MODELING THE ENVIRONMENTAL AND THERMAL EFFICIENCY COST OF CYLINDER-TO-CYLINDER VARIATION

by

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LIST OF ABBREVIATIONS

AI – Autoignition Interval

AFT – Adiabatic Flame Temperature

BSNOx – Brake Specific Nitrogen Oxides

BTE – Brake Thermal Efficiency

CFD – Computation Fluid Dynamics

DoE – Design of Experiments

GGE – Gallon Gas Equivalent

GIMEP – Gross Indicated Mean Effective Pressure

ICE – Internal Combustion Engine

LFS – Laminar Flame Speed

MCE – Multi-Cylinder Engine

RoI – Return on Investment

SCRE – Single Cylinder Research Engine

SI – Spark Ignited

TOC – Total Cost of Ownership

GLOSSARY

Apparent Heat Release – The calculated heat release based the in-cylinder pressure measurement. (LaPointe, 2014)

Autoignition Interval – The time delay between the charge reaching the critical temperature of autoignition and the time the autoignition occurs. (LaPointe, 2014)

Brake Specific Nitrogen Oxides – The amount of nitrogen oxides measured in grams divided by the brake power output having the units of gm/hp-hr. (Heywood, 1988)

Centroid – The center of the moment of apparent heat release to 95% of total fuel mass burn. (LaPointe, 2014)

Energy Flow – The energy supplied by the fuel mass flow rate based on the lower heating value of the fuel supply. (LaPointe, 2014)

Ignition Delay Parameter – The crank angle duration between spark timing and centroid. (LaPointe, 2014)

Lambda – The ratio of the observed air/fuel ratio to the Stoichiometric air/fuel ratio; the inverse of the equivalence ratio. (Heywood, 1988)

Large-bore – Engines with cylinder bores in excess of 150 mm in diameter. (LaPointe, 2014)

Lean Burn – Engines operating at Lambdas in excess of 1.50. (LaPointe, 2014)

Nitrogen Oxides– The group of Nitrogen based compound in the form of NO and NO_2 found to be harmful to the environment. (Heywood, 1988)

Spark Timing – The crank angle degree that current is supplied to the primary side of the ignition coil. (Heywood, 1988)

Single Cylinder Research Engine – A single cylinder engine design to represent the power cylinder of a multi-cylinder engine sharing the bore, stroke, connecting rod, piston and cylinder head of the multi-cylinder engine. (Taylor, 1985)

ABSTRACT

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Environment concerns are adding additional focus to the reduction of greenhouse gas emissions from internal combustion engines. Internal combustion engines operating on natural gas have become an alternative to coal-fired power plants due to the lower carbon content of the natural gas. The reduction in carbon content of the natural gas reduces the CO2 emissions associated with electrical power generation. This drives an ever increasing need to reduce CO2 emissions from spark ignited natural gas engines used for power generation. One of the sources for the CO2 emission from power generation engines is the cylinder-to-cylinder variation. The capital requirement for the large-bore natural gas power generation engines produces challenges for research testing on multi-cylinder engines to determine root causes of cylinder-to-cylinder variation. This Capstone Project proposes and evaluates an analytical method to model the likely root causes for the observed cylinder-to-cylinder variation on a multi-cylinder engine. The method uses regression based correlations developed during single-cylinder research engine development testing to analytically determine the likely lambda and energy flow going into each of the cylinders of a multi-cylinder engine. The method also evaluates the additional CO2 produced because of the cylinder-to-cylinder variation.

CHAPTER 1. INTRODUCTION

1.1 The Basics

2019's industrial world internal combustion engines (ICE) are used for a variety of applications, including power generation. The use of fossil fuels for these engines results in the production of CO_2. CO_2 emissions contribute to global warming (Greenhouse Gas Emissions, 2018) therefore it is imperative that the engines produce the least amount of CO_2 required to meet consumer's energy requirements. Natural gas spark ignited (SI) engines produce less CO_2 emissions than their diesel counterparts because of the lower amount of carbon contained in the fuel (Frequently Asked Question, 2019). The lower carbon content in the fuel results in natural gas SI engines being used for power generation to reduce CO_2 emissions (Comparing Natural Gas and Diesel Generator Sets, 2015).

1.2 Natural Gas SI Engines

Natural gas SI engines burn a pre-mixed charge of air and fuel that is delivered through the intake system of the engine. The intake system is designed to produce a homogenous mixture of fuel and air before it reaches the power cylinder (Cho & He, 2006). The ratio of air to fuel is adjusted in lean burn engines to ensure that the engine does not produce brake specific nitrogen oxides (BSNOx) in excess of the regulatory limit (Natural Gas-Fired Reciprocating Engines, 2019). The requirement to meet BSNOx limits are a design constraint with packaging requirements providing further limitations in engine design and development (Saad, 2014). The intake system is designed around the packaging constraints resulting in a well packaged engine and non-uniform distribution of charge between the cylinders (Kassa, Hall, Ickes, & Wallner, 2016). The non-uniform distribution and challenges associated with trying to reach a homogenous mixture results in cylinder-to-cylinder variation. The cylinder-to-cylinder variation results in reductions in engine brake thermal efficiency (BTE) and an increase in CO_2 emissions (LaPointe, 2014).

