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Energy Research and Development Division

FINAL PROJECT REPORT

Heavy-Duty Natural Gas Near-Zero NOx Engine Development

Cummins ISX15-G Engine

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Heavy-duty Natural Gas Near Zero NOx Engine Development is the final report for the Low NOx Natural Gas Engine Development for Heavy-Duty Vehicles project (Contract number: 500-12-012) conducted by Cummins, Inc. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

In the South Coast Air Basin, onroad heavy-duty diesel vehicles are currently the largest source of oxides of nitrogen (NOx) emissions — precursors to ozone formation and a human health risk factor. The development and commercialization of a new generation of on-road heavy-duty engines that achieve NOx emission levels far below regulated standards is a critical component for achieving the federal ambient air quality standards in the South Coast Air Basin, improving air quality throughout California, and safeguarding the health of Californians.

Cummins Inc. is a global leader in the design, development and sales of diesel and natural gas engines. Through a joint venture with Westport, Cummins manufactured and marketed state-of-the-art on-road 9-liter and 12-liter natural gas engines in increasing numbers and are rounding out the lower end of the power range with the development of a 6.7-liter engine. The development of these products was accomplished through funding support of the South Coast Air Quality Management District, the California Energy Commission, and the Southern California Gas Company.

Cummins is now undertaking a research effort to develop a heavy-duty natural gas engine designed specifically for natural gas operation. The research captured in this report has demonstrated that a well-designed heavy-duty natural gas engine can match a diesel engine in performance and has the capability to deliver extremely low emissions with a cost effective after treatment system. This report summarizes the results of that development effort with ambitious targets for emissions, efficiency, performance, and robustness. With technology additions, a heavy-duty natural gas engine can be nearly as efficient as a modern diesel engine, but with the advantage of near-zero tailpipe emissions and significantly lower greenhouse gas emissions.

Keywords: NOx emissions, natural gas, engines, development, heavy-duty, vehicles

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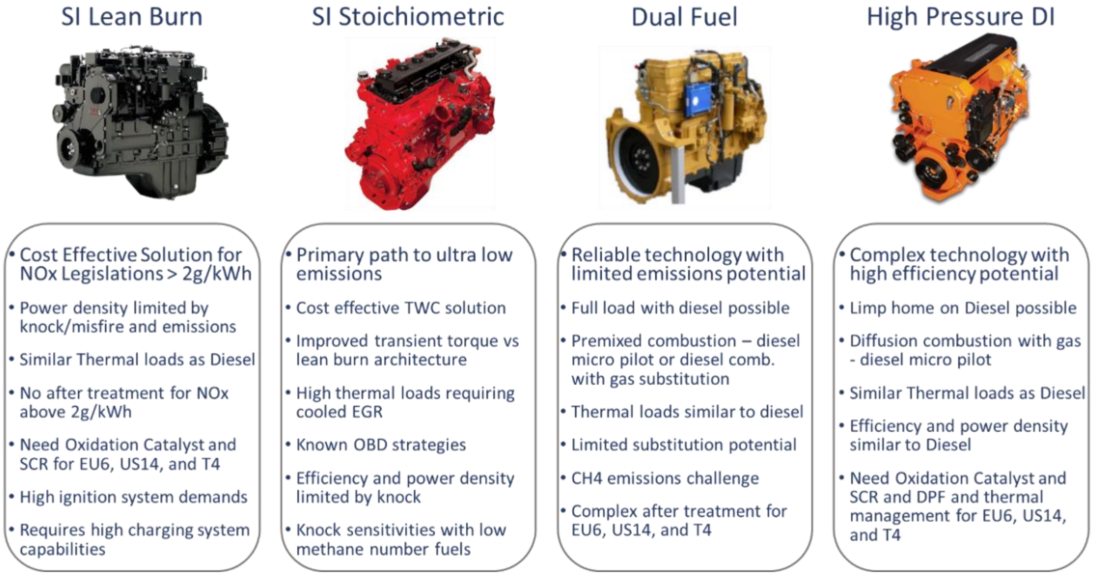
Introduction

To protect people and the environment, the United States Environmental Protection Agency sets air quality standards that define the maximum amount of various pollutants that can be present in outdoor air. Among these pollutants are oxides of nitrogen (NOx) which contribute to the formation of ozone, a main ingredient in smog, that can aggravate or cause respiratory problems like asthma, particularly in children and the elderly. NOx can also affect the environment through the formation of acid rain. As a result, California's air quality and climate change policies have promoted the development and use of strategies and technologies to reduce NOx emissions.

According to the California Air Resources Board, around 80 percent of NOx emissions in California come from cars, trucks, and other mobile sources powered by fossil fuels. In the South Coast Air Basin, heavy-duty on-road diesel vehicles are currently among the top ten sources of NOx. One way to mitigate this problem is through adoption of near-zero NOx emission natural gas engines.

Natural gas as a fuel for heavy-duty engines is receiving more interest due to its potential to reduce criteria pollutant and greenhouse gas emissions. However, natural gas engines in this class typically are conversions of diesel engines mainly driven by market volumes that have not yet reached levels that justify the expense in design of a dedicated to natural gas from the ground up. The market prospects for heavy-duty natural gas engines suggests that a fundamental assessment of engine architecture (structure and purpose) and system design (implementation and operation) should be performed to reach their full potential. Figure ES-1 summarizes Cummins' assessment of four heavy-duty natural gas engine architectures.

Figure ES-1: Architecture Options for Heavy-Duty Natural Gas Engines



SI Lean Burn

- Cost Effective Solution for NOx Legislations > 2g/kWh
- Power density limited by knock/misfire and emissions
- Similar Thermal loads as Diesel
- No after treatment for NOx above 2g/kWh
- Need Oxidation Catalyst and SCR for EU6, US14, and T4
- High ignition system demands
- Requires high charging system capabilities

SI Stoichiometric

- Primary path to ultra low emissions
- Cost effective TWC solution
- Improved transient torque vs lean burn architecture
- High thermal loads requiring cooled EGR
- Known OBD strategies
- Efficiency and power density limited by knock
- Knock sensitivities with low methane number fuels

Dual Fuel

- Reliable technology with limited emissions potential
- Full load with diesel possible
- Premixed combustion – diesel micro pilot or diesel comb. with gas substitution
- Thermal loads similar to diesel
- Limited substitution potential
- CH4 emissions challenge
- Complex after treatment for EU6, US14, and T4

High Pressure DI

- Complex technology with high efficiency potential
- Limp home on Diesel possible
- Diffusion combustion with gas - diesel micro pilot
- Similar Thermal loads as Diesel
- Efficiency and power density similar to Diesel
- Need Oxidation Catalyst and SCR and DPF and thermal management for EU6, US14, and T4

SI = spark ignited; DI = direct injection; g/kWh = grams per kilowatt-hour; SCR = selected catalytic reduction; TWC = three-way catalyst; EGR = exhaust gas recirculation; OBD = on-board diagnostics; CH4 = methane; DPF = diesel particulate filter.

Source: Cummins, Inc.

Based on its assessment, Cummins chose the stoichiometric cooled exhaust gas recirculation heavy-duty natural gas engine architecture as the preferred approach. The architecture is characterized by good efficiency potential, a cost-effective engine system, a cost-effective and simple after treatment with known on-board diagnostic strategies, and ability to deliver diesel-like power, torque, and transient response. Recent market introduction of advanced stoichiometric, cooled exhaust gas recirculation medium, heavy-duty, and heavy heavy-duty natural gas engines by Cummins-Westport, Scania, and Daimler, among others, support the above assessment and conclusion.

Given the selected architecture, the challenge was then to design the overall system of the engine and after treatment to meet an ambitious set of project objectives. These objectives are directed by both the requirements of the project as well as Cummins internal goals:

- Emissions of 0.02 grams per brake horsepower-hour (g/bhp-hr) NOx and less than 10 parts per million ammonia without increasing after treatment system cost.
- Cycle average brake thermal efficiency improved by more than 10 percent over a baseline engine with capability to increase efficiency another 10 percent to 15 percent through appropriate technology integrations.
- Demonstrate ability to match diesel power and torque ratings.
- Diesel-like transient performance.

The resulting system design can be scaled over the entire 6.5-liter to 15-liter engine displacement range. The demonstration platform chosen for this project was based on the Cummins ISX15 heavy-duty engine. Table ES-1 shows select ISX15 engine specifications.

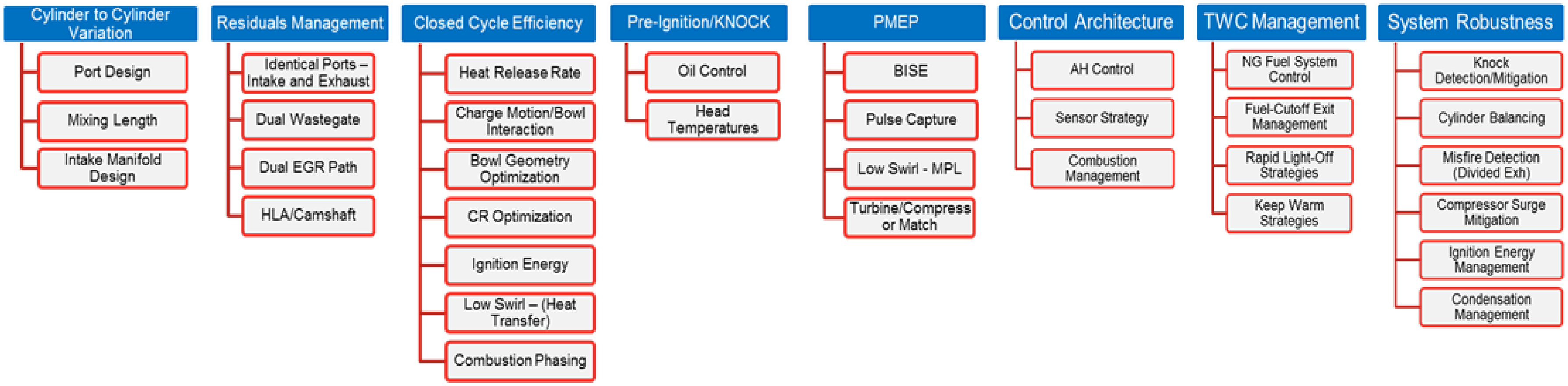
For the proposed engine, there were no planned design changes for the main cylinder block. Some weight and cost reductions can result from accounting for the lower peak cylinder pressure from natural gas combustion compared to diesel. These benefits can be assessed through computational analysis and have been left out of scope for this project. The focus areas for the project are highlighted in Figure ES-2, and their impact on system design, especially air and fuel handling and the combustion system.

Table ES-1: ISX15 Engine Specifications

Displacement	15 Liter
Configuration	Inline 6
Bore x Stroke	137x169 millimeters
Power	Up to 600 horsepower (447 kilowatts)
Torque	Up to 2050 pound feet (2779 Newton meter) at 1200 revolutions per minute

Source: Cummins, Inc.

Figure ES-2: Research Program Focus Areas



Source: Cummins, Inc.

Project Purpose

The purpose of this project was to develop a near-zero NOx and viable natural gas alternative for heavy heavy-duty diesel trucks, which generated about 80 percent of truck and bus emissions in 2014 and are anticipated to generate about 70 percent in 2023 (Table ES-2).

Table ES-2: Data from South Coast Air Quality Management District 2012 Air Quality Management Plan

NOx Emission Source Category	2014 tons/day	2023 tons/day
Heavy Heavy-Duty Gas Trucks	1.02	0.96
Heavy Heavy-Duty Diesel Trucks	76.43	32.63
Diesel Urban Bus	13.4	11.03
Gas Urban Bus	0.76	0.70
Diesel School Buses	2.15	1.81
Gas Other Buses	0.86	0.53
Total	94.62	47.66

Source: Cummins, Inc.

Focusing on the vehicle category with the greatest emissions contribution to the inventory provides the most likely path to achieving the project goal of a 90 percent reduction in NOx.

Project Process

The focus of this project entailed development of an advanced 15-liter natural gas engine that could demonstrate tailpipe emissions of 0.02 g/bhp-hr NOx, 0.01 g/bhp-hr particulate matter, 0.14 g/bhp-hr non-methane hydrocarbons, 15.5 g/bhp-hr carbon monoxide, and less than 10 ppm ammonia. In addition, the engine will be 10 percent more efficient compared to current stoichiometric cooled exhaust gas recirculation natural gas engines. This will substantially address the secondary objective of the project: to show minimal or zero fuel economy penalty compared to 2010 United States Environmental Protection Agency and California Air Resources Board-certified diesel engines. Further improvements were aimed at performance, durability, and reliability attributes to be substantially similar to Cummins' class leading diesel products. As mentioned previously, this led to selecting the stoichiometric cooled exhaust gas recirculation architecture as a basis to build on. Innovations have been pursued in various engine subsystems and controls to determine the best overall architecture and integrated system design.

Project Results

This project resulted in the first purpose-designed heavy-duty natural gas engine, compared to previous diesel engine-based natural gas engine designs. The project demonstrated significant advances in these engine performance characteristics:

- Improved scavenging and low in-cylinder residual gases.
- Improved cylinder-cylinder and cycle-cycle variability.

- Improved robustness.
- Reduced cylinder head temperatures.
- Exhaust, exhaust gas recirculation, and turbine designed for high temperature.
- Improved transient reference tracking.
- Improved brake thermal efficiency.
- Improved three-way catalyst architecture.
- Improved exhaust gas recirculation and air handling system.

As a result of these improvements, all program objectives were met or exceeded, in some cases considerably:

- Emissions: cold/hot Federal Test Procedure NOx: 0.0030 g/bhp-hr.
- Brake specific fuel consumption: Same as diesel, approximately 10 percent lower brake thermal efficiency.
- Brake thermal efficiency improved by 12 percent compared to ISX12-G engine.
- 45 percent reduction in after treatment cost (on a per liter displacement basis) compared to the 8.9-liter ISL-G Near-Zero engine.
- Torque density at 1,000 revolutions per minute improved by 74 percent compared to ISX12-G engine.
- Peak power density improved by 20 percent compared to ISX12-G engine.
- Significantly more robust hardware system and software controls provide significant room for further improvements or protection against off-nominal conditions (for example, fuel quality, or extreme environmental conditions).

Benefits to California

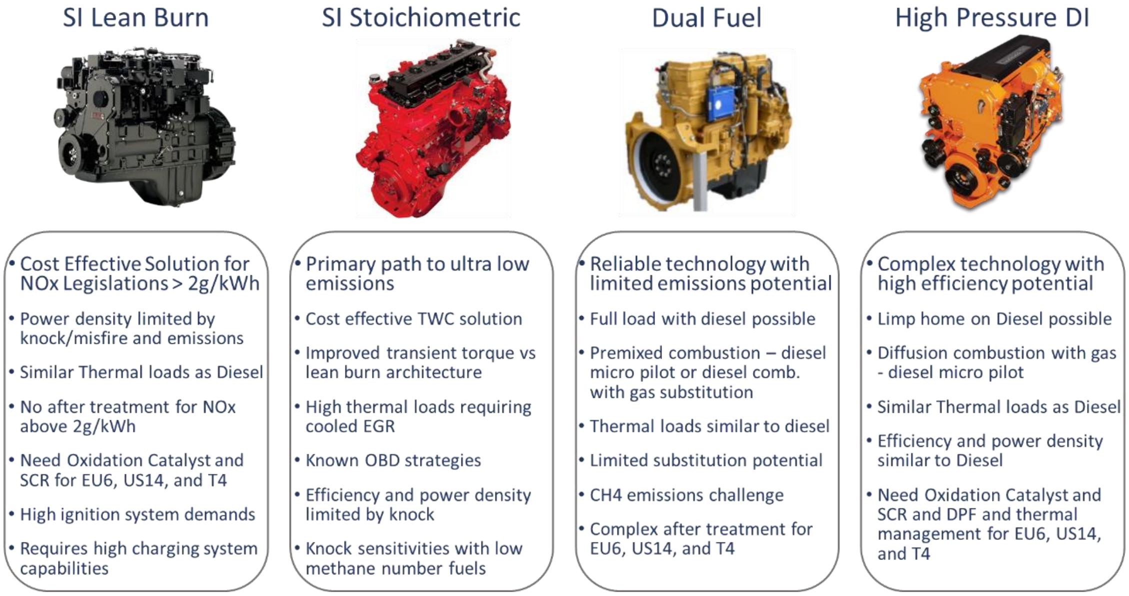
When new Cummins natural gas engines are introduced to the North American market, they will leverage the design elements developed under this project. The engines will be certified to comply nationally with the "near zero" or 0.02 g/bhp-hr NOx standard. Equally important, these engines will perform just like a diesel engine and be very efficient and reliable. The improved performance will provide an overall package that is much more attractive to users compared to currently available natural gas engines. Also, by offering a more competitive, low-emission engine, Cummins will help reduce air pollutants by displacing high emission diesel engines and help California reach its emission reduction goals.

CHAPTER 1:
Technical Approach

The purpose of this project was to develop an advanced 15 liter (L) natural gas engine that would demonstrate tailpipe emissions of 0.02 grams per brake horsepower-hour (g/bhp-hr) of oxides of nitrogen (NO_x), 0.01 g/bhp-hr particulate matter (PM), 0.14 g/bhp-hr non-methane hydrocarbons (NMHC), 15.5 g/bhp-hr carbon monoxide (CO), and less than 10 parts per million (ppm) ammonia (NH_3). In addition, the engine would be 10 percent more efficient compared to current stoichiometric cooled exhaust gas recirculation (SEGR) natural gas engines. Achieving this would substantially address the secondary objective of the project: to show minimal or zero fuel economy penalty compared to 2010 United States Environmental Protection Agency (USEPA) and California Air Resources Board (CARB) certified diesel engines. Further improvements are aimed at performance, durability, and reliability attributes so as to be substantially similar to Cummins' class leading diesel products.

Cummins examined four heavy-duty natural gas engine architectures (Figure 1): spark ignition lean burn, dual fuel, high pressure direct injection, and spark ignition stoichiometric.

Figure 1: Architecture Options for Heavy-Duty Natural Gas Engines



SI Lean Burn	SI Stoichiometric	Dual Fuel	High Pressure DI
• Cost Effective Solution for NOx Legislations > 2g/kWh • Power density limited by knock/misfire and emissions • Similar Thermal loads as Diesel • No after treatment for NOx above 2g/kWh • Need Oxidation Catalyst and SCR for EU6, US14, and T4 • High ignition system demands • Requires high charging system capabilities	• Primary path to ultra low emissions • Cost effective TWC solution • Improved transient torque vs lean burn architecture • High thermal loads requiring cooled EGR • Known OBD strategies • Efficiency and power density limited by knock • Knock sensitivities with low methane number fuels	• Reliable technology with limited emissions potential • Full load with diesel possible • Premixed combustion – diesel micro pilot or diesel comb. with gas substitution • Thermal loads similar to diesel • Limited substitution potential • CH4 emissions challenge • Complex after treatment for EU6, US14, and T4	• Complex technology with high efficiency potential • Limp home on Diesel possible • Diffusion combustion with gas - diesel micro pilot • Similar Thermal loads as Diesel • Efficiency and power density similar to Diesel • Need Oxidation Catalyst and SCR and DPF and thermal management for EU6, US14, and T4

SI = spark ignited; DI = direct injection; g/kWh = grams per kilowatt-hour; SCR = selected catalytic reduction; TWC = three-way catalyst; EGR = exhaust gas recirculation; OBD = on-board diagnostics; CH4 = methane; DPF = diesel particulate filter.

Source: Cummins, Inc.

The appropriate architecture selection had to be made in the context of expected timing of market introduction, product platform life, and anticipated market and regulatory drivers. In this context, the expected architecture selection drivers were:

- Efficiency or fuel cost per mile.
- Engine system acquisition cost and total cost of ownership.

