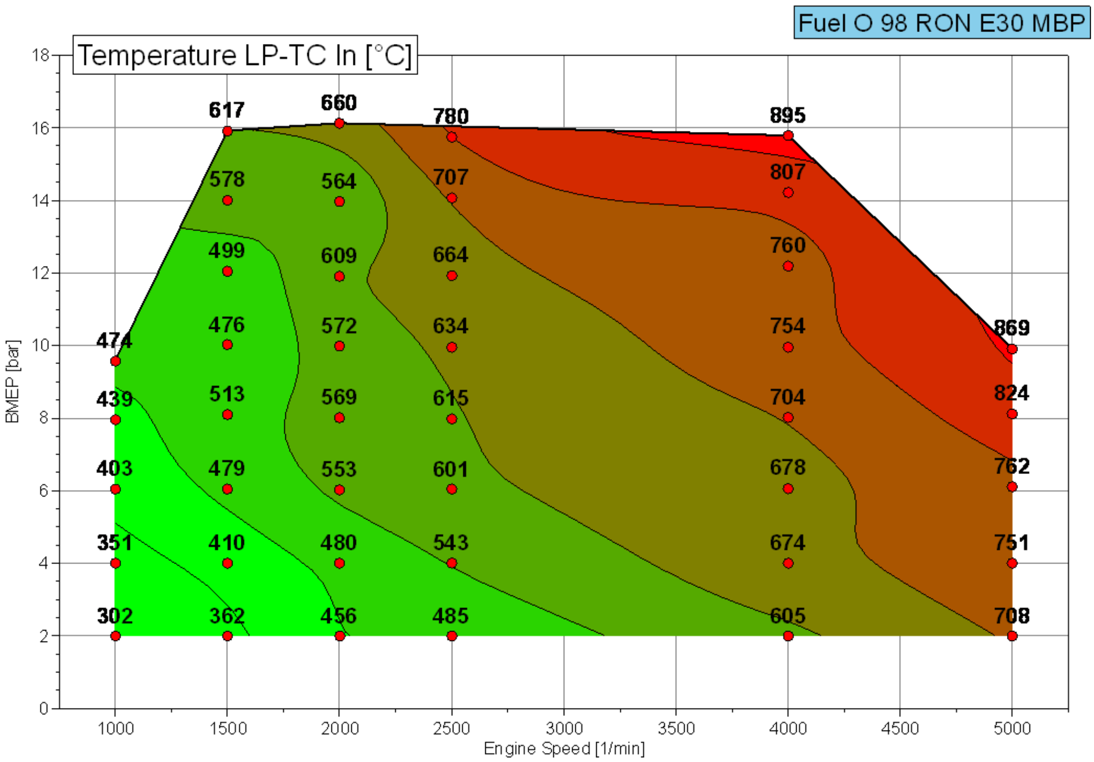

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

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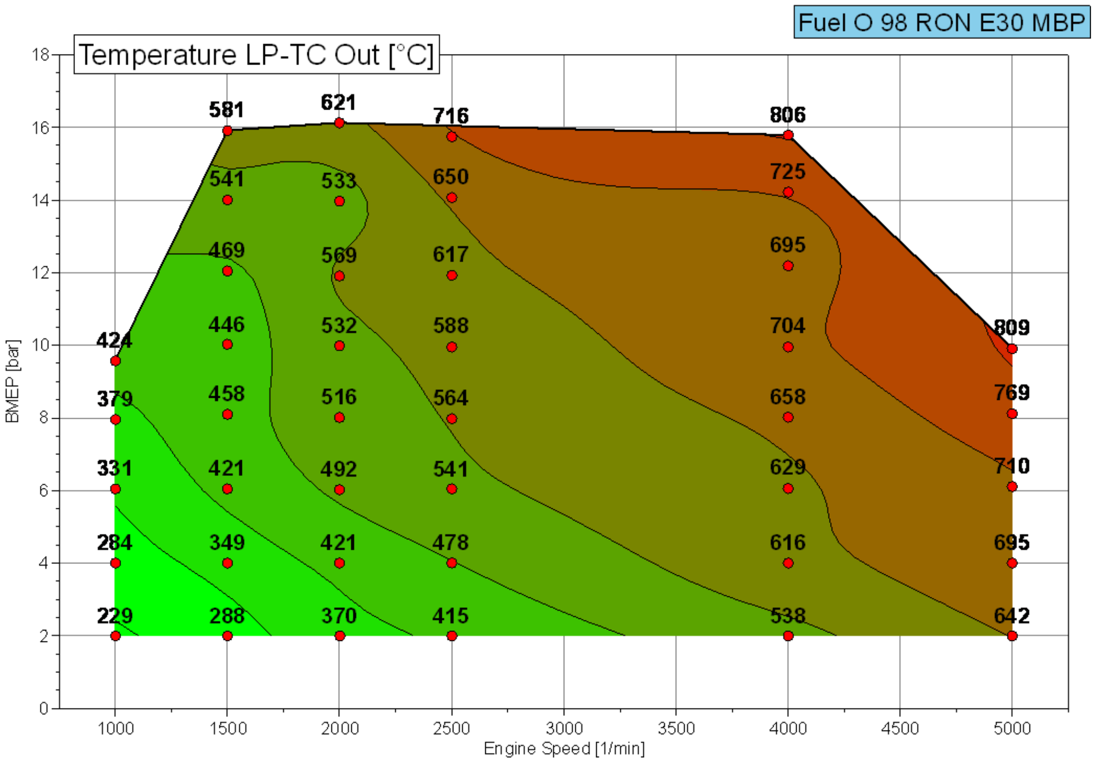

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

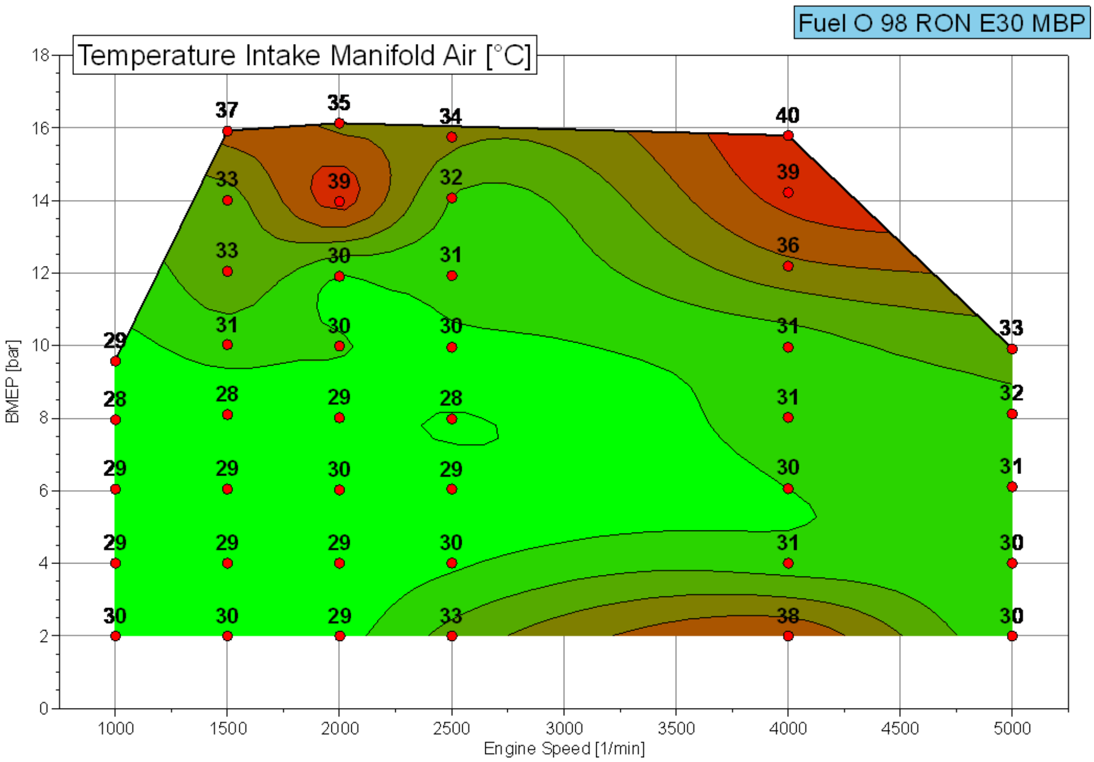

Figure 40: Intake Manifold Air Temperature

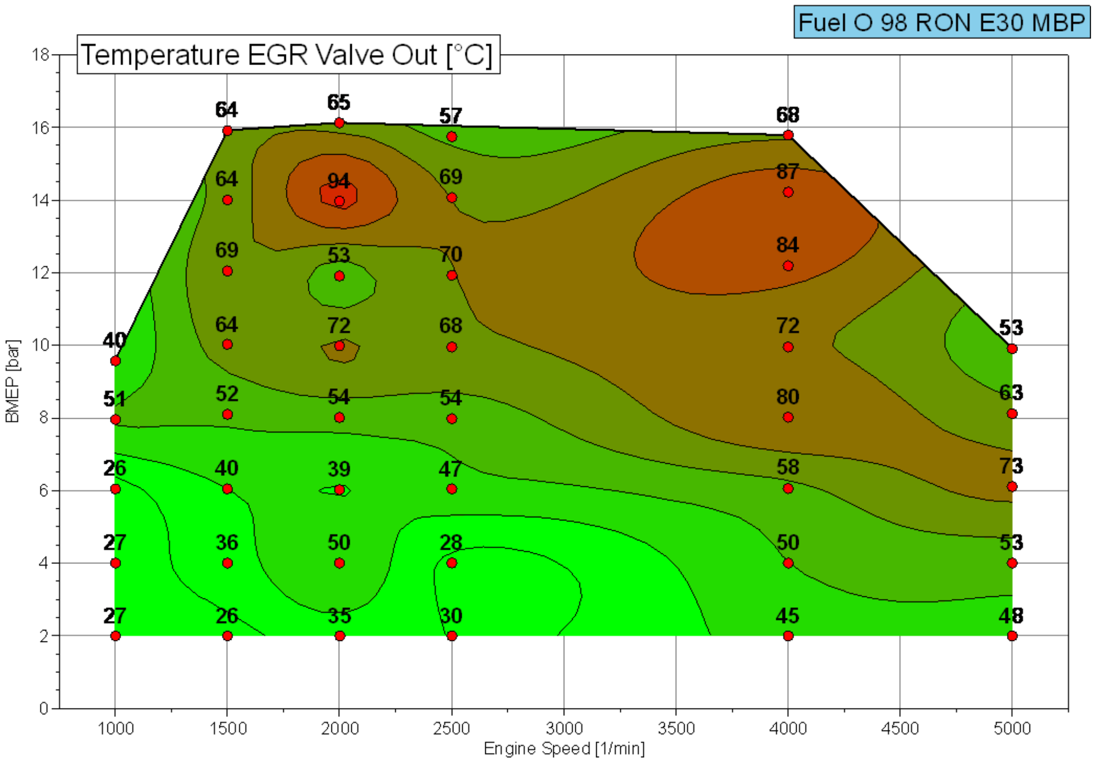

Figure 41: EGR Valve Out Temperature

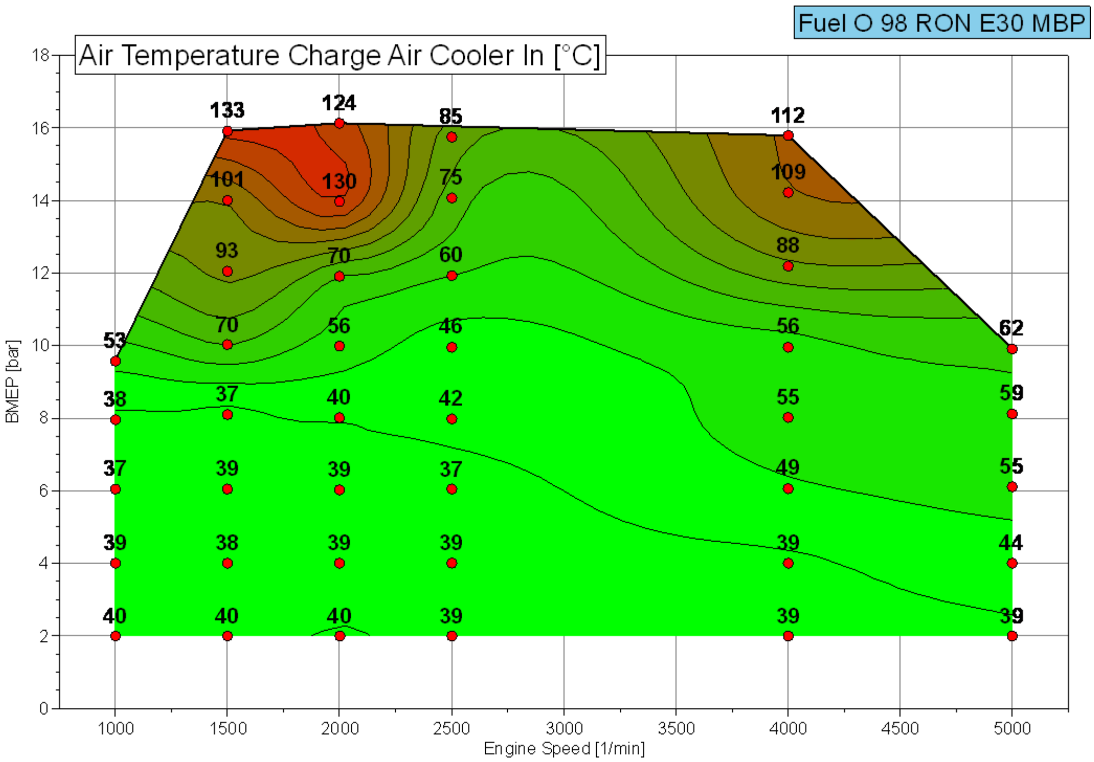

Figure 42: Charge Air Cooler Inlet Air Temperature

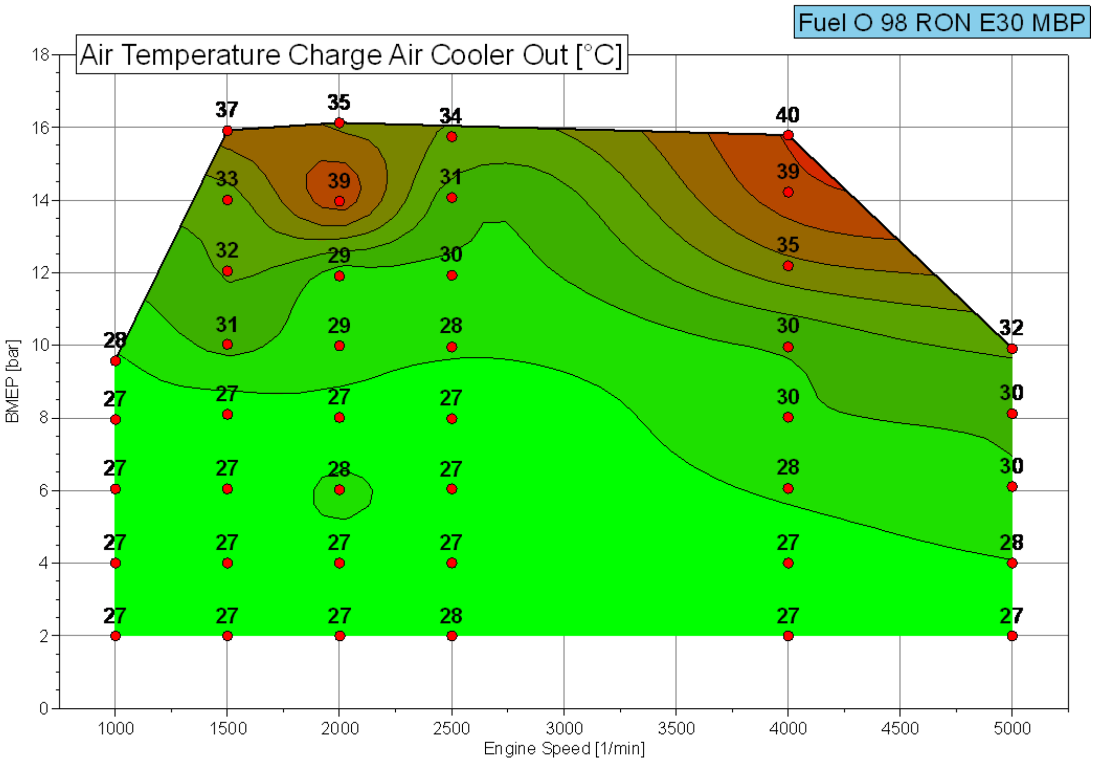

Figure 43: Charge Air Cooler Outlet Air Temperature

Fuel P Calibration Results

98 Ron 0% Ethanol Medium Boiling Point

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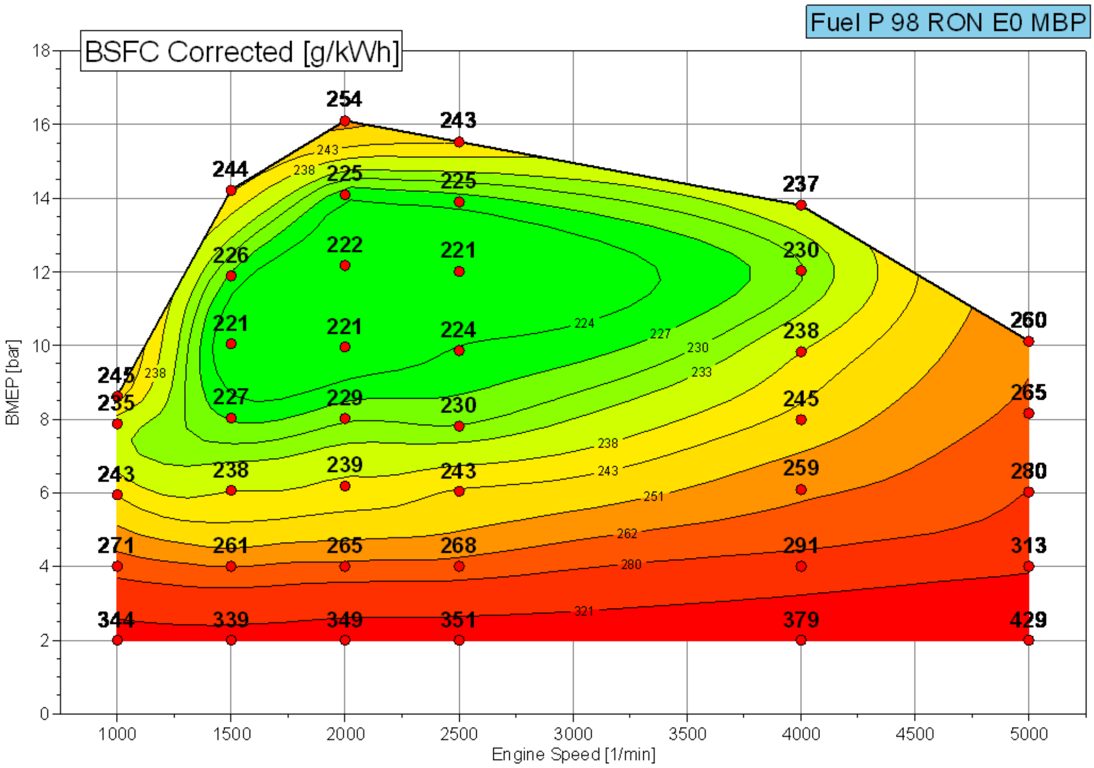

