Energy Research and Development Division
FINAL PROJECT REPORT

ULTRA-LOW EMISSIONS 12 LITER HEAVY DUTY NATURAL GAS ENGINE DEVELOPMENT

Prepared for: California Energy Commission

Prepared by: Gas Technology Institute (GTI) and Cummins Westport Inc. (CWI)

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PREFACE

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- Transportation

This report is the final deliverable for the Ultra-Low Emissions 12-Liter Heavy-Duty Natural Gas Engine Development project (CEC PIR 08-044), conducted by Gas Technology Institute (GTI) and subcontractor Cummins Westport Inc (CWI). The information from this project contributes to Energy Research and Development Division's Transportation Program.

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ABSTRACT

The project team designed and developed the early stage of a new, heavy-duty natural gas engine in a laboratory. Stoichiometric, cooled exhaust gas recirculation, three-way catalyst, spark ignition technology was applied to a new Cummins 11.9-liter engine platform. Stoichiometric refers to a process in which enough air is provided to completely burn all of the fuel in the engine. The resulting natural gas engine was identified as "ISX11.9 G." The project team confirmed the ISX11.9 G technical feasibility for Class 8 regional haul and vocational truck applications by demonstrating that it met the following criteria: pollutant emissions at or below the United States Environmental Protection Agency/California Air Resources Board 2010 on-highway emission standards and a peak rating of 400 horse power/1350 pound-foot. The project team obtained preliminary fuel economy data that demonstrated a marginal fuel consumption improvement for ISX11.9 G-powered Class 8 trucks when compared with existing spark-ignited, natural gas-powered Class 8 trucks. The project team believed that further fuel economy improvement during the next phase of engine development will lead to commercialization of an ISX11.9 G engine that delivers five percent to 10 percent better fuel economy compared to existing spark-ignited natural gas powered Class 8 trucks. The project team forecasted full fuel cycle greenhouse gas benefits ranging from 10 percent to 44 percent for ISX11.9 G-powered Class 8 trucks versus diesel-fueled Class 8 trucks. The project team recommended proceeding with the next phase of engine development, demonstration, and commercialization to enable commercial availability of the ISX11.9 G engine in a wide range of Class 8 regional haul and vocational truck chassis.

Keywords: Natural gas, low emissions, heavy-duty engine, Class 8 trucks, greenhouse gas reduction

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Using diesel fuel in trucks and other vehicles results in emissions of greenhouse gases and other pollutants that contribute to climate change and air pollution. Gas Technology Institute (GTI) teamed with Cummins Westport Inc. (CWI) to develop and demonstrate an ultra-low emissions, high-performance, spark-ignited natural gas engine. GTI performs energy-focused contract research for the government, gas industry, and its private clients. CWI is a joint venture company between Cummins Inc. and Westport Innovations Inc. CWI develops and commercializes advanced, low-emission, alternative fuel engines.

Project Purpose

The purpose of this project was to determine if CWI's spark ignition technology could be feasibly applied to a 12- to 13-liter, heavy-duty natural gas engine platform, with performance and emissions results suitable for large capacity regional haul and vocational truck applications. Developing a 12- to 13-liter natural gas engine would fill a gap in the sizes available for natural gas engines and conducting research to develop advanced engine designs would increase engine efficiency while lowering tailpipe emissions.

The scope of this project included design, early-stage development, and demonstration of the new heavy-duty natural gas engine using spark ignition technology in a laboratory.

The objectives of this project were to:

- Design, develop, and demonstrate a 12- to 13-liter heavy-duty natural gas engine that could be certified at or below United States Environmental Protection Agency (U.S. EPA)/California Air Resources Board (ARB) 2010 emission standards (grams/brake horsepower-hour [g/bhp-hr]): 0.20 nitrogen oxides (NOx), 0.14 nonmethane hydrocarbons (NMHC), 0.01 particulate matter (PM), 15.5 carbon monoxide (CO).
- Demonstrate a peak rating of 400 horsepower (hp) and 1350 pound-foot (lb-ft) peak torque.
- Demonstrate improved fuel economy of 5 percent to 10 percent compared to current spark-ignited, natural gas-powered trucks in specific vocational and regional haul Class 8 truck/tractor duty cycles.
- Measure the greenhouse gas (GHG) emission reductions of the proposed new engine versus diesel and existing spark ignition natural gas engines in specific vocational and regional haul Class 8 truck/tractor duty cycles.
- Create technical data that would communicate the preliminary engine design and operating characteristics to enable continued product development and commercialization through a subsequent project. This technical data would include computer-aided design models, bills of material, preliminary component design drawings, emissions data, detailed fuel maps, and vehicle emission simulations.

Project Results

The project team selected a new Cummins 11.9 liter heavy-duty engine platform for this development project. The resulting natural gas engine was identified as "ISX11.9 G." The project successfully addressed each of the project objectives. The key project results included:

- Designed, demonstrated, and conducted preliminary development of an alpha-stage, 12–liter, heavy-duty natural gas engine, with emissions at or below U.S. EPA/ARB 2010 emission standards (g/bhp-hr): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO.
- Demonstrated 400 hp, 1350 lb-ft peak performance.
- Demonstrated fuel economy improvement of about two percent compared to existing spark-ignited, natural gas-powered trucks in specific vocational and regional haul Class 8 truck/tractor duty cycles. The fuel economy data generated to date did not meet the project target. The project team was confident that further fuel economy improvement could be realized during the next stage of the engine development program. The project team believed that the ISX11.9 G engine could deliver five percent to 10 percent better fuel economy than existing spark-ignited natural gas powered Class 8 regional haul and vocational trucks.
- The project team forecasted full fuel cycle GHG benefits ranging from 10 to 44 percent for ISX11.9 G-powered Class 8 trucks versus diesel-fueled Class 8 trucks. The forecast was based on two components: 1) there will be a proportion of renewable and conventional fuel sources in the future California natural gas transportation fuel supply; and 2) ISX11.9 G fuel economy improvements versus comparable diesel engines once the final ISX11.9 G engine design was completed.
- The ISX11.9 G development project was conducted in accordance with the Cummins-prescribed process for new product introduction programs. The project team created a comprehensive set of technical data that was shared and reviewed regularly among a cross-functional team that was responsible for directing the overall engine development, demonstration, and commercialization program within CWI. All technical and nontechnical functions involved in the project were fully engaged in the ISX11.9 G development program and were proceeding toward commercial availability by 2013.

The project team's primary conclusion was that the spark ignition technology could feasibly be applied to an 11.9-liter heavy-duty engine platform and could achieve the performance and emission targets established for the program. Additionally, the project team drew the following conclusions related to the specific objectives established for this project:

- The spark ignition technology applied to an 11.9–liter, heavy-duty engine platform was capable of criteria pollutant emissions that are lower than the U.S. EPA/ARB 2010 on-highway emission standards (g/bhp-hr): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO.
- The ISX11.9 G engine could achieve a peak rating of 400 hp and 1350 lb-ft peak torque, with sufficient combustion margin to ensure robust operation in a variety of duty cycles and operating conditions.

- The ISX11.9 G engine fuel economy data collected to date indicated a marginal fuel economy improvement when compared with existing spark-ignited natural gas engines used in Class 8 trucks, despite a lack of focus on fuel economy improvement at this stage of the ISX11.9 G development program.
- ISX11.9 G-powered Class 8 trucks were projected to deliver full fuel cycle GHG advantages ranging from 10 percent to 44 percent when compared to diesel-fueled Class 8 trucks. These projections were dependent on the proportion of renewable and conventional natural gas fuel sources in the future California transportation natural gas fuel supply and the ISX11.9 G fuel economy relative to diesel engines at launch.

CWI recommended proceeding with the next stage of the overall ISX11.9 G engine development, demonstration, and commercialization. CWI intended to proceed with this next phase of work immediately, with an objective of initiating customer field demonstrations leading to commercial availability of the ISX11.9 G engine in a broad range of Class 8 regional haul and vocational truck chassis by 2013. CWI anticipated that the total expense to enable ISX11.9 G commercial availability would be in the range of $6 million to $8 million.