- Greenhouse gas emissions (carbon dioxide and methane).
- Criteria pollutants, specifically tailpipe oxides of nitrogen (NOx) capable of meeting limits of 0.02 grams/brake horsepower-hour (g/bhp-hr).
- Diesel-like performance (power and torque, transient response).

Given these drivers, the following general statements can be made for the architecture options identified in Figure 1:

- Spark ignition lean burn is incapable of delivering diesel-like performance and involves high after treatment system cost and complexity.
- Dual fuel has very high after treatment system cost and complexity, high engine system acquisition cost, and poses a potential greenhouse gas challenge due to methane emissions.
- High pressure direct injection has high engine system acquisition cost and very high after-treatment system cost and complexity, but also has the highest efficiency potential.
- Spark ignition stoichiometric is able to meet all anticipated requirements but is not the ideal option in terms of efficiency.

The assessment led to selecting the stoichiometric cooled exhaust gas recirculation (SEGR) heavy-duty natural gas engine architecture as a basis to build on. Innovations have been pursued in various engine sub-systems and controls to determine the best overall architecture and integrated system design. Subsystems under consideration include:

- Combustion system.
- Cylinder head and valve train.
- Fuel system.
- Air handling including turbo charging and exhaust gas recirculation (EGR).
- After treatment system
- Control system.
- Ignition system.

The powertrain is an integrated system that must deliver a range of customer requirements to successfully penetrate the marketplace, and it is appropriate to discuss the optimum architecture options by focusing on some of the more critical aspects of engine layout as fundamental drivers for cost, performance, emissions, durability, reliability, and efficiency for heavy heavy-duty (HHD) natural gas engines.

Natural Gas Engine Technology Status

Virtually all on-road spark ignited (SI) engines today operate under homogeneous charge conditions. Emissions regulations have long forced homogeneous charge SI engines to operate at stoichiometry (in which the air-to-fuel ratio is such that exactly enough air is provided to completely burn all of the fuel). To maintain stoichiometric operation under all load conditions, SI engines are throttled to ensure the appropriate amount of air enters the cylinder for the amount of fuel injected. Homogeneous charge engines are sensitive to engine knock. As the flame propagates through the cylinder mixture after ignition, the unburned, or end gases, are compressed. Under high pressure and temperature conditions this end gas will spontaneously ignite. This spontaneous combustion of the end gases results in a rapid and extreme pressure rise, causing an audible "knocking" sound.

Several important loss mechanisms reduce the efficiency of current natural gas engines compared to diesel engines: compression ratio limitations due to engine knock, engine throttling, and cylinder charge composition.

Engine thermal efficiency is a strong function of the compression ratio. Because diesel engines are not susceptible to knock, they can operate at a much higher compression ratio than a natural gas engine.[1] Typically, a diesel engine operates at a compression ratio of 18 or higher, while a natural gas engine is limited to a compression ratio of around 12.

Since diesel engines can operate with any level of excess air, they do not have a throttle. Natural gas engines, however, must operate at stoichiometry under all conditions and must therefore be throttled. Turbocharging of a natural gas engine limits throttling to light load conditions, but still results in greater pumping losses compared to diesel engines.

Cylinder charge composition also affects efficiency. Specifically, a larger ratio of specific heats, or γ, leads to greater efficiency. Dilution of the stoichiometric mixture with either air or EGR will increase efficiency. Air is the preferred diluent for highest efficiency but to maintain stoichiometry an inert diluent like EGR is the only option. Additional benefits of EGR dilution are the reduction in flame temperatures and resulting lower NOx emissions from the engine. However, EGR dilution has its limits as well. EGR temperatures are considerably higher than ambient temperature and will thus raise the cylinder charge temperature, leading to higher NOx emissions and increased propensity for engine knock. For this reason, current natural gas engines use cooled EGR. Peak EGR rates for natural gas engines are typically limited to 20 percent to 25 percent.

The combination of these loss mechanisms results in typical natural gas engines being approximately 15 percent to 20 percent less efficient than diesel engines. The fact that current natural gas engines are derived from diesel engines and as a result have embodied design decisions that are not optimal for natural gas also contributes to loss of efficiency.

Dilution Strategy

While lean burn technologies can operate with high catalyst reduction efficiencies that allow them to achieve a 0.20 g/bhp-hr NOx emission level, they add significant cost and complexity to the powertrain. It is also unclear whether this technology can successfully and cost effectively be applied to robustly achieve a NOx emission level of 0.02 g/bhp-hr in production. This is the primary reason to eliminate a lean burn architecture from consideration for this project. The choice therefore was to employ EGR to drive both the requisite NOx reductions as well as efficiency improvements.

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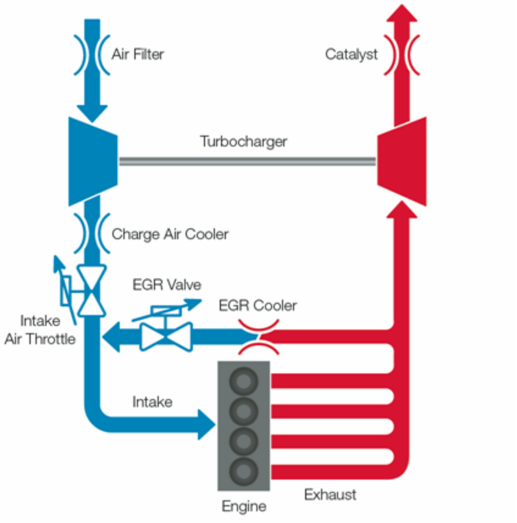
[1] In a piston engine, the compression ratio is the ratio between the volume of the cylinder and combustion chamber when the piston is at the bottom of its stroke and the volume of the combustion chamber when the piston is at the top of its stroke. For example, if the volume of the cylinder and combustion chamber is 1,000 cubic centimeters at the bottom of the stroke and 100 cubic centimeters at the top of the stroke, the compression ratio would be 10:1.

A number of EGR architecture options that could achieve efficiency benefits were considered before the researchers proposed a path of investigation and are discussed below.

High Pressure Loop Cooled Exhaust Gas Recirculation

Engine pressure differential is normally adverse at lower loads where an intake throttle is used to lower the air flow rate. This means the intake pressure is lower than the exhaust pressure and the engine is moving the intake charge from this lower pressure state to a higher-pressure state. This is the basic problem of a "pumping loss." At high loads, especially with turbocharged engines, it is possible to create a "favorable" pressure difference with a good turbocharger match, in which the intake manifold pressure is higher than exhaust manifold pressure. However, that makes it impossible to use a conventional EGR system that connects the exhaust manifold to the intake manifold, known as a "high pressure" EGR system because the pressure difference doesn't support EGR flow. This is the conventional EGR system approached used in the majority of diesel engines today. A schematic of the high-pressure loop EGR approach is shown in Figure 2.

Figure 2: High-Pressure Loop Exhaust Gas Recirculation Layout



Source: Cummins, Inc.

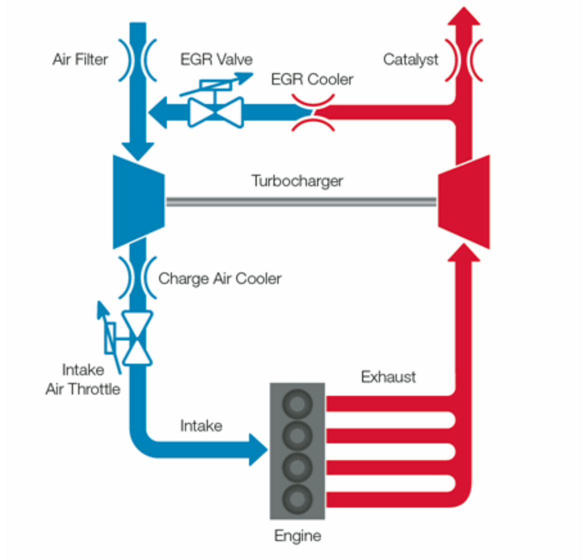
In this case, turbocharger designs which produce higher exhaust manifold pressures than intake manifold pressure are used to flow EGR at high torques and low speeds. On a diesel engine, this can be a good compromise between emissions and fuel economy; however, on a spark ignited engine that is sensitive to combustion knock, this high exhaust manifold pressure leads to a new problem known as high "internal residual." High internal residual represents hot exhaust that was not fully expelled from the cylinder and results in high in-cylinder temperatures contributing to combustion knock. This issue of applying cooled EGR in the "high pressure" method tends to also limit the engine designer's ability to consider "engine downsizing." Downsizing involves using a smaller engine displacement for a given application, and generally requires the engine to produce higher torque per liter of engine displacement to meet the original vehicle functionality. However, applying high pressure loop (HPL) cooled EGR makes increasing torque per liter from the engine more difficult due to the natural tendency to trap this hot exhaust gas.

Designs which allow for the application of cooled EGR in the absence of adverse engine pressure gradients have the opportunity to run more optimum combustion processes with higher efficiency and should be considered for natural gas applications.

Low-Pressure Loop Cooled Exhaust Gas Recirculation

An alternative to a HPL EGR engine system that offers breathing improvement potential is the "low pressure" loop (LPL) EGR system (Figure 3).

Figure 3: Low-Pressure Loop Exhaust Gas Recirculation Layout



Source: Cummins, Inc.

This type of EGR configuration removes exhaust gas after a turbocharger and introduces it upstream of the compressor thereby breaking the link between intake and exhaust manifold pressure differential and EGR flow. It is possible to flow substantial EGR fractions on such a system and still maintain a favorable pressure gradient on the engine over a broad range of engine operating conditions including low speed peak torque. Such systems have found their way into diesel applications for passenger cars and HHD engines in the past 10 years, and are now also options for advanced natural gas systems. The benefits such systems provide include lower pumping work combined with more favorable internal residuals at high load.

However, significant obstacles remain unresolved for natural gas applications. One of the most problematic issues in applying an LPL EGR system would be the propensity of water vapor, unburned hydrocarbons, and acid-forming exhaust gas species to condense in the intake system as the exhaust gases are cooled and further mixed with the cool intake air. This can cause myriad mechanical issues associated with erosion or corrosion of various intake system components including the turbo compressor, charge air coolers, sensors, fuel introduction systems, and valves. This is a particular concern for stoichiometric natural gas engines that have relatively high water concentrations compared to lean burn engines. The issues with intake system condensation must be considered as a trade-off against the potential efficiency gains that can be achieved by applying such a system.

These condensed components can also find their way into the combustion chamber where several issues arise. The exhaust condensate, primarily water, can enter the engine's cylinders in liquid form under certain conditions. The presence of the water can interfere with the ignition process by interacting with the spark plug or other ignition devices, and water can also impede the stable propagation of flames which is critical for low cyclic variability by interfering with cylinder turbulence and fuel/air mixing. Low pressure EGR systems can also exhibit difficulties with transient performance if the EGR quantity is desired to be changed quickly. These systems tend to have large volumes between the EGR valve and the location where the intake charge actually enters the engine. This large volume serves as a delay mechanism regarding certain transient engine maneuvers.

Air Handling Architecture Summary

For the purposes of this project, the primary interest was to develop a better understanding of the LPL option, since the HPL EGR option is already in production on the Cummins ISL-G and ISX12-C engines. However, HPL EGR options may also be considered in combination with advanced solutions for another major component of the air handling system, namely the turbo charger. For the turbocharger, an evaluation will be done on the use of an asymmetric turbine to allow EGR to be driven with reduced pumping losses. The project team will also investigate the use of pulse capturing devices, along with a split exhaust manifold, to aid in driving EGR. The use of an ejector to aid EGR flow shall be investigated. More experimental means of efficiently driving EGR will also be investigated.

The turbine used will likely be a wastegate unit, capable of withstanding high turbine inlet temperatures typically associated with stoichiometric natural gas engine operation. The benefit of using a variable geometry turbocharger (VGT) will be evaluated using modeling and there may be a small amount of experimental work with a VGT to validate the modeling results. An evaluation shall be made of the capability of the VGT to withstand the expected turbine inlet temperatures.

Excellent mixing of the air and EGR is required for this project. Different mixer designs will be evaluated using transient computational fluid dynamics modeling.

Advanced Control Systems

Controls are the software that integrates engine hardware components with feedback from sensors to ensure that the overall system is functioning as intended. The control system has to use the sensory feedback in the best way to ensure best system performance. In addition, it must ensure the natural gas engine system maintains system efficiency and emissions during its lifetime under various environmental factors as components begin to age.

To meet the highly challenging requirements that modern natural gas engines have to meet, the control system should be able to control the air-handling system (including turbo-charging systems) to ensure the proper amount of charge and EGR composition; actively coordinate the port fueling and spark systems to ensure efficient combustion; and accurately control the three-way catalyst (TWC) to ensure the best performance. With the introduction of advanced air-handling architectures, better control of these systems during transients leads to improved transient emission performance.

Proper design of the control system ensures that:

- The system meets performance requirements robustly over a wide range of operating conditions and environmental conditions.
- Proper tradeoffs are made with respect to the sensing and actuation systems to ensure the system can meet the market pressures of cost and reliability.
- Improved collaboration and coordination between the various subsystems is enhanced with advanced control concepts like real-time system optimization working to optimize the cost function of brake specific fuel consumption to help ensure that the degradation in one system is compensated for by active control of other components.
- The ability of the system architecture to be diagnosed is evaluated so that the systems can meet the stringent EPA/CARB regulations. This ensures that one of the major challenges in the introduction of high efficiency natural gas engines into the marketplace is well understood from the initial design stage onwards and challenges are proactively addressed.

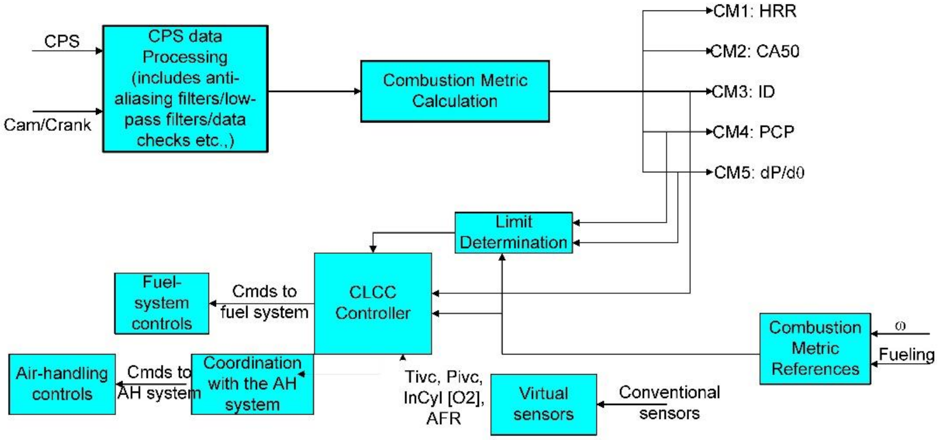
To substantially improve the performance of the TWC, a full-time high-accuracy lambda control using high performance wide-band O_2 sensing with dynamic range augmented response model was developed. In combination with a move to a more synchronized port fuel injection this will lead to improvements in transients lambda control. The objective is to achieve the improved NOx emissions transiently so higher overall engine performance can be achieved.

Cummins has a significant expertise with the closed-loop control of the combustion process using cylinder pressure sensors (CPS). Through various programs Cummins has developed combustion control algorithms to attenuate the impact of uncertainty (for example, flow uniformity in the intake manifold) to ensure reduced system variation. An example of an implementation of a combustion controls architecture using cylinder pressure sensor is shown in Figure 4.

Various low-cost cylinder pressure measurement systems based on either piezo-resistive or piezo-capacitive mechanisms are available commercially. But these sensors have been developed to meet the light-duty application specifications. Hence, low-cost cylinder pressure sensors meeting the durability targets of the heavy-duty applications were developed as a part of this project.

In this project, the CPS was used to control the combustion process to ensure that the centroid of combustion is robustly controlled while being as close as possible to optimum efficiency. The discrepancy in the dynamics of the port-fuel injected system and the air-handling dynamics to deliver EGR have traditionally led to transient NOx spikes which could be mitigated using the combustion control algorithm resulting in improved transient performance.

Figure 4: Controller Architecture for Control of Natural Gas Engine with Cylinder Pressure Sensors



Source: Cummins, Inc.

In addition, the combustion control process can be used to compensate for cylinder-to-cylinder imbalance, adjust for flow uniformity variations, and determine and respond to incipient knock.

Various knock algorithms published in the controls literature (for example, the stochastic knock detection algorithm) have been shown to improve the system efficiency. These algorithms were developed in this project to further improved engine efficiency.

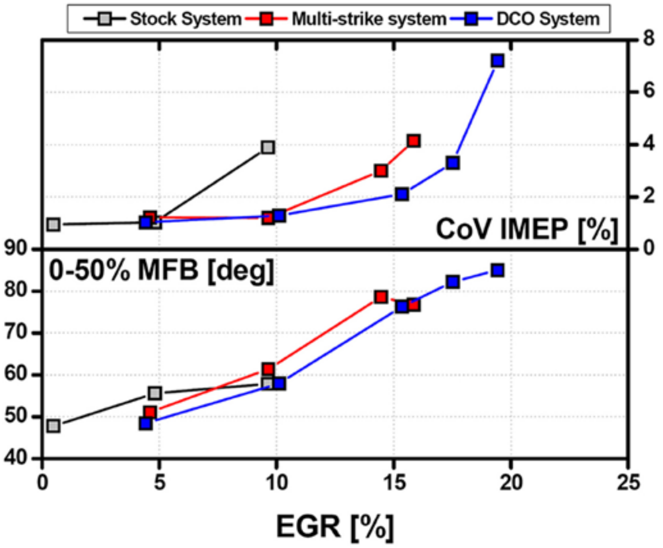
For improved fuel control, the controller was developed to provide engine synchronized port fuel injection. The software development for this project was based on the Core II OS and existing application code with modifications necessary to incorporate the new algorithms that were developed as a part of this program. Core II OS is the flagship operating system and software standards that Cummins uses in all its worldwide products.

One key feature of Cummins' controls development process is the extensive use of simulations to ensure that the behavior of the delivered closed-loop system meets the requirements. Hence, Monte-Carlo simulations are used to understand the system behavior when presented with variation. These results are utilized to help modify the design of the controller as needed.

Ignition Systems

The ignition system serves as a critical subsystem for high-efficiency natural gas engines. The ignition systems in widespread use today include conventional inductive systems, capacitive discharge systems, and hybrids of each. Inductive systems are well developed, inexpensive, and reliable. Capacitive discharge systems offer slightly more ignition energy at a substantial cost premium. However, it is clear from the research literature that charge dilution is a path toward higher efficiency, although dilute engines—whether they are based upon lean non-EGR systems or cooled EGR systems—are fundamentally limited by the ignition energy available to tolerate dilution (air or EGR). An example of the improvements that can be made with high energy systems is shown in Figure 5.

Figure 5: Stability and Burn Rate Results



2000 revolutions per minute / 2 bar brake mean effective pressure condition.

Source: Alger, et. al. (SAE 2011-01-0661)

The figure demonstrates the increase in EGR tolerance that can be obtained when increasing the energy level of the spark ignition system. Coefficient of variation (CoV) of indicated mean effective pressure (IMEP) is a measure of cycle-to-cycle combustion variation that is commonly used to assess engine stability. Clearly, the increasing energy level associated with the multi-strike and dual coil offset ignition systems depicted shift equivalent levels of combustion variation to higher EGR fraction levels. This is described as increased tolerance of EGR which comes with a commensurate increase in engine efficiency.