Figure 1: Brake Specific Fuel Consumption

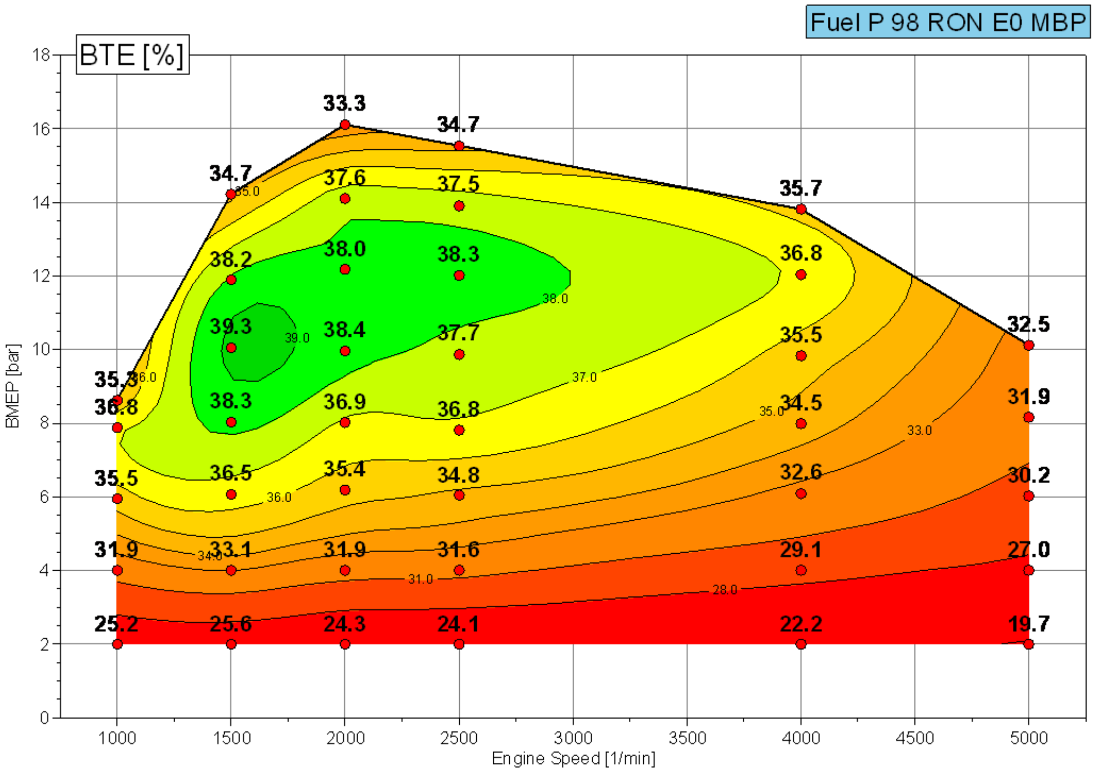

Figure 2: Brake Thermal Efficiency

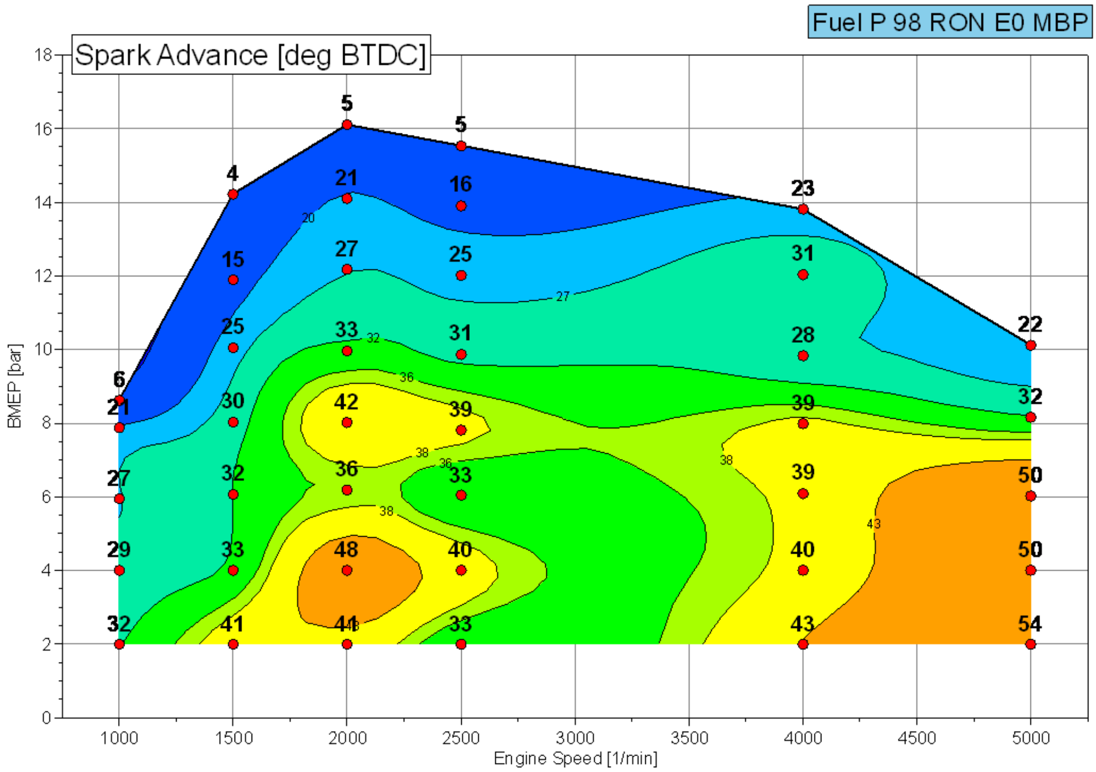

Figure 3: Spark Advance

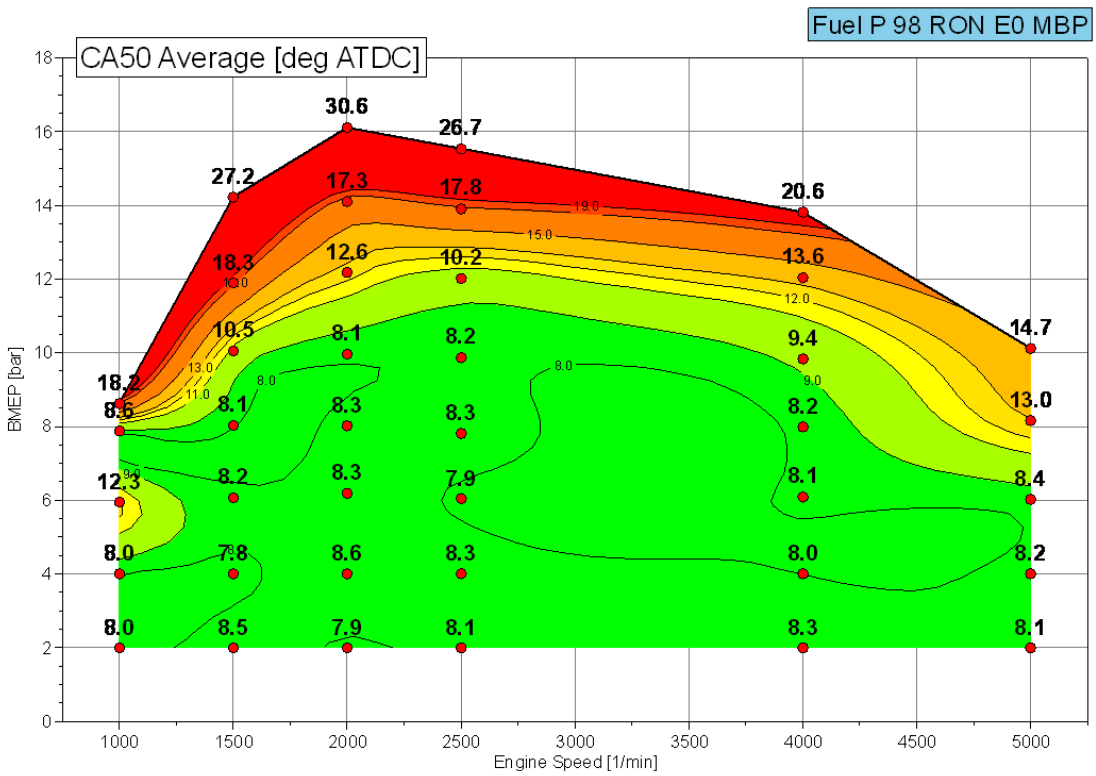

Figure 4: CA50 Average of Cylinders 1-4

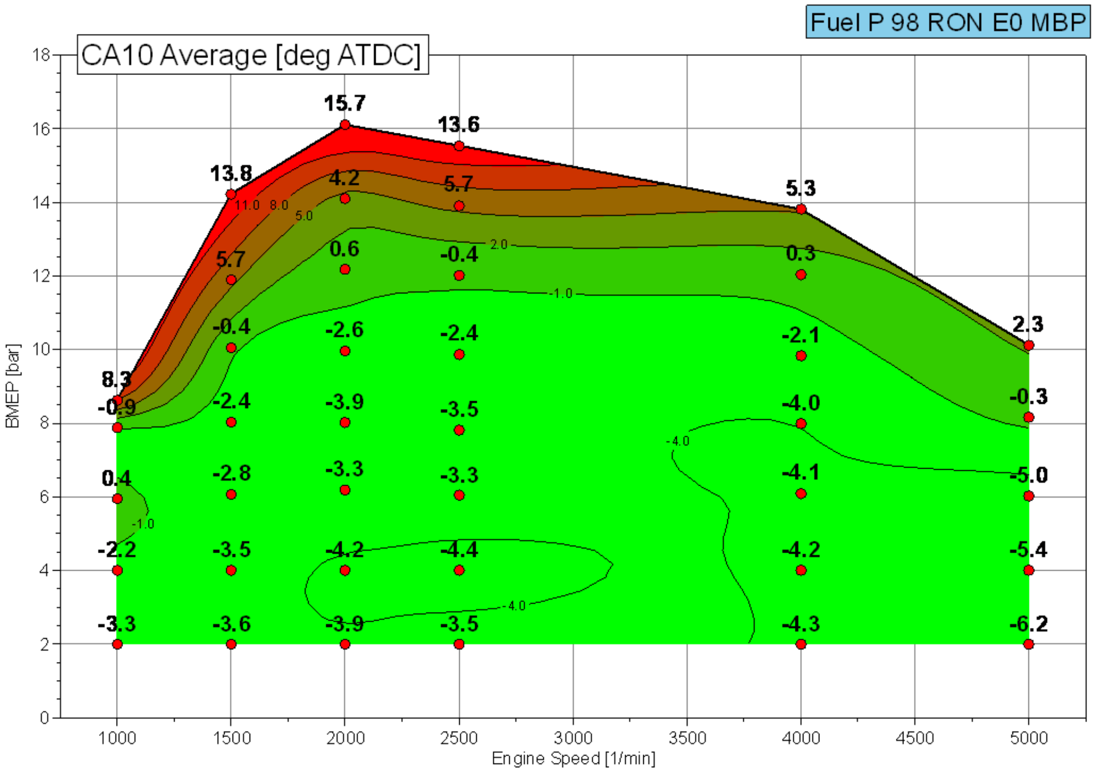

Figure 5: CA10 Average of Cylinders 1-4

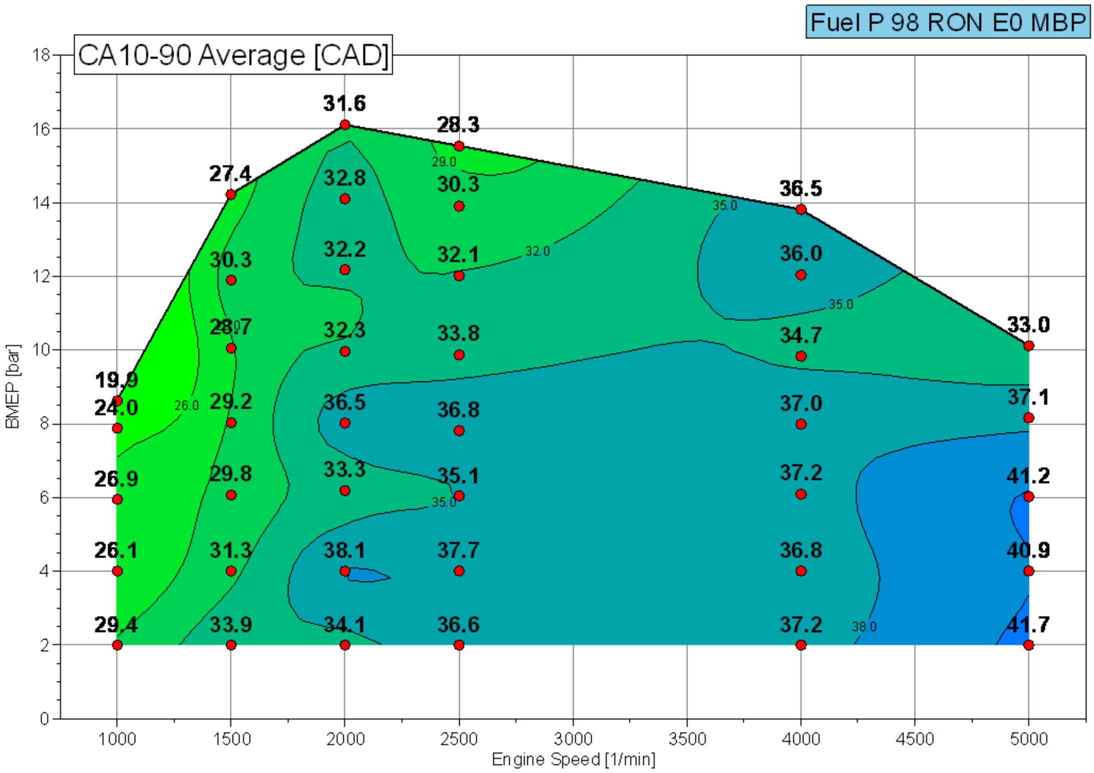

Figure 6: CA10-90 Average of Cylinders 1-4

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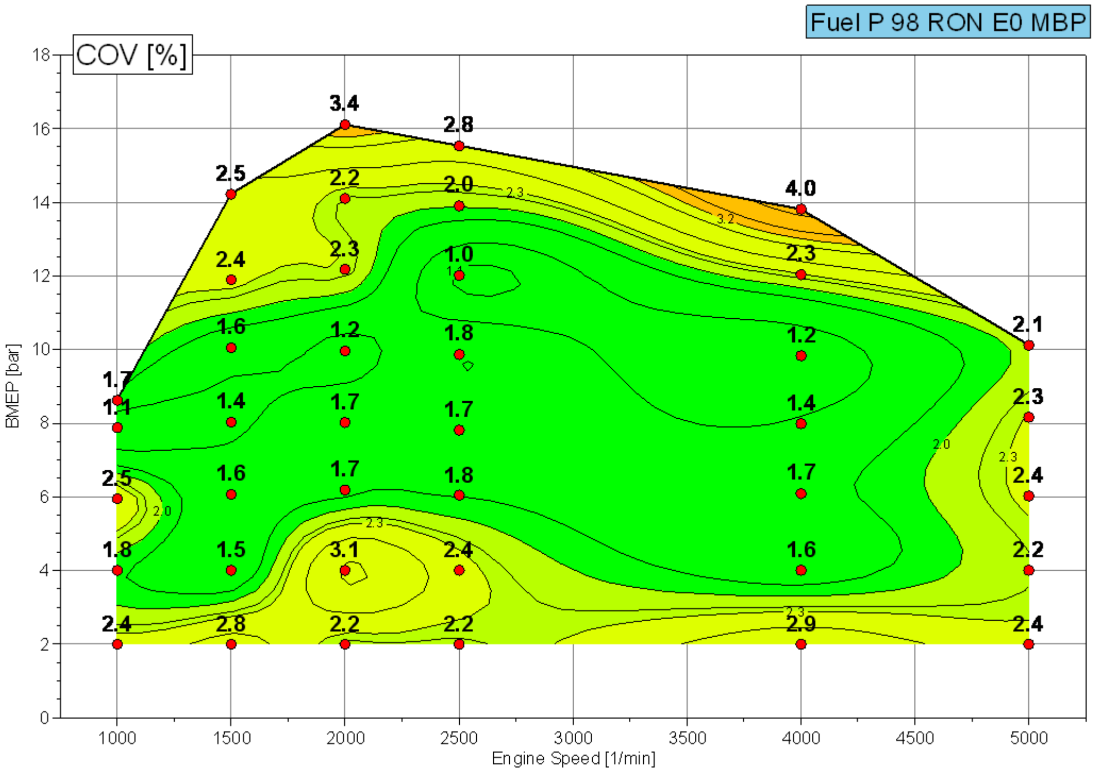