Project Benefits

This project successfully completed the first stage of an engine development program that was expected to lead to commercial availability of a more fuel-efficient natural gas engine for heavy duty vehicle applications that are currently served predominantly by diesel engines. California natural gas ratepayers were expected to directly benefit from the development of advanced engine technology that improves natural gas engine efficiency while reducing emissions. Higher engine efficiency will reduce the emissions of criteria pollutants and greenhouse gases per vehicle mile traveled. Compared to diesel engines, the emissions control technology needed to meet ARB 2010 NOx standards for spark-ignited natural gas engines will not require the use of ammonia as the NOx reducing agent, improving the cost of the natural gas vehicle technology. With an approximate 10 percent heavy-duty market penetration, approximately 97,500,000 gallons of diesel and 13 million metric tons of equivalent carbon dioxide (CO_2e) could be displaced per year. CO_2e is the concentration of CO_2 that would cause the same level of radiative forcing as other types of greenhouse gas such as methane, perfluorocarbons, and nitrous oxide. Radiative forcing is the difference between radiant energy received by the earth and energy radiated back to space.

Another benefit of this project was reduced consumption of diesel fuel because the ISX11.9 G natural gas engine will directly displace diesel fuel consumption in target market applications. Natural gas use would lessen petroleum imports used in the heavy-duty truck market. This reduced demand for diesel should enable gasoline production in the capacity-constrained refinery industry, which will help address volatility in gasoline prices.

California ratepayers will further benefit from the commercial launch of the ISX11.9 G engine as it was integrated with other technological advancements under development, including advanced power trains, hybrid vehicle platforms, and waste heat recovery. These improvements will result in additional reductions in transportation fossil energy and greenhouse gas emissions.

CHAPTER 1: Introduction

1.1 Background and Overview

Gas Technology Institute (GTI) teamed with Cummins Westport Inc. (CWI) to develop and demonstrate an ultra low emissions, high performance spark ignited natural gas engine. GTI performs energy-focused contract research for the government, gas industry, and other private clients. CWI, a joint venture company between Cummins Inc. and Westport Innovations Inc., is responsible for developing and commercializing advanced, low-emission, alternate fuel engines. CWI's mission is to develop and commercialize low emission engines for medium and heavy duty applications. CWI develops and markets the world's widest range of high-performance low-emissions engines for transit and commercial vehicles.

The technology to be developed will lead to a product introduction for reducing fossil fuel consumption, greenhouse gases, and criteria pollutants from heavy-duty vehicles. In this project, CWI applied its stoichiometric, cooled exhaust gas recirculation (EGR), three way catalyst (TWC), spark ignition (SESI) technology to a new 11.9 liter heavy duty engine platform. The scope of this project includes design and early-stage development of the new heavy duty natural gas engine in a laboratory environment.

The goal of this project was to design, develop, and demonstrate a pre-commercial heavy duty spark ignited natural gas engine with ultra low emissions, high performance, and best in class fuel economy in specific vocational and regional haul Class 8 truck duty cycles. At the outset of the project, CWI and GTI anticipated a follow-on project to complete development and commercialization of the new 11.9 liter natural gas engine, with the follow-on project commencing upon successful demonstration of the project goals at the conclusion of this PIER project.

This project sought to demonstrate that the SESI technology can achieve or exceed EPA / CARB 2010 on-highway emission standards when applied to an 11.9 liter engine. Through calibration and catalyst development, CWI planned to target NOx and PM emission levels lower than the EPA / CARB 2010 emission standards. In addition to criteria pollutant reductions, the proposed engine will provide significant greenhouse gas (GHG) emission reductions versus diesel vehicles. GTI and CWI anticipate the proposed new engine to achieve significant market share in the aforementioned target market segments. Natural gas is abundantly available from domestic sources. Therefore, increasing natural gas penetration in the heavy-duty transportation market will reduce petroleum fuel consumption, thus diversifying California's energy mix, and reducing the dependence of California's economy on imported oil.

1.2 Project Objectives

The objectives of this project are to:

- Design, develop, and demonstrate (on dynamometer) an Alpha stage 12 to 13 liter heavy duty natural gas engine that can be certified at or below U.S. EPA / CARB 2010 emission standards (g/bhp-hr): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO,
- Demonstrate a peak rating of 400 hp and 1350 lbs. ft. peak torque,
- Demonstrate improved fuel economy of 5 to 10 percent when compared to current spark ignited natural gas powered trucks in specific vocational and regional haul Class 8 truck / tractor duty cycles,
- Quantify the GHG emission reductions of the proposed new engine versus diesel and existing SI natural gas engines in specific vocational and regional haul Class 8 truck / tractor duty cycles,
- Create technical data, including CAD models, bills of material, preliminary component design drawings, emissions data, detailed fuel maps, and vehicle mission simulations, to validate the preliminary engine design and document operating characteristics, and thereby enable continued product development and commercialization via a follow-on project.

CHAPTER 2:
Project Tasks

The Scope of Work for this project was structured into six technical tasks. The objectives and key work performed within each of these tasks is described below.

2.1 Task 2.1 Concept Design

The goal of this task was to create a Concept design for a 12 to 13 liter heavy duty natural gas engine using CWI's SESI technology. This task defined the engine architecture by identifying existing engine subsystems and components that can be utilized from existing Cummins and CWI engines, identifying the quantity of new components that must be designed for the new engine, and creating preliminary designs for all new components.

2.1.1 Engine Architecture

CWI defined the high-level architecture for the new engine. This was accomplished by identifying engine subsystems and components that can be utilized from existing Cummins and CWI engines, as well as specifying the new components that must be designed for the new engine.

At the outset of the engine development program, Cummins was developing two new heavy-duty diesel engine platforms:

- ISX11.9 (2010 launch for North American Class 8 vocational and regional haul truck / tractor markets)
- ISZ13 (2010 launch for Asian heavy-duty truck markets)

The primary target market opportunity for CWI's new natural gas engine is the North American Class 8 truck market, with a focus on vocational and regional haul truck and tractor applications. CWI, in consultation with Cummins, evaluated the technical, marketing, and manufacturing feasibility of using the ISX11.9 and ISZ13 engines as the base engine platform for natural gas engine development. CWI's early market research indicated that peak performance of 400 hp and 1350 to 1450 lb-ft is required to succeed in the target North American market segments. Technical evaluation and performance modeling indicated that this target peak rating could be achieved with either base engine platform, and suggested that improved combustion margin may be available with the 11.9 liter configuration. Specifically, the lower 11.9 liter displacement resulted in fewer geometric constraints in the power cylinder design, thus enabling additional design flexibility in the shape of the piston bowl, which is a key factor to increase combustion margin. In addition, selecting the ISX11.9 platform would enable CWI to leverage Cummins' North American ISX11.9 diesel manufacturing and supply base and ISX11.9 Class 8 truck original equipment manufacturers (OEM) installations. As a result, CWI selected the Cummins ISX11.9 diesel engine as the base engine platform for this natural gas engine development program. Accordingly, CWI decided to refer to the new engine as the "ISX11.9 G." The majority of the ISX11.9 diesel engine components can be used for the new natural gas engine without modification, including the engine block, crankshaft, bearings, engine mounts, belt drives, accessories, and so forth.

The ISX11.9 G engine will use stoichiometric SESI technology in conjunction with a three way catalyst, which is the same technology utilized by CWI's 8.9 liter ISL G engine. As a result of the technology commonality, much of the high-level engine architecture is consistent with ISL G. Existing ISL G components that can be utilized without modification include the electronic control module (ECM), ignition control module (ICM), and fuel system sensors.

Many components will need to be re-designed or up-sized for the production-intent design to accommodate the higher performance and larger displacement of the ISX11.9 natural gas engine versus CWI's ISL G engine. New components required for the production-intent design will include the cylinder head, fuel module, turbo-charger, pistons, catalyst, ignition coils, and spark plugs.

The high-level engine architecture is summarized in Table 1 below.