The need to increase ignition energy as a means to improve engine efficiency is driving innovations in ignition technology development; however, high energy ignition systems require improved control functionality to optimize their application. Also, high levels of ignition energy are not required under all operating conditions and, if not required, result in faster ignition system deterioration without performance benefit. Further, if the ignition system has deteriorated, through spark plug wear for example, a flexible ignition system may represent a tool for maintaining efficiency.

This type of flexibility in ignition system control requires system development to optimize the interaction between combustion system design, ignition system capability, and the resulting system performance. Any serious consideration of advanced natural gas engine development must include a review assessment and application of the appropriate high energy ignition system.

After Treatment System

While TWC catalytic converters are often described as passive and maintenance free, in reality this oversimplifies the need to precisely control the exhaust gas constituents and temperature to allow the TWC perform its intended function. The engine system and controls strategies necessary to enable near zero NOx emissions have already been described in this chapter. Additional challenges will be to meet the methane (CH_4) limits and to ensure tailpipe exhaust concentrations of NH_3 remain below 10 ppm. Solutions for CH_4 reductions were sought in both catalyst formulations as well as after treatment system design. One option considered was the development and integration of an advanced CH4-ethane oxidation catalyst mounted close to the exhaust manifold. NH_3 control will be achieved through catalyst formulations in combination with advanced air-fuel ratio control strategies.

Cummins has worked closely with Johnson Matthey, a longtime partner to Cummins Emissions Solutions. The Cummins Catalyst Technology and Emission Chemistry Laboratories include facilities for comprehensive, in-depth characterization and diagnostics of after treatment systems. The laboratory features a number of sophisticated, in-house developed bench reactor systems, providing unique insights into performance and degradation of catalysts and exhaust gas sensors, including transient conditions. The information developed serves as a basis for mathematical models development and validation, after treatment architecture selection, system design, as well as for catalyst diagnostics and postmortem analysis.

For this project, Johnson Matthey leveraged its knowledge of three-way catalysts from mobile applications, as well as its vast experience from supplying catalysts to stationary rich-burn compressed natural gas applications, globally. Johnson Matthey used its development resources, such as reactors and modeling tools, to provide catalyst recommendations for this project. Johnson Matthey supplied coated catalysts throughout the project, as well as provided support for post-mortem analysis of catalysts evaluated within this project.

Base Engine Design

Current heavy-duty natural gas engines are all derivatives of diesel engines. Unfortunately, this practice produces compromises that limit the potential of natural gas engines in on-road applications. Limitations include performance, reliability, durability, and cost. Cummins has addressed these limitations with gas-engine-specific designs for critical components. This section discusses some of the key opportunities.

Cylinder Head

To achieve optimum performance and durability, it is critical that the cylinder head is designed for gas-only operation. An important difference between gas and diesel operation comes from delivering the fuel premixed with the charge air. This difference alone demands significant changes to the port flow/charge motion, valve selection, cooling, structural limitations, crevice volume, and sensor locations. Using a component not designed for the purpose leads to reduced ability to meet essential customer and regulatory requirements.

Valve Train

Manipulating the intake and exhaust events is another area where optimized gas engine performance and reliability can be achieved. With a very low sensitivity to variations in charge flow, diesel engines have valve trains with limited flexibility. In contrast, gas engines manipulate power by changing the trapped mass of premixed fuel and air. Flexibility in the valve events can yield improvements in efficiency, transient response, diagnostics, and safety to name but a few. It is essential that design consideration be made for these systems from the very start to ensure an optimum cost-benefit tradeoff.

Fuel System

There are considerable differences in delivering a high-pressure gaseous fuel and liquid fuel. A well-integrated and purpose-built gaseous fuel system is required to meet performance and safety considerations. Even something as basic as pressure regulation becomes a non-trivial issue for mobile applications that experience extremes in temperature and vibration. Fuel injection is an area where considerable industry work is underway to define and develop high performance and compact designs allowing better integration into the engine.

Crankcase Ventilation

Gas-fueled engines operate at a considerable manifold vacuum at light load conditions, leading to challenges in oil carryover in the gases ventilated from the crankcase. Diesel engines do not experience an intake manifold vacuum and so technology for oil separation under these conditions does not readily exist. Light-duty experience is not appropriate either since light-duty engines do not operate under the same longevity and performance requirements as heavy-duty engines.

CHAPTER 2:
Design

Manifold and Port Breathing

A key objective for the research project was to reduce cylinder-to-cylinder and cycle-to-cycle variation. The major contributor to achieving this goal was redesigning the manifolds and ports for more efficient air handling (Figure 6). Some key attributes of the final manifold and port designs are:

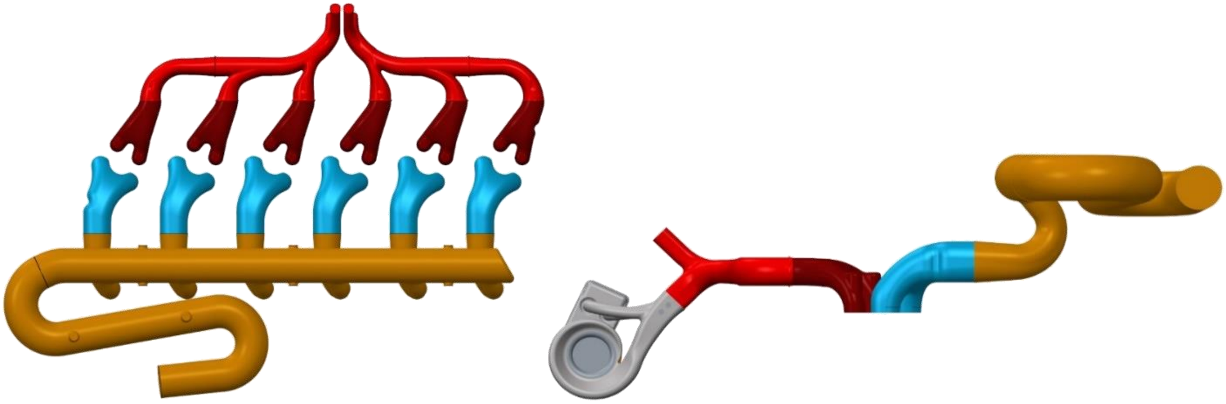
- Patterned design, all intake ports exactly the same, and all exhaust ports exactly the same.
- Individual, drop-down runners from the plenum to the intake ports.
- All cylinders pull off charge flow exactly the same way.
- No crosstalk between cylinders.
- Long mixing length to achieve flow uniformity.
- Larger intake port to reduce flow losses into the cylinder.
- Smaller exhaust port for higher velocity flow to support the pulse EGR system.
- Fully divided, pulse capture exhaust manifold, isolated front bank from rear bank.
- Optimized trajectory and area schedule of exhaust and EGR system components.

Figure 6: Air Handling Top View

Source: Cummins, Inc.

The cylinder head for this program implemented a big intake small exhaust diamond valve pattern. The diamond pattern allows for generation of swirl and the bigger intake valves enable bigger intake ports, contributing to improved engine breathing. Developed through multiple iterations and flow bench testing, the intake ports have high flow capability and low losses on par with world class benchmarks. The intake manifold is a front end-inlet design with the plenum above the intake port center line, as shown in Figure 6. Individual, equal length runners pull off of the plenum to feed each cylinder for consistent charge distribution. The runners are angled towards the incoming charge where they connect to the plenum to help direct flow down the runners to feed each cylinder. The individual runners offer additional benefits such as further separation of cylinders, meaning fuel cross talk is very unlikely with a port fuel injection architecture.

Figure 7: Manifold (L), Port, and Turbo Cores (R)



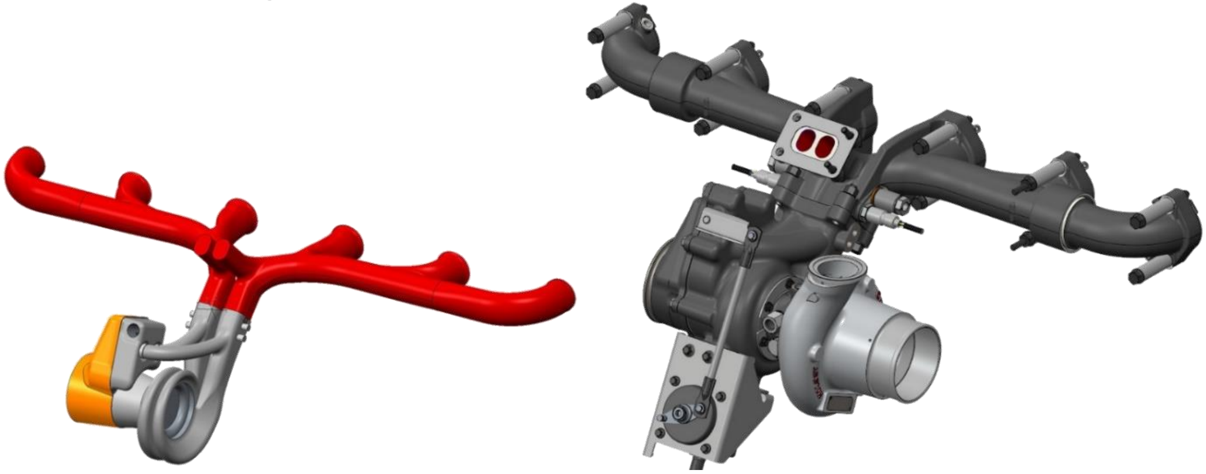
Source: Cummins, Inc.

The big intake small exhaust also affected the exhaust ports. Smaller exhaust valves and ports result in higher exhaust flow velocities that positively affect performance of the pulse EGR system. The pulse EGR system will be discussed in a later section in more detail. For good pulse EGR system performance it is critical to design efficient exhaust flow passages and junctions to minimize losses. The goal was not only to minimize the loss coefficient but also to minimize the variation in loss coefficient cylinder to cylinder. Compared to early design concepts, the final design offered a drastically lower loss factor to the turbine and EGR system.

Turbomachinery

During the redesign of the exhaust manifold, the project team worked closely with Cummins Turbo Technologies on a new turbocharger as well (Figure 8). The design philosophy for the new turbocharger was the same as for the manifolds: give every cylinder the same experience and minimize loss coefficient. This was achieved by minimizing the loss coefficient through optimizing the trajectory and the area schedule as a system, coupled to the exhaust manifold. The team provided the same experience for every cylinder by maintaining fully divided flows up to the turbine wheel. The new turbocharger also integrated a twin port electronically controlled wastegate which allowed the team to pull flow off both banks, further providing an identical breathing experience for all cylinders.

Figure 8: Turbocharger and Exhaust Manifold. Flow Cores (L), Assembly Model (R)

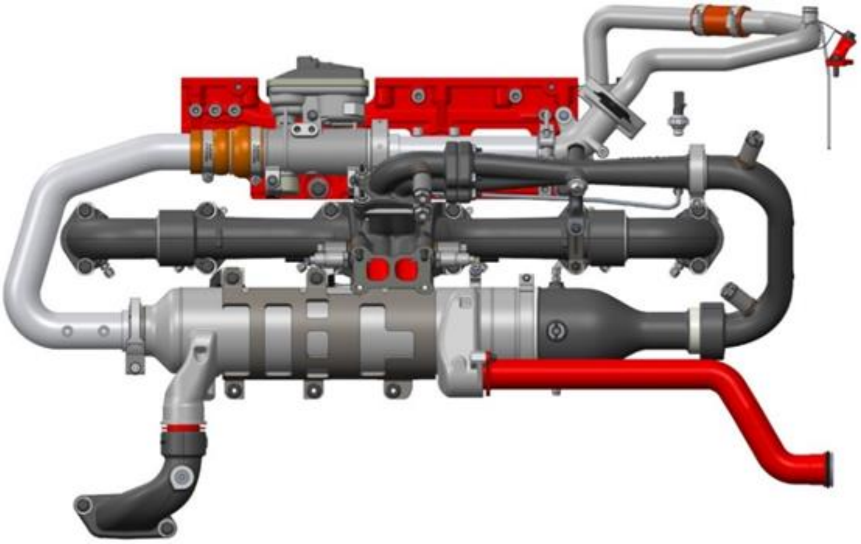


Source: Cummins, Inc.

Exhaust Gas Recirculation

Another key architectural feature of this design was the pulse EGR system (Figure 9). This engine operates with a stoichiometric air-fuel ratio and charge diluted with up to 25 percent EGR, while minimizing residuals. To achieve this, in addition to the exhaust manifold features already discussed, a very efficient flow junction to combine the flows was implemented. The hot components of the EGR system were developed concurrently and coupled to the exhaust manifold. Concurrent with computational fluid dynamics (CFD) analysis of the flow domain, the project team also performed thermal mechanical fatigue analysis of the designs to ensure durability.

Figure 9: Exhaust Gas Recirculation System Assembly



Source: Cummins, Inc.

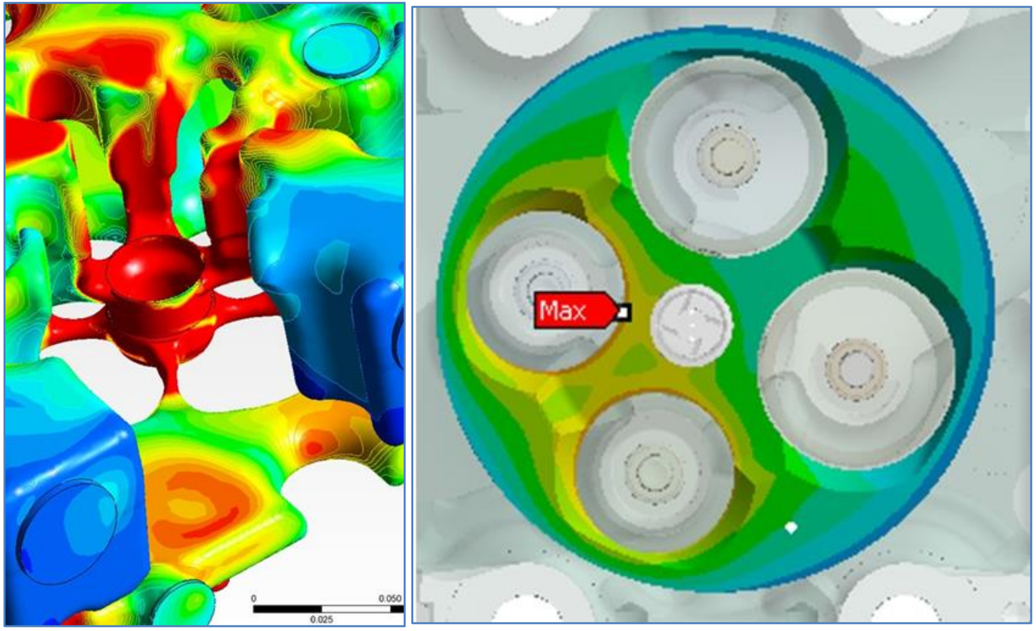
Oil Control

To achieve a stable spark ignited architecture, sources of knock and pre-ignition must be pursued and eliminated. One root cause is oil control and two sources addressed in this project were the piston rings and valve stem seals. Oil intrusion from the valve stem was addressed with an updated seal which is four times drier than the previous production diesel seal. The updated seal is also rated for vacuum; this is critical on a throttled engine, which frequently operates with a vacuum in the intake manifold. The research team addressed oil intrusion past the piston rings through use of a three-piece oil ring that has improved ring dynamics (compared to a two-piece oil ring) therefore providing improved oil control.

Cylinder Head and Spark Plug Cooling

As discussed earlier, sources of knock and pre-ignition must be pursued and eliminated. A potential source of pre-ignition addressed in this project was an overheated spark plug. Figure 10 (L) shows that heat transfer coefficients are highest in the bridges and surrounding the entire ignitor bore. All of the coolant flow must pass by the ignitor bores, providing exceptional cooling to the spark plug. The engine has not encountered any pre-ignition during testing of the high energy ignition system and j-gap spark plugs. Just as the spark plug can overheat and cause pre-ignition, the combustion face (particularly the edges) must also be effectively cooled to prevent hot spots and pre-ignition. Figure 10 (R) shows that the combustion face is relatively cool and well below design targets. This not only prevents pre-ignition, it also ensures a durable and robust cylinder head with tolerance to brief periods of knock and temperature rise.

Figure 10: Heat Transfer Coefficients in Water Jacket around Valve Seats, Bridges, and Ignitor Bore (L) and Predicted Combustion Face Temperatures (R)



Source: Cummins, Inc.

Fuel System

For research purposes, the cylinder head and intake manifold were designed with flexibility in mind to enable investigation of multiple fuel systems. The engine hardware allows placement of port fuel injectors in 2 possible locations and use 2 possible injectors. The injectors can be placed in the intake manifold runners and/or they can be placed above the intake ports in the cylinder head. The engine can operate with 100 percent single point fuel injection (SPFI or upstream mixed) or 100 percent multipoint fuel injection (injected in the individual ports).

Additionally, the engine can run with any mix of SPFI and multipoint fuel injection (MPFI). Analysis predicted that 100 percent SPFI and 100 percent MPFI with the injector above the ports were the leading two fuel system candidates and offered various tradeoffs (Table 1) that required exploration through testing. Combustion CFD predicted a benefit to using a port fuel distribution tube and engine testing proved this to be the case.

Table 1: Single Point versus Multipoint Fuel Injection Tradeoffs

Tradeoff	MPFI	SPFI
Feedforward Air Fuel Ratio Control	+	+
Feedback Air Fuel Ratio Control	+	-
Dither	+	-
Fuel Cutoff Recovery	+	-
Air Fuel Ratio Imbalance	-	+
Cost	Similar	Similar
Advanced Thermal Management	+	N/A
Cylinder Deactivation	+	N/A

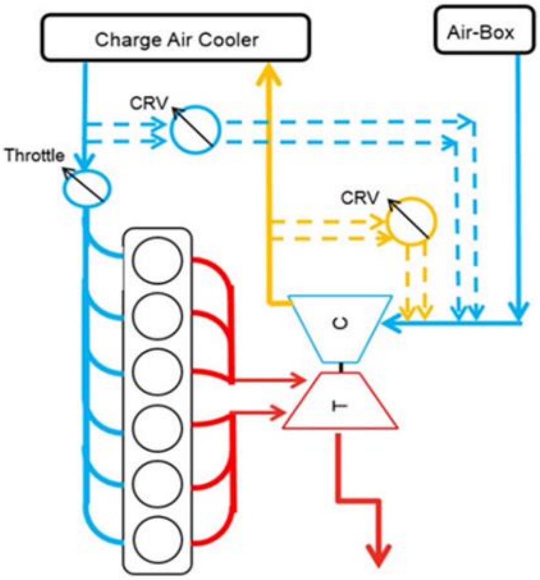
Source: Cummins, Inc.

An additional benefit of locating the fuel injectors above the port is intake manifold over-pressure (IMOP) or intake backfire mitigation. With a single point injection near the intake throttle, the entire intake manifold contains a stoichiometric combustible mixture. With an MPFI system, most of the manifold will be filled with air or possibly a very lean mixture beyond the ignition limits.

Compressor Bypass Valve

Stoichiometric gas engines are throttled by air (opposed to a diesel throttled by fueling) which can pose a challenge for the turbocharger compressor. When the engine quickly transitions from a high-boost condition to a no-boost condition (tip-out), the throttle plate slams shut and the high-speed, high-pressure charge between the compressor and the throttle needs somewhere to go. Otherwise, the pressure will spike and find its way to low pressure through the only available path, which is back through the compressor. This compressor surge causes a loading reversal of the compressor blades that can quickly lead to fatigue failures. To prevent this, an electronically controlled compressor recirculation valve was implemented (Figure 11). The compressor recirculation valve opens to provide a path to bleed off the high-pressure air to prevent compressor surge, particularly during tip-out events, although since it is electronically controlled it could be fully commanded anytime to help prevent surge.