Figure 7: Coefficient of Variation Average of Cylinders 1-4

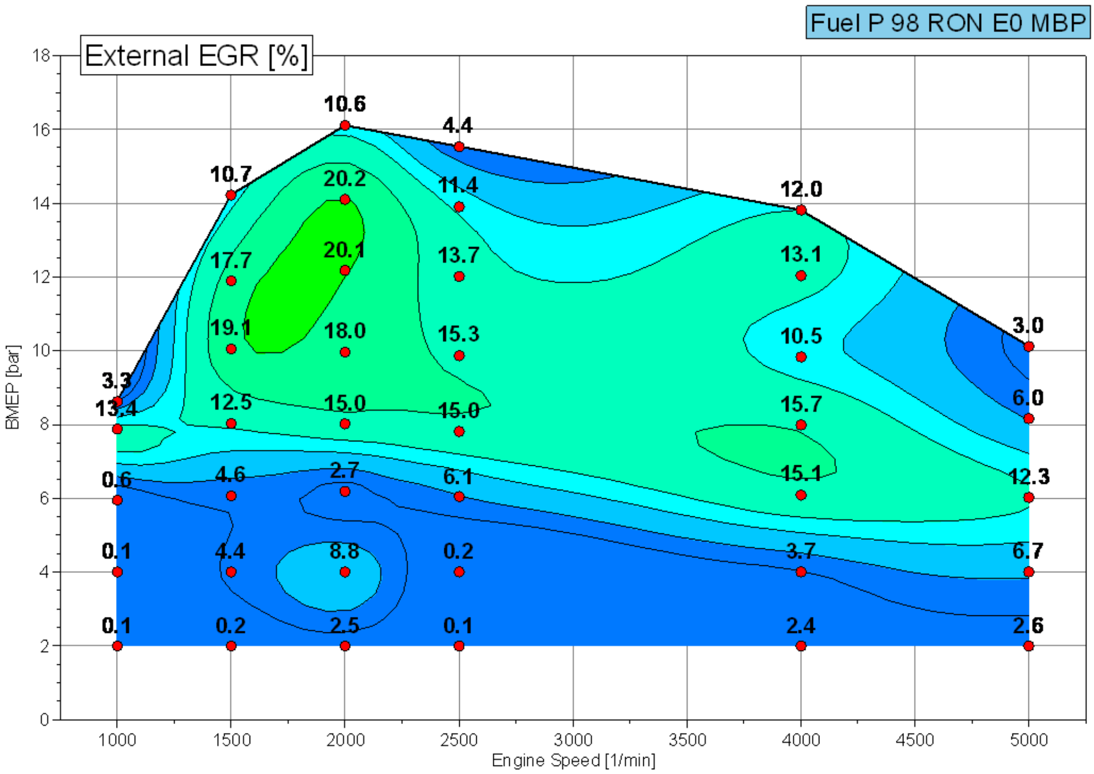

Figure 8: External EGR Percent of Intake Air

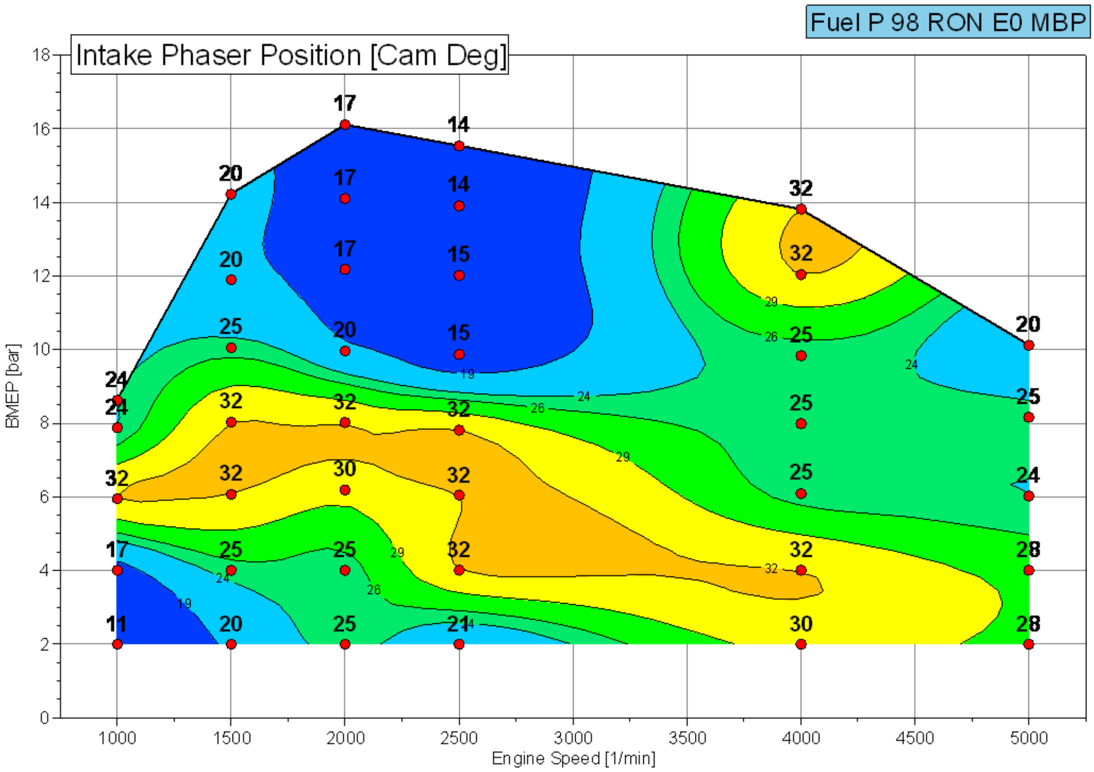

Figure 9: Intake Camshaft Phaser Position

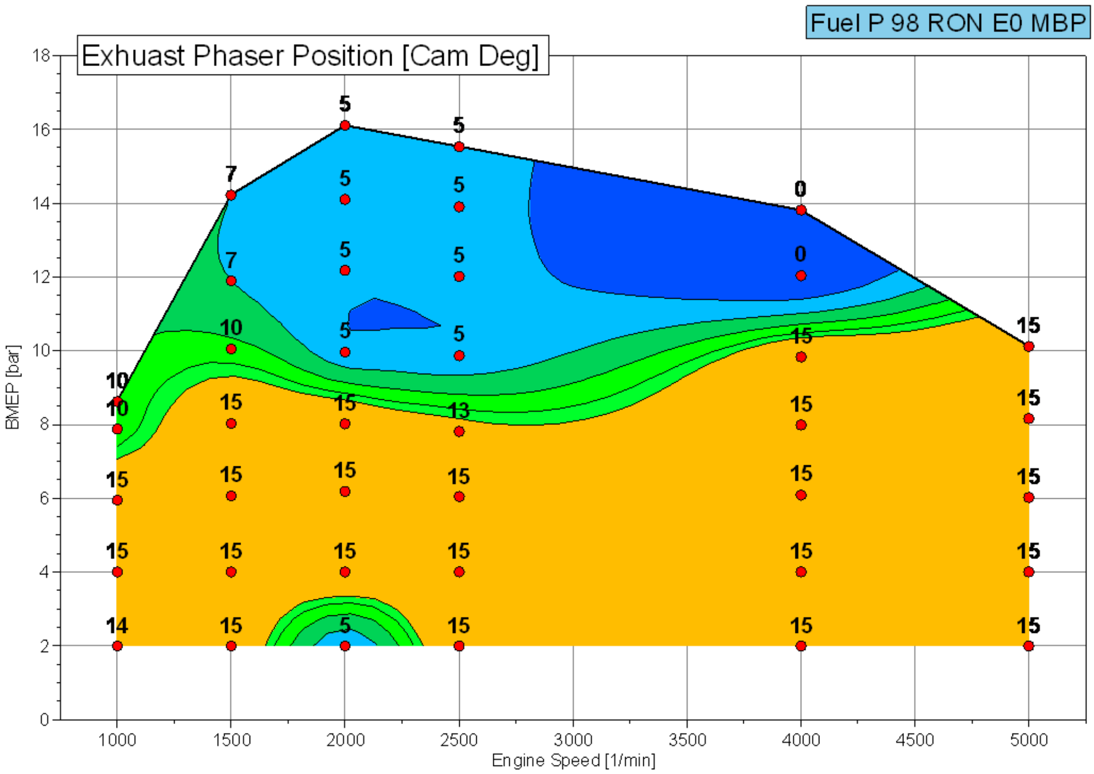

Figure 10: Exhaust Camshaft Phaser Position

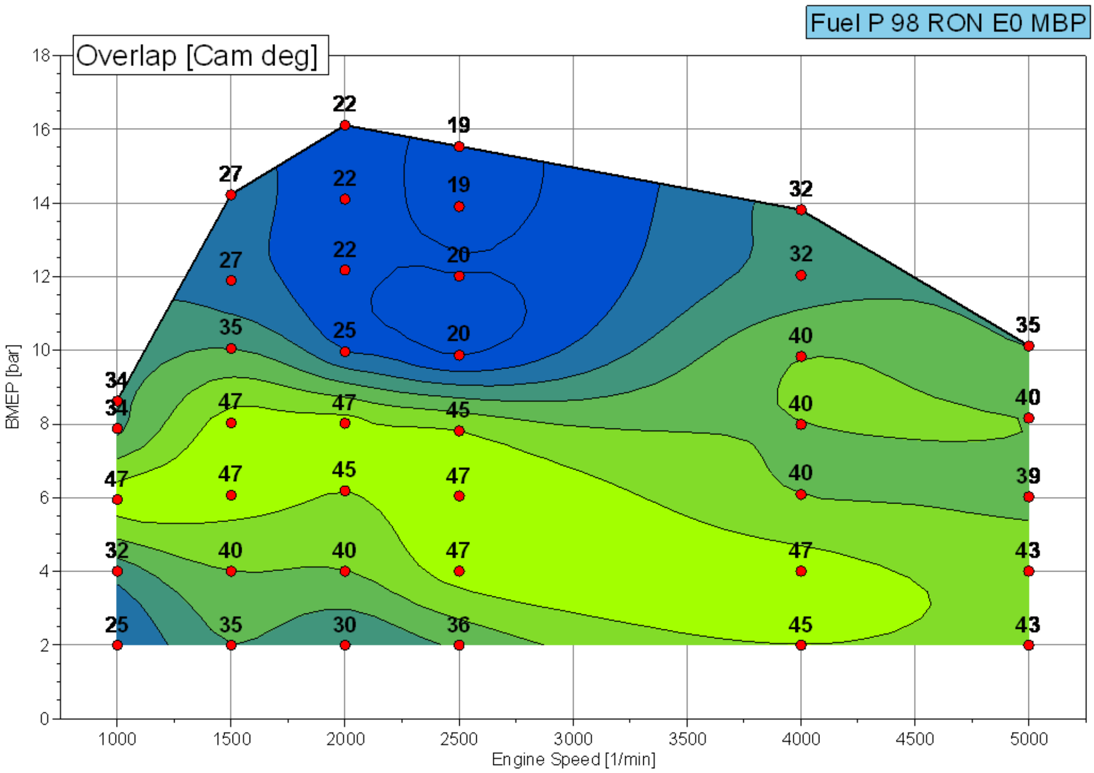

Figure 11: Camshaft Overlap

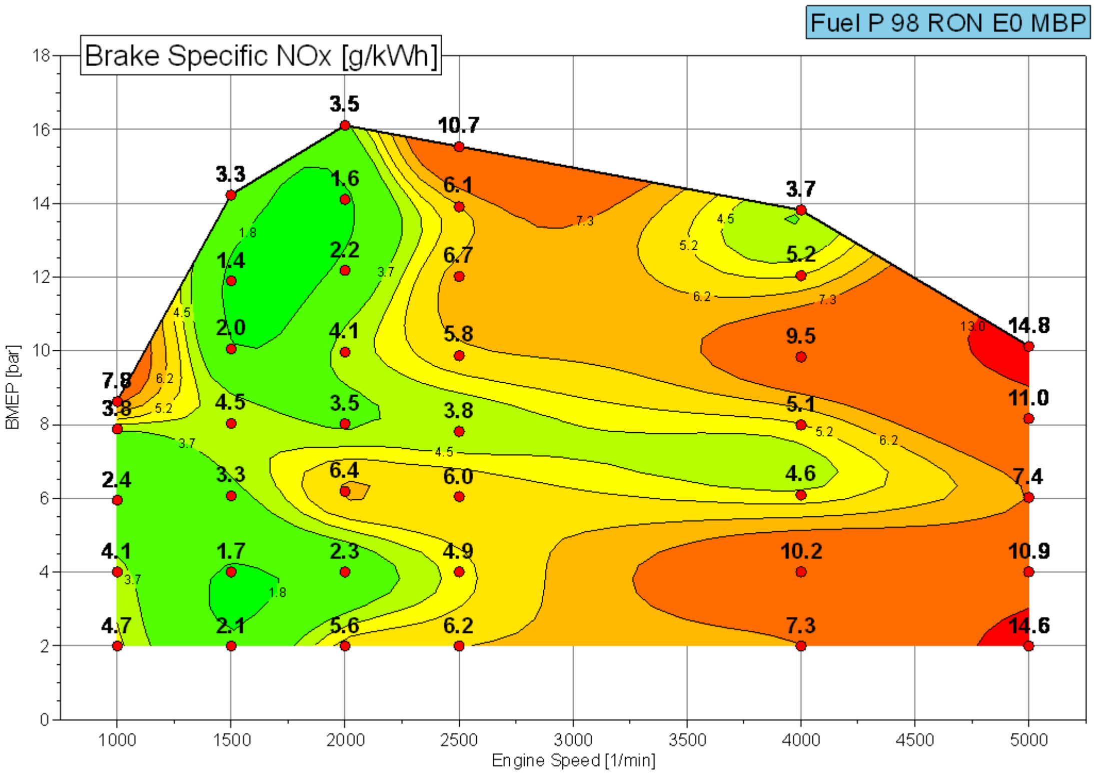

Figure 12: Brake Specific NOx Emissions

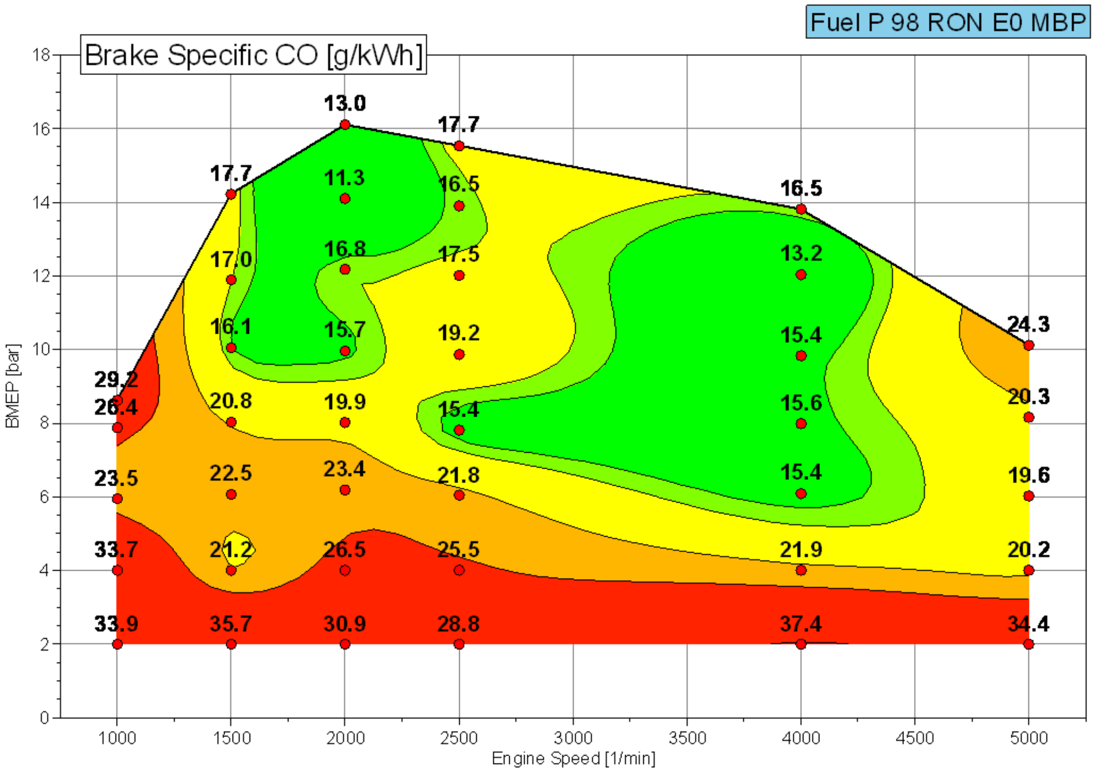

Figure 13: Brake Specific Carbon Monoxide Emissions