1.3 Cylinder-to-Cylinder Variation

Cylinder-to-Cylinder variation results in each cylinder of a multi-cylinder engine (MCE) running differently. The difference in performance between each cylinder is similar to a dog sled team that are all connected to the same point on the sled. The dogs are generating power however it is not as efficiently delivered to the sled as when the dogs are connecting in a line. Cylinder-to-cylinder variation reduces overall engine efficiency (LaPointe, 2014) and therefore increases CO_2 emissions. The cylinder-to-cylinder variation of MCEs are the reason that single cylinder research engines (SCRE) are used to help develop fundamental combustion relationships. The usage of a SCRE allows for improved understanding of the boundary conditions of the power cylinder. The improvement in understanding comes from the lack of interactions with the other cylinders. The lack of interactions with other cylinders means that the measured mass flow is for only the cylinder of interest.

1.4 Single Cylinder Research Engines

Single cylinder research engines are used to develop fundamental engine performance relationships. The removal of the uncertainty associated with MCE testing improves correlations between lambda, energy flow, and centroid with engine performance (LaPointe, 2014). The improvement in the with respect to Ignition Delay Parameter and gross indicated mean effective pressure GIMEP improves the ability to determine boundary conditions. Energy flow has a strong correlation with energy flow and Ignition Delay Parameter has a strong correlation with lambda. The improvement in the correlations, typically a 10% in R^2 value, produced by SCRE between power cylinder performance in boundary conditions were used to determine the boundary conditions for each power cylinder on a MCE and the effects on BTE and CO_2 emissions.

1.5 Problem Statement

Cylinder-to-Cylinder variation on multi-cylinder natural gas power generation engines results in reduced overall engine efficiency at statutory NOx emission levels (LaPointe, 2014). The reduction in engine efficiency increases production of the greenhouse gas, CO_2 (Greenhouse Gas Emissions, 2018) increasing the levels in the atmosphere. Analytical modeling of each cylinder's emissions based on relationships established on a single cylinder research engine determined the magnitude of CO_2 reduction possible with zero cylinder-to-cylinder variation. The goal of the Grand Engineering Challenge of Carbon Sequestration (NAE Grand Challenges for Engineering, 2018) is to reduce CO_2 levels in the atmosphere and reducing the production of CO_2 reduces atmospheric CO_2 levels.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Internal Combustion Engines

Internal combustion engines have been in use for over a century (Heywood, 1988). Internal combustion engine applications have changed over the years as technology has advanced. During the early years of the industrial revolution IC engines were used to provide power directly to industrial equipment. The invention of electric motors saw the replacement of IC engines with electric motors in industrial equipment. The usage of an electric motor improves the efficiency of the system as the electric motor only consumes energy during active usage. The IC engine was disengaged from the drive system of the equipment during periods of inactivity, but continued to run. One of the ways electricity is generated today to drive the industrial equipment is by using IC engines. The engines have changed from the single cylinder engines used during the turn of the 20th century to multi-cylinder engines of variable displacements range from less than 20 liters to over 200 liters (Bremmer, 2018).

2.2 Multi-Cylinder Engines

Multi-Cylinder Engines have intake manifolds to distribute fuel and air to each power cylinder. The distribution of fuel and air to each of the power cylinder results in complex pressure dynamics inside the intake manifold (Heywood, 1988). The complex nature of the intake manifold results in each cylinder having a different mean intake manifold pressure during the intake stroke resulting in each cylinder receiving a different volume of fuel and air mixture. Traditionally researching issues facing MCEs are addressed by conducting testing on a MCE

(Taylor, 1985). The conducting of tests on MCEs allows for direct validation of the results. Engine performance development testing is conducted on engines for everything from garden tractors to large stationary industrial generators. Engines designed for use in on-highway applications have the benefit of production volumes that make MCE readily available. The available of MCE for on-highway applications makes testing on the MCE to resolve cylinder-to-cylinder variation economically feasible. However, the typical Class 8 truck consumes nearly 13000 GGEs (Average Annual Fuel Use of Major Vehicle Categories, 2018) per year and is several times the consumption level of a typical passenger car. Although the energy consumption level of a Class 8 truck is large compared to a passenger car it still requires over two percent improvement in BTE before the consumer sees $1000 saving from fuel consumption at $3.50 a GGE. The small return on investment (RoI) from the reduction in energy usage reduces the advantage of reducing cylinder-to-cylinder variation. Large-bore industrial power generation engines can generate over two-megawatt of electricity resulting in orders of magnitude larger fuel consumption levels. The resulting fuel consumption levels reduce the required improvement in BTE to net a noticeable cost saving level. The lowered threshold makes addressing cylinder-to-cylinder variation more desirable. However, industrial engines do not have the production volumes that are associated with on-highway applications. The lower production volumes of industrial engines reduce the availability of MCE for develop testing. The reduced availability of MCE has driven close-cycle development of combustion recipes to take place on SCRE.