Figure 11: Compressor Recirculation System Schematic



Source: Cummins, Inc.

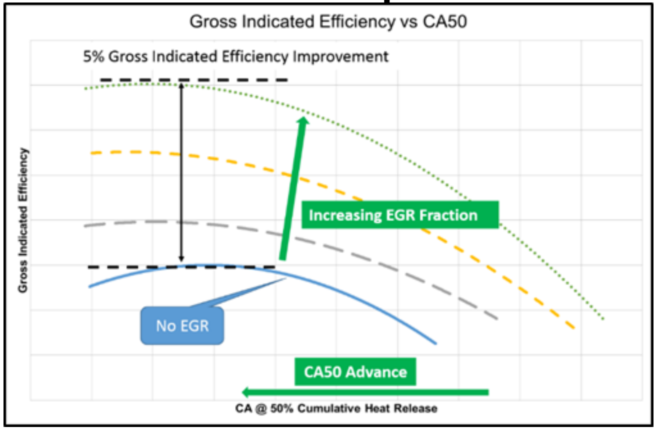
CHAPTER 3:
Engine Optimization

A stoichiometric with cooled EGR combustion system was chosen for this engine as it has the capability to deliver high brake mean effective pressure, extremely low emissions, and robust operation. The performance optimization & development of the engine subsystems was split into three critical areas—combustion system, fuel system, and charging system—that are discussed in this chapter. A high energy capable ignition system was selected prior to the start of this project and was carried forward.

Combustion System

Development of the combustion system focused on improvements in closed cycle efficiency, reduced heat transfer, and capability of short burn durations under highly dilute conditions and short ignition delay times. High dilution was chosen to control component temperatures and to realize closed-cycle efficiency improvements through reduced heat transfer (Figure 12).

Figure 12: Exhaust Gas Recirculation Impact to Gross Indicated Efficiency

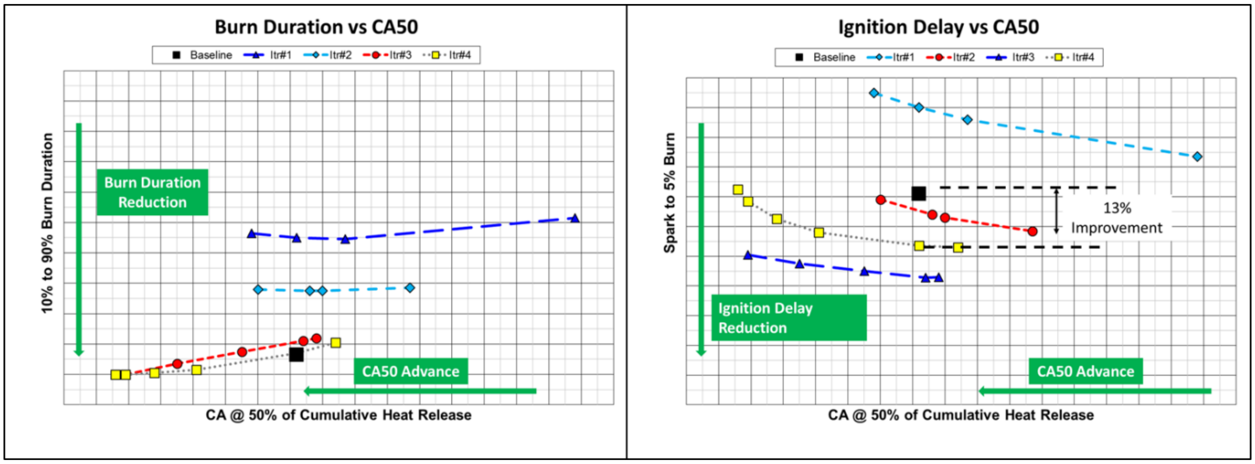


Source: Cummins, Inc.

Initial combustion system work was done using a full combustion cycle analysis on a calibrated combustion CFD model. Prior work had yielded a baseline combustion system that delivered on 10 percent to 90 percent burn durations capable of tolerating high levels of EGR dilution. The goal of the current research was to maintain that burn duration with improved efficiency and ignition delay.

Trends in burn duration and ignition delay are shown in Figure 13. The progression from iteration #1 to iteration #4 represents the investigation of swirl level along with charge motion development during the cycle and the impact to combustion. Iteration #1 represents the best efficiency that could be achieved because charging penalties were minimized representing the entitlement for efficiency. Iterations #2 to #4 represent iterations to improve the burn duration with minimal impact to efficiency by influencing the in-cylinder charge motion.

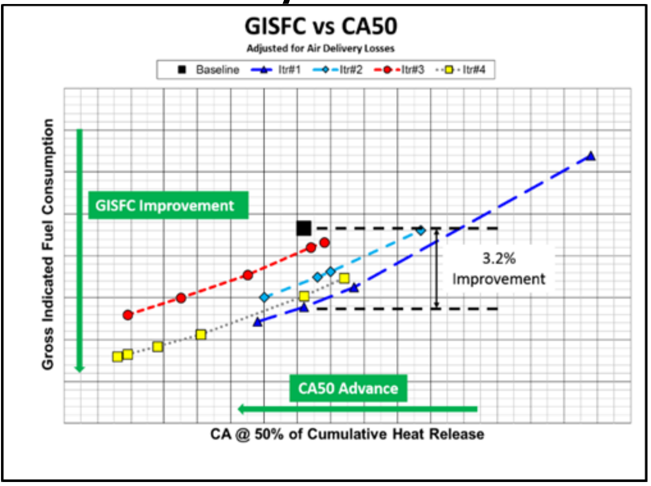
Figure 13: Computational Fluid Dynamics – Burn Duration and Ignition Delay versus CA50



Source: Cummins, Inc.

Iteration #4 was chosen as the combustion system for this engine because it was the best tradeoff for key deliverables. Fuel consumption trends are shown in Figure 14 for constant EGR levels.

Figure 14: Computational Fluid Dynamics – Indicated Fuel Consumption

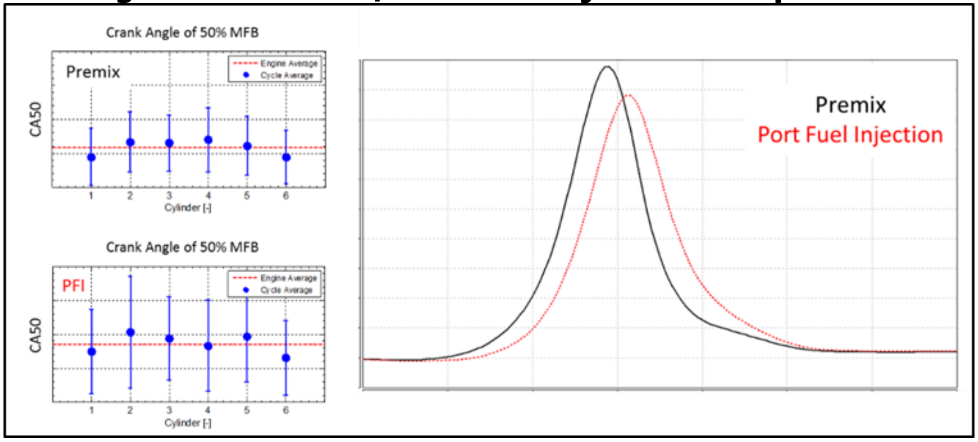


Source: Cummins, Inc.

Fuel System

The focus of the fuel system development was to investigate the use of a premix fuel system versus a port fuel injection system. The benefit of a premix combustion system is homogeneity of the fuel and air mixture. Disadvantages are transport delays, catalyst dither amplitude attenuation, and mitigation techniques in the event of cylinder misfire. Challenges of port fuel injection are mixture stratification, number of physical parts and injection pressure requirements. The benefits to MPFI are cost, fuel control cylinder-by-cylinder, transient response time, and TWC control. Initial experiments provided evidence to support degraded combustion due to port fuel injection (PFI) as shown in Figure 15.

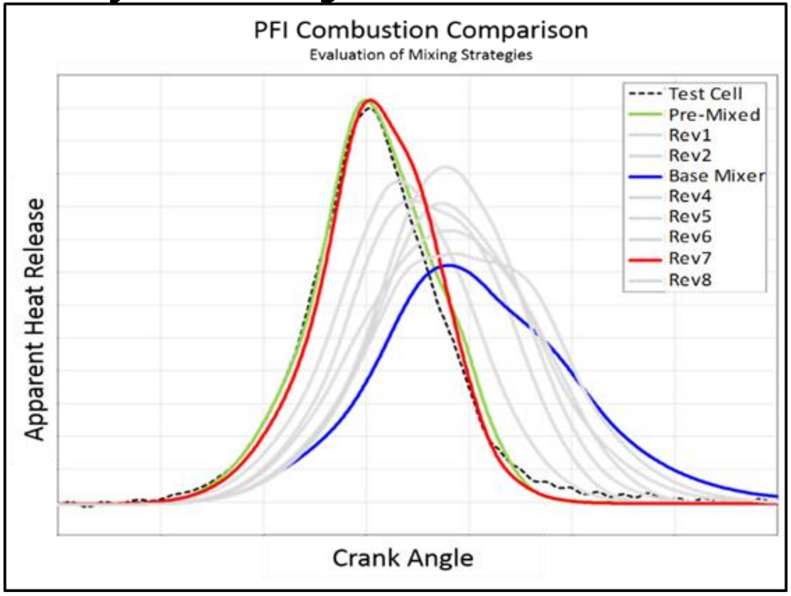
Figure 15: Premix/Port Fuel Injection Comparison



Source: Cummins, Inc.

Further work was done to understand if MPFI stratification could be improved to match performance of the premixed combustion. Many iterations of mixing devices as well as injection strategies were assessed via combustion CFD to compare combustion performance as shown in Figure 16. The MPFI mixing work yielded a design and injection strategy that was transparent to the premix injection strategy allowing for advantages of PFI to be realized.

Figure 16: Port Fuel Injection Mixing Assessment Heat Release Rate Comparison

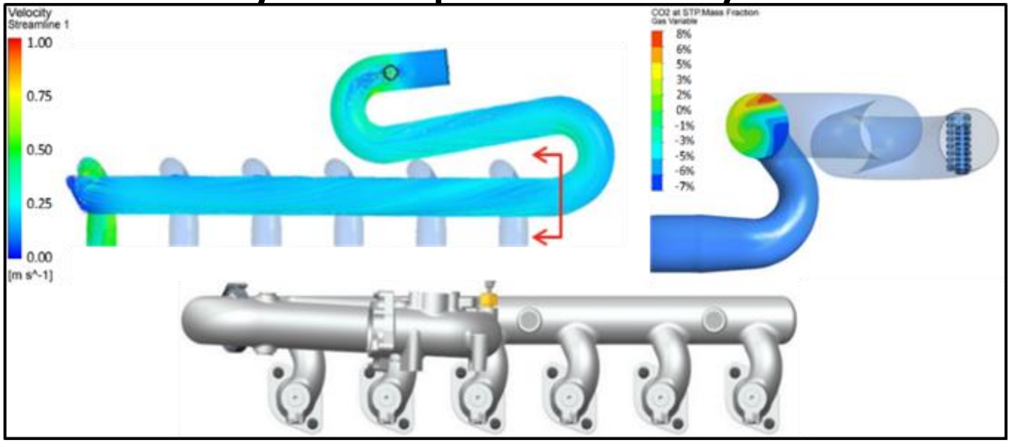


Source: Cummins, Inc.

Charging System

The focus for the charge system was multifaceted. The charging system needed to provide a uniform and equal mixture of air and EGR to each cylinder. In addition, the system was designed such that it could minimize the trapped residuals. Additionally, the turbocharger machinery was sized such that it could accommodate the lower flowrates of a stoichiometric engine with EGR and provide the necessary pressure balance to drive the desired EGR levels. The intake system was assessed for charge delivery and mixture uniformity. With stringent requirements for charge uniformity and charge distribution, the team chose the final intake configuration shown in Figure 17.

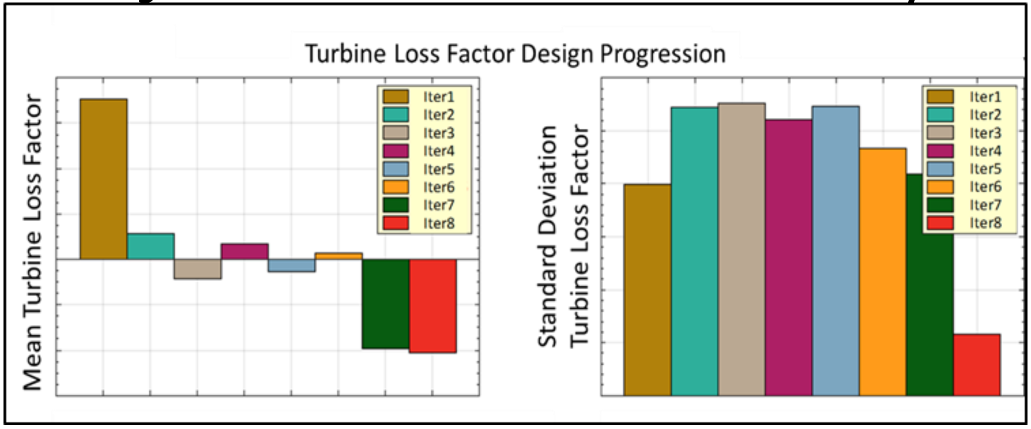
Figure 17: Intake System Computational Fluid Dynamics Performance



Source: Cummins, Inc.

The exhaust system was extensively tested and developed to ensure good cylinder balance as well as facilitate an efficient exhaust event. Figure 18 shows a summary of iterations assessed using a novel modeling approach in CFD. The iterations were focused on geometric changes that improved losses in the manifold and balanced the losses cylinder by cylinder. Iteration #8 was chosen as the exhaust manifold configuration for the new engine.

Figure 18: Exhaust Manifold Loss Factor Summary



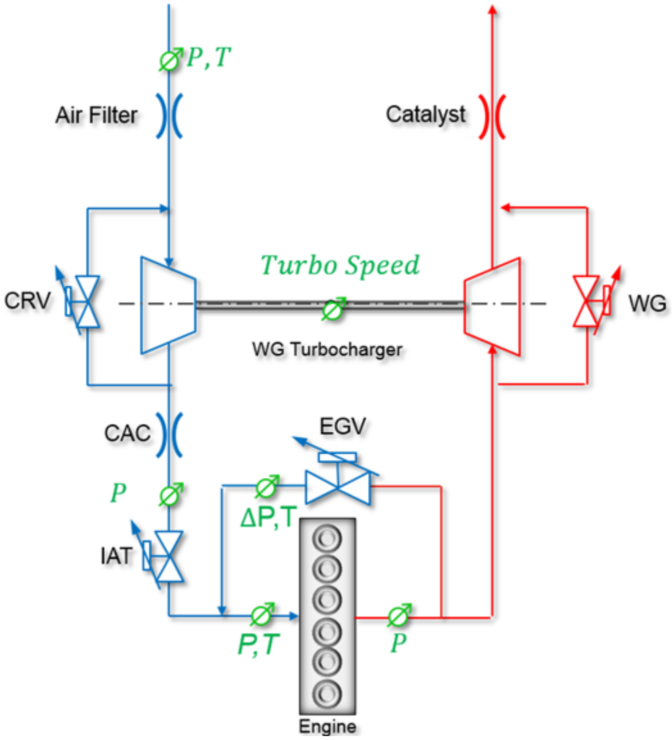
Source: Cummins, Inc.

CHAPTER 4:
Controls

Air Handling Control

The air handling architecture is shown in Figure 19. Fresh air enters the system through the air filter. Pressure is raised by the turbocharger compressor and temperature is reduced by the charge air cooler (CAC). This air reservoir together with an intake air throttle (IAT) is used to control the air flow going into the intake manifold. Similarly, the EGR flow diverted from the exhaust manifold is controlled by the EGR valve (EGV). Both air and EGR are mixed in the intake manifold at rates controlled by the valves. Lastly, the compressor is maintained away from the surge region by actuating the compressor recirculation valve.

Figure 19: Air Handling Architecture Schematic



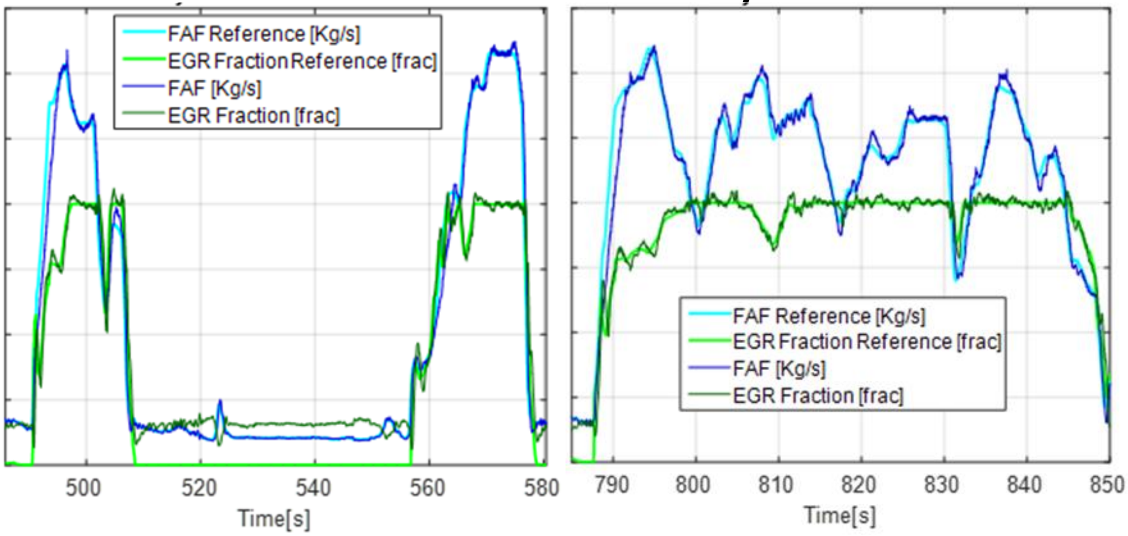
Source: Cummins, Inc.

The exhaust gas not diverted to the intake manifold goes to the wastegated turbine where a valve (WG in Figure 19) is used to control the portion of the flow that is bypassed. By doing so, the energy going to the turbocharger, and consequently the boost, can be controlled within certain limits.

The control problem is calculating the IAT, EGV, and WG actuator commands to achieve the target engine fresh air flow, EGR fraction, and boost. In stoichiometric engines, fresh air flow is directly related to engine power so the target fresh air flow is calculated from the driver torque request and engine speed. EGR fraction, on the other hand, is used to reduce knock and pumping mean effective pressure and NOx. The EGR fraction target is usually calibrated as a function of (at least) load and engine speed. Finally, having three actuators allows the tracking of three references (when feasible). The last target for the air handling control is turbocharger boost, which allows trade off of transient performance with pumping efficiency. A common target to exercise this tradeoff is the pressure drop on the IAT, which can be stored as a function of engine load and speed for example.

The control was designed using physical models of the air handling components, which significantly reduced the need for empirical table lookups to address system nonlinearities and changes in environmental conditions. The fresh air flow and EGR fraction control performance is shown in Figure 20. Overall, the fresh air flow and EGR fraction remain on top of the reference with few exceptions, most of them related to turbo spooling. The large EGR fraction deviation during idle regions corresponds to EGR flow measurement errors at low flows. In fact, the actual tracking error is zero since the EGR valve remains closed during those regions.