Table 1: ISX11.9 Natural Gas Engine Architecture Summary

Component / System	Description
Displacement	• 11.9 liters
Technology	• Stoichiometric Cooled Exhaust Gas Recirculation Spark Ignition (SESI)
Platform	• ISX11.9
Cylinder Head	• ISX11.9 head, modified for spark plugs
ECM	• Same as ISL G
Ignition System	• Spark ignition, coil-on-plug • ICM: Same as ISL G • Ignition coils: Unique design for new engine • Spark plugs: Unique design for new engine
Fuel System	• Integrated housing combining fuel, charge air and EGR flows • Unique design for new engine
Air Handling System	• Turbo-charger: Waste gated turbo (new design) • EGR cooler: Same as ISX11.9 diesel • EGR valve: Same as ISL G
After treatment	• Three way catalyst (new design required to suit increased exhaust gas flow)

Crankcase Ventilation	Open crankcase ventilation
Power Cylinder	New piston design
Engine Braking	Compression release brake; unique hardware required N/A for concept design; to be developed for Alpha design

2.1.2 Concept Design

CWI developed a Concept design, with the main elements described below and in Figures 1-4. To the extent feasible, the Concept design is consistent with the engine architecture summarized in Table 1. However, due to the long lead time associated with some of the unique components identified in Table 1, and given that the Concept engine design is intended to demonstrate the feasibility of applying SESI technology to a larger engine platform, CWI has determined that some of the ISL G components can be used for the Concept design. These components include the ISL G spark plugs, ignition coils, and fuel module.

Figure 1: Concept Engine CAD Model (Left Side View)

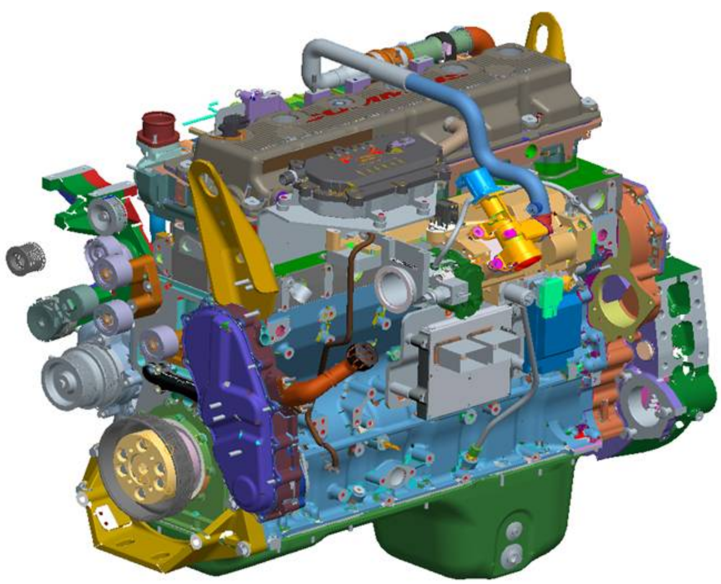
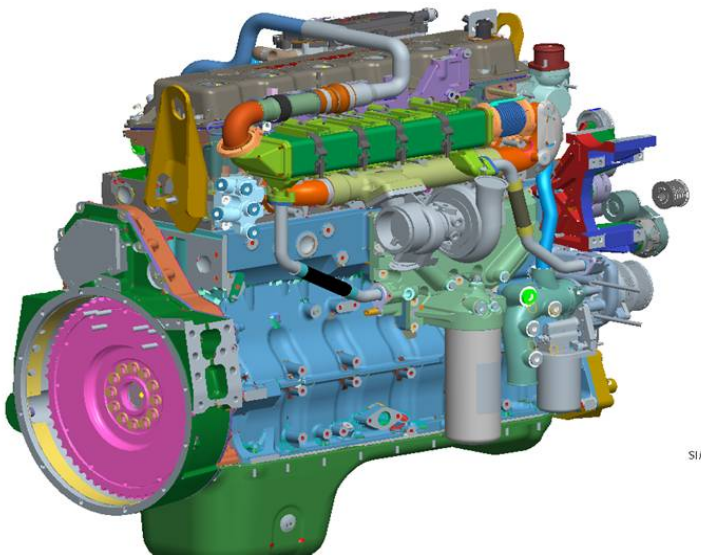


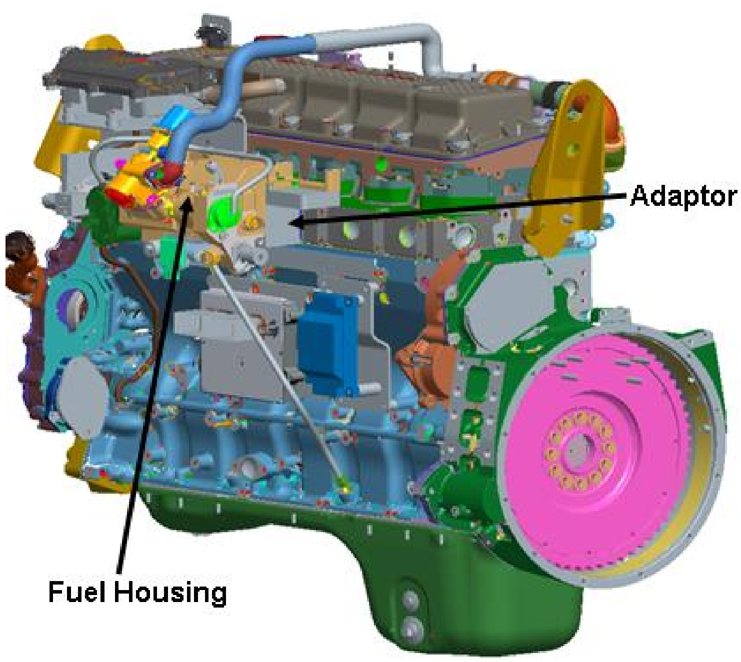
Figure 2: Concept Engine CAD Model (Right Side View)



A design was completed for the cylinder head to facilitate installation of the spark plug. Additional casting and machining changes were identified in the design to improve combustion dynamics, based on analytical modeling results. Cylinder head castings were procured from the diesel platform team and special prototype machining was completed.

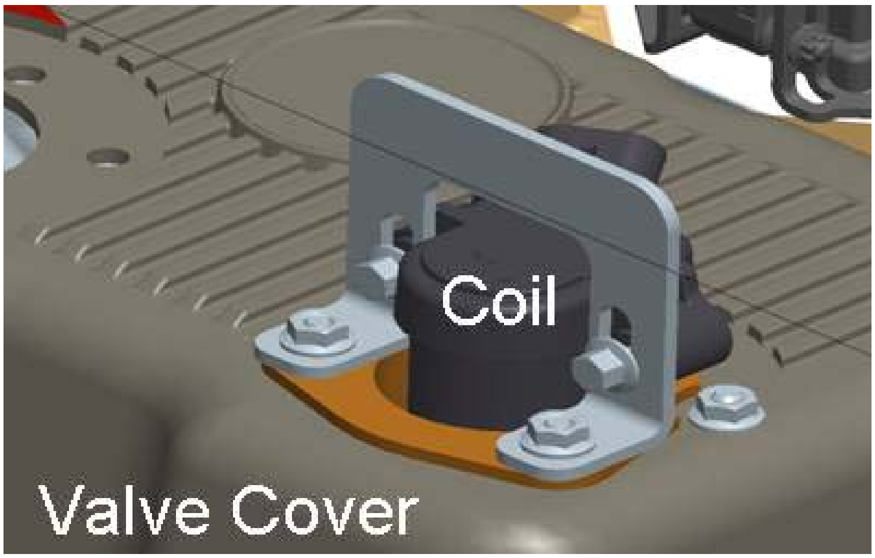
An adaptor was designed and a prototype was procured which allowed use of a current CWI fuel housing on the Concept engine. Analysis was completed which confirmed that this arrangement will provide sufficient fuel flow for the initial engine operation.

Figure 3: Concept Engine Design, Highlighting Fuel Housing and Adaptor



An initial design was completed for the ignition system. An existing ignition coil design was selected that had the required characteristics and an extension was designed and procured to complete the connection to the spark plug. The spark plug was procured from a CWI supplier that also had the needed characteristics. Design modifications were also made to the current diesel valve cover to allow mounting of the ignition coils. A prototype part was procured to this design and used on the Concept engine.

Figure 4: Concept Ignition Coil and Mounting Bracket on Valve Cover



A number of potential piston designs were developed based on analytical modeling. The ISX11.9 G piston design is unique from the ISX11.9 diesel piston. The new design provides the required compression ratio for the SESI technology, which is much lower than a typical diesel engine compression ratio. Prototype hardware was produced for a number of potential piston designs. The combustion characteristics and temperature profile for multiple candidate designs and piston bowl geometries were evaluated during Concept engine testing in an engine dynamometer.