2.3 Single Cylinder Research Engines in Industrial Application

The usage of SCRE for close-cycle development also produces a wealth of additional data. The testing conducted on SCRE has been used to develop fundamental relationships. The fundamental relationships developed on SCRE have been used to develop predictive models for non-standard fuels (Xu & LaPointe, 2015).The predictive models illustrated a robust relationship between the boundary conditions of lambda, energy flow and centroid with laminar flame speed (LFS), adiabatic flame temperature (AFT), and autoignition interval (AI) based on chemical kinetic models and the responding combustion duration, BSNOx and propensity to knock (Xu & LaPointe, 2015). The ability to produce high fidelity data with an SCRE illustrates SCRE are used to generate information in addition to pass fail testing of combustion recipes.

2.4 Cylinder-to-Cylinder Variation

Cylinder-to-cylinder variation reduces overall BTE by not allowing all cylinders to operate at their optimal conditions for a given BSNOx level (LaPointe, 2014). Cylinder-to-cylinder variation has been historically addressed on MCE applications. There have been experiments aimed at addressing fuel mixing (Park, Lee, Lim, Choi, & Kim, 2013) by modifying engine mixers and evaluating the resulting change in cylinder-to-cylinder variation which did not result in positive results. The application of a mixer does not address fundamental manifold designs that would result in non-uniform distribution of charge to all of the power cylinders. Methanol injection has been used on diesel engines to evaluate cylinder-to-cylinder variation however it was conducted on a four-cylinder small displacement diesel engine (Chen, et al., 2016). Uniform air flow distribution is not at the same level of concern as in a SI engine as in a diesel, fuel is not delivered with the air it is injected directly into the cylinder. Studies have evaluated the effects of valve timing addressing late intake valve closing and how that increases cylinder-to-cylinder variation however this was also conducted on an on-highway size engine (Kassa, Hall, Ickes, & Wallner, 2016). Addressing cylinder-to-cylinder variation on large bore power generation application is limited. Due to the high capital expenditure required for testing on power generation engine in the range of two-megawatt output studies addressing cylinder-to-cylinder variation is limited to smaller on-highway application engines.

2.5 A Novel Approach

Cylinder-to-Cylinder variation has historically been addressed using MCE platforms and evaluated means to reduce the variation with additional hardware. Due to budget limitations and program develop time the feasibility to address cylinder-to-cylinder variation on the large-bore lean burn natural gas SI power generation applications is limited. The proposed approach of using an SCRE to develop an analytical tool to evaluate the root cause of cylinder-to-cylinder variation appeared novel and allowed the evaluation of the BTE and CO_2 emission cost of cylinder-to-cylinder variation. The novel approach represented a new application of SCRE and allowed a cost-efficient evaluation of design changes to improve cylinder-to-cylinder variation. Current practices for modeling cylinder-to-cylinder variation on large-bore lean burn natural gas SI power generation engines is limited to inputting different combustion phasing in to GT-Power models and evaluating the impact on BTE without taking into consideration combustion phasing's effect on BSNOx (Dane, 2018). The application of relationships established from an SCRE to determine the lambda and energy flow going into each power cylinder also allowed adjustments to gross lambda and energy flow required to meet regulatory limits. The ability to make the required adjustments to gross lambda and energy flow allowed a better determination of the reduction in BTE at regulatory limits.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Engine Testing Basics

Engine testing for Cummins Inc is conducted at several different locations globally (Claflin, 2018). The testing of the large bore natural gas SI SCRE is limited to the [redacted]. The test system for the SCRE consist of support rigs to supply oil, coolant, compressed air and fuel. The fuel is supplied at roughly 150 psig and measured with a CMFS025 Micromotion (Micro Motion Elite , 2019) with a Lisk valve repurposed from a production fuel control system to control the fuel flow rate. The compressed air is supplied to the air control rig at 100 psig and is controlled with two control valves with a CMF200 Micromotion located between the two valves. The objective of the two control valves is to ensure that the pressure is never reduced by more than 50% across a single control valve. The pressure reduction limit is to ensure that the system is not operated in choke flow to allow the downstream pressure to be related to the flow rate in the system. The oil and coolant support rigs are designed to allow the system to be preheated before testing and to manage heat rejection during testing simulated the flow rates supplied to a single cylinder of the MCE. The exhaust rig is also used to control the pressure in the exhaust system to allow the simulation of the exhaust manifold pressure associated with a turbocharged engine. Both the intake and exhaust support rigs use surge tanks that are roughly 50 times the engine displacement to reduce pulsations.

3.2 Low-Speed Measurements

[redacted] uses the low speed data acquisition system CyFlex supplied by SGS (SGS Test Automation Technology, 2018) to record measurements sampled at rates less than 20 Hz. CyFlex is used to measure both the air mass flow rate and the fuel mass flow rate as well as several other general engine systems measurements. The general engine system parameters include intake manifold pressure, exhaust manifold pressure, oil and coolant pressure and flow rates. Exhaust composition including unburnt hydrocarbons, nitrogen oxides, CO_2 and CO was collected with the CyFlex system. The CyFlex system was also used to calculate targeted intake manifold pressures, fuel flow rates, and exhaust manifold pressures. The CyFlex system handles control of the basic engine functions including oil and coolant flow rates and temperatures. Testing on the SCRE engine is conducted using the CyFlex system to acquire data from both low-speed measurement system and the AVL IndiCom high-speed data acquisition system.