Figure 20: Fresh Air Flow and Exhaust Gas Recirculation Fraction Tracking during Federal Test Procedure Cycle

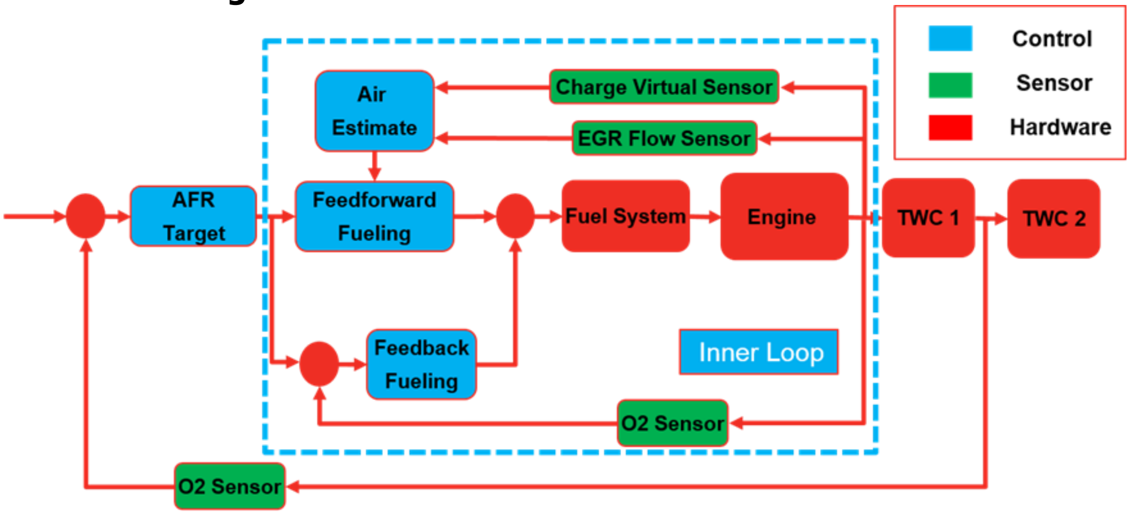


Source: Cummins, Inc.

Air Fuel Ratio Control

The conversion efficiency of the three-way-catalyst (TWC) is directly related to the air-fuel ratio (AFR). Therefore, AFR is a strong lever to control the system out emissions. The structure of the AFR control is shown in Figure 21. It is a cascade control system with two loops (inner loop and outer loop). The inner loop adjusts the on-time of the fuel injectors to precisely track the AFR target, while the outer loop determines the AFR target based on the catalyst states for best conversion efficiency of the emission constituents.

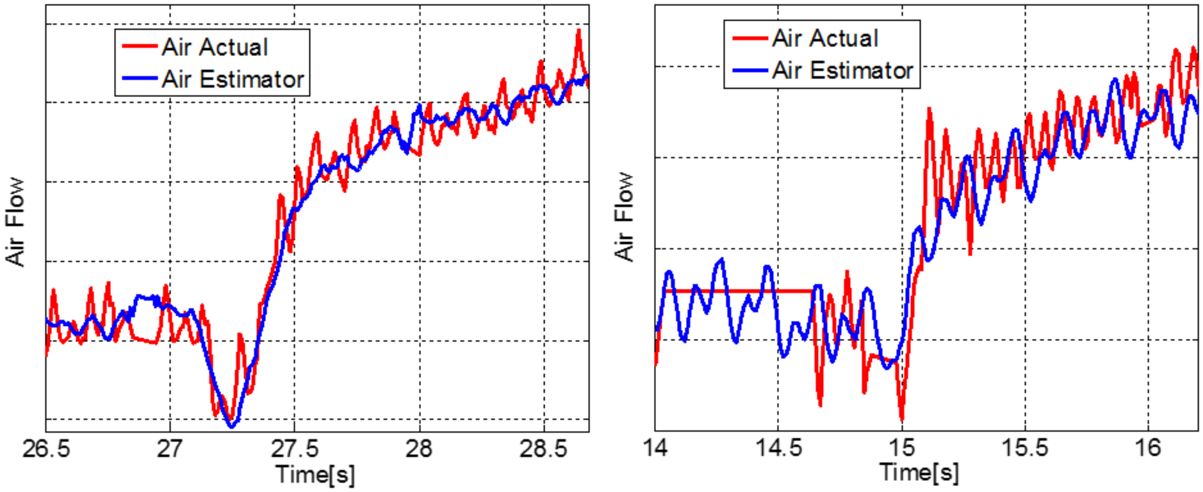
Figure 21: Schematic of Air-Fuel Ratio control



Source: Cummins, Inc.

The inner loop consists of feedforward and feedback fuel scheduling. The feedforward fueling schedules fuel injector on time based on the estimated air mass in the cylinder, while the feedback trims the feedforward calculation based on a wideband lambda sensor located after the turbocharger. Due to the slow response of the feedback loop, the transient performance of the AFR control is mainly determined by the feedforward fueling. The dynamics of the injectors can be neglected due to its fast response time compared to the air dynamics. Therefore, accuracy of the air estimator plays the most important role in defining the inner loop control performance. A physics-based approach, which uses a charge virtual sensor and an EGR flow sensor, was developed to accurately predict air flow to the cylinder. Figure 22 shows the on-engine validation of the air estimator at different engine speeds.

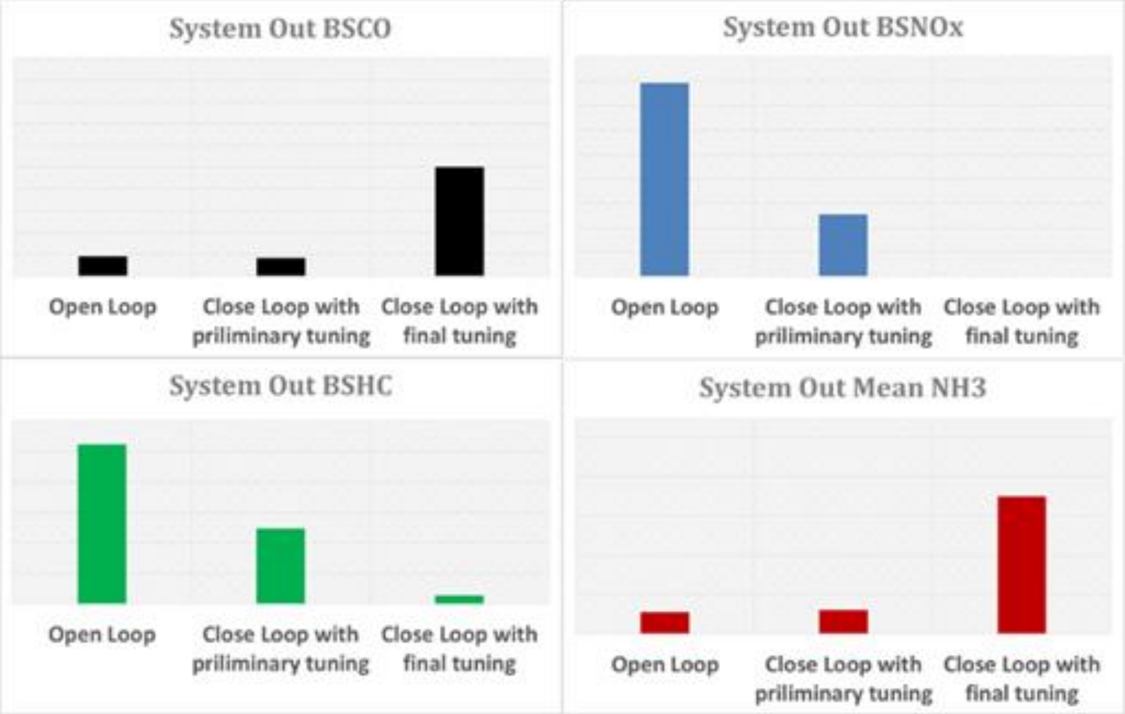
Figure 22: Air Estimator Performance at Speed A (L) and Speed B (R)



Source: Cummins, Inc.

The outer loop consists of a feedforward mean AFR target table. A feedback control trims the AFR target based on a wideband O_2 sensor located at midbed (between the first catalyst TWC1 and second catalyst TWC2). The feedforward mean lambda are predetermined via steady state catalyst characteristic testing at various engine operating conditions. The objective is to maintain a constant AFR target at the midbed location that optimizes the conversion of all the emissions constituents. Figure 23 shows the influence of the outer loop on the system out emissions. The benefit of having the outer loop can be seen clearly from the individual plots. However, to meet the ultra-low NOx requirement, a trade-off among the emissions constituents can also be observed.

Figure 23: Influence of Outer Loop on System Out Emissions Constituents

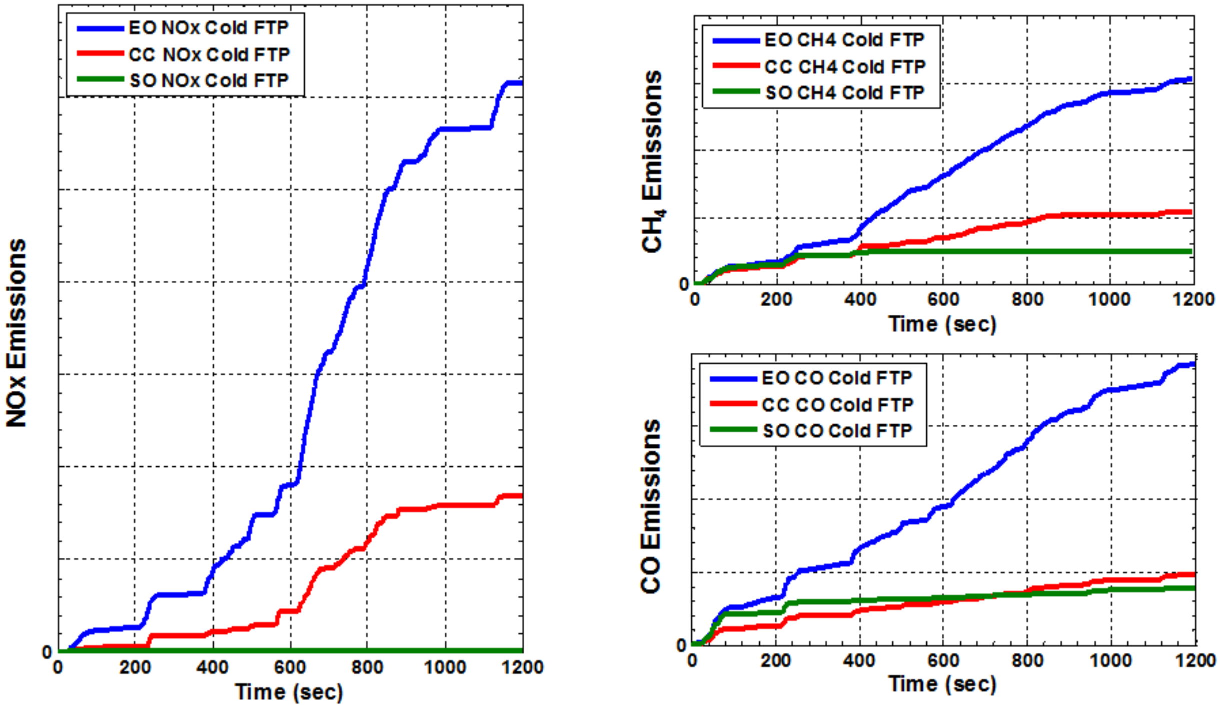


Source: Cummins, Inc.

CHAPTER 5:
After Treatment

A close-coupled after treatment architecture has been applied in this research work to meet the system out ultralow NOx emission requirement. The after-treatment architecture consists of a close-coupled TWC and underfloor TWCs. This architecture provides the best compromise between high system efficiency and packaging constraints. This development work has demonstrated clear performance excellence of using the close-coupled architecture to manage both cold-start and warm-start transient emissions control. Furthermore, through benchmarking evaluation, "TWC technology A" has been selected to achieve both high NOx conversion and methane (CH_4) conversion at near stoichiometric lambda. The platinum-group metal loading of the afte- treatment system was engineered differently between the close-coupled and underfloor TWCs.

Figure 24: Oxides of Nitrogen, Methane, and Carbon Dioxide Emissions during Heavy-Duty Cold Federal Test Procedure Transient Cycle



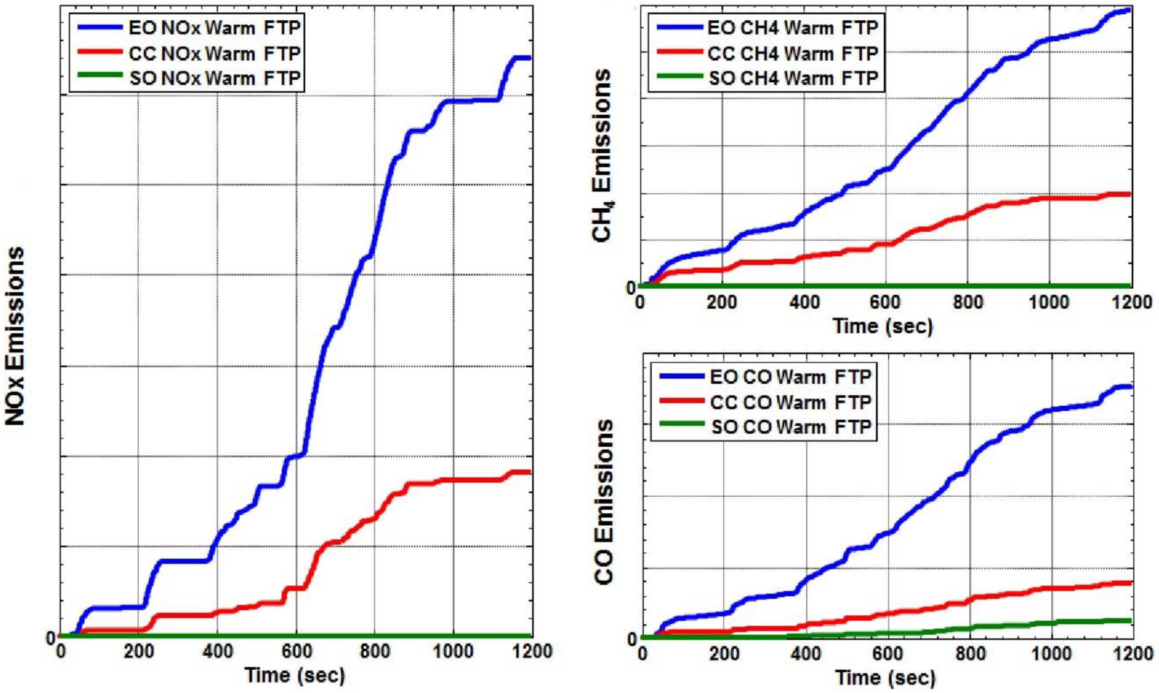
Emissions are reported at engine out (EO), close-coupled catalyst out (CC), and system out (SO) locations.

Source: Cummins, Inc.

During the cold FTP transient cycle (as shown in Figure 24), the close-coupled TWC effectively managed the first 0-50 seconds NOx emissions control before warming up the underfloor catalyst. CH_4 emissions were largely controlled through close-coupled TWC for the first 380 seconds. The close-coupled TWC successfully converted more than 70 percent of the cumulative engine-out NOx emissions and more than 60 percent of the cumulative engine-out CH4 emissions during the cold FTP cycle. During the warm FTP transient cycle (as shown in

Figure 25), the close-coupled architecture converted more than 70 percent of the cumulative engine-out NOx emissions and more than 65 percent of the cumulative engine-out CH4 emissions during the warm FTP cycle.

Figure 25: Oxides of Nitrogen, Methane, and Carbon Dioxide Emissions during Heavy-Duty Warm Federal Test Procedure Transient Cycle



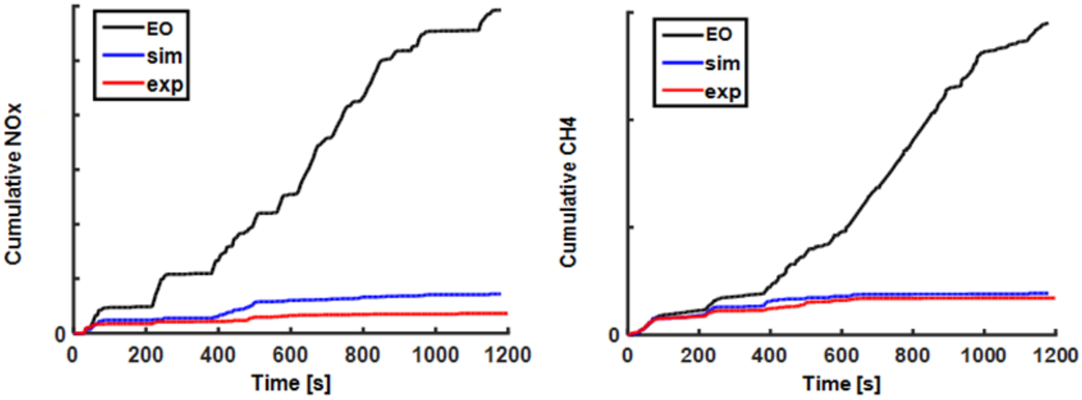
Emissions are reported at engine-out (EO), close-coupled-catalyst-out (CC), and system-out (SO) locations.

Source: Cummins, Inc.

There are many critical needs for developing a TWC model that can closely predict the application cycles emissions for natural gas applications. Key challenges of developing such a model include a dynamic oxygen storage mechanism, complex CH_4 oxidation and reforming kinetics and its interaction with the oxygen storage dynamics, and the highly transient nature of the AFR control during the TWC application. The success of developing such a TWC model also relies on obtaining the right kinetic mechanisms through well-designed tests and reliable data collection.

A global-kinetic TWC model was developed in this study. The model prediction was validated using a production natural gas engine with an underfloor-only after treatment system during transient emissions cycles (for example cold Federal Test Procedure [FTP] cycle, warm FTP cycles and World Harmonized Transient Cycles). As shown in Figure 26, this model has high predictability of after treatment CH_4 and NOx performance during the cold FTP cycle against engine bench testing results.

Figure 26: Cold Federal Test Procedure Transient Cycle Oxides of Nitrogen and Methane Conversion Performance Predictions against Testing Data



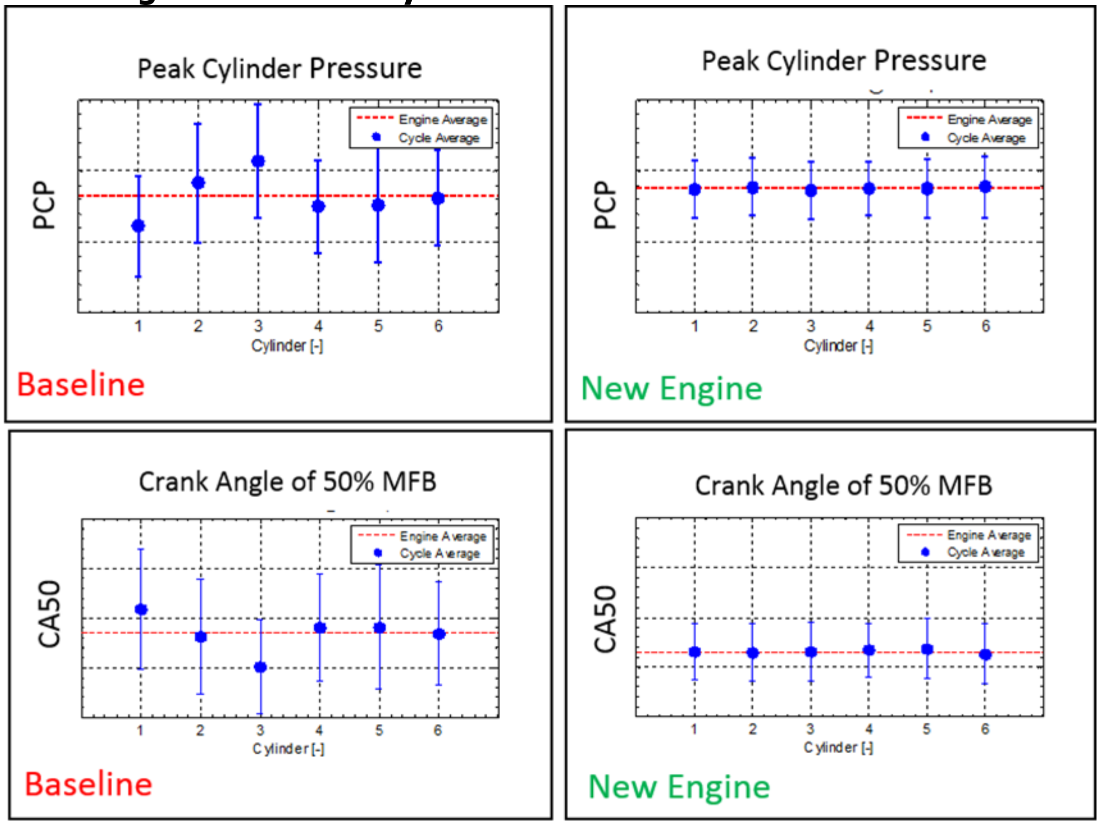
Source: Cummins, Inc.