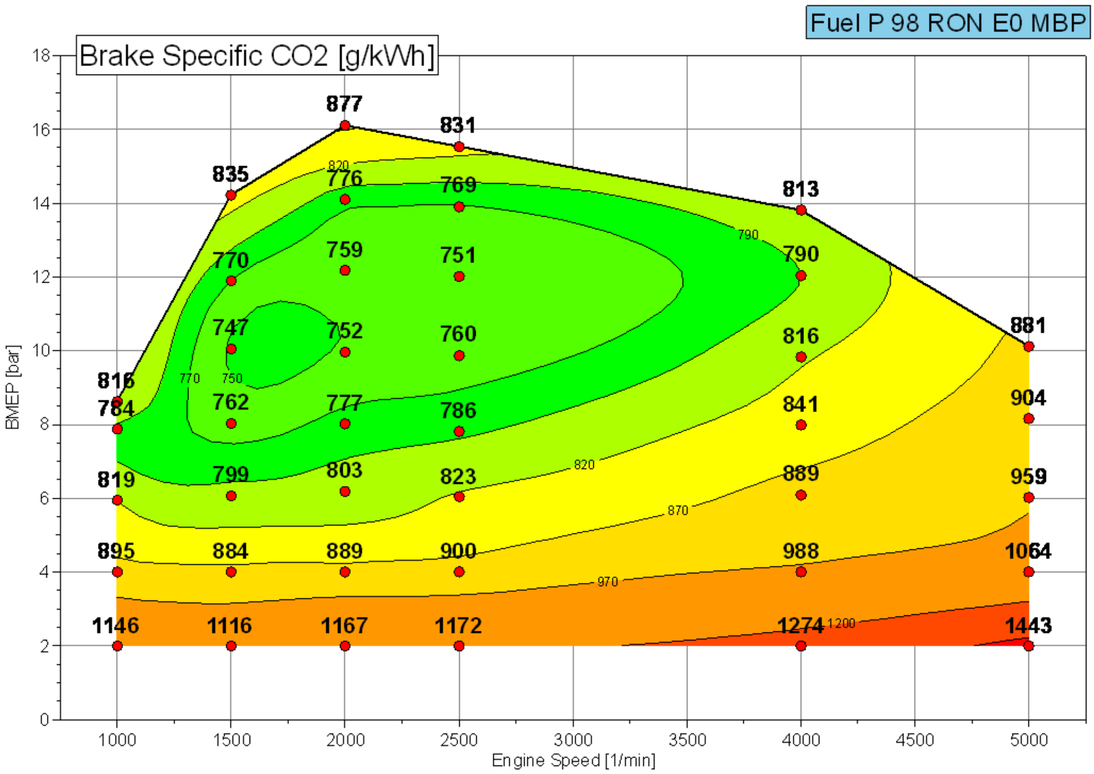

Figure 14: Brake Specific Carbon Dioxide Emissions

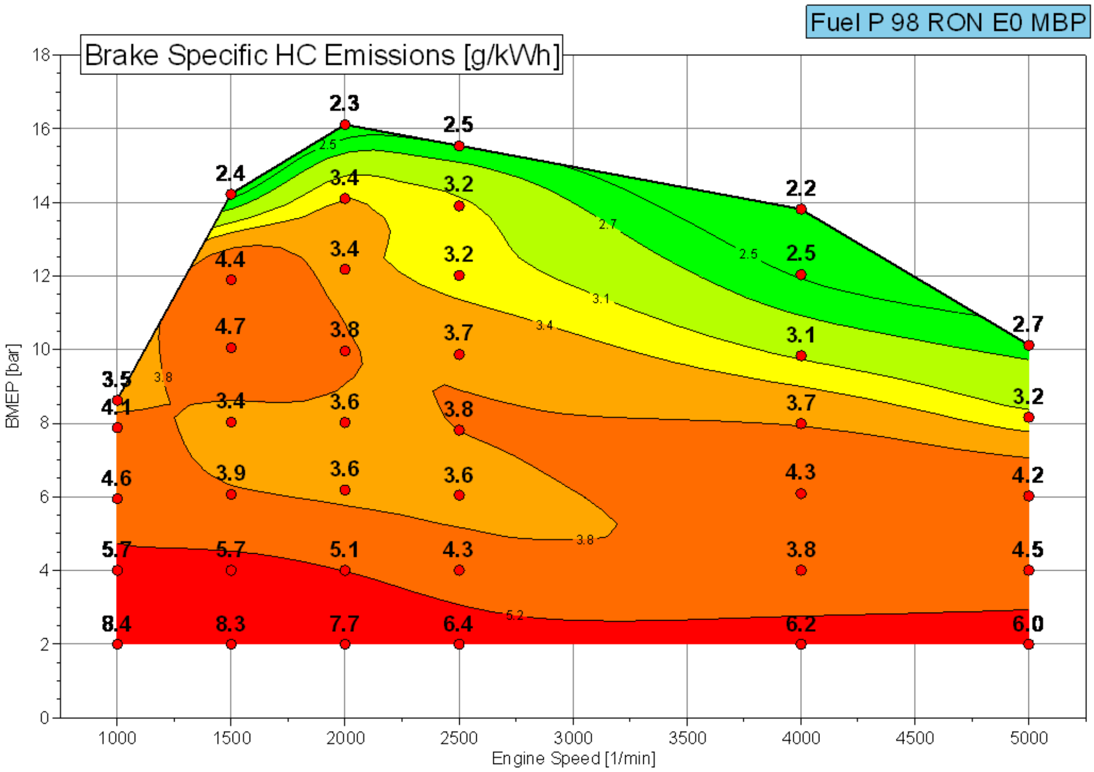

Figure 15: Brake Specific Hydrocarbon Emissions

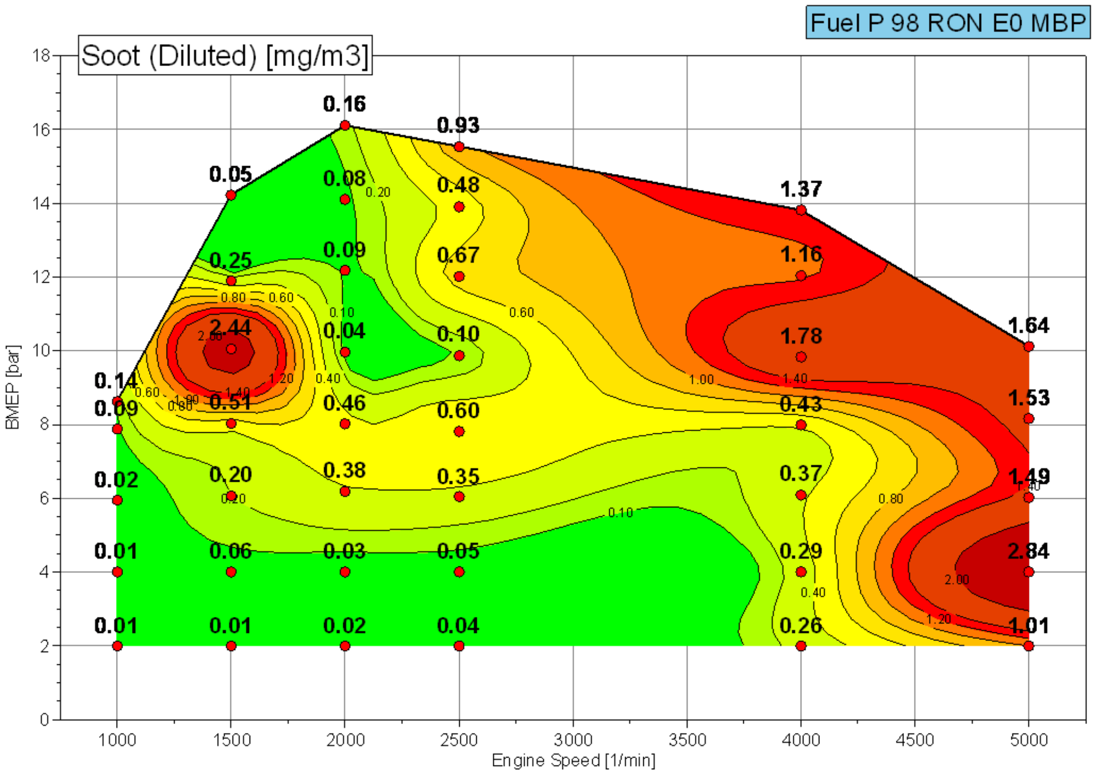

Figure 16: Particulate Soot Emissions

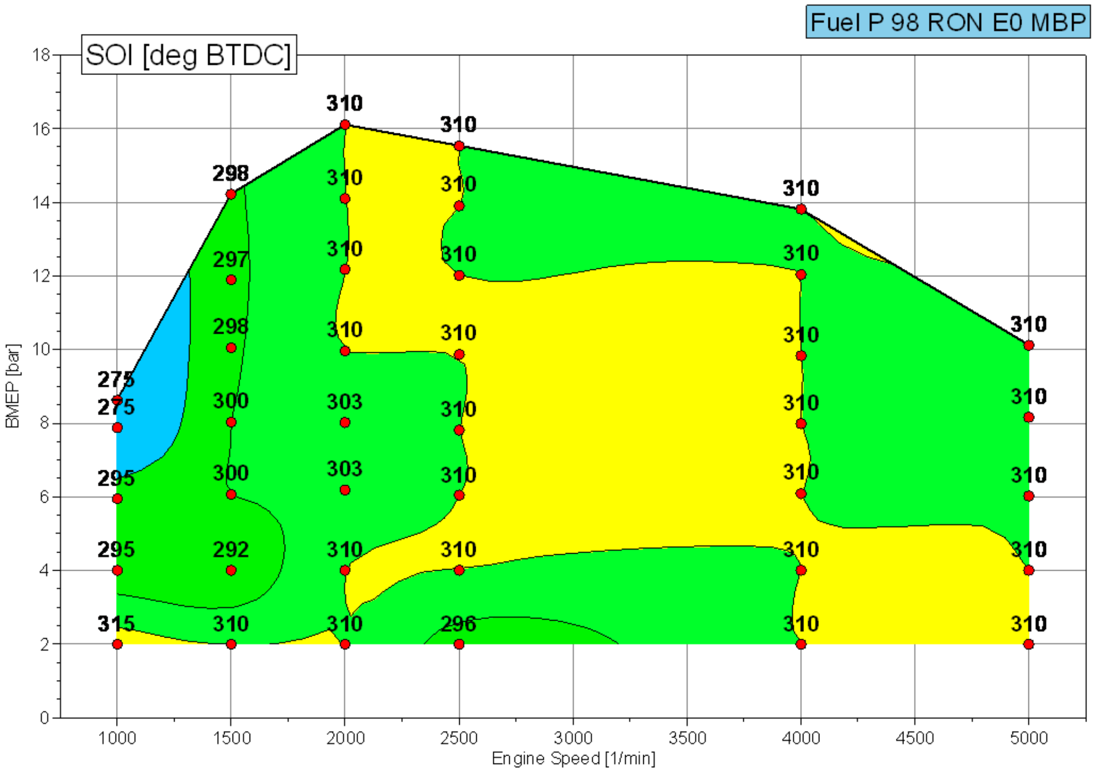

Figure 17: Start of Injection

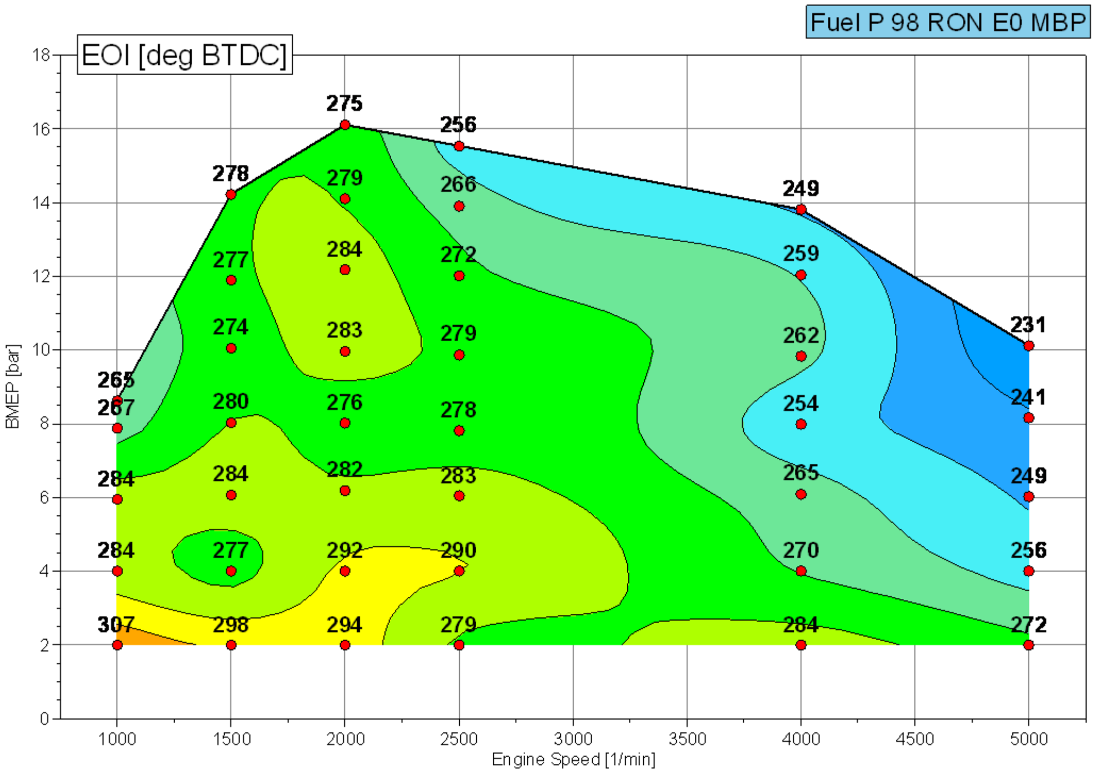

Figure 18: End of Injection

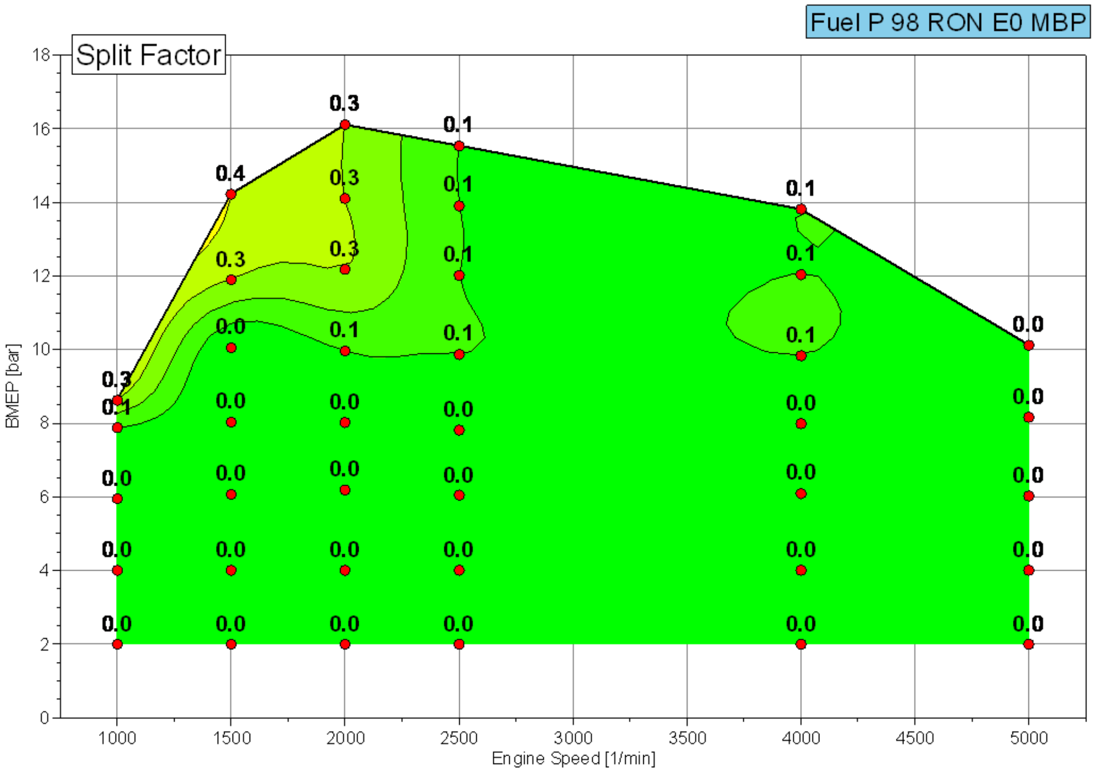

Figure 19: Injection Split Factor

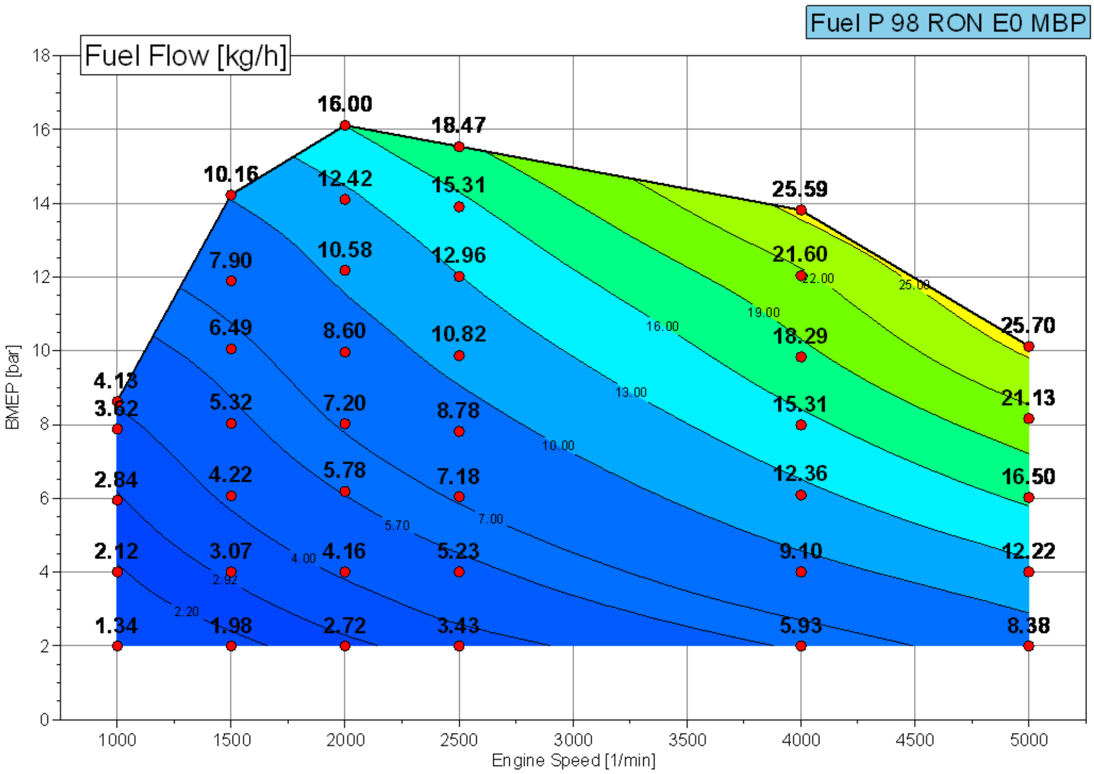