3.3 High-Speed Measurement

The AVL IndiCom data acquisition (IndiCom Indicating Software, 2019) system acquires data at a sample rate above 80kHz. The increase sample rate was used to collect measurements in a crank synchronous protocol. The system collects in-cylinder pressure in addition to the intake manifold pressure and exhaust manifold pressure. The data generated by the AVL system was used in GT-Power to estimate in-cylinder conditions for calculations of LFS, AFT and AI. The system uses a combination of AVL and Kistler piezoelectric and piezo resistant sensors to measure the in-cylinder pressure and the intake manifold and exhaust manifold pressure. The built-in thermodynamic pegging process was used to peg cylinder pressure.

3.4 SCRE Engine Testing

Engine testing was conducted by collecting of DoE data. The data collected includes the values recorded with the low-speed and high-speed data systems. The testing varies lambda, energy flow and centroid. The DoE was bounded in lambda space by combustion stability limits. Figure 3.1 Operating Space Combustion Limits illustrates how the rich and lean combustion stability limits are change as the centroid of heat release moves from and advance combustion phasing to a retarded combustion phasing.

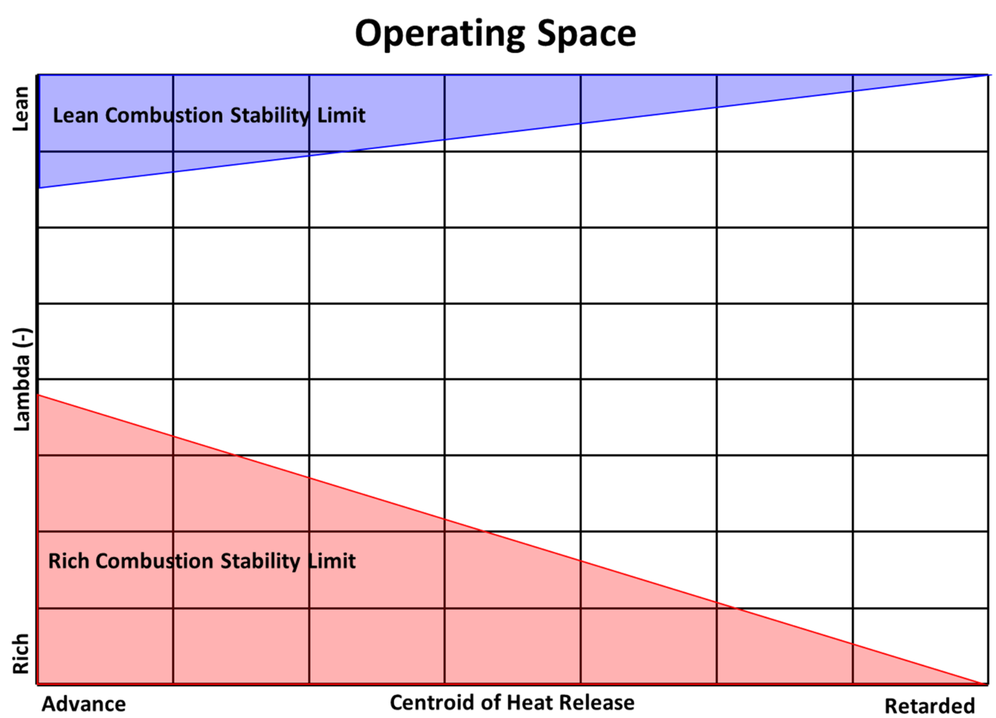

Figure 3.1 Operating Space Combustion Limits

The limits applied to the energy flow was based on MCE power delivery requirements. The centroid range was subdivided into two ranges to allow robust unattended operation. The limitations placed on lambda, energy flow and centroid results in the DoEs being a series of 3 factors, face center DoEs. The addition of repeat conditions in the data collecting for evaluation of measurement equipment drifts during testing resulted in over 150 data points being collected. Table 3.1 Sample DoE Sequence shows the layout of the DoE sequence for the upper energy flow level. The sequence was repeated for the middle and lower energy flow level.

Table 3.1 Sample DoE Sequence

Centroid Target	**Lambda Target**	**Energy Flow Target**
Advance Centroid	Rich Lambda	Upper Energy Flow
Middle Centroid	Rich Lambda	Upper Energy Flow
Retarded Centroid	Rich Lambda	Upper Energy Flow
Advance Centroid	Rich Lambda	Upper Energy Flow
Advance Centroid	Middle Lambda	Upper Energy Flow
Middle Centroid	Middle Lambda	Upper Energy Flow
Retarded Centroid	Middle Lambda	Upper Energy Flow
Advance Centroid	Middle Lambda	Upper Energy Flow
Advance Centroid	Lean Lambda	Upper Energy Flow
Middle Centroid	Lean Lambda	Upper Energy Flow
Retarded Centroid	Lean Lambda	Upper Energy Flow
Advance Centroid	Lean Lambda	Upper Energy Flow

The robust dataset that was generated allowed the application of 2nd order regression analysis to develop robust correlations between independent factors of lambda, energy flow and centroid with the responses of Ignition Delay Parameter and GIMEP in addition to general engine performance parameters.