Based on discussions with OEMs and prospective truck fleet customers in the target market segments, CWI determined that engine braking will be a required feature for the majority of Class 8 truck users. Using CAD modeling, CWI found that the engine compression release brake (aka “jake brake”) developed for the ISX11.9 diesel engine will not be compatible with the natural gas engine because of interference with the spark plugs and ignition coil extensions required for the natural gas engine. CWI’s current engines are not available with compression release brakes; therefore, a new design is required for compression release brake hardware. The compression release brake is not required for Concept engine demonstration and testing in an engine dynamometer test cell; therefore, the Concept engine design does not address the compression release brake. In order to develop a compression release brake as part of the Alpha Design, CWI initiated discussions with a third-party compression release brake manufacturer.

Table 2 summarizes the number of new and existing parts that comprise the Concept engine design.

Table 2: Concept Design Parts Summary

Category	Number	Percentage of Total Parts
Common Diesel Engine Parts	537	84.4%
Commons Natural Gas Engine Parts	29	4.6%
New Natural Gas Engine Parts	70	11.0%
Total	636	100.0%

2.2 Task 2.2 Performance Modeling and Analysis

The goal of this task was to conduct analysis to refine the preliminary component designs and to model engine performance and system interactions, including air handling, combustion, fuel system, and catalyst operation.

Extensive analysis was conducted using engine modeling software including GT-Power and KIVA. A GT-Power model was established by combining existing models for the Cummins ISX11.9 diesel engine and CWI's ISL G natural gas engine. The following text summarizes the work performed within this task for the major engine sub-systems.

2.2.1 Air Handling System

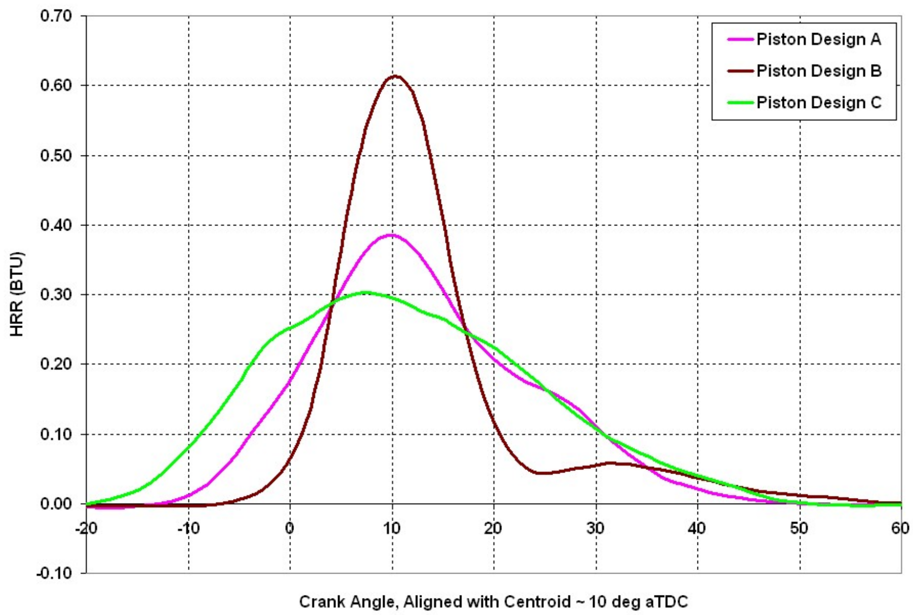
The ISX11.9 G engine will utilize stoichiometric, cooled EGR, spark ignition (SESI) technology. Due to stoichiometric operation, versus lean operation for diesel engines, the charge-air flow rates for the ISX11.9 G engine will be substantially lower than for heavy duty diesel engines of similar displacement. Therefore, the turbo-charger that will be selected for the ISX11.9 G engine will be significantly smaller than the turbo-chargers supplied by Cummins Turbo Technologies for Cummins heavy-duty diesel engines used in Class 8 truck applications.

To select a turbo-charger, CWI conducted extensive modeling to determine the optimal turbo-charger turbine, compressor, and waste-gate characteristics for the ISX11.9 G engine. GT-Power modeling was used to analyze a variety of turbo-charger configurations that meet requirements for charge-air flow, engine exhaust manifold pressure requirements to drive EGR flow, and turbo-charger speed limits during operation at altitude. Based on the results of this GT-Power modeling, CWI and Cummins Turbo Technologies have identified the necessary turbo-charger attributes.

2.2.2 Combustion Chamber

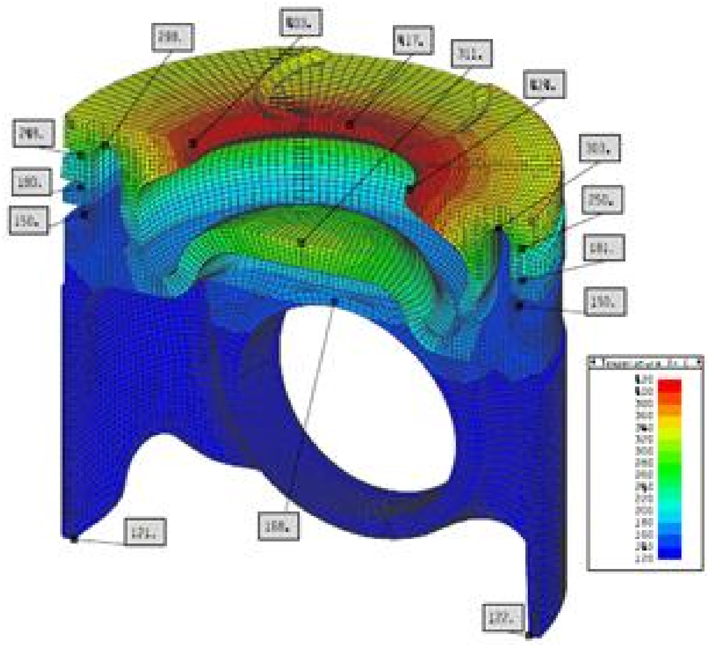
Modeling was used to help guide the combustion chamber design. Several piston designs were modeled evaluated using KIVA analysis to predict the combustion rates (Figure 5). Based on the results, two primary designs (Piston Designs A & B in Figure 5) with fast combustion rates were selected for evaluation by engine tests. These piston designs were evaluated with the aim to select options for test evaluation that provide fast combustion rates. Parts were procured for test evaluation from the piston supplier.

Figure 5: Heat Release Rate for Various Potential Piston Designs



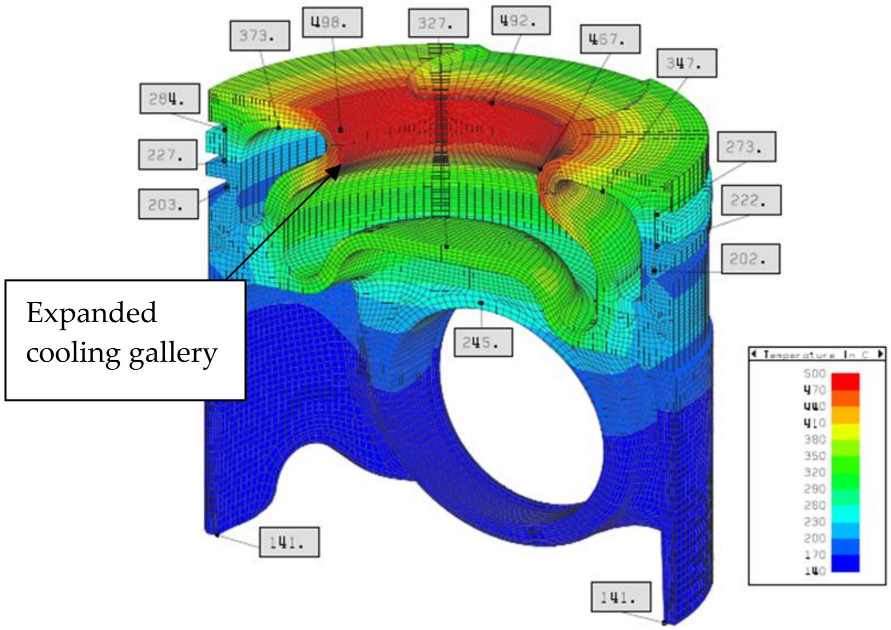
Finite Element Modeling (FEM) was used to predict the temperature distribution of the piston. Figure 6 shows the temperature distribution for Piston Design B. Analysis results showed high temperatures in the bowl rim which reduces the safety factor and limits endurance capability. This design was selected based upon fast combustion predictions as a result of high squish velocities. Concept engine testing using prototype pistons manufactured per this design validated the analysis result, with high piston temperatures observed during testing.