CHAPTER 6:
System Integration

In this project, the research team used a systems approach to develop a system able to reduce NOx emissions 90 percent below current standards, be equivalently efficient to a 2010 diesel, and be a benchmark on which to conduct further technology advancements. Focusing on air handling, combustion, after treatment, fuel system, and controls resulted in a system capable of delivering these objectives and much more.

With the revised intake, EGR/exhaust, and combustion systems discussed previously, the robustness of the engine was dramatically improved. Figure 27 illustrates the robustness of the engine by improvements in cylinder-to-cylinder and cycle-to-cycle variation at peak torque with three sigma error bars for reference. The reduction in variation across the engine allows for better control of the engine, enables lower emissions capability, improved robustness and operating range, higher engine efficiency, and capability for increased power density.

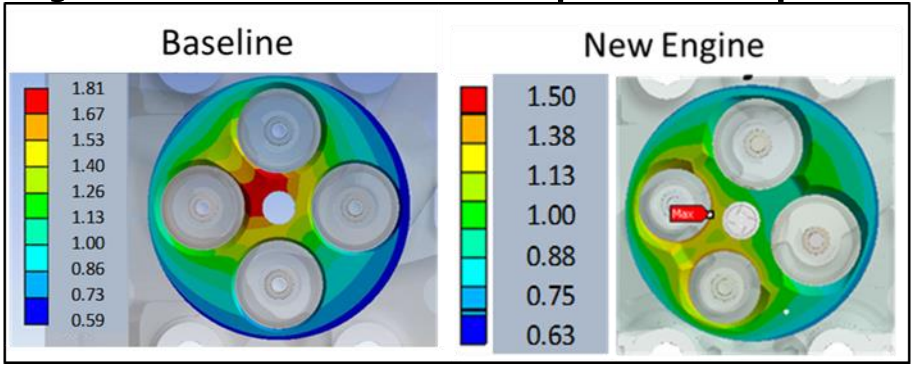
Figure 27: Peak Cylinder Pressure and CA50 Variation



Source: Cummins, Inc.

In addition to variation reduction, component durability was also a key focus of the project. A critical component for engine durability is the cylinder head. The focus was not only to reduce the maximum temperatures, but also to provide uniform cooling of the combustion face. Figure 28 shows a comparison of the head temperatures in the baseline and new engine.

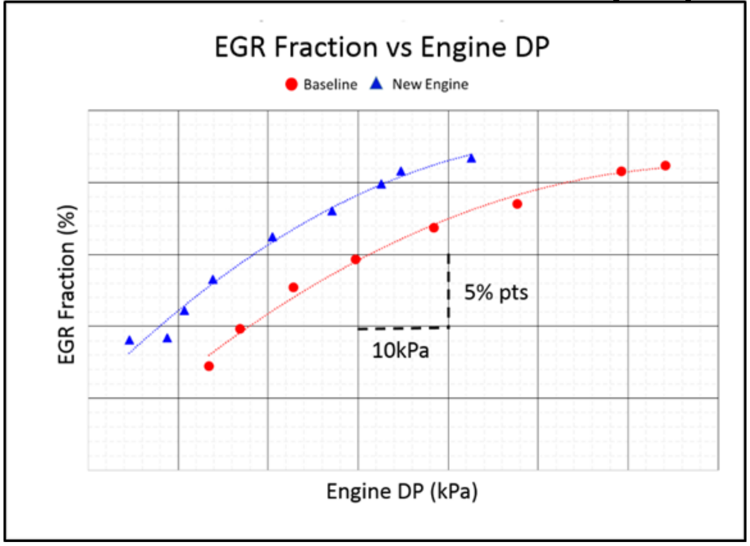
Figure 28: Combustion Face Temperature Comparison



Source: Cummins, Inc.

In addition to the cylinder head, the exhaust system used improved high-temperature materials for durability as well as revised designs to improve the loss coefficient of the manifold and improve the relationship between EGR fraction and engine delta p (DP or pressure difference) as shown in Figure 29.

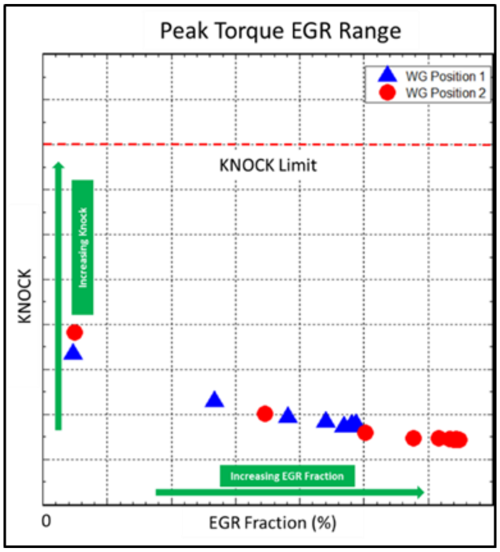
Figure 29: Exhaust Gas Recirculation Delivery Improvement



Source: Cummins, Inc.

The ability to drive large amounts of EGR with low engine delta p is crucial because it allows for reduced residuals supporting a wide operating range for EGR at high load conditions which provides further robustness to knock. Figure 30 shows an example of the EGR range at high load for the peak torque condition.

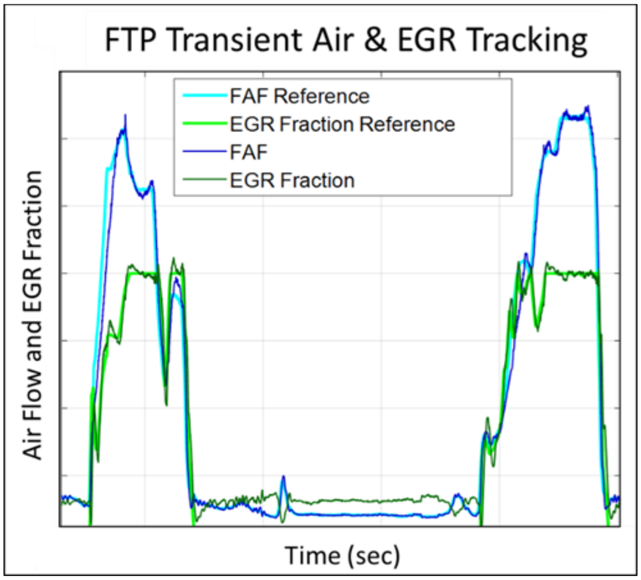
Figure 30: Exhaust Gas Recirculation Variation Robustness



Source: Cummins, Inc.

With a much-improved engine design, controls were redesigned as well to enable improved air handling, combustion and AFR controls. A highly capable control system is critical to delivering the transient response, robustness, and efficiency while also delivering tight control for NOx emissions reduction. Figure 31 shows the tracking performance of the air handling system.

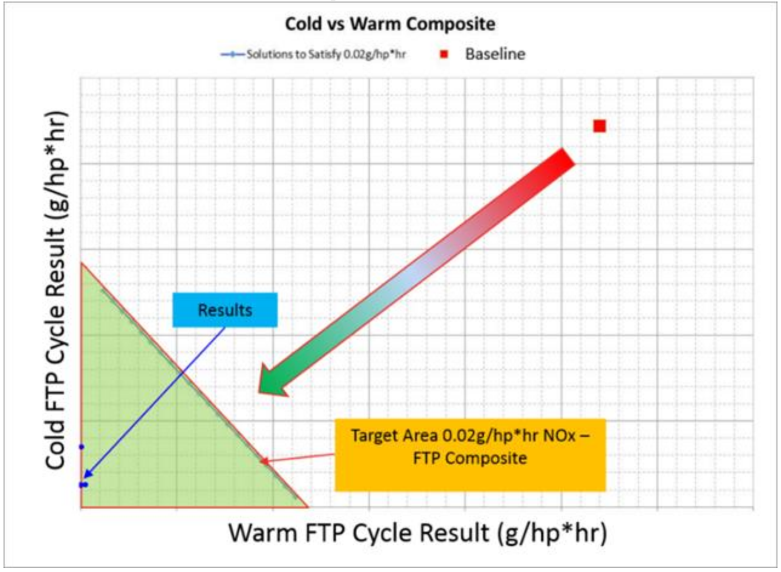
Figure 31: Air and Exhaust Gas Recirculation Tracking During Portion of Federal Test Procedure



Source: Cummins, Inc.

Using the improvements described above, the primary deliverables of the project were met. The first of those deliverables was demonstrating a NOx reduction of 90 percent below current standards. As shown in Figure 32, a cold/hot FTP emissions test was used to demonstrate compliance with the program objectives of 0.02g/bhp-hr.

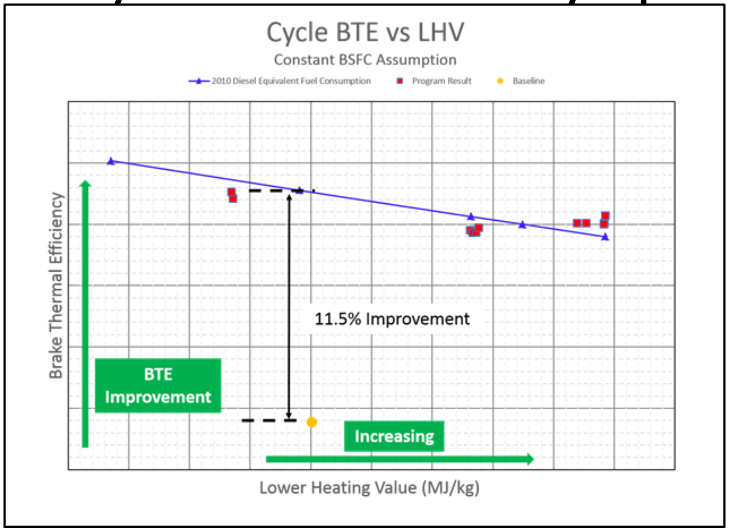
Figure 32: Emission Results for Cold/Hot Federal Test Procedure Emissions Test



Source: Cummins, Inc.

In addition to the reduced NOx emissions, the new engine greatly improved fuel economy compared to the baseline engine. As Figure 33 shows, cycle average brake thermal efficiency was improved by more than 10 percent over the baseline.

Figure 33: Cycle Brake Thermal Efficiency Improvement



Source: Cummins, Inc.

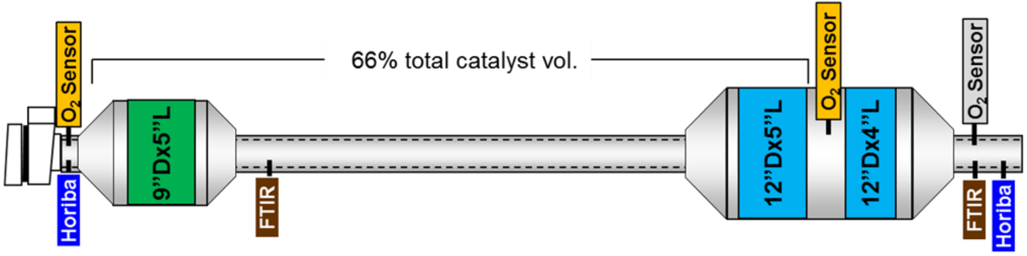
CHAPTER 7:
Discussion of Results

Emissions

One key criterion for this project was to demonstrate near-zero NOx tailpipe emissions. Specifically, emissions targets were 0.02 grams per brake horsepower-hour (g/bhp-hr) NOx, 0.01 g/bhp-hr PM, 0.14 g/bhp-hr NMHC, and 15.5 g/bhp-hr CO or lower as determined by the heavy-duty engine FTP.

Figure 34 shows the final aftertreatment system layout employed during heavy-duty FTP emissions testing. The project team employed a close-coupled catalyst strategy to facilitate quick catalyst light, critical to meeting near zero emissions levels. Because of this aftertreatment system design, this section shows three sets of emissions test results: engine out, close-coupled catalyst out, and tailpipe out.

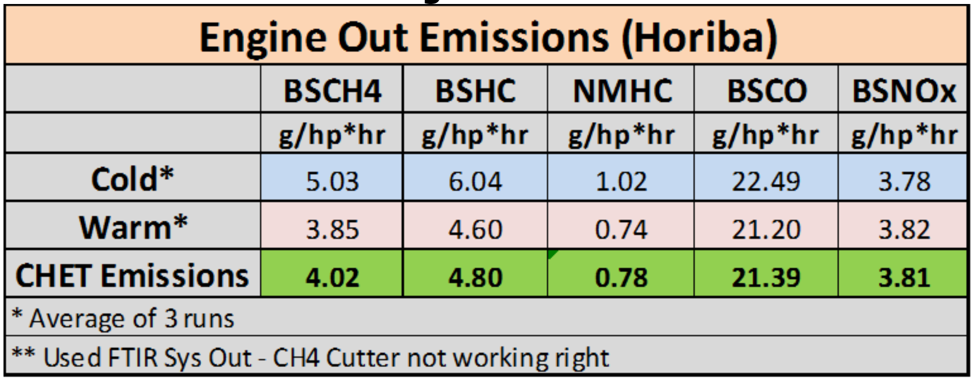
Figure 34: Aftertreatment System Layout



Source: Cummins, Inc.

Table 2 shows the engine-out emissions for both cold and hot FTP test runs.

Table 2: Engine-Out Emissions

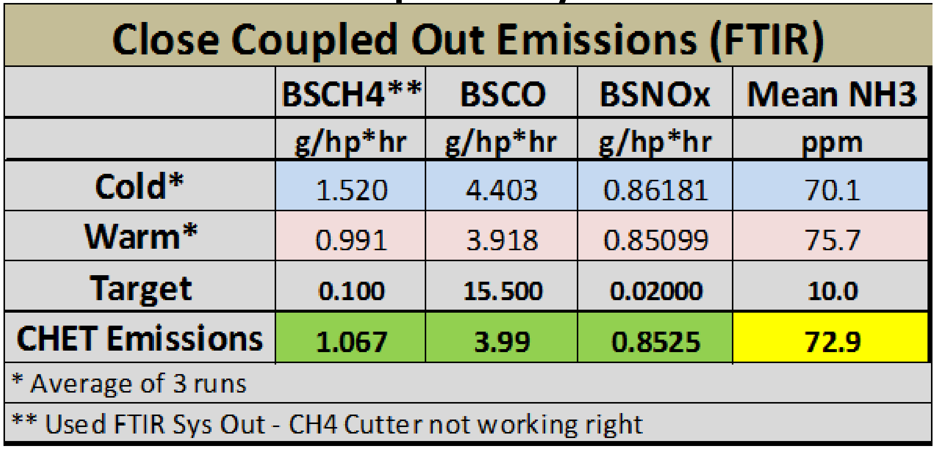


Engine Out Emissions (Horiba)					
	BSCH4	BSHC	NMHC	BSCO	BSNOx
	g/hp*hr	g/hp*hr	g/hp*hr	g/hp*hr	g/hp*hr
Cold*	5.03	6.04	1.02	22.49	3.78
Warm*	3.85	4.60	0.74	21.20	3.82
CHET Emissions	4.02	4.80	0.78	21.39	3.81
* Average of 3 runs					
** Used FTIR Sys Out - CH4 Cutter not working right					

Source: Cummins, Inc.

Table 3 shows close-coupled-catalyst-out emissions, including NH_3. On average, the close-coupled catalyst is between 70 percent and 80 percent efficient in removing criteria pollutants. One note is that the close coupled catalyst did generate a little more than 70 ppm NH_3.

Table 3: Close Coupled Catalyst Out Emissions

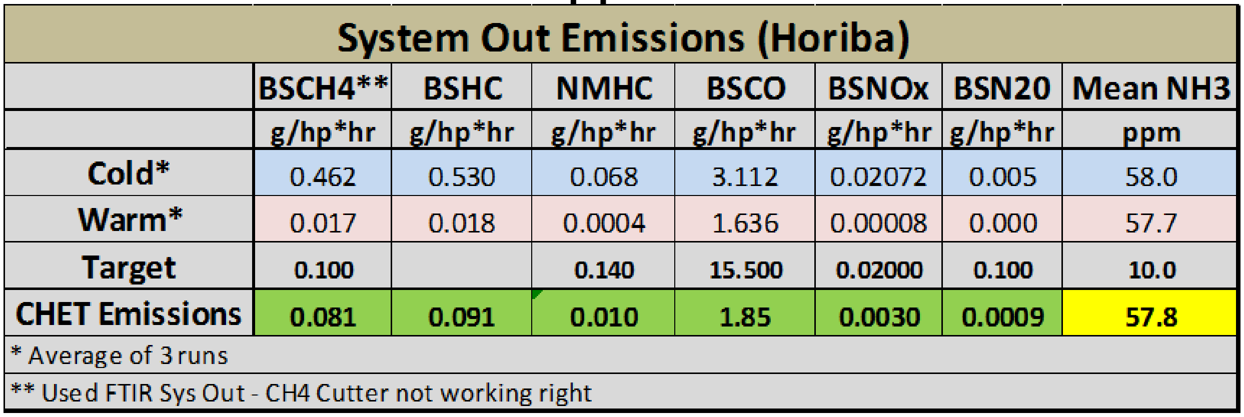


Close Coupled Out Emissions (FTIR)				
	BSCH4**	BSCO	BSNOx	Mean NH3
	g/hp*hr	g/hp*hr	g/hp*hr	ppm
Cold*	1.520	4.403	0.86181	70.1
Warm*	0.991	3.918	0.85099	75.7
Target	0.100	15.500	0.02000	10.0
CHET Emissions	1.067	3.99	0.8525	72.9
* Average of 3 runs				
** Used FTIR Sys Out - CH4 Cutter not working right				

Source: Cummins, Inc.

The emissions levels shown in Table 4 demonstrate that this system is capable of meeting the targeted NOx emissions level of 0.02 g/bhp-hr. In addition, many of the other criteria pollutant levels are well below current or projected future standards. The exception is NH_3, which came in just below 60 ppm. Subsequent additional transient calibration tuning highlighted that throttle tip-in and tip-out events were at the root of the elevated NH_3 emissions. Additional calibration work around these events reduced NH_3 levels below 20 ppm, with confidence high that a production calibration can achieve sub-10 ppm levels for NH_3.