3.5 SCRE Data Processing

The data generated by the SCRE engine was processed using MATLAB. MATLAB is a software package developed by MathWorks (MATLAB, 2018). MATLAB allows the processing of large volumes of data with ease. The version of MATLAB that was used for the analysis was MATLAB 2013B. The function ‘regstat’ using a quadratic fit was used to generate correlations based on lambda, energy flow and centroid. The usage of second order regressions allows the fitting of data that is not linear which is common with engine performance data (LaPointe, 2014). The regressions generated by the SCRE are considered a pedigree dataset for comparison to the data generated by the MCE.

3.6 Multi Cylinder Test Data

Multi Cylinder Testing was used for robustness testing of the combustion recipes developed on the SCRE. Testing requires operating at steady state conditions for hundreds of hours to represent the conditions that a consumer subjects engines to. The robustness testing allows the collection of hundreds of data points at the same operating condition. The same low-speed and high-speed data acquisition systems are used for MCE testing that were employed in SCRE testing. The engine control system was actively controlling the engine resulting in operating in a state that satisfies all regulatory requirements. The data generated was mined to generate a subset that characterizes the cylinder-to-cylinder variation observed on the MCE. The performance parameters of Ignition Delay Parameter, GIMEP, lambda, energy flow and centroid. The sample size was selected that resulted in the standard deviation of the centroid for each cylinder to each a point of stability. Stability was defined as the point that the coefficient of variation was than 0.1. The data was evaluated to ensure that other performance parameters were consistent through the data set.

3.7 Evaluation Process

Once the data set was defined from the MCE testing the regressions generated with SCRE testing was used to evaluate the required changes in lambda and energy flow to generate the observed cylinder-to-cylinder variation. MathCad 15 (PTC Mathcad, 2019) and MATLAB 2013B were used for the evaluation. The regression equations that define the relationship between the independent factors and the responses of Ignition Delay Parameter and GIMEP were combined into a single equation. The single equation was configured so that the error produced for both responses are in the form of percent error. The final output of the single equation was the summation of the percent error for both responses. The minimize function in MathCad 15 was used to determine the values for lambda and energy flow that resulted in the least error for each cylinder. The results for each of the twelve cylinders of the MCE were used to generate boundary conditions for each cylinder in a twelve-cylinder MathCad 15 model. The MathCad 15 model used the regression equations generated in MATLAB 2013B from the SCRE testing to predicted overall engine performance for BSNOx, BTE and CO_2 emissions. The results from the MathCad 15 model were compared against the observed performance of the MCE as a means to validate the results. After the results are validated the MathCad 15 model were used to generate DoE results similar to those generated during SCRE testing. The corresponding results were loaded into the MATLAB 2013B processing tools used for SCRE testing to determine the optimal boundary conditions for meeting the regulatory emission limits and maximizing BTE.

The results from the optimization of the MCE model data were compared against the results generated during the SCRE testing to determine the net impact on BTE and CO_2 emission levels.

3.8 Return on Investment

The return on investment (RoI) for an analytical tool that evaluates the root cause of cylinder-to-cylinder variation is not clear as there is no had direct end market impacts. The cost of the tool development does not result in a marketable good. The tool however generates the ability to assign a cost of cylinder-to-cylinder variation. The assignment of cost to cylinder-to-cylinder variation provides the means of robustly modeling the RoI for any projects proposed for addressing cylinder-to-cylinder variation. The ability to determine how much value will be added to the final product will serve the basis for CFD analysis of the intake system and CFD modeling of design changes to address cylinder-to-cylinder variation. The value in the proposed analytical model is the ability to determine the benefit of reduced cylinder-to-cylinder variation for both the customer and the environment. The ability to provide a RoI calculations for work concerning cylinder-to-cylinder variation allows program management to make databased decisions. The ability to make databased decisions increases the ability to go forward with cylinder-to-cylinder variation reduction programs.

CHAPTER 4. RESULTS

4.1 Foundation

Addressing the Grand Engineering Challenge of Carbon Sequestration (NAE Grand Challenges for Engineering, 2018) comes in different forms. Capturing carbon once it has been released is the normal approach however keeping the carbon from being released from its original source also keeps the carbon from forming atmospheric CO_2. Improving IC engine BTE results in carbon not being released from the fuel source and into the atmosphere. Cylinder-to-cylinder variation decreases BTE (LaPointe, 2014). Developing a process to address cylinder-to-cylinder variation by using data generated on a SCRE will provide a more CO_2 efficient means relative to MCE testing. Characterizing the root cause of the cylinder-to-cylinder variation and the amount of additional CO_2 being generated by the reduction in BTE allows program management to allocate funds to address cylinder-to-cylinder variation.

The [redacted] for large-bore natural gas engines generates the data required to for the development of the analytical tool. The development of the analytical tool facilitates the RoI calculation for programs to reduce cylinder-to-cylinder variation without requiring unique testing. The analytical process was limited to exploring causes for cylinder-to-cylinder variation that were explored during the development process. The factors of lambda, energy flow and centroid were used during the development process therefore these factors were explored for the root cause of cylinder-to-cylinder variation.