Figure 6: Predicted Temperature Distribution for Prototype Piston



The piston was re-designed to alleviate the temperature concerns while maintaining good combustion characteristics. Working in conjunction with the production-intent piston supplier, a new piston design was selected that provided space for a bigger cooling gallery to lower the piston surface temperatures. The design was evaluated using KIVA analysis to predict the combustion rates and was found acceptable. FEM analysis also indicated significant reduction in surface temperatures (Figure 7). Parts were procured for test evaluation on engines.

Figure 7: Predicted Temperature Distribution for Re-designed Piston



GT-Power cycle simulation analysis was used to assess the camshaft design and potential improvements possible with variation in cam timings for valve opening and closing. The results of the analysis indicated there are no significant advantages to changing the current design.

2.2.3 Fuel System

CWI's fuel system design target is to reduce the fuel pressure drop from the engine inlet to the intake manifold, to enable lower fuel inlet pressures than are currently compatible with CWI's existing natural gas engines. Lower inlet pressures allow use of more residual CNG for more range, colder LNG, and perhaps OEM use of existing pressure regulators and plumbing, all of which improve engine-to-vehicle integration and/or vehicle performance. Specifically, CWI established a design target of enabling a minimum allowable fuel supply pressure, measured at the engine inlet, of 60 psig, whereas CWI's ISL G engine requires fuel inlet pressure no lower than 70 psig. CWI conducted analysis to define the maximum allowable pressure drop at peak fuel flow rates to deliver peak power at the minimum allowable fuel inlet pressure. This maximum allowable pressure drop will be a factor in the Alpha design of the integrated fuel housing for the ISX11.9 G engine.

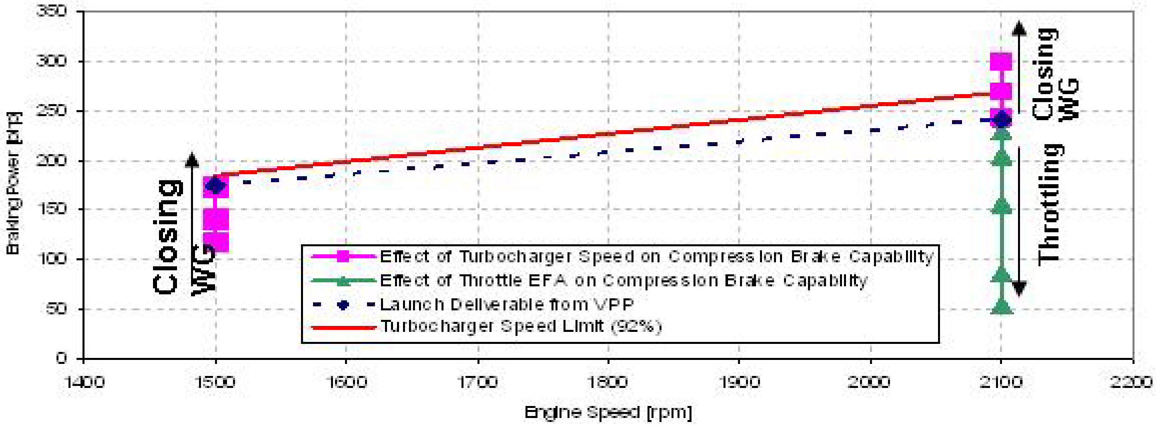
2.2.4 Engine Brake

Based on discussions with OEMs and prospective truck fleet customers in the target market segments, CWI has determined that engine braking will be a required feature for the majority of Class 8 truck users. CWI determined via CAD modeling that the engine compression release brake (aka "jake brake") developed for the Cummins ISX11.9 diesel engine will not be compatible with the natural gas engine due to interference with the spark plugs and ignition coil extensions required for the natural gas engine. CWI's current engines are not available with compression release brakes; therefore, a new design is required for compression release brake hardware.

CWI conducted performance modeling using GT-Power to predict the maximum braking performance achievable with a compression release brake applied to the ISX11.9 G engine (Figure 8). Compression release braking performance is a function of engine speed and compression ratio; therefore, due to the lower compression ratio required for the natural gas engine compared to the base diesel engine, the maximum braking performance is inherently lower than for the Cummins ISX11.9 diesel engine. Through discussions with Class 8 truck OEMs and fleets, CWI established an engine brake performance target of 240 hp. CWI's performance modeling indicated capability to achieve the target braking performance. For diesel engines, the brake performance is modulated by selecting the number of engine cylinders providing braking power. For the ISX11.9 G engine, in addition to the number of cylinders providing braking, brake performance can be modulated by manipulating the turbocharger waste gate and the throttle plate. Therefore, CWI's analysis indicates that peak braking power will be lower than a diesel engine of comparable displacement, will provide sufficient peak braking performance for the target regional haul Class 8 truck applications, and will offer finer resolution of braking control than existing compression release brakes.

CWI has initiated discussions with a third-party compression release brake manufacturer to design engine brake hardware specific to the ISX11.9 G engine. Analysis conducted by the brake manufacturer confirms CWI's analysis.

Figure 8: Predicted Compression Release Brake Performance



2.2.5 Exhaust Catalyst

CWI and Cummins Emission Solutions (CES) analyzed the exhaust catalyst requirements for the ISX11.9 G engine. The new engine will use a three way catalyst, which is highly effective at controlling NOx, CO and HC. Because the new engine will use SESI combustion technology, consistent with CWI's ISL G engine, the ISX11.9 G engine-out emissions are predicted to be similar to ISL G. Therefore, the existing ISL G catalyst formulation is anticipated to be suitable for ISX11.9 G.

CES will package the TWC in a number of configurations to suit the various target chassis, packaged as a replacement muffler. To determine the required size of the catalyst substrate, CES and a catalyst substrate supplier conducted pressure drop modeling using the ISL G catalyst substrate and anticipated ISX11.9 G exhaust flow rates. Pressure drop modeling indicated that the ISL G catalyst will produce excessive back-pressure. CWI validated this modeling by measuring the engine back-pressure using an ISL G catalyst installed with the ISX11.9 G Concept engine. CES and the supplier have modeled a number of alternative catalyst configurations to reduce exhaust back-pressure within CWI's specifications, including larger diameter substrates and catalysts with lower cell density. Based on the results of this analysis, the design direction for the ISX11.9 G TWC is to use a catalyst substrate that is dimensionally similar to a substrate used with heavy-duty, EPA 2010-certified diesel engine after treatment systems and a catalyst wash coat formulation developed for CWI's ISL G engine. Maintaining the dimensions of the diesel after treatment equipment will facilitate OEM integration of the ISX11.9 G engine by enabling OEMs to use existing diesel after treatment mounting hardware.

2.3 Task 2.3 Control System Development

The goal of this task was to initiate product development of an electronic control system that meets the requirements for heavy-duty vehicle operation, including onboard diagnostic (OBD) capability. This section of the report will describe the control system development in terms of architecture, design, and testing / validation work performed during this task.

2.3.1 Architecture

The electronic control system consists of the following components:

- Electronic control module (ECM)
- Sensors
- Actuators
- Wire harness
- Software and calibrations

The ISX11.9 G control system architecture was defined as follows:

- Common ECM (CM2180A) and software with CWI's 8.9 liter ISL G natural gas engine
- Common engine sensors with Cummins' ISX11.9 diesel engine
- Common fuel system sensors with ISL G
- Common actuators with ISL G and ISX11.9, except for the Fuel Shutoff Valve and Fuel Control Valve, which require unique actuators required for the ISX11.9 G engine
- Software and calibrations based on ISL G with added features and compression release brake control capability, to suit the requirements of the target markets

The selected control system architecture includes components (ECM and sensors) that are capable of satisfying EPA and Euro OBD regulations, as demonstrated by CWI in achieving Euro V OBD compliance for the ISL G engine.

The electronic control system also includes the ignition system, which consists of the following components:

- Ignition control module (ICM)
- Ignition harness
- Ignition coils
- Ignition coil extensions (to connect the ignition coil to the spark plug)
- Spark plugs
- Calibration

The ignition system architecture consists of "coil-on-plug" technology, consistent with CWI's ISL G engine, and a unique ICM incorporating additional diagnostic capability not currently supported by the ISL G ICM.