Table 4: Tailpipe Out Emissions

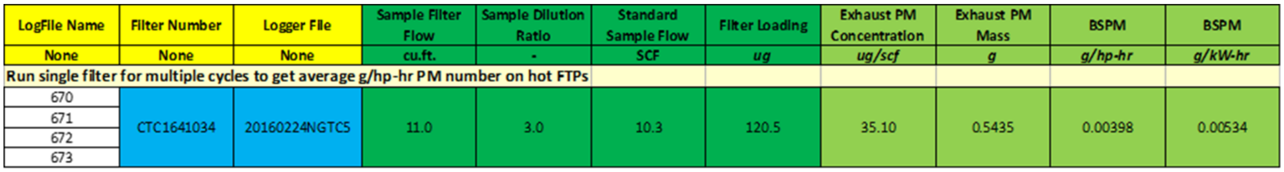


System Out Emissions (Horiba)							
	BSCH4**	BSHC	NMHC	BSCO	BSNOx	BSN20	Mean NH3
	g/hp*hr	g/hp*hr	g/hp*hr	g/hp*hr	g/hp*hr	g/hp*hr	ppm
Cold*	0.462	0.530	0.068	3.112	0.02072	0.005	58.0
Warm*	0.017	0.018	0.0004	1.636	0.00008	0.000	57.7
Target	0.100		0.140	15.500	0.02000	0.100	10.0
CHET Emissions	0.081	0.091	0.010	1.85	0.0030	0.0009	57.8
* Average of 3 runs							
** Used FTIR Sys Out - CH4 Cutter not working right							

Source: Cummins, Inc.

Finally, particulate emissions were not expected to be a challenge for this natural gas engine. Test results averaged over several test cycles, as shown in Table 5, confirmed this expectation.

Table 5: Particulate Emissions



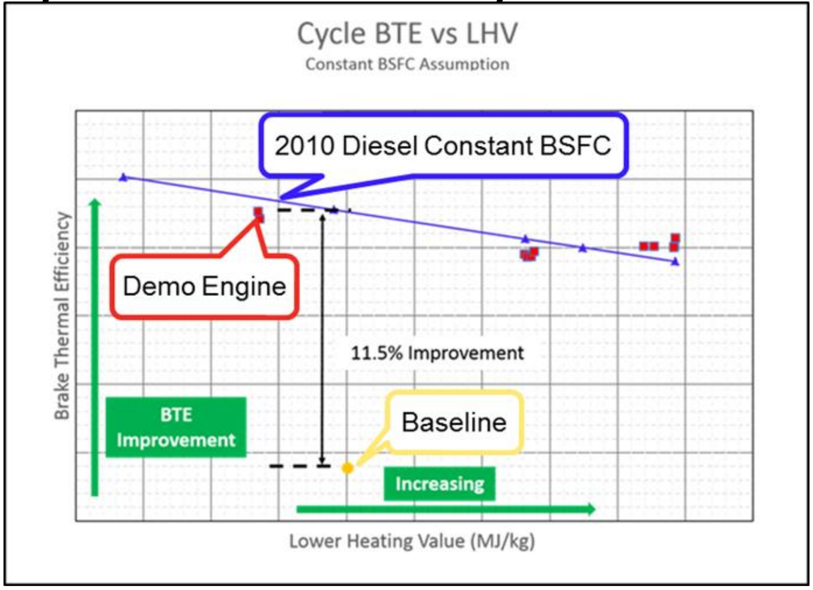
LogFile Name	Filter Number	Logger File	Sample Filter Flow	Sample Dilution Ratio	Standard Sample Flow	Filter Loading	Exhaust PM Concentration	Exhaust PM Mass	BSPM	BSPM
None	None	None	cu.ft.	-	SCF	ug	ug/scf	g	g/hp-hr	g/kW-hr
Run single filter for multiple cycles to get average g/hp-hr PM number on hot FTPs										
670	CTC1641034	20160224NGTC5	11.0	3.0	10.3	120.5	35.10	0.5435	0.00398	0.00534
671										
672										
673										

Source: Cummins, Inc.

Efficiency and Performance

With respect to efficiency, the project objective was to get close to matching the fuel consumption of a comparable 2010 diesel engine. As shown in Figure 35, that objective was achieved. The natural gas engine brake specific fuel consumption matched that of a 2010 diesel engine. This represents a more than 10 percent improvement in fuel consumption compared to a current state-of-the-art natural gas engine.

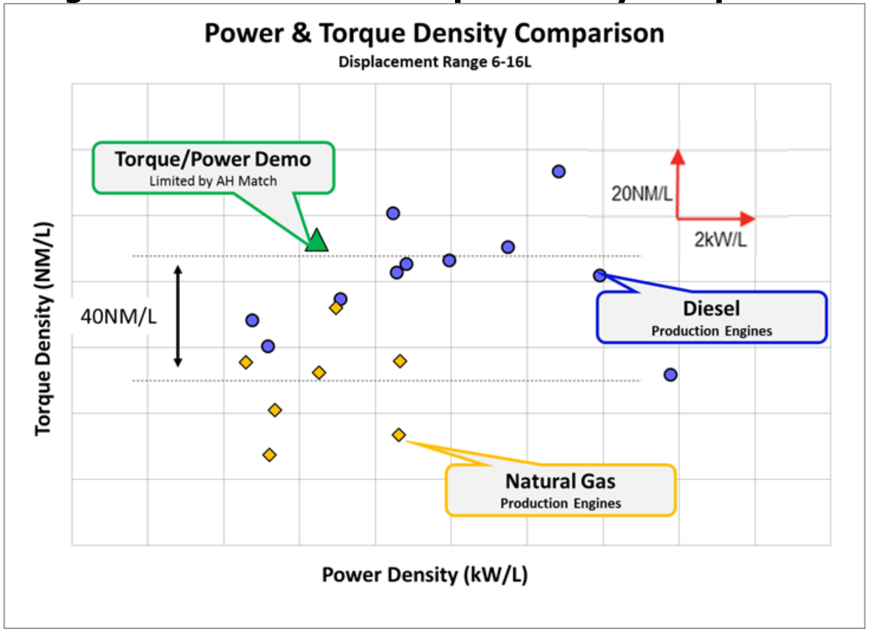
Figure 35: Cycle Brake Thermal Efficiency versus Lower Heating Value



Source: Cummins, Inc.

Finally, although performance was not an explicit goal of the program, to be viable a product needs to have performance levels that are attractive to customers. In this respect, even current state-of-the-art natural gas engines are perceived to be inferior to diesel engines. However, a well-designed natural gas engine can in fact match a diesel engine in performance, as shown in Figure 36 which illustrates the power and torque density of a range of natural gas and diesel engines. Turbine wheel speed limitations prevented the team from exploring the true performance limits of this natural gas engine design, but even the levels shown are quite impressive and competitive with diesel engines.

Figure 36: Power and Torque Density Comparison



Source: Cummins, Inc.

GLOSSARY

Term	Definition
After treatment	Method or device for reducing harmful exhaust emissions from an internal combustion engine
Air handling	System for controlling intake air conditions for an internal combustion engine
Air-fuel ratio	Mass ratio of air to fuel present in the combustion process
Asymmetric turbine	Turbocharger that incorporates two scrolls or spirals of different sizes for separate exhaust gas recirculation
Brake horsepower-hour	Unit of energy used for emission standards for internal combustion engines
Brake thermal efficiency	Ratio of brake power obtained from the engine to the fuel energy supplied to the engine
Capacitive discharge system	Type of ignition system that stores power in a capacitor before sending it to the spark plug to ignite the air-fuel mixture
Catalyst dither amplitude attenuation	Reduction in the window of allowable air-fuel ratio deviations where catalytic converter performance is maintained
Catalytic converter	Exhaust emission control device that reduces harmful pollutants in exhaust gas by catalyzing a redox reaction
CA50	Crank angle position where 50 percent of the total heat release occurs
Close-coupled three-way catalyst	Catalytic converter located near the engine's exhaust manifold that reduces oxides of nitrogen, carbon monoxide, and hydrocarbons
Coefficient of variation of indicated mean effective pressure	Defines variability in indicated work per cycle, commonly used to assess engine stability
Cold start	Starting of an engine at a low temperature relative to its operating temperature
Combustion control algorithms	Set of controls dictating the timing and conditions for combustion
Compression ratio	Ratio between volume of the cylinder and combustion chamber to the volume of the combustion chamber when the piston is at the top of its stroke, or top dead center

Term	Definition
Computational fluid dynamics analysis	Analysis of fluid flows using numerical solution methods
Crankcase ventilation	System for removing unwanted gases from the crankcase in an internal combustion engine
Criteria pollutant	Air pollutants that can harm human health, the environment, and cause property damage
Crosstalk	Undesired event where exhaust gases from one cylinder affects the flow of gases in another cylinder through the exhaust manifold
Cycle-to-cycle variability	Variability of combustion processes in an internal combustion engine over consecutive cycles
Cylinder head	Component of an internal combustion engine that sits above the cylinders on top of the engine block
Cylinder pressure sensors	Sensors installed into an engine cylinder to measure pressure
Cylinder-to-cylinder variability	Variability of combustion processes in an internal combustion engine across multiple cylinders
Diluent	Fluid used for diluting the air-fuel mixture in an internal combustion engine
Drop-down runners	Tubes extending to from the plenum to each intake port on the cylinder head
Dual coil offset ignition system	Ignition system that uses two ignition coils to create a continuous spark of variable duration for high-dilution engines
Ejector	Device used to pump the exhaust gases to the engine intake for an exhaust gas recirculation system
Engine breathing	Refers to intake systems of an internal combustion engine
Engine delta p	Difference between the engine intake pressure and exhaust pressure
Engine-out emissions	Exhaust emissions of an internal combustion engine upstream of the aftertreatment system
Exhaust gas recirculation	Emissions reduction technique used in internal combustion engines by recirculating a portion of an engine’s exhaust gas back to the engine cylinders
Exhaust manifold	Component of an internal combustion engine that collects exhaust gas from multiple cylinders and delivers it to the exhaust pipe

Term	Definition
Federal Test Procedure	Standard test procedure used for emission certification by the U.S. Environmental Protection Agency
Feedforward	Type of control where the system's output can change without any reaction from the controller
Flow bench testing	Testing of internal aerodynamic qualities of an engine component
Flow junction	Component of the exhaust manifold that combines the exhaust flows from multiple cylinders
Fuel economy penalty	Compromise of fuel economy in reference to the lower fuel economy of natural gas engines compared to equivalent diesel engines
Fuel system	Vehicle system that is responsible for delivering fuel to the engine
Global-kinetic model	Model used to analyze the chemical activity of fuel combustion
High-boost condition	Engine operating condition with high pressure airflow produced by the turbocharger
Homogeneous charge engine	Internal combustion engine that ignites a thoroughly and completely mixed air-fuel mixture
Ignitor bore	Hole in the cylinder head to house the spark plug
Indicated mean effective pressure	Average pressure produced in the combustion chamber during an engine operating cycle, disregarding friction loss
Intake backfire mitigation	Strategies to avoid instances where fuel combustion occurs when the intake valve is open
Intake manifold	Component of an internal combustion engine that supplies the air-fuel mixture to the multiple cylinders
Knock	Abnormal auto-ignited combustion in a spark-ignited engine that does not occur at the optimum moment
Lambda control	Control system to regulate the air-fuel mixture of an engine
Midbed	Location between the first and second three-way catalysts
Miller cycling	Engine cycle where the intake valve is left open longer than it would be in an Otto cycle
Mixture stratification	Separation of the air-fuel mixture into smaller charges
Monte-Carlo simulation	Type of model used to predict system behavior in response to randomly generated inputs

Term	Definition
Multipoint fuel injection	Method of injecting fuel in an internal combustion engine through multiple ports upstream of each cylinder's intake valve
Multistrike ignition system	Ignition system that uses multiple sparks during each ignition
Non-methane hydrocarbons	Regulated hydrocarbon emissions excluding methane, such as ethane and propane that contribute to poor air quality
Oil intrusion	Undesired entry of oil into a spark-ignited engine's cylinder that can induce engine knock and pre-ignition
On-board diagnostics	System in an engine's on-board computer that monitors the performance of emission-related components for malfunctions
Oxidation and reforming kinetics	Refers to the understanding of the rates of oxidation and reforming reactions
Oxidation catalyst	Exhaust emission control device that is used to oxidize compounds such as carbon monoxide and methane
Oxygen storage mechanism	Mechanism for storing oxygen for precise use in a methane oxidation catalyst
Particulate matter	Mixture of many types of solids and aerosols found in air that can induce adverse health effects if inhaled
Peak power density	Ratio of peak power capability to volume or engine displacement
Piezo resistive/capacitive	Refers to types of pressure sensors
Platinum-group metal loading	Amount of platinum-group metals (such as platinum, rhodium, and palladium) used in a catalyst
Plenum	Component of the intake manifold that facilitates the transfer of the air-fuel mixture to the cylinders
Pre-ignition	Ignition of the air-fuel mixture prior to the spark plug firing
Pulse capture exhaust manifold	Exhaust manifold that uses exhaust gas pressure to assist in recirculating the exhaust gas back to the cylinders
Pulse capturing device	Device used to capture exhaust gas pressure to assist in recirculating the exhaust gas back to the cylinders
Pumping mean effective pressure	Average pressure from work per cycle done by the piston on the in-cylinder gases during the intake and exhaust strokes
Residual gases	Gases remaining in the cylinder of an internal combustion engine after the exhaust stroke has been completed

Term	Definition
Sigma error bars	Graphical representation of data variability to indicate error or uncertainty in a reported measurement in terms of standard deviations
Single point fuel injection	Method of injecting fuel in an internal combustion engine through a single point near the intake throttle
Spark system	Ignition system that uses a spark plug to control the ignition of the air-fuel mixture in an internal combustion engine
Split exhaust manifold	Divided exhaust manifold that collects exhaust gas from separate subsets of cylinders
Stochastic knock detection algorithm	Method for detecting combustion knock in a spark-ignited engine using a model-based approach
Stoichiometric	Refers to the ideal fuel ratio where all fuel and air is consumed during combustion without any excess fuel or air
Swirl	Rotation of the air-fuel mixture about the cylinder axis induced for rapid combustion
Thermal mechanical fatigue analysis	Analysis of the effects of mechanical loads and thermal loads on material fatigue and durability
Three-way catalyst	Engine emissions control device that reduces oxides of nitrogen, carbon monoxide, and hydrocarbons
Throttle	Device used to control the flow of fuel and/or air into an engine
Tip-in and tip-out events	Sudden event where engine torque is abruptly increased or decreased, respectively
Torque	Rotating force produced by an engine
Torque density	Ratio of torque capability to volume or engine displacement
Transient response	Response of a system to a change from steady state
Turbine inlet	Component of a turbocharger that takes in engine exhaust to drive the turbine
Turbocharge	The forcing of extra compressed air into an engine’s combustion chamber using a turbine-driven device
Underfloor three-way catalyst	Catalytic converter located beneath the floor of the vehicle that reduces oxides of nitrogen, carbon monoxide, and hydrocarbons
Valve train	Component of an internal combustion engine that controls operation of the intake and exhaust valves

Term	Definition
Variable geometry turbocharger	Turbochargers that can vary their aspect ratio as conditions change
Variable valve timing	Process of altering the timing of valve lift events to improve performance, fuel economy, or emissions
Warm start	Starting of an engine after it has been recently run at operating temperature
Wastegate/wastegated turbine	Turbocharger that uses a wastegate valve to control the flow of exhaust gases to the turbine wheel
World Harmonized Transient Cycles	Heavy-duty engine dynamometer cycle defined by the global technical regulation for engine exhaust emissions

LIST OF ACRONYMS

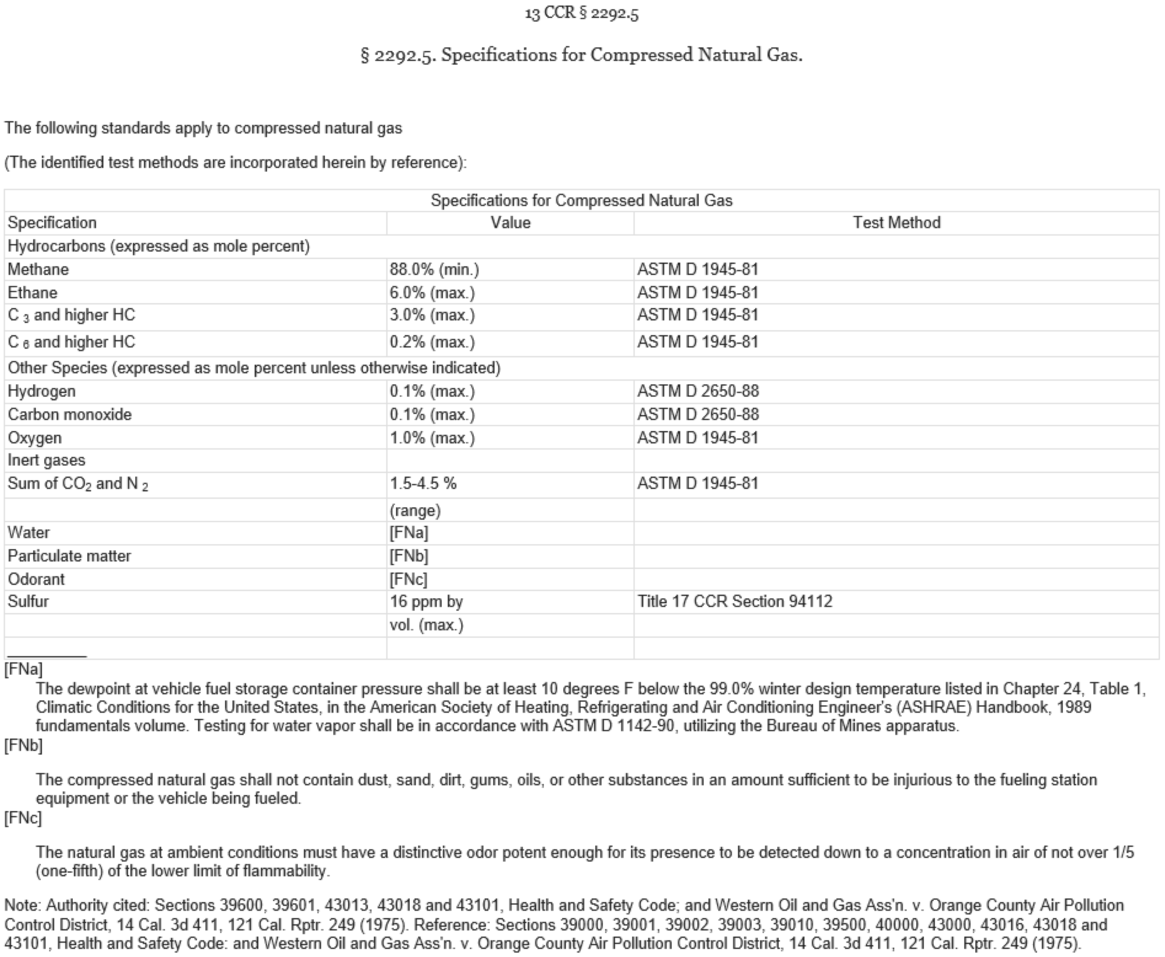
Acronym	Definition
AFR	Air-fuel ratio
BTE	Brake thermal efficiency
CAC	Charge air cooler
CARB	California Air Resources Board
CFD	Computational fluid dynamics
CH_4	Methane
CLCC	Closed Loop Combustion Control
CO	Carbon monoxide
CoV	Coefficient of variation
CPS	Cylinder pressure sensors
CRV	Compressor recirculation valve
DI	Direct ignition
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
FTP	Federal Test Procedure
g/bhp-hr	Grams per brake horsepower-hour
g/kWh	Grams per kilowatt-hour
HHD	Heavy heavy-duty (engine or vehicle)
HPL	High pressure loop
IAT	Intake air throttle
IMEP	Indicated mean effective pressure
IMOP	Intake manifold over-pressure
L	Liter
LPL	Low pressure loop
NH_3	Ammonia
NMHC	Non-methane hydrocarbons
NOx	Oxides of nitrogen
O_2	Oxygen

Acronym	Definition
OBD	On-board diagnostics
PFI	Port fuel injection
Ppm	Parts per million
SCE	Selected catalytic reduction
SEGR	Stoichiometric cooled exhaust gas recirculation
SI	Spark ignition
SPFI	Single-point fuel injection
TWC	Three-way catalyst
USEPA	United States Environmental Protection Agency
VGT	Variable geometry turbocharger

APPENDIX A:
Test Fuel Analysis

Compliance with Specifications for Compressed Natural Gas

The project required that the gaseous fuel be checked prior to and after emissions testing for compliance with CCR-13-2292.5.