4.2 Engine Testing

The foundation of engine develop is experimental testing (Heywood, 1988) (Taylor, 1985) (LaPointe, 2014). Large-bore natural gas engines develop combustion recipes on SCRE. SCRE testing is followed with MCE testing for validation of the combustion recipe. The test includes extended duration endurance testing in addition to combustion recipe validation testing. The extended testing facilitates the collection of data that can also characterizes the cylinder-to-cylinder variation on an MCE engine. The data collected on the MCE was summarized to quantify the typical combustion phasing variation from cylinder-to-cylinder. The data was collected during the standard data collection processed used during engine development. The fundamental relationships developed on the SCRE during development was used to evaluate the observed cylinder-to-cylinder variation on the MCE.

4.3 Multi-cylinder Testing

The data collected on the MCE involved several months of testing. The data collected was reduced to allow the characterizing of typical cylinder-to-cylinder variation. The performance parameters of centroid Ignition Delay Parameter and GIMEP are the key parameters for defining cylinder-to-cylinder variation. Table 4.1 Normalized Typical Variation below provides a summary of the variation between the twelve cylinders on a [redacted] MCE for centroid, Ignition Delay Parameter and GIMEP normalized by the mean value for each parameter.

Table 4.1 Normalized Typical Variation

	Centroid	Ignition Delay Parameter	GIMEP
Cylinder 1	0.999	0.989	0.987
Cylinder 2	0.932	0.957	1.003
Cylinder 3	0.900	0.974	1.022
Cylinder 4	0.953	0.983	1.010
Cylinder 5	1.070	1.032	0.978
Cylinder 6	0.967	0.996	0.995
Cylinder 7	1.169	1.056	1.000
Cylinder 8	0.978	1.003	0.996
Cylinder 9	1.050	1.022	0.982
Cylinder 10	1.044	1.019	1.000
Cylinder 11	0.940	0.987	1.024
Cylinder 12	0.997	0.982	1.001

As illustrated in Table 4.1 Normalized Typical Variation each of the twelve cylinders produce different values for the key parameters. The variation of centroid was 25% of the mean with a 10% variation in GIMEP. The variation in Ignition Delay Parameter of 10% of the mean is an indication of the variation of lambda across the twelve cylinders. The variation clearly indicates that the boundary condition for each cylinder was not the same.

4.4 Single Cylinder Testing

The SCRE data was collected during part of the standard combustion recipe development [redacted]. The data was then reprocessed to generate a response curve of the key parameters of Ignition Delay Parameter and GIMEP. The data was reprocessed using the MATLAB 2013B tool develop to processing SCE test data. The tool optimizes engine BTE at legal emission limits and generates response curves with respect to the three independent factors used during the DoE testing. Figure 4.1 Key Parameters Response was generated with MATLAB 2013B to illustrates the response curves.

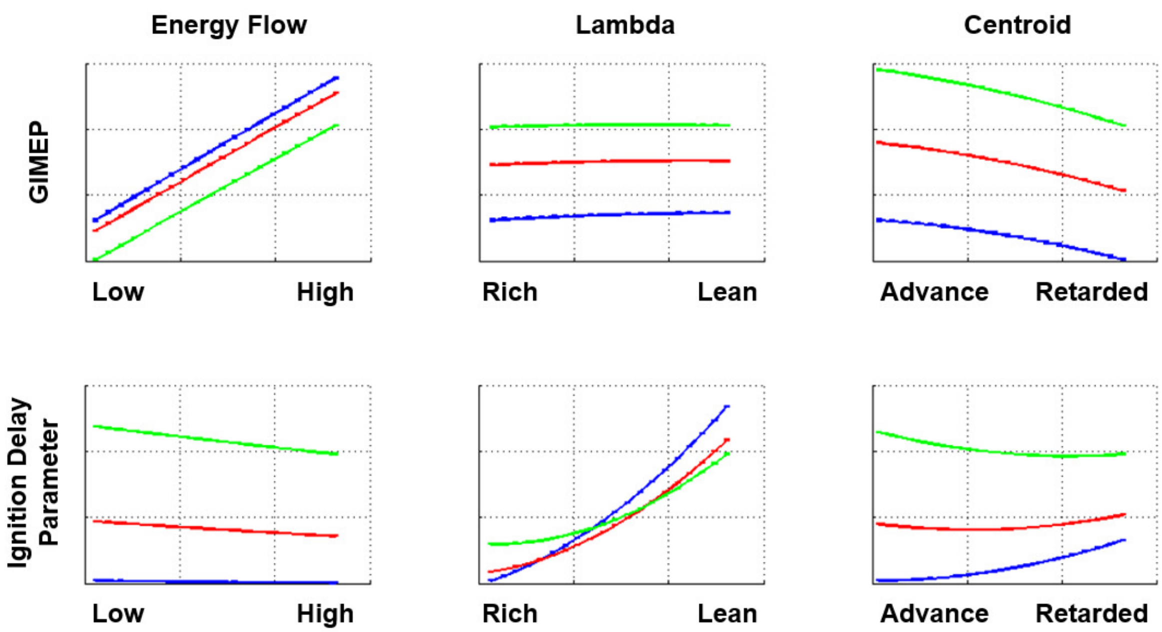

Figure 4.1 Key Parameters Response

The three lines in Figure 4.1 Key Parameters Response represent response curves with 95% confidence intervals for the swept variables with the two remaining variable at their numerical minimum (blue) mean (red) and maximum (green) values. The confidence intervals blur together with the trendline when all three are plotted together. Starting on the left and proceeding to the right the plots illustrate the response of GIMEP (top) and Ignition Delay Parameter (bottom) with respect to the swept independent factor of energy flow, lambda, and centroid. The Ignition Delay Parameter plot with respect to lambda illustrates the complex interaction between the three independent factors and how simple first order regressions would not capture the true relationship.