2.3.2 Design

Based on discussion with prospective OEM and end-user customers in the regional haul and vocational Class 8 truck / tractor target markets, as well as with Cummins experts in Customer Engineering, CWI Engineering defined the electronic feature requirements for the ISX11.9 G engine, including features such as cruise control, power-take-off operation, road-speed governing, gear down protection, and engine braking, which are controlled by the engine ECM during vehicle operation.

Based on review of the electronic features and the associated interfaces with the vehicle instrument panel, the team concluded that no ECM hardware modifications were required. However, unique software and calibrations were required to enable certain electronic features that have not previously been developed for CWI's natural gas engines. For example, compression release braking is required for the ISX11.9 G target market but is not used elsewhere within CWI's product line. Also, unique software and algorithms were developed to allow the ECM to interface with the engine position sensing scheme utilized with the ISX11.9 diesel engine, which is the engine platform for CWI's development program. The position sensing scheme software and algorithms were first validated on a test bench prior to testing on the Concept engine. The Alpha-level wiring harness design was completed, to interconnect all components within the electronic control system, Figure 9.

Additional software and calibrations will be required to comply with the applicable OBD requirements; however, OBD-specific development is not included within the scope of the Alpha development. OBD development and validation will be conducted during the next phase of the ISX11.9 G engine development program.

While the ignition system architecture is identical to CWI's existing ISL G engine, the design required unique elements imposed by the packaging limitations in the target Class 8 truck / tractor applications. Many Class 8 tractors used in regional haul applications feature air cleaner assemblies mounted beneath the hood of the truck to enhance vehicle aerodynamics. The air cleaner assembly is often mounted to the engine, directly above the engine valve cover, with minimal clearance between the valve cover and the underside of the air cleaner assembly. The ISX11.9 G ignition coils are mounted to the valve cover, directly above the spark plugs which are mounted in the cylinder head, with ignition coil extensions connecting the coils to the plugs. To accommodate the packaging limitations imposed by the air cleaner assembly, the ignition coil design provides minimal clearance above the valve cover, while enabling ignition harness connections. Figures 10 through 12 identify the ignition system components and their mounting configuration.

Figure 9: Alpha Wire Harness

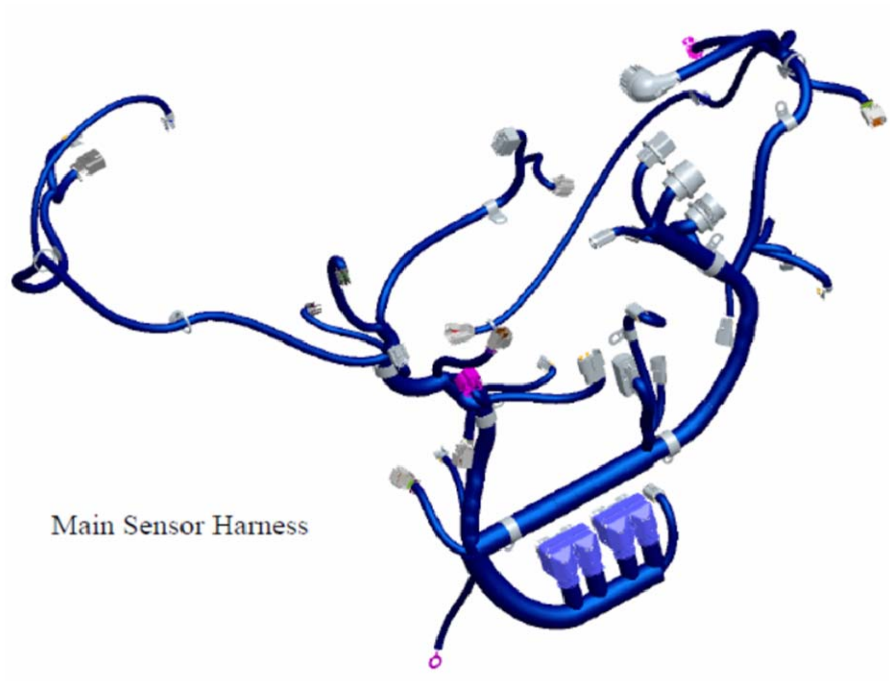


Figure 10: Ignition Control Module

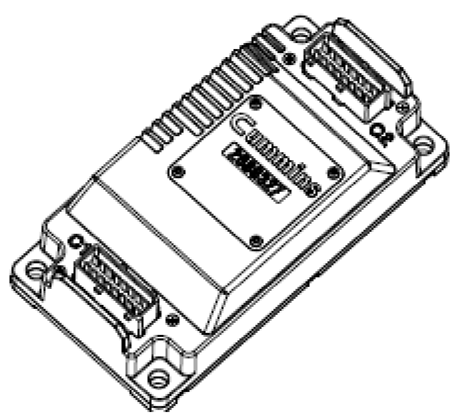


Figure 11: Ignition System Hardware

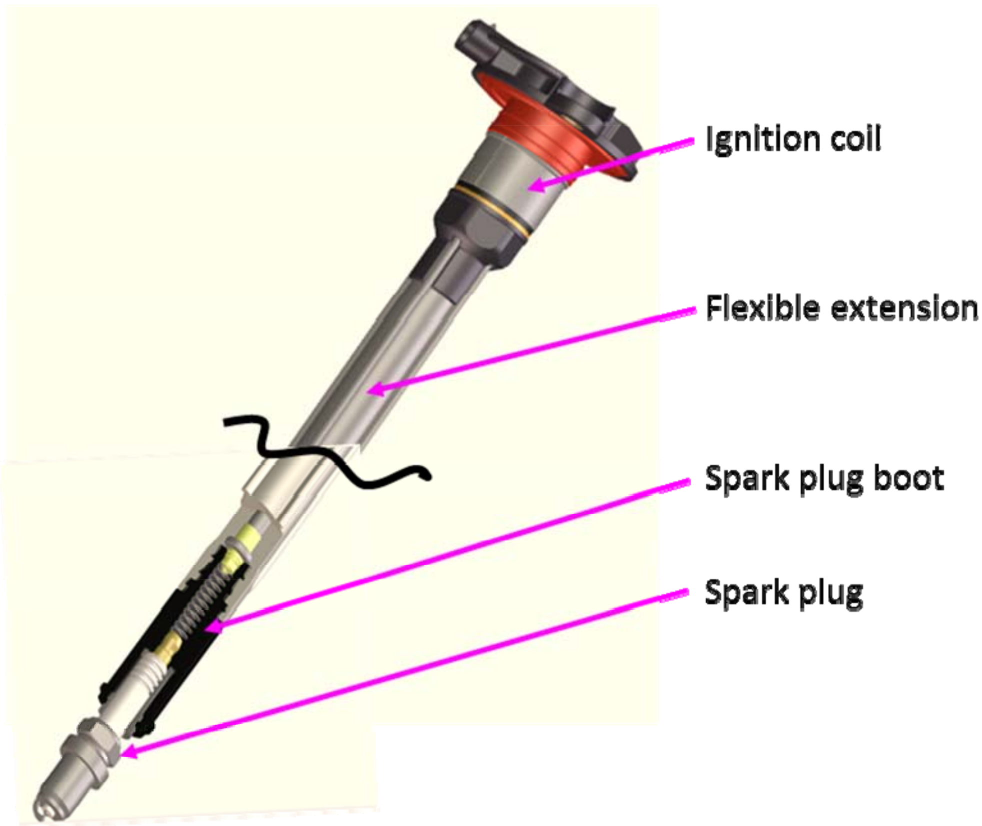
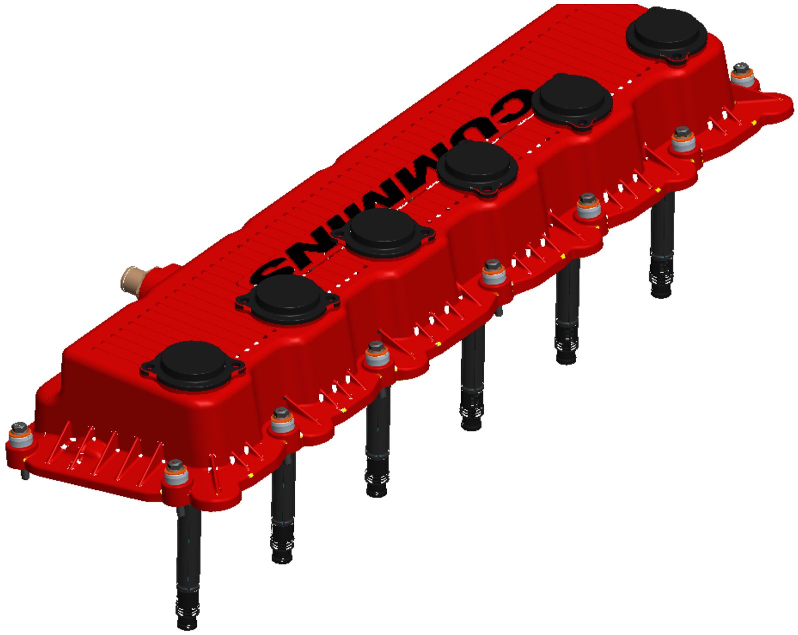
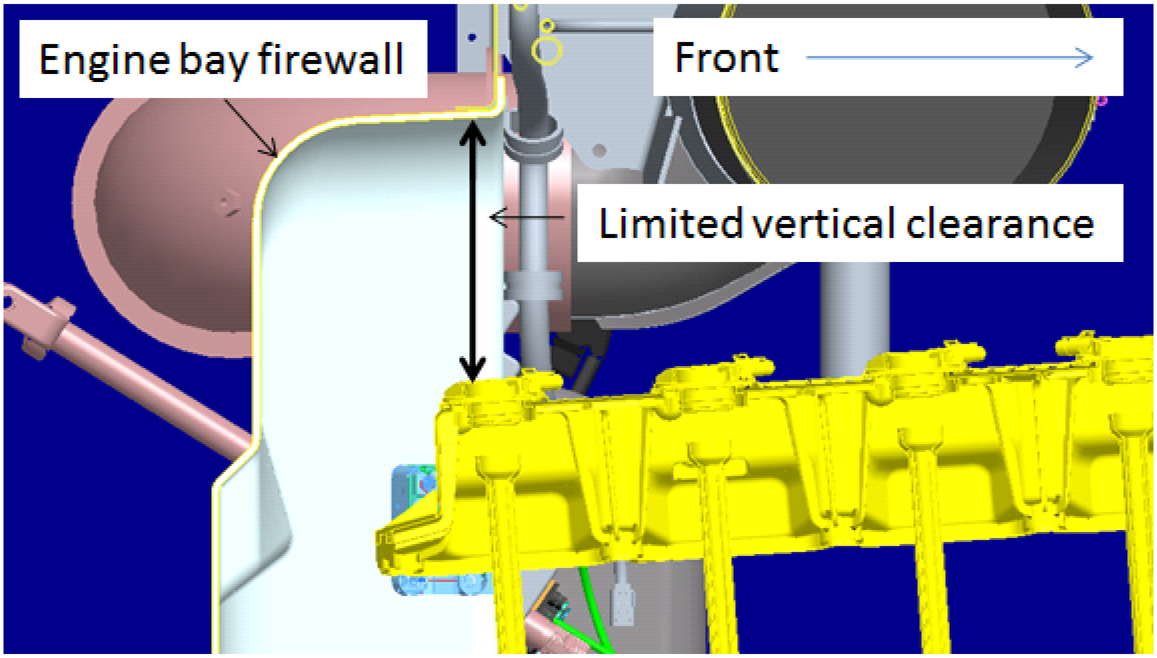