Figure 20: Fuel Flow

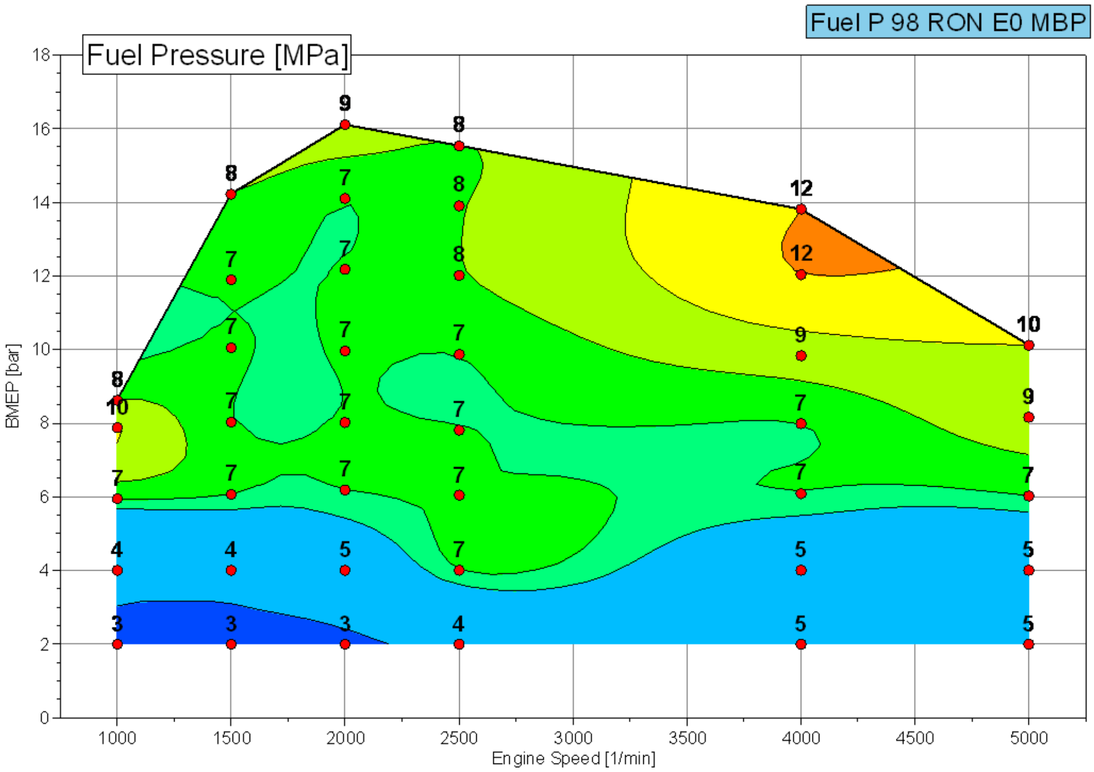

Figure 21: Fuel Rail Pressure

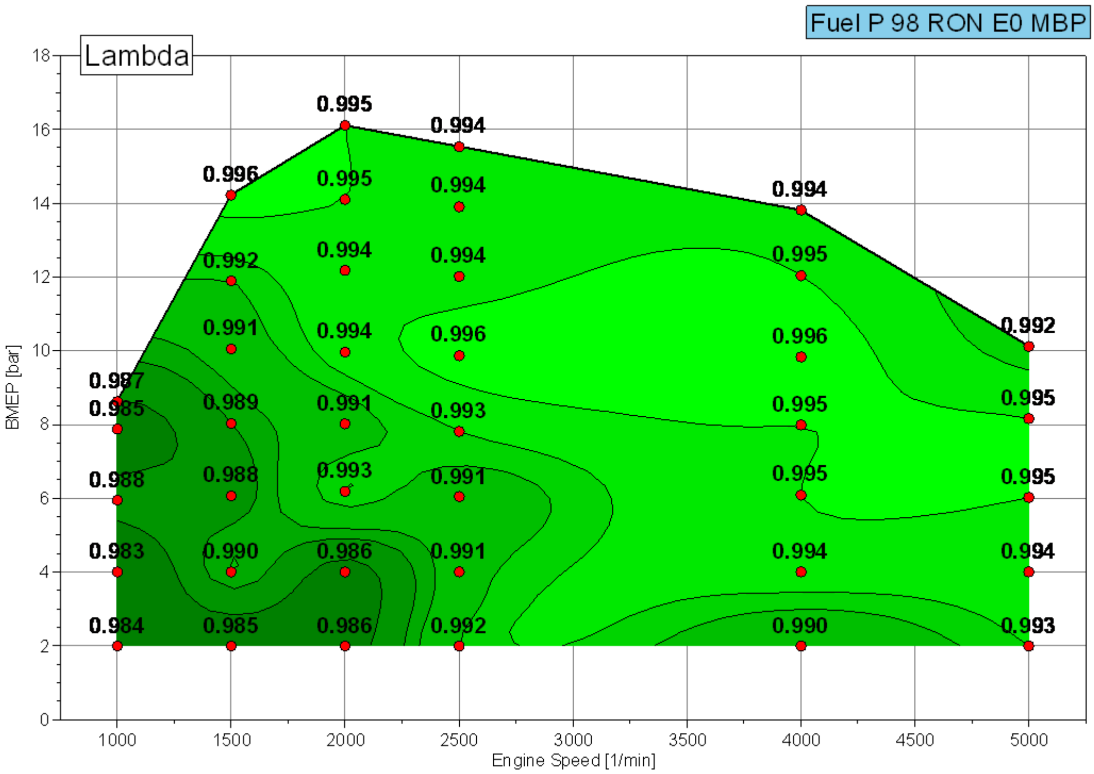

Figure 22: Lambda

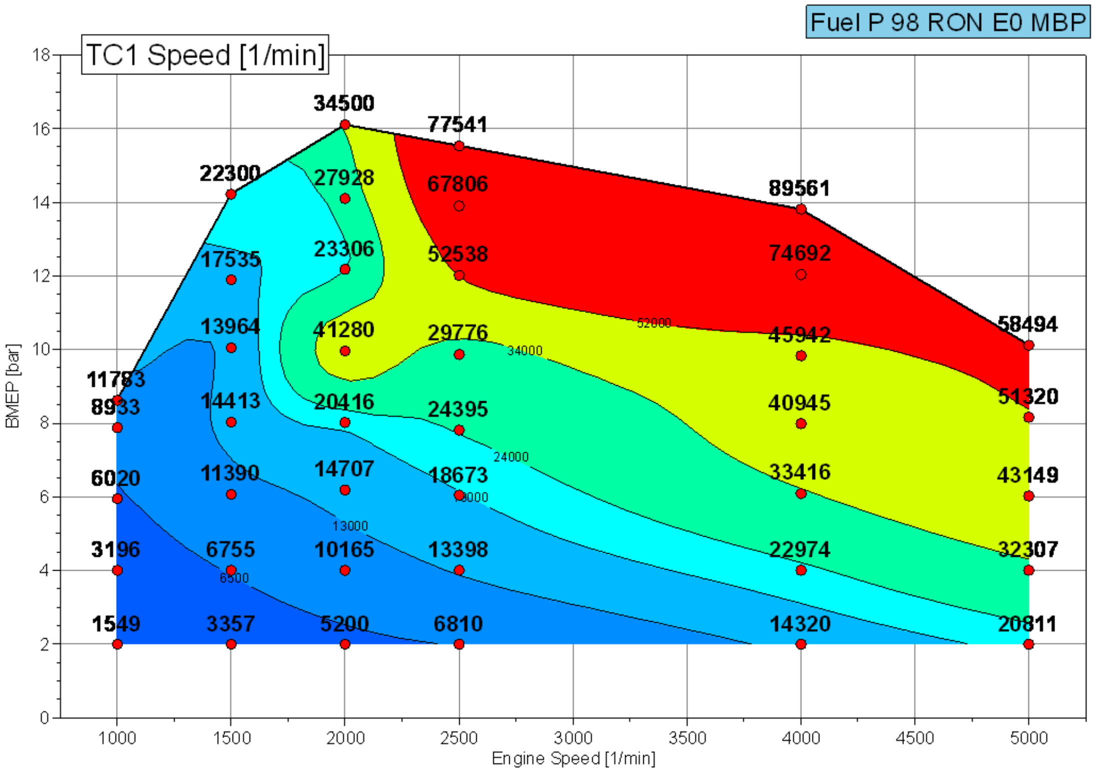

Figure 23: Low Pressure Turbocharger Speed

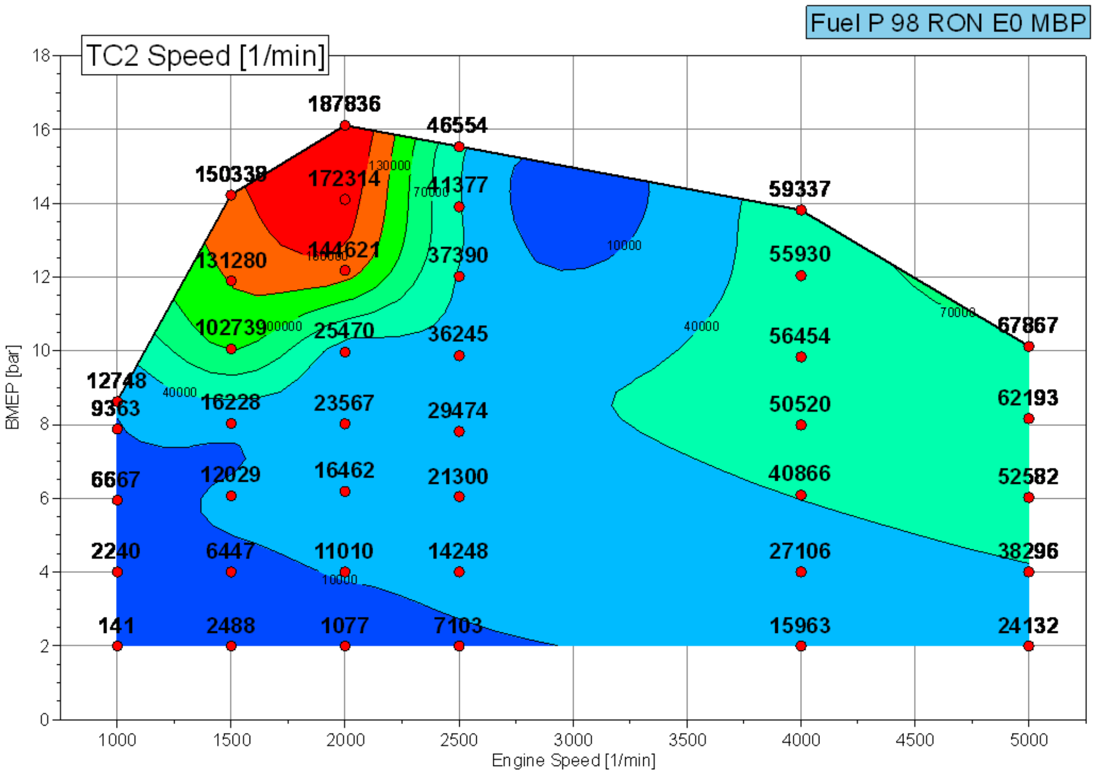

Figure 24: High Pressure Turbocharge Speed

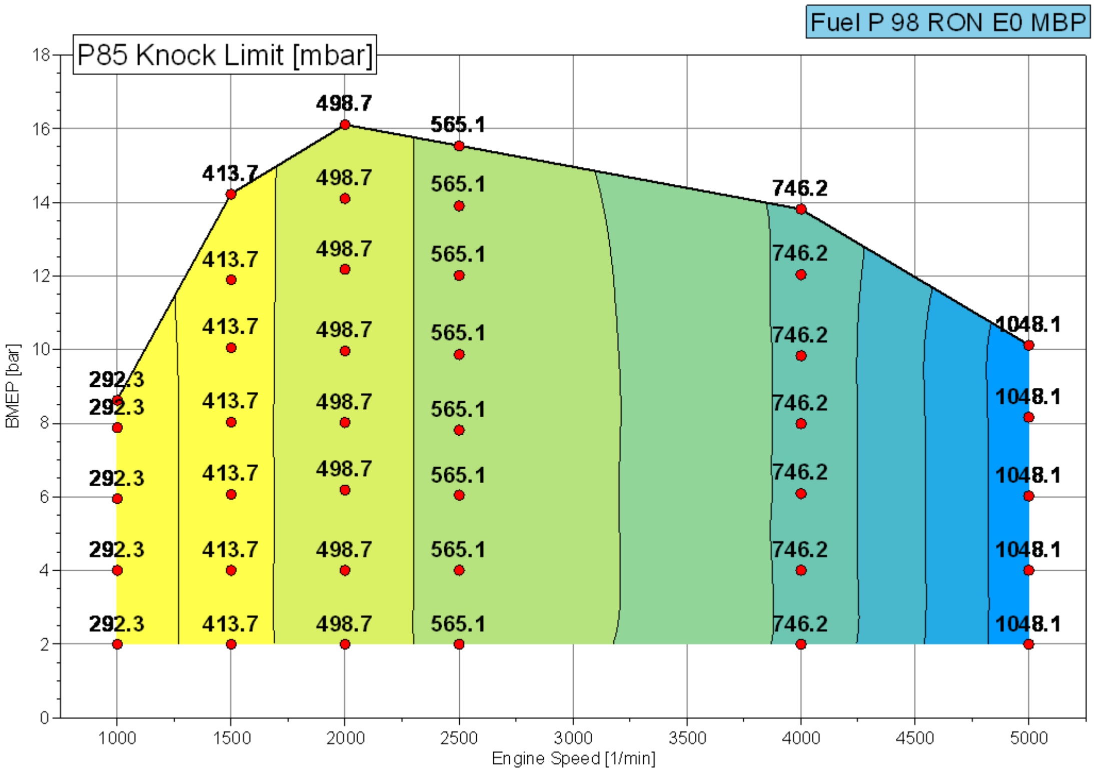

Figure 25: P85 Knock Limit

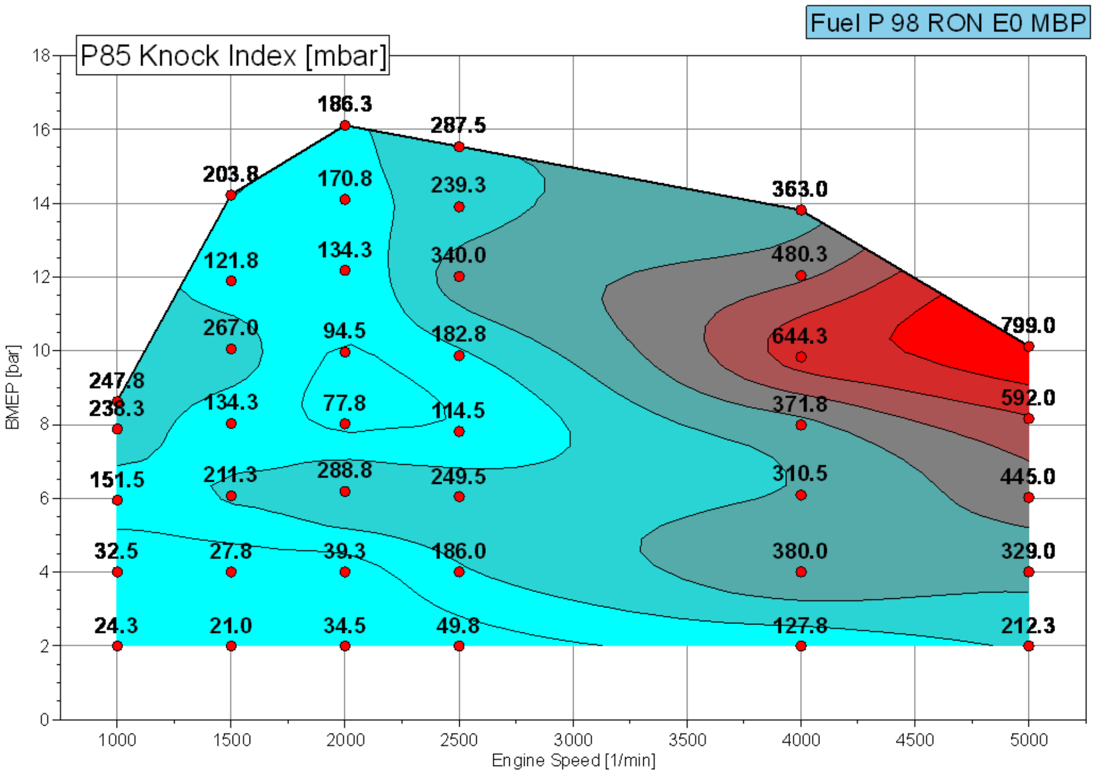

Figure 26: Averaged P85 Knock Index

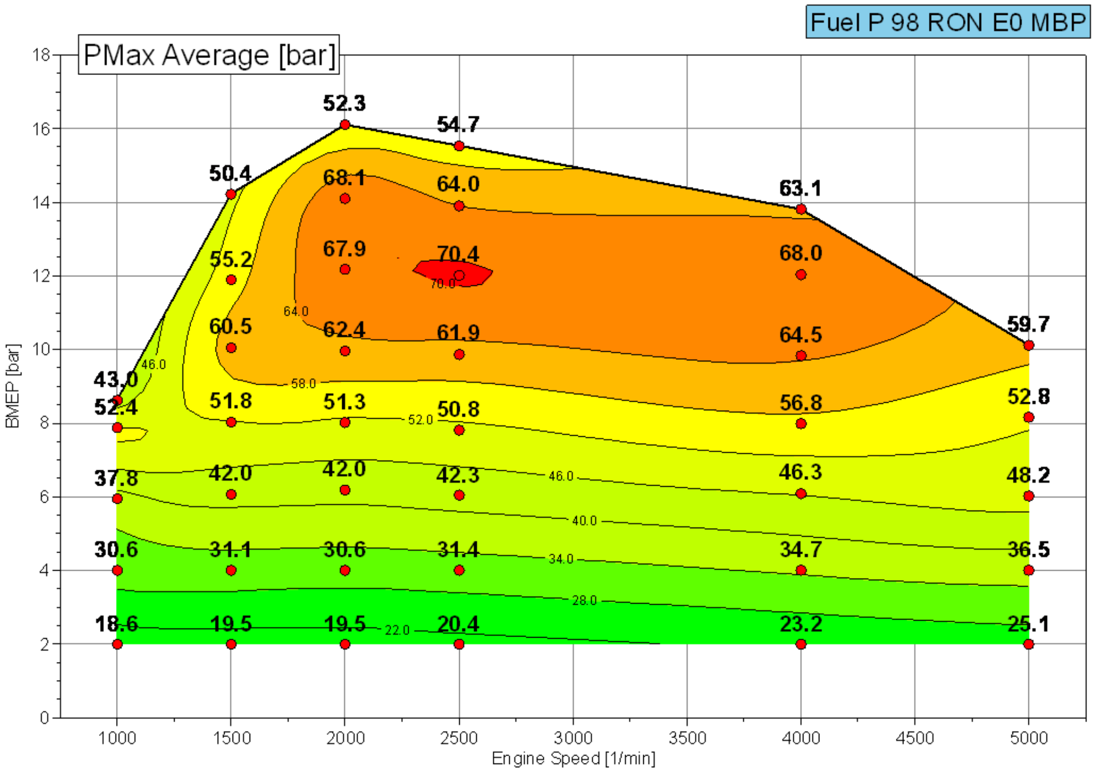