4.5 Modeled Boundary Conditions

The relationships established with the MATLAB 2013B code was programed into MathCad 15. MathCad 15 was used to generate the boundary conditions for each of the twelve cylinders by using the built-in minimize function. Table 4.2 Normalized MCE Boundary Conditions shows the normalized values from the minimize function for each cylinder and the scaling factor.

Table 4.2 Normalized MCE Boundary Conditions

	Lambda	**Energy Flow**	**Scaling Factor**
Cylinder 1	0.998	0.987	0.986
Cylinder 2	0.993	0.998	0.991
Cylinder 3	0.996	1.012	1.007
Cylinder 4	0.997	1.004	1.001
Cylinder 5	1.005	0.985	0.990
Cylinder 6	0.999	0.993	0.992
Cylinder 7	1.011	1.016	1.026
Cylinder 8	1.000	0.994	0.994
Cylinder 9	1.003	0.988	0.991
Cylinder 10	1.004	1.003	1.007
Cylinder 11	0.999	1.020	1.017
Cylinder 12	0.998	1.000	0.997

The lambda variation is in the range of 2% with a variation in energy flow in the range of 3.5%. The variation of energy flow and lambda were combined to generate a scaling factor for the charge flow differences between each cylinder. Table 4.2 Normalized MCE Boundary Conditions third column shows the scaling factors which has a variation in the range of 4%. The original operating points collected during SCRE testing were scaled down. The overall range was reduced to ensure the data was not being extrapolated past the range that the original dataset. The values above the mean were reduced by the percent of variation on the MCE above the mean.

The values below the mean were increased by the percent of variation on the MCE below the mean. The scaled DoE was used in conjunction with normalized variation values to predict the output for each cylinder. The output of each cylinder was then average using the scaling factor to account for the charge flow difference between each cylinder.

The results of the MathCad 15 calculations were compiled into the correct format to use the MATLAB 2013B SCRE data processing tool. The MATLAB 2013B tool was used to generate the optimal BTE at various emission levels as were conducted for the original SCRE data. Figure 4.2 Optimized BTE at various BS NOx levels illustrates the trend of BTE across a range of BS NOx levels. The blue line shows the results for the SCRE with 95% confidence intervals.

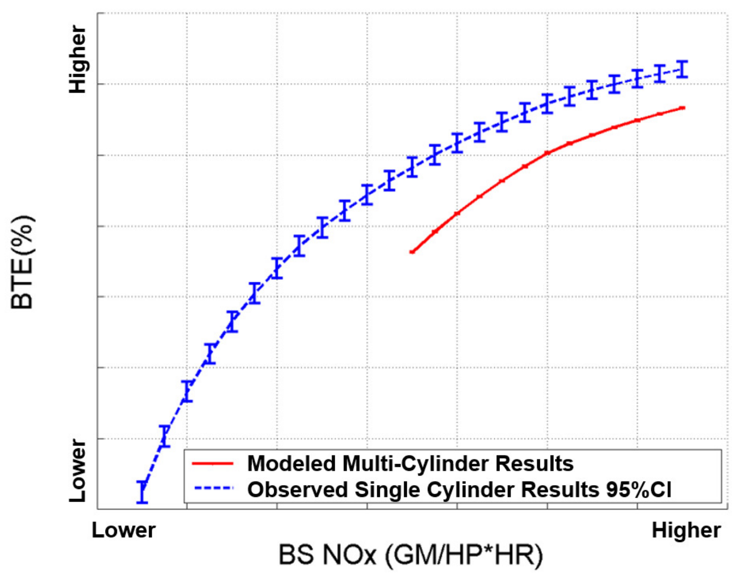

Figure 4.2 Optimized BTE at various BS NOx levels

The red line illustrates the model results for the MCE applications. Comparing the results of the two optimizations at legal emission levels resulted in the cylinder-to-cylinder variation reducing BTE by 0.45% relative to the SCRE performance.

4.6 Impact on Carbon Emissions

The development of the analytical process to evaluate the root cause of the cylinder-to-cylinder variation provides value by predicting reduction in BTE. The reduction in BTE also provides for the reduction in CO_2 emissions as illustrated in Figure 4.3 $BSCO_2$ vs Brake Thermal Efficiency. In Figure 4.3 $BSCO_2$ vs Brake Thermal Efficiency the blue line shows the brake specific CO_2 emissions as a function of the BTE of a natural gas engine with the typical natural gas consumed in North America.