Figure 12: Ignition Coils and Extensions Mounted to Valve Cover



The spark plugs require periodic replacement in accordance with the maintenance schedule; therefore, the ignition system design must enable easy serviceability of the ignition coils, extensions, and spark plugs. Many of the target chassis include a recessed firewall, such that the rear of the engine is surrounded by the engine bay above and on both sides. As a result, there is limited vertical clearance above the valve cover to service the ignition system components in the rearmost cylinder of the engine (see Figure 13). To enable spark plug replacement in cylinder 6, the ISX11.9 G ignition system design features a flexible ignition coil extension that enables removal in vehicle configurations that feature limited vertical clearance. The flexible extension is shown in Figure 11. The targeted spark plug replacement interval for the ISX11.9 G engine is 1500 hours, which is consistent with Cummins Westport's existing natural gas engines.

Figure 13: Elevation View of ISX11.9 G Engine in Class 8 Truck Engine Bay



2.3.3 Testing and Validation

The operation of the control system was demonstrated in an engine dynamometer test cell across the full operating range of the engine. Basic control system capability was demonstrated during extensive engine dynamometer operation. Preliminary development of various electronic control features was conducted in preparation for vehicle-based field demonstrations, including knock control logic, turbocharger boost control and high speed governing. Further work will be required during the next phase of the engine development program to refine these control system capabilities via vehicle and engine dynamometer testing. Further system refinements are also underway for engine transients in preparation for transient emissions testing. Available compression release brake logic and software from Cummins diesel engines have been imported into the ECM and adapted for the ISX11.9 G control system architecture. A system Failure Modes and Effects Analysis (FMEA) was conducted for the compression release brake control features, with no issues identified.

A Pre-Alpha engine was installed in an Engineering truck, which was operated by CWI Engineering for performance validation. See Figures 14 and 15. Initial Engineering truck trials identified various areas for development of the control system, which will continue during the next phase of the ISX11.9 G engine development program.

Figure 14: Pre-Alpha ISX11.9 G Engine Installed in Kenworth T800 Tractor

Figure 15: Kenworth T800 Tractor with Pre-Alpha ISX11.9 G Engine

Instability of engine speed during idle-speed operation in the Engineering truck is under investigation. Increasing ignition arc strength by increasing the spark plug gap did not resolve the issue. Cylinder-to-cylinder mixture variation as well as control system tuning will be investigated to help assess their effects and resolve the issue. This development work will continue in the next phase of the ISX11.9 G development program, which is beyond the scope of this Grant Agreement.

Required upgrades to the Cummins electronic service tool (Insite) have been identified and communicated to the Insite development team, to develop a version of the Insite tool that can support ISX11.9 G field demonstration engines beginning in 2011.

2.4 Task 2.4 Concept Demonstration

The goal of the Concept Demonstration task was to demonstrate that the Concept engine design is functional, and to quantify the initial engine performance versus design targets. Within this task, CWI planned to:

- Generate a preliminary bill of material for the concept engine to facilitate concept engine assembly, and to communicate the design details to the broader CWI Product Development Engineering team for further engine analysis, testing, and development.
- Acquire prototype hardware and build a demonstration engine based on the concept design.
- Install and operate the concept engine in an engine dynamometer test cell to obtain initial performance and emissions data relative to the project targets.

One engine was built based upon the Concept design defined in Task 2.1. The Concept engine is shown in Figure 16.

Figure 16: Concept Engine

CWI installed the Concept engine, equipped with the first of two prototype piston designs identified using analytical modeling, in an engine dynamometer test cell at the Cummins Technical Center in Columbus, Indiana. The engine was instrumented with temperature and pressure sensors to characterize the combustion and correlate actual engine operating data with the combustion characteristics predicted by performance modeling and analysis in Task 2.2.

The Concept engine was started and operated to confirm basic engine operation, to commission the test cell, and to confirm basic engine and test cell control system functionality.

Following engine and test cell commissioning, the engine was operated extensively in the test cell over a period of numerous months, to characterize the engine operation and validate engine performance and stability under a variety of operating speeds and loads. The test program included a variety of elements, as described below.

The engine was operated under a variety of speed and load conditions to measure the exhaust back-pressure imposed by the prototype three-way catalyst. As previously reported for Task 2.2, analysis indicated that the preferred catalyst configuration would be based on catalyst substrates that are dimensionally similar to a substrate used with heavy-duty, EPA-certified diesel engine after treatment systems, in conjunction with a catalyst wash coat formulation developed for CWI's ISL G engine. The Concept engine testing confirmed that this catalyst configuration provides acceptable back-pressure.

Throughout this testing, in-cylinder temperatures were measured to determine if piston temperature is within the acceptable limits as defined by Cummins and Cummins Westport based on extensive experience with prior engine development programs. The engine was operated at full load to define the torque curve across the engine's operating speed range.

The testing included a sweep of various engine control strategies (including varying spark timing and EGR flow rates) to improve engine performance with the applicable power cylinder and turbo-machinery hardware.

Following preliminary torque curve mapping and control system assessment, the engine was partially disassembled and re-assembled with a second prototype piston design installed. The previous engine tests were repeated, included control system sweeps, in-cylinder temperature and pressure mapping, and torque curve mapping.