Figure 27: Averaged Max Pressure for Cylinders 1-4

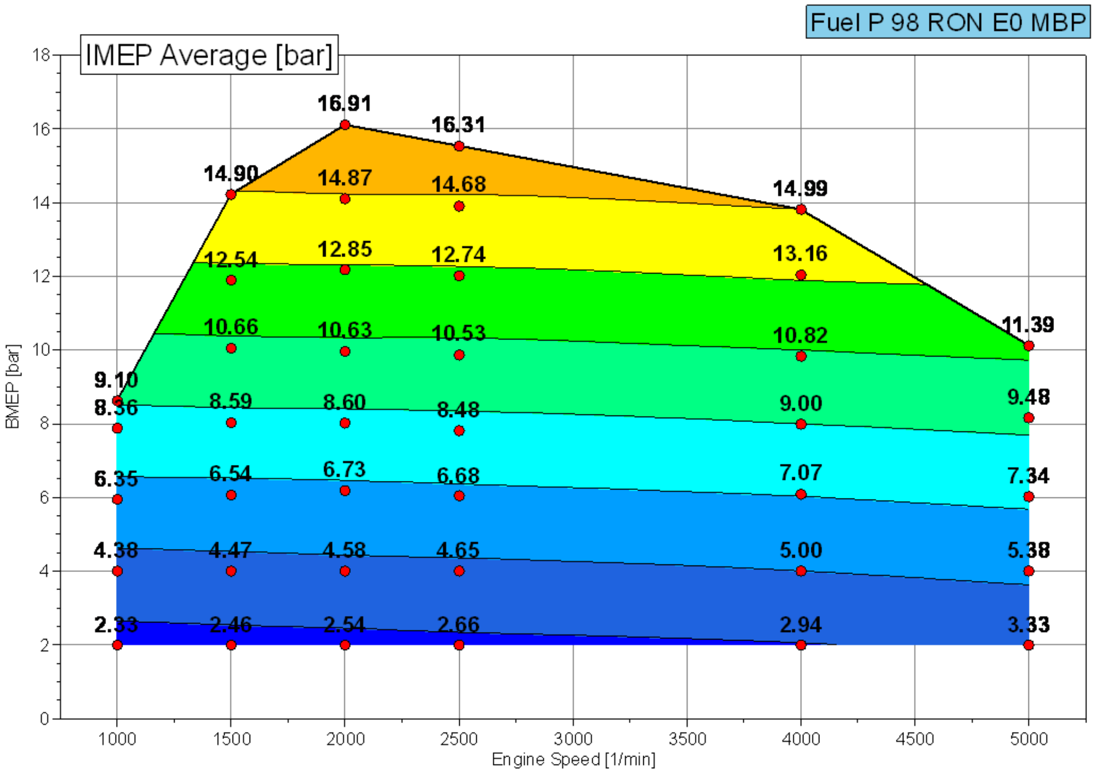

Figure 28: Indicated Mean Effective Pressure

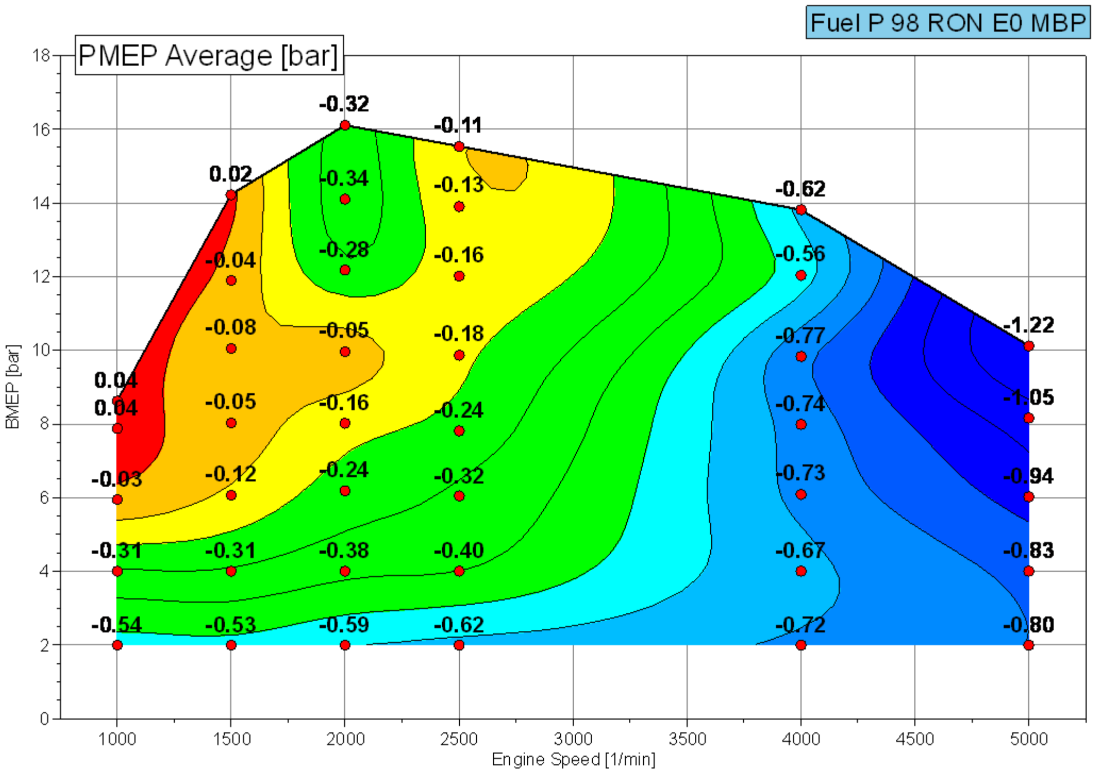

Figure 29: Pumping Mean Effective Pressure

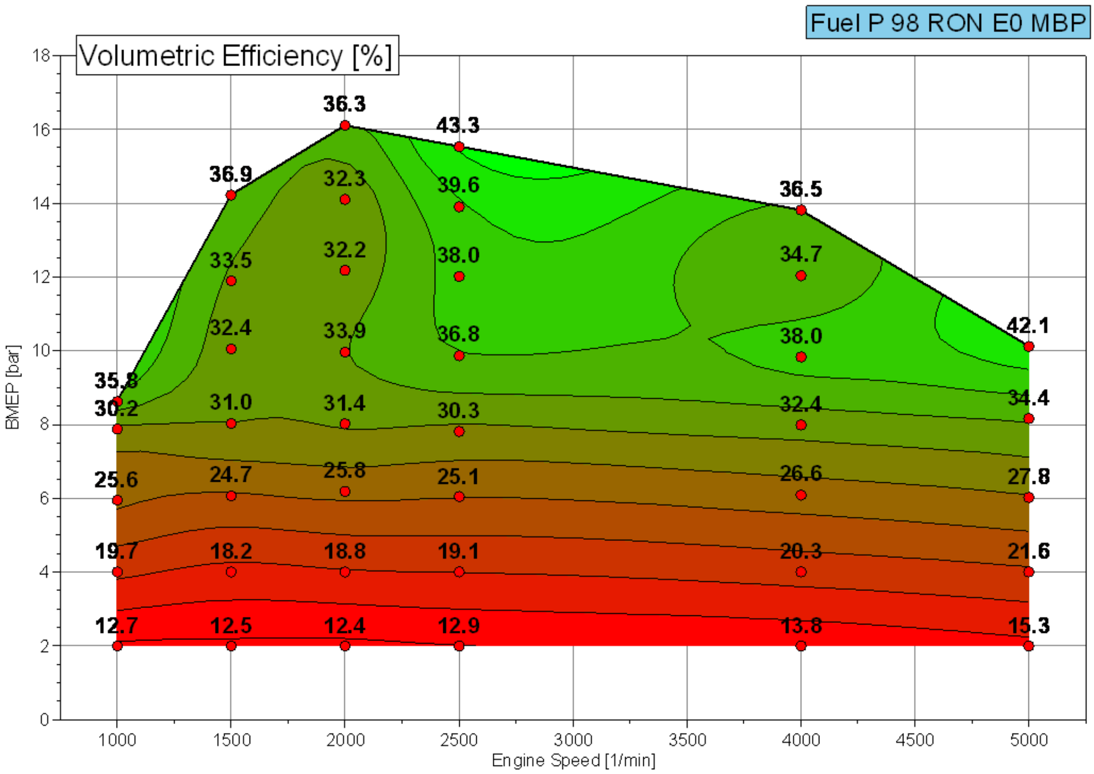

Figure 30: Calculated Volumetric Efficiency

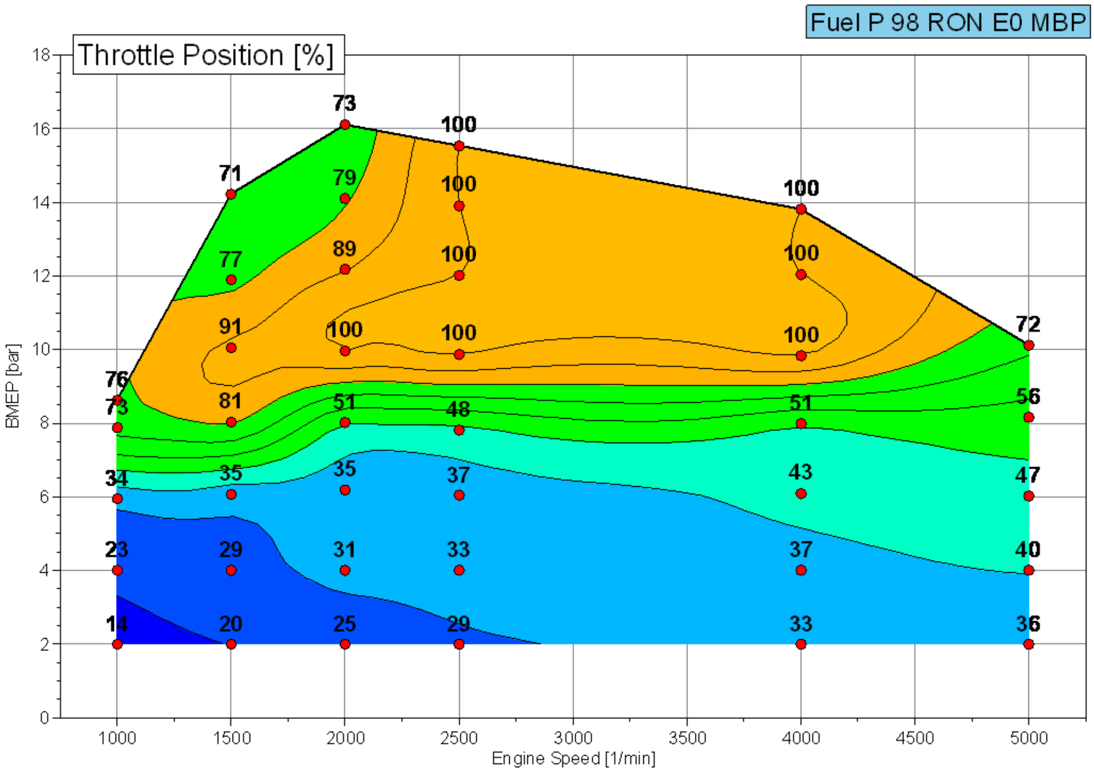

Figure 31: Throttle Position

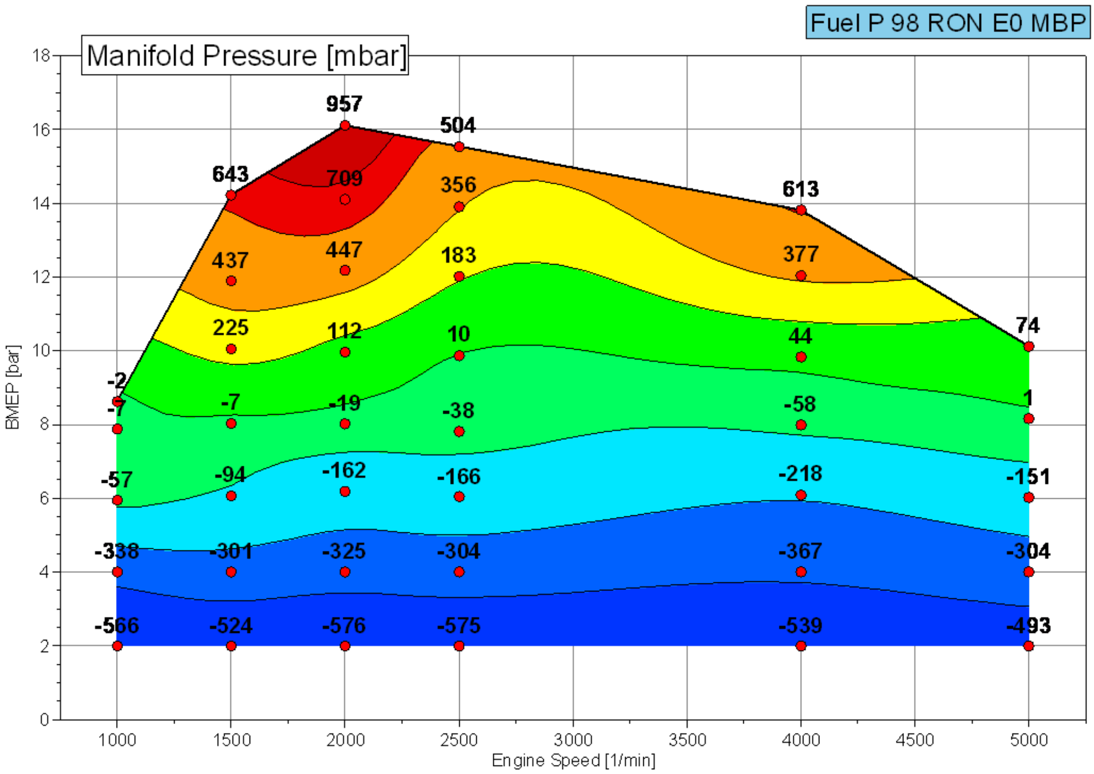

Figure 32: Intake Manifold Pressure

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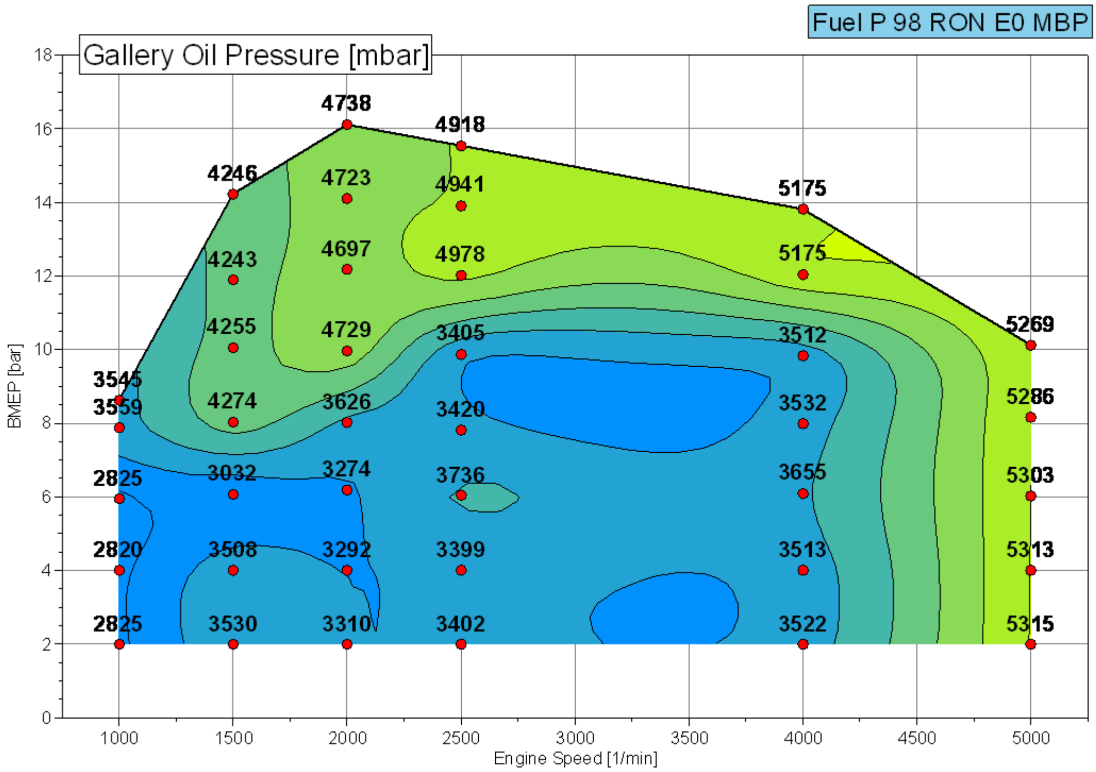