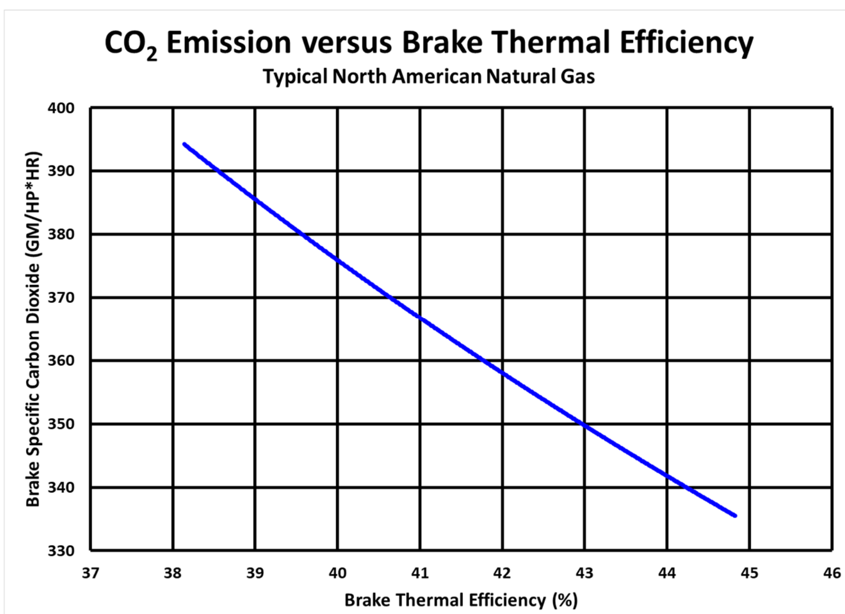

Figure 4.3 $BSCO_2$ vs Brake Thermal Efficiency

The 0.045% reduction in BTE associated with cylinder-to-cylinder variation results in roughly two-grams per horsepower-hour reduction in CO_2 emissions. two-gram reduction may seem small but when compounded by the near 2700 horsepower required for a two-megawatt generator that results in a reduction of over 43 metric tons of CO_2 per year.

CHAPTER 5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The analytical process developed using both MathCad 15 and MATLAB 2013B to process SCRE test data has proven a method to evaluate the likely boundary conditions for each cylinder of a MCE. The application of the built-in regression function of MATLAB 2013B has proven robust during normal engine development data process and in this new analytical approach. The application of MathCad 15 to use the regression from MATLAB 2013B and the built-in solving functions allowed the determination of the likely boundary conditions using the three key performance parameters of Lambda, Energy Flow and Centroid.

Lambda, Energy Flow and Centroid were selected as the parameters to study as they are used during the standard development process. The additional parameters of swirl and pressure delta across each cylinder were excluded for this study. The data available for this study did not include variation of swirl levels or the pressure delta across the engine. The excluding of swirl and pressure delta originally caused concern on the ability of the analytical approach to converge. The results from the analytical study using Lambda, Energy Flow, and Centroid illustrated that these variables allowed the process to converge. The resulting variation associated with the converged results are within expectations for the variation (Choi, Hwang, Poompipatpoing, Lee, & Kim, 2012).

5.2 Conclusion

The predicted variation of ~2% for lambda and ~3.5% variation in total charge flow across the MCE resulted in ~0.045% reduction in BTE. The resulting reduction in BTE increase CO_2

emissions by 2 grams per horsepower for every hour of engine operation. Primary power applications are assumed to operate 8000 hours a year at rated power (Saad, 2014). The impact of the reduction in BTE and increase in CO_2 emission results in a two-megawatt prime power generation application generates roughly 43 metric tons of additional CO_2 a year. The typical passenger vehicle in the United States produces roughly 4.6 metric tons of CO_2 a year. Therefore, the cylinder-to-cylinder variation in the two-megawatt application is equivalent to an additional nine cars on the road. The reduction in fuel rate using 0.0053 metric tons of CO_2 per Therm of natural gas results in a reduction of 8150 Therms of natural gas used per engine per year.

The analytical approach proposed has provided a means to determine both the environment impact and the fuel cost to end users without requiring additional engine testing. The value of this approach allows Program Leaders to evaluate total cost of ownership (TCO) impact of cylinder-to-cylinder variation. The knowledge allows Program Leaders to fund additional analysis to reduce cylinder-to-cylinder variation in the framework of TCO models. The ability to understand cylinder-to-cylinder variation in the framework of TCO is key to engine development to reduce cylinder-to-cylinder variation. The absence of the ability to frame cylinder-to-cylinder variation in the framework of TCO has reduced funding to address the cylinder-to-cylinder variation.

5.3 Recommendations

The exclusion of swirl and pressure delta across the power cylinder is an area that should be explored. The approach did converge for results for the boundary condition of each cylinder however it does not negate the possibility that the response curves of swirl or pressure delta across the power cylinder could be similar to those for parameters already studied. Future studies need to focus on the effects of swirl and pressure delta. These parameters can be directly measured however there are interactions between pressure delta and swirl therefore the net result is less understood. The aforementioned interactions are a product of the pulse dynamics of both the intake and exhaust systems. The quantification of the pulse dynamics requires additional measurements on the MCE application which are not currently available.

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