13 CCR § 2292.5

§ 2292.5. Specifications for Compressed Natural Gas.

The following standards apply to compressed natural gas

(The identified test methods are incorporated herein by reference):

Specifications for Compressed Natural Gas		
Specification	Value	Test Method
Hydrocarbons (expressed as mole percent)		
Methane	88.0% (min.)	ASTM D 1945-81
Ethane	6.0% (max.)	ASTM D 1945-81
C_3 and higher HC	3.0% (max.)	ASTM D 1945-81
C_6 and higher HC	0.2% (max.)	ASTM D 1945-81
Other Species (expressed as mole percent unless otherwise indicated)		
Hydrogen	0.1% (max.)	ASTM D 2650-88
Carbon monoxide	0.1% (max.)	ASTM D 2650-88
Oxygen	1.0% (max.)	ASTM D 1945-81
Inert gases		
Sum of CO_2 and N_2	1.5-4.5 %	ASTM D 1945-81
	(range)	
Water	[FNa]	
Particulate matter	[FNb]	
Odorant	[FNc]	
Sulfur	16 ppm by	Title 17 CCR Section 94112
	vol. (max.)	

[FNa]
The dewpoint at vehicle fuel storage container pressure shall be at least 10 degrees F below the 99.0% winter design temperature listed in Chapter 24, Table 1, Climatic Conditions for the United States, in the American Society of Heating, Refrigerating and Air Conditioning Engineer's (ASHRAE) Handbook, 1989 fundamentals volume. Testing for water vapor shall be in accordance with ASTM D 1142-90, utilizing the Bureau of Mines apparatus.

[FNb]
The compressed natural gas shall not contain dust, sand, dirt, gums, oils, or other substances in an amount sufficient to be injurious to the fueling station equipment or the vehicle being fueled.

[FNc]
The natural gas at ambient conditions must have a distinctive odor potent enough for its presence to be detected down to a concentration in air of not over 1/5 (one-fifth) of the lower limit of flammability.

Note: Authority cited: Sections 39600, 39601, 43013, 43018 and 43101, Health and Safety Code; and Western Oil and Gas Ass'n. v. Orange County Air Pollution Control District, 14 Cal. 3d 411, 121 Cal. Rptr. 249 (1975). Reference: Sections 39000, 39001, 39002, 39003, 39010, 39500, 40000, 43000, 43016, 43018 and 43101, Health and Safety Code: and Western Oil and Gas Ass'n. v. Orange County Air Pollution Control District, 14 Cal. 3d 411, 121 Cal. Rptr. 249 (1975).

Cummins employs a continuous fuel analysis system online natural gas analysis (ONGA). The Cummins Technical Center receives gas directly from the commercial natural gas pipeline. Historically, gas composition has been stable and well within the CCR 13 2292.5 specification. Starting in late 2014, however, gas composition has been quite variable. After more than six months of this high variability and confirmation with the gas utility that this is "the new normal," a capital improvement project was approved to install a large liquefied natural gas tank to ensure stable fuel quality. At the time this report was prepared, that project was scheduled for completion in May 2016. All testing for the South Coast Air Quality Management District program therefore has been done with the available gas from the pipeline.

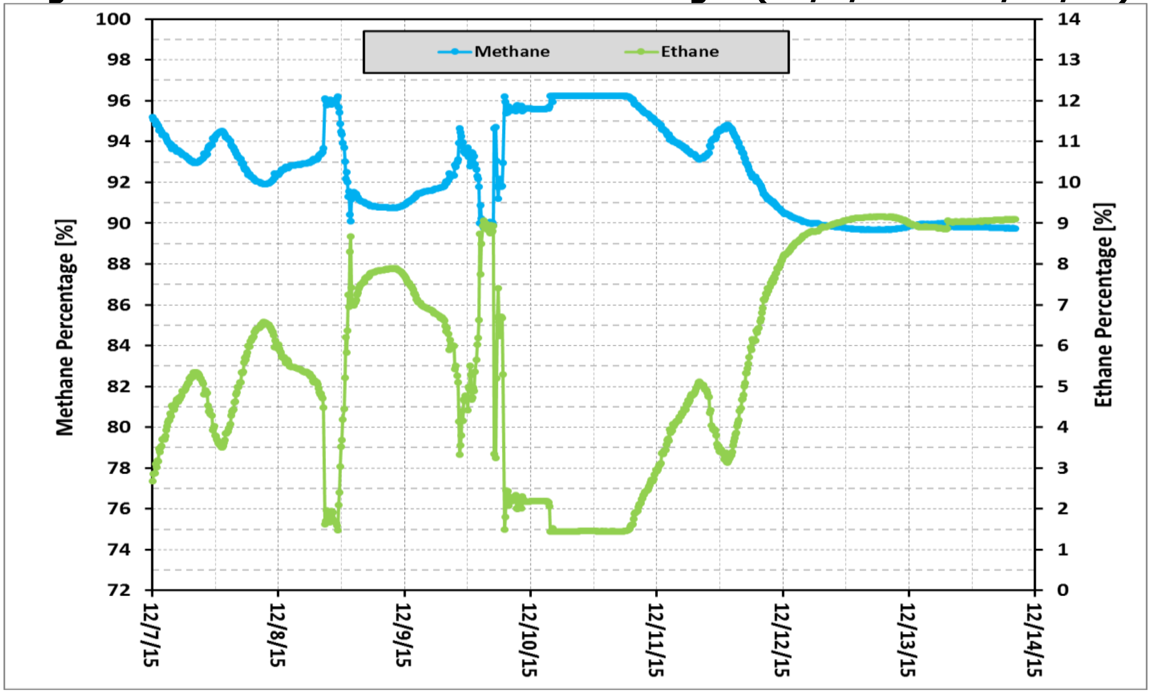
The impact is that calibrating the system is far more complicated. However, as test results have shown, a robust system should be able to handle these fuel composition variabilities without a problem. This is especially true as the fluctuations in gas composition seen in Columbus, Indiana, are quite common in other areas of the country. These conditions therefore represent a real-world condition for engines operating in the field and should not affect emissions or performance.

This appendix provides the ONGA data for the two weeks in December 2015 during which all emissions testing took place.

Methane and Ethane

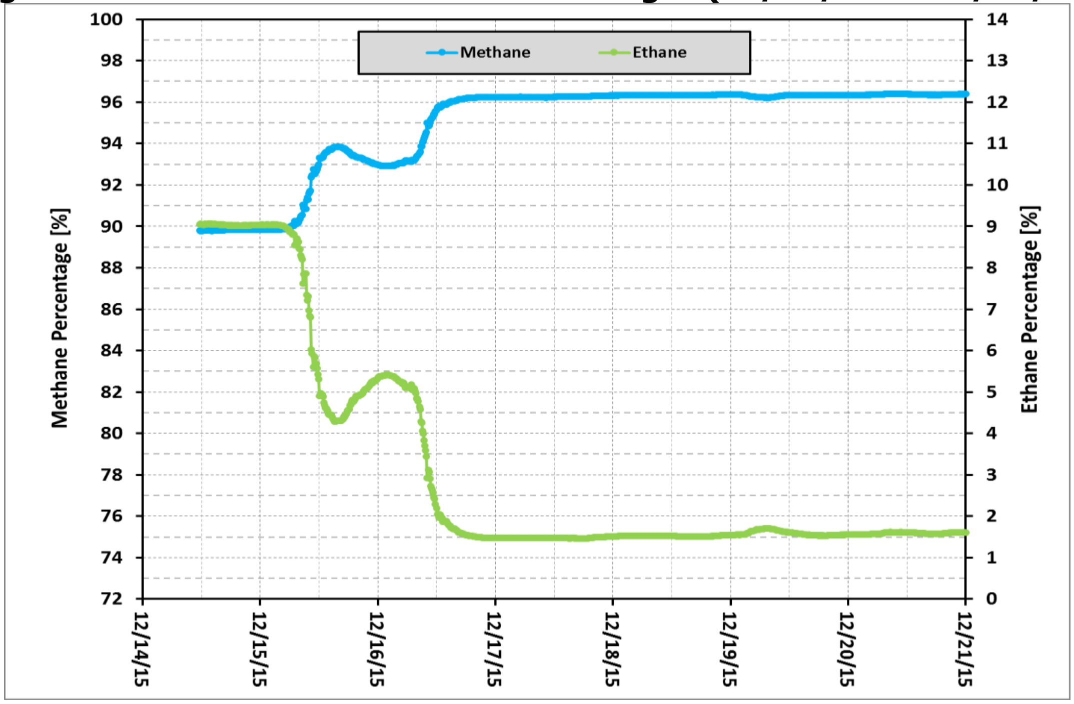
Figure A-1 and Figure A-2 detail the methane and ethane percentages. Most of the time these percentages were within specification, although fluctuating substantially at times. Ethane percent did exceed the six percent limit on several days (no testing was done on the weekend of December 12-13, 2015). The engine system was calibrated to deal with these fluctuations and no adverse effect was seen in emissions, performance, or efficiency.

Figure A-1: Methane and Ethane Percentages (12/7/15 to 12/14/15)



Source: Cummins, Inc.

Figure A-2: Methane and Ethane Percentages (12/15/15 to 12/21/15)

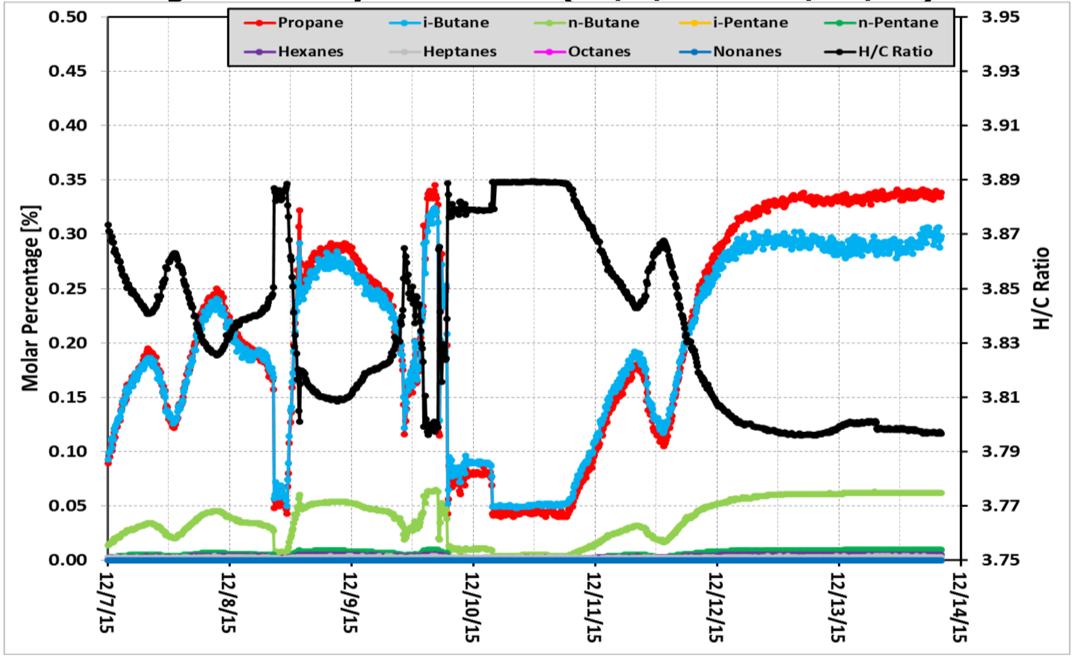


Source: Cummins, Inc.

Higher Hydrocarbons

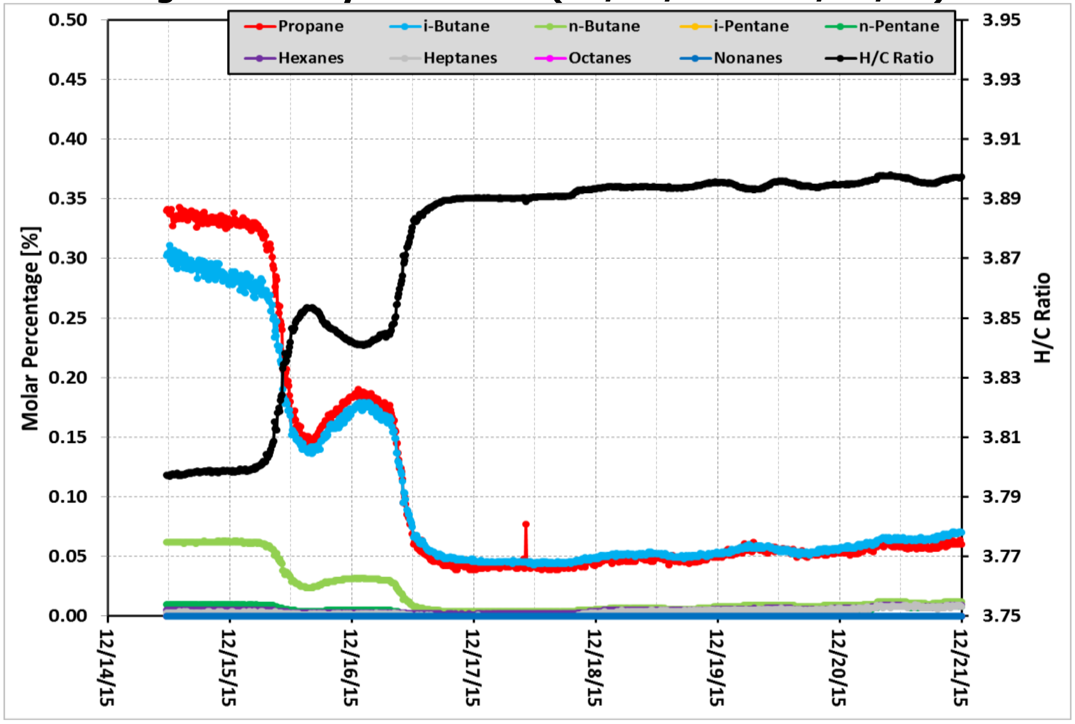
In aggregate, C3+ and C6+ hydrocarbons were both within specifications during the testing period.

Figure A-3: Hydrocarbons (12/7/15 to 12/14/15)



Source: Cummins, Inc.

Figure A-4: Hydrocarbons (12/14/15 to 12/21/15)

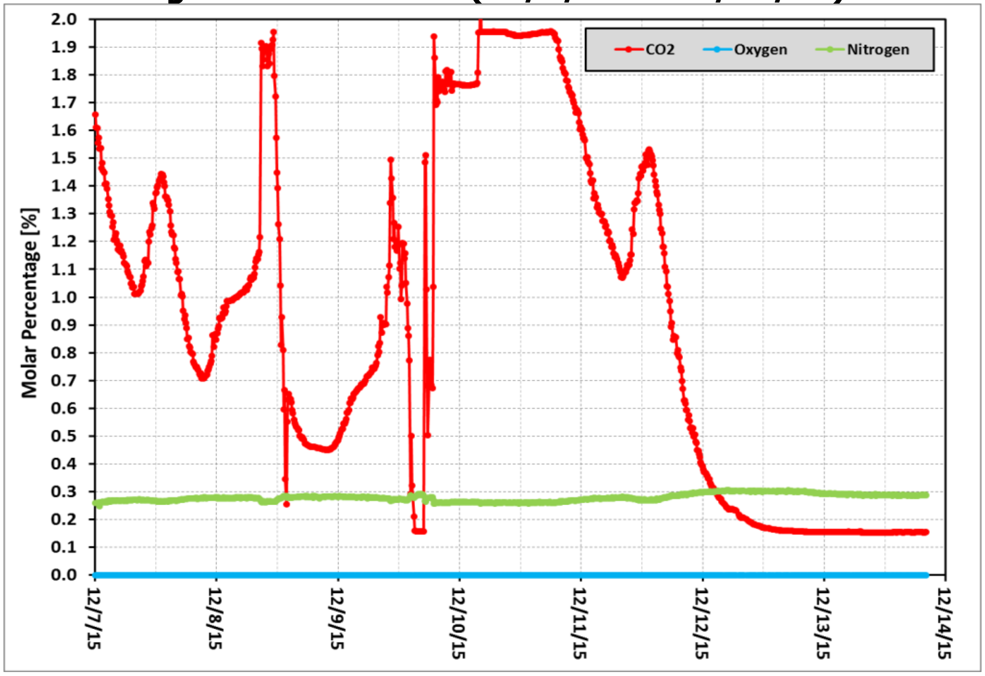


Source: Cummins, Inc.

Diluents

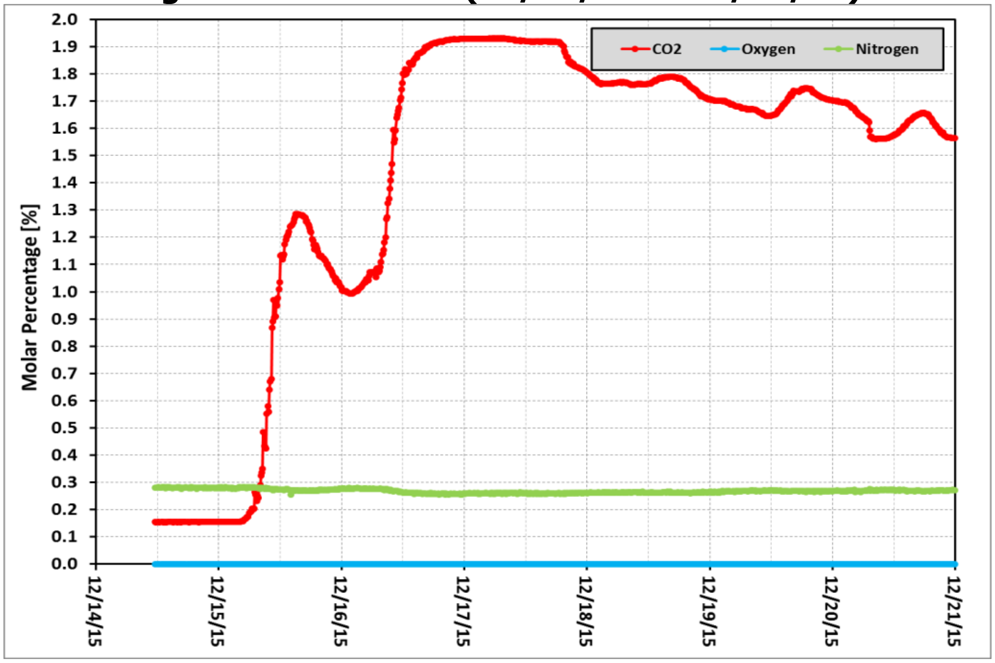
Oxygen and (CO_2 + N_2) were within specifications during the testing period.

Figure A-5: Diluents (12/7/15 to 12/14/15)



Source: Cummins, Inc.

Figure A-6: Diluents (12/15/15 to 12/21/15)



Source: Cummins, Inc.