Figure 33: Gallery Oil Pressure

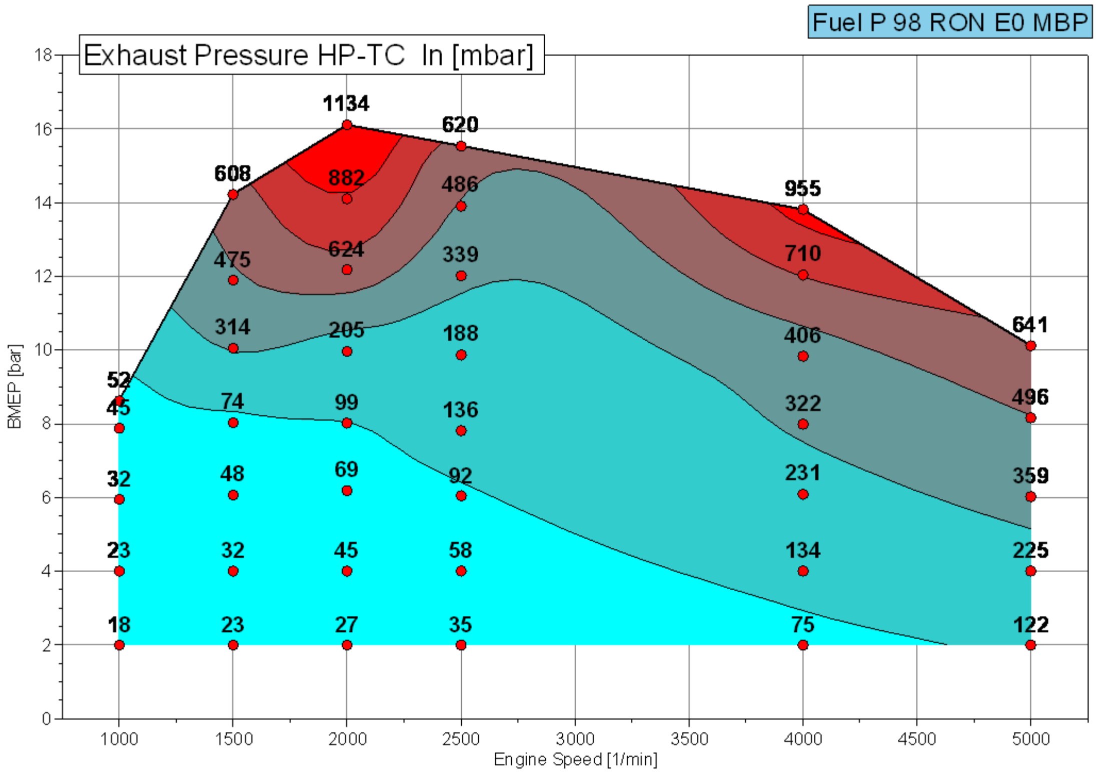

Figure 34: Exhaust Pressure High Pressure Turbocharger In

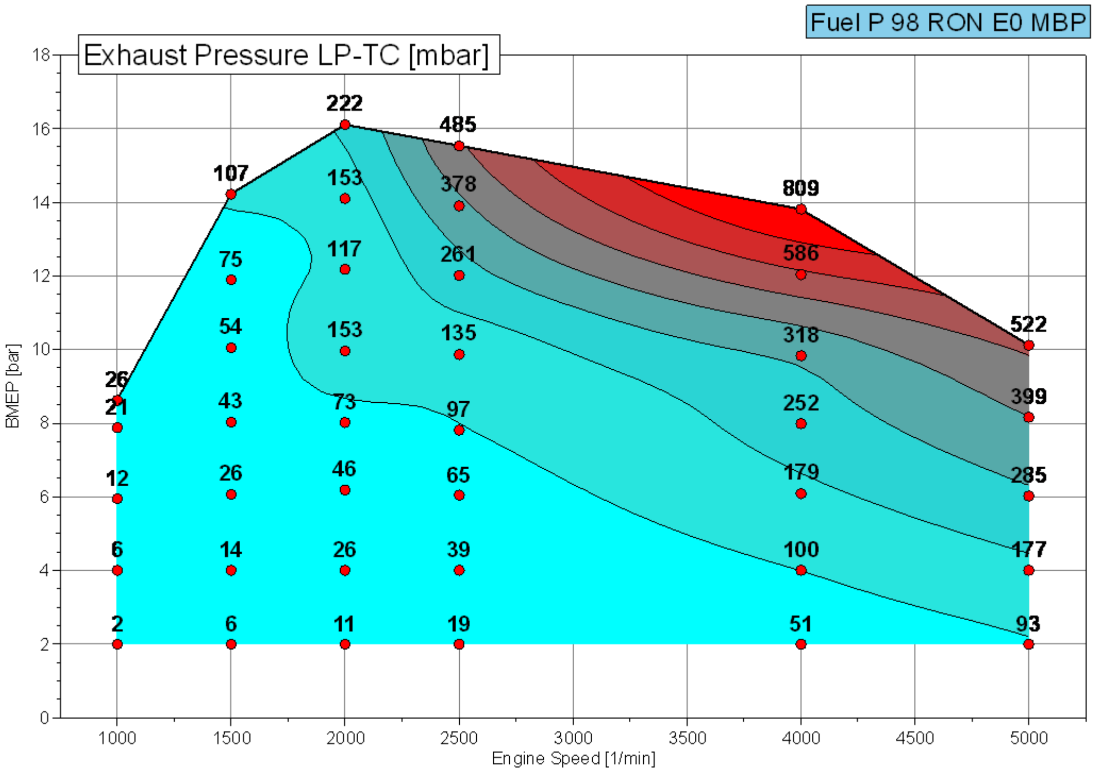

Figure 35: Exhaust Pressure Low Pressure Turbocharger In

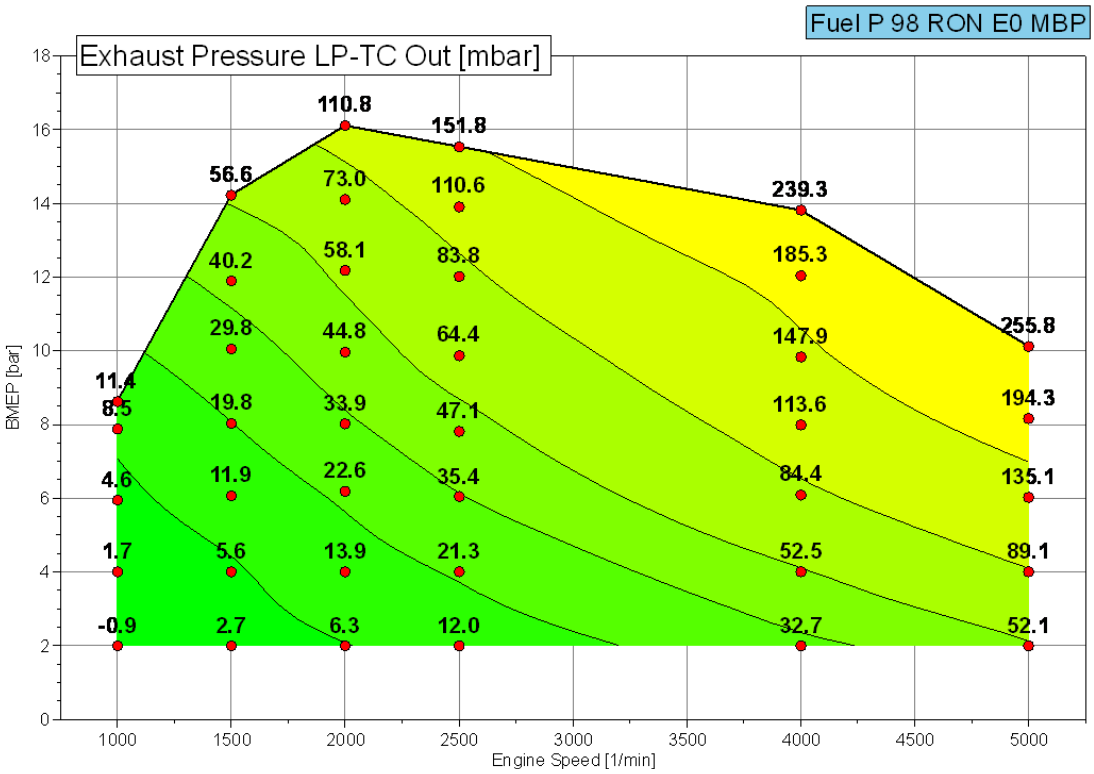

Figure 36: Low Pressure Turbocharger out Exhaust Pressure

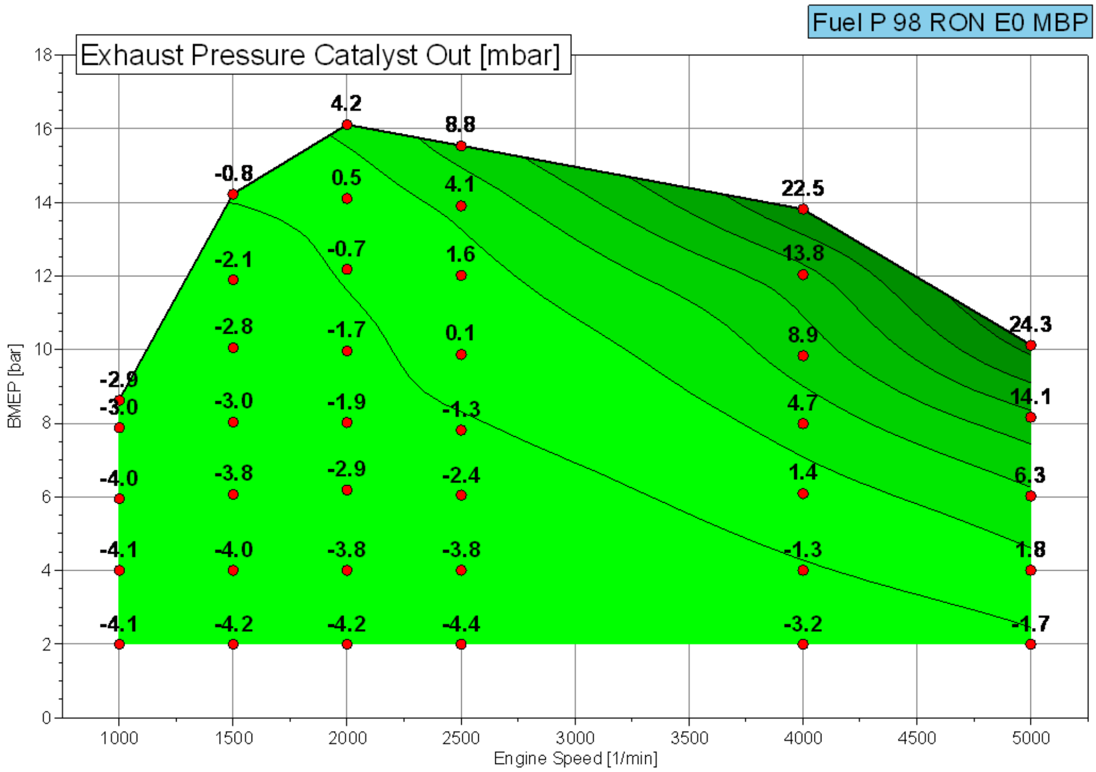

Figure 37: Exhaust Pressure Catalyst Out

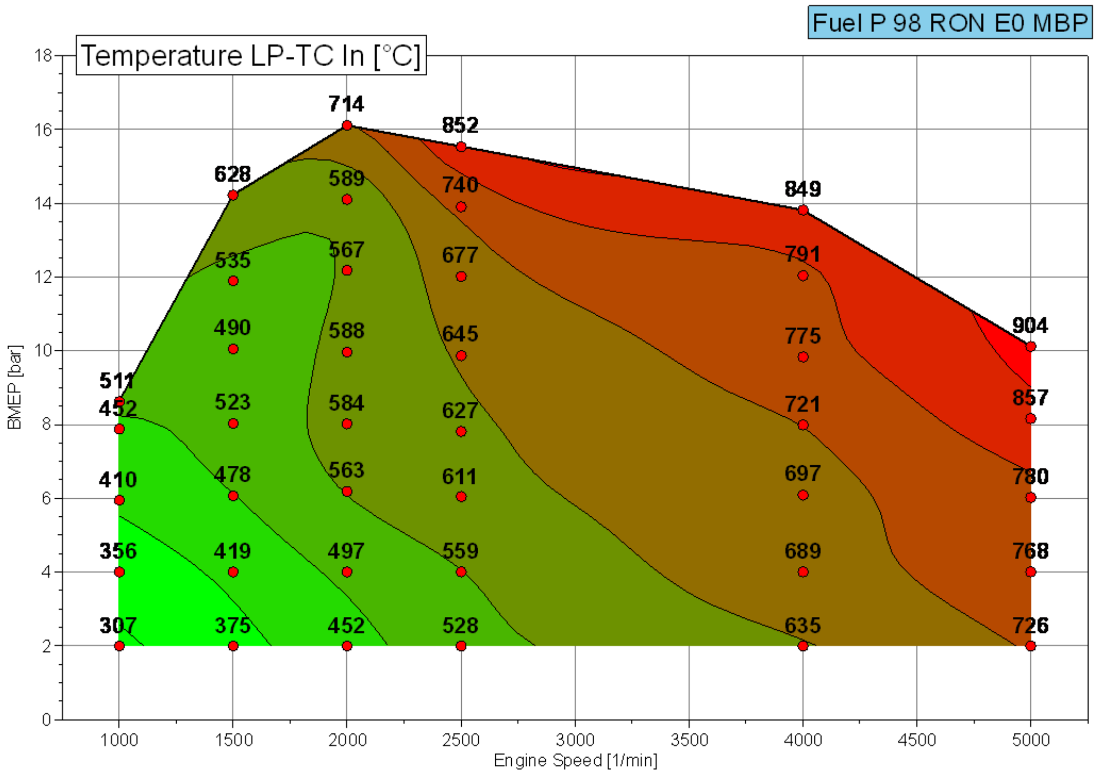

Figure 38: Exhaust Temperature Low Pressure Turbocharger In

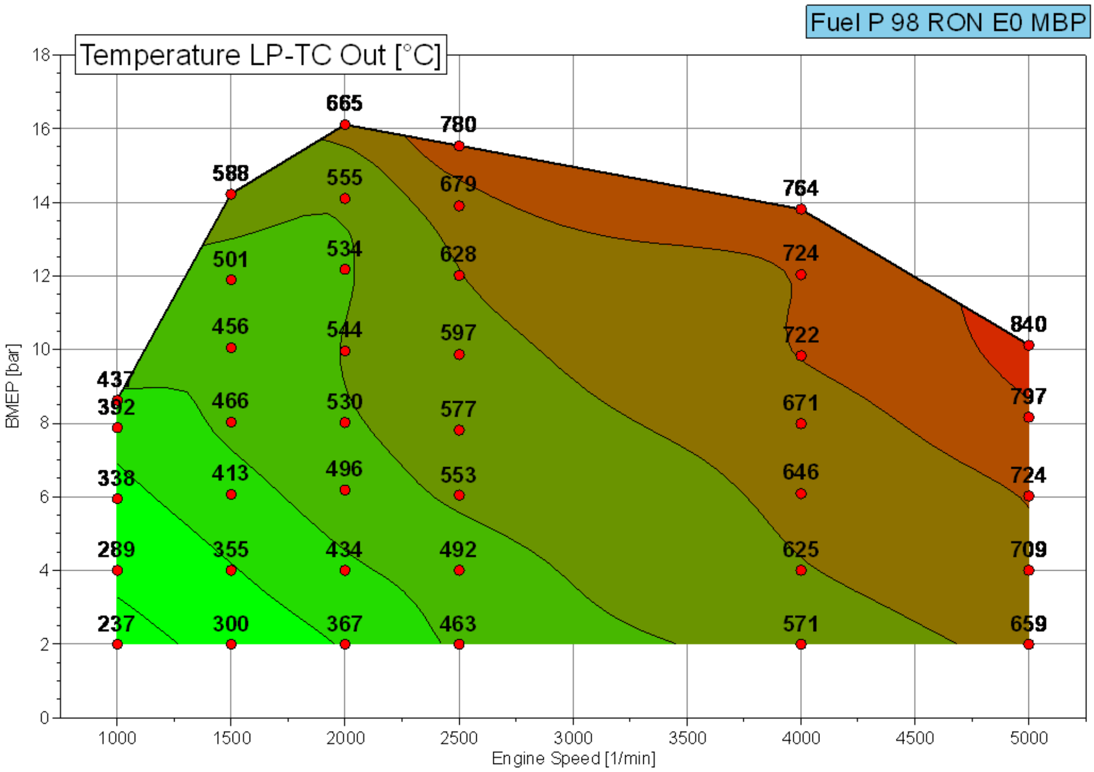

Figure 39: Exhaust Temperature Low Pressure Turbocharger Out

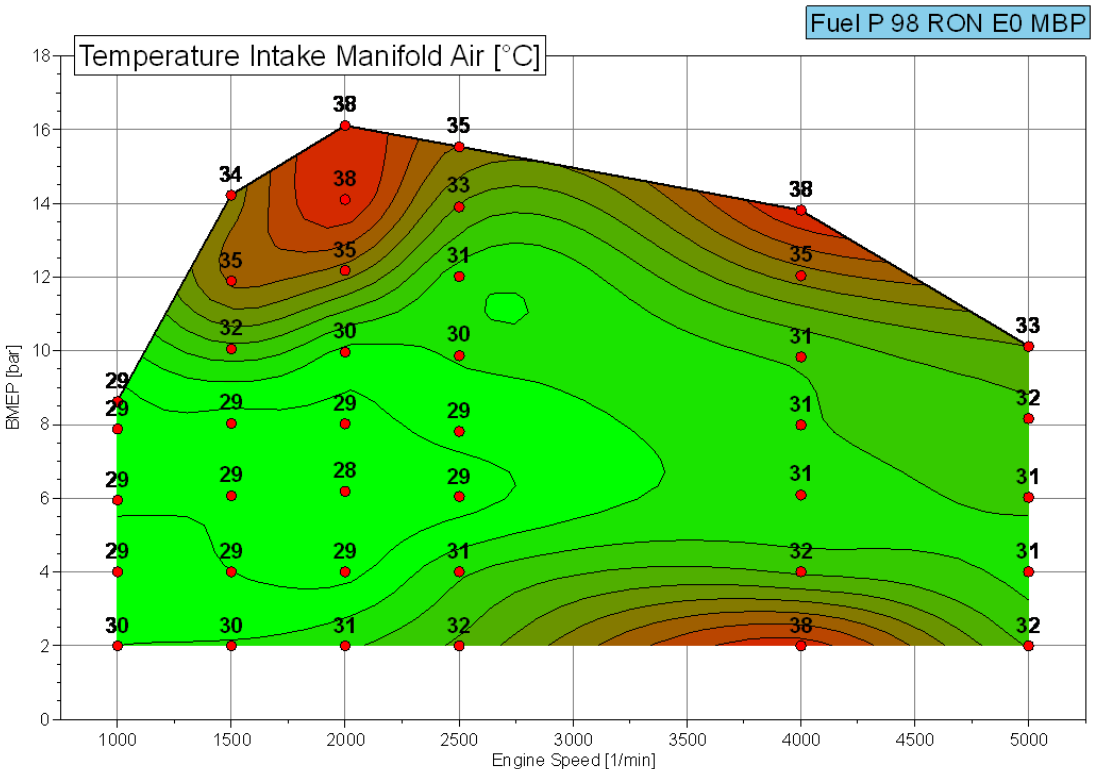

Figure 40: Intake Manifold Air Temperature

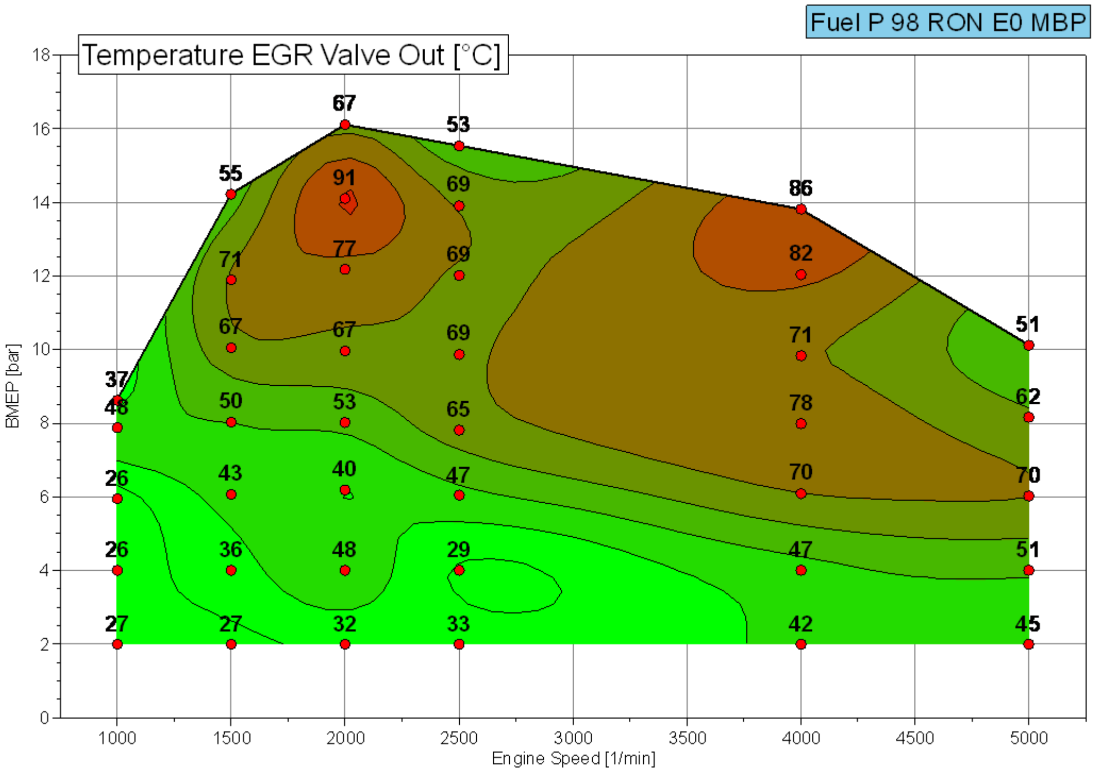

Figure 41: EGR Valve Out Temperature

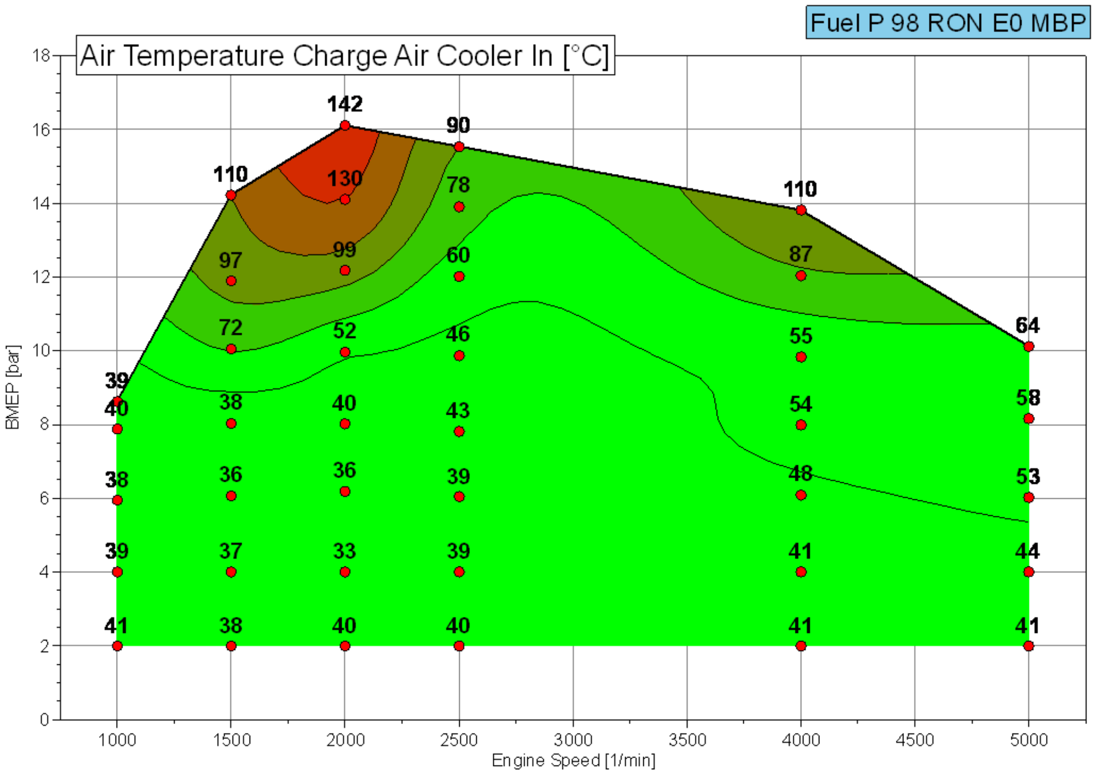

Figure 42: Charge Air Cooler Inlet Air Temperature

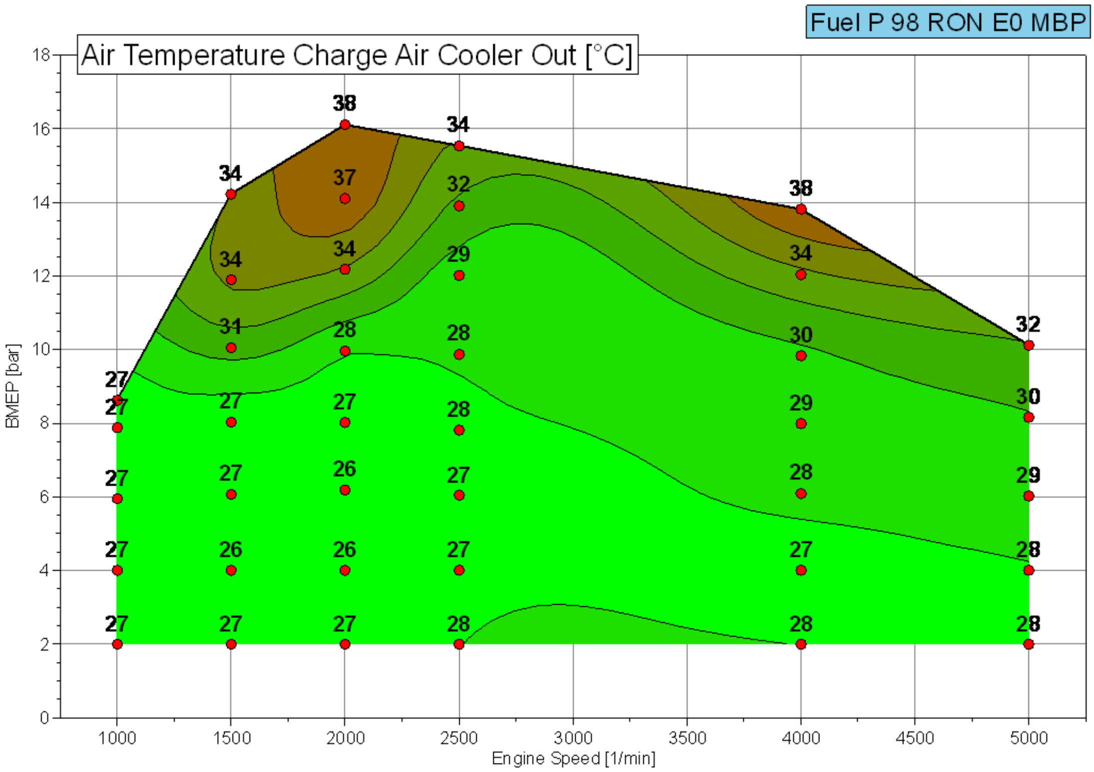

Figure 43: Charge Air Cooler Outlet Air Temperature