The prior analytical modeling for the turbo-machinery and air handling system identified a preferred turbo-charger configuration. Turbo-machinery selection involves a trade-off between design for peak torque and rated power conditions. Specifically, operation at peak torque is dictated by the pressure differential across the engine to drive sufficient EGR flow, and by waste gate margin to allow for torque curve shaping at high altitude operation. These considerations generally require that the turbine housing have a small critical area. However, operation at rated power is limited by waste gate flow capability and turbine speed, which are optimal with large turbine housing. The prior analytical modeling identified an appropriate trade-off between these two conflicting design directions. The Concept engine testing included an evaluation of the turbo-machinery and air handling system performance throughout the engine speed and load operating range, and concluded that the prototype turbo-charger configuration was appropriate to meet the engine operating targets.

In general, the combustion data indicated good overall agreement with the combustion predicted from analytical modeling. The torque curve mapping demonstrated that the engine can achieve the peak power (400 bhp) and torque (1350 lb-ft) targets – see Figure 17. The tests demonstrated adequate operating margin at peak torque. Figure 18 identifies the operating margin at peak torque conditions, whereby the engine can accommodate moderate offsets in actual versus commanded EGR fraction and/or spark timing without encountering design limits for EGR tolerance, knock, and turbine inlet temperatures. The X and Y axes in Figure 18 encompass a range of 10 crank-angle degrees and 10 percent EGR fraction, respectively. However, at rated power, there is insufficient operating margin. While the testing demonstrated that the engine can achieve 400 bhp, there is insufficient operating margin to accommodate variability in actual versus commanded EGR and/or spark timing without encountering design limits in vehicle applications. The consequence of inadequate operating margin is that while it is possible to achieve 400 bhp in closely-controlled test cell conditions, the ability to achieve 400 bhp in vehicle installations without exceeding engine design limitations is less certain. Work will continue in the next phase of the engine development program to increase the operating margin at rated power conditions, to ensure robust engine performance in the target vehicle applications.

Figure 17: Preliminary Torque Curve for ISX11.9 G Peak Rating

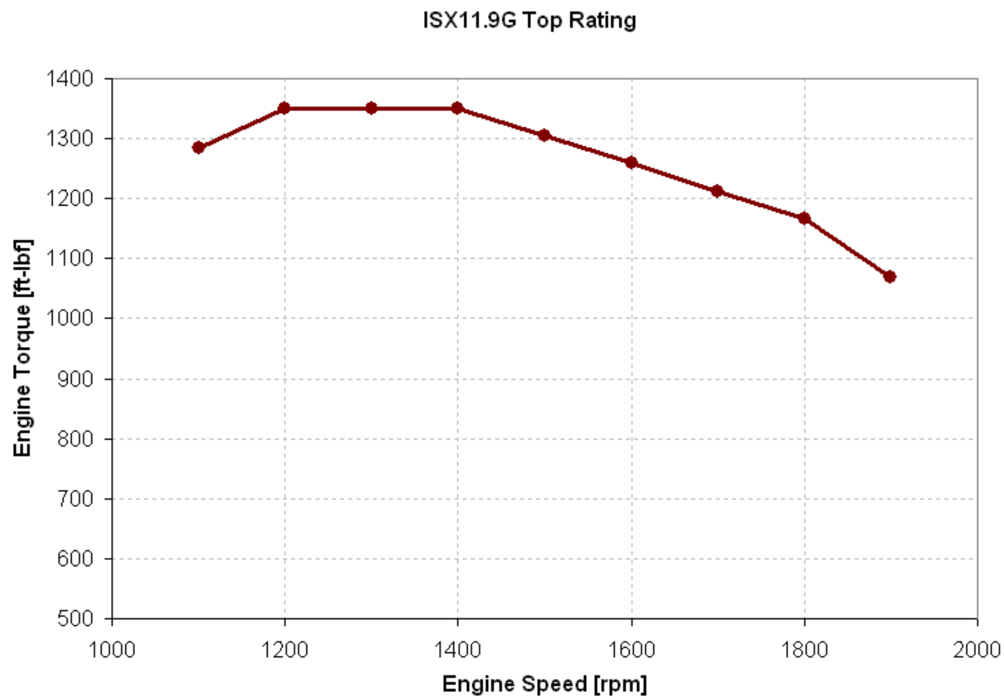
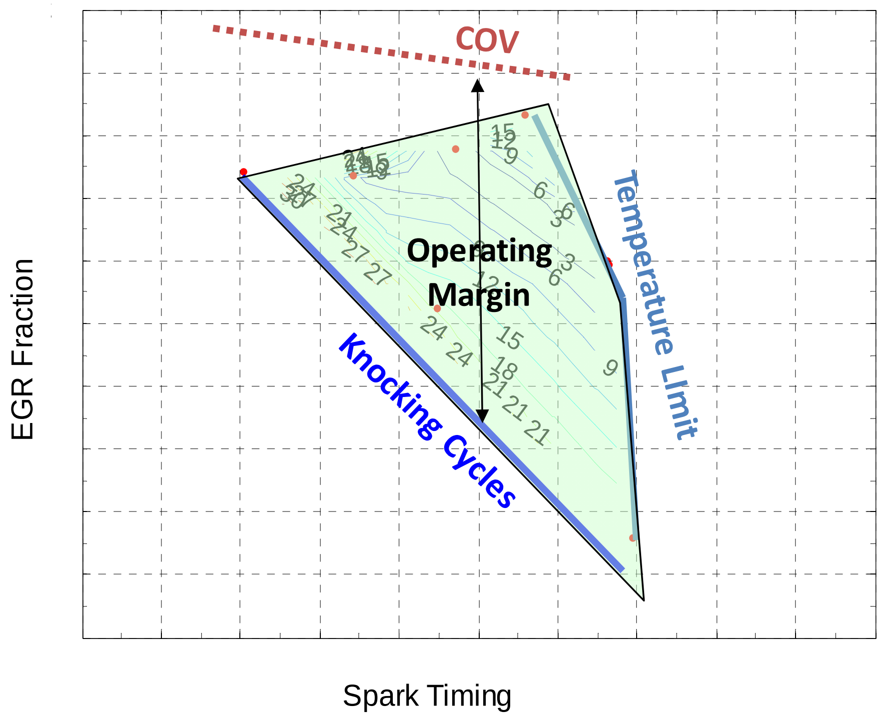


Figure 18: ISX11.9 G Combustion Margin at Peak Torque Conditions



Piston temperature data also showed that temperature limits were exceeded, especially at the piston bowl rim. The ISX11.9 G engine analytical models were re-calibrated using the measured engine operating data, and further analysis was performed to arrive at a piston design with an improved piston cooling gallery that could reduce the rim temperatures without significantly impacting combustion performance. Several iterations were assessed with KIVA combustion models and a new design was selected for hardware assessment.

2.5 Task 3.1 Performance and Emissions Development

The goal of this task was to initiate a development program to refine the concept engine combustion, performance, and emissions. This task required extensive calibration development and engine testing in an engine dynamometer test cell. In this task, detailed fuel maps were used to model the fuel economy benefits of the engine versus existing SI natural gas engines, with a target of achieving a 5 to 10 percent benefit in the target heavy-duty truck applications. In addition, GHG advantages of this product in the intended application were be quantified.

The following section documents the results of Task 3.1 in terms of performance and emissions, fuel economy data, and projected GHG advantages.

2.5.1 Performance and Emissions

During this task CWI demonstrated the capability of the ISX11.9 G engine design to achieve the target peak rating of 400 hp and 1350 lb-ft. Figure 19 depicts the torque and power curves obtained from Pre-Alpha torque curve mapping in an engine dynamometer test cell. Test cell operation demonstrated acceptable combustion margin (for example, the margin between the engine's operating conditions at a given speed and load point, and various performance limits, including engine knocking, temperature, and turbo-machinery limitations) at peak torque speed (1200 rpm). However, the operating margin was initially unacceptable at rated and higher speeds. With insufficient operating margin, engine operation at rated power can be achieved under tightly controlled operating conditions such as a test cell, but variable operating conditions in a vehicle (such as fluctuating ambient temperature) could cause the engine to encounter in-cylinder limits for knock, temperature, and/or turbo-machinery performance thresholds.

A number of piston design iterations were identified and tested to improve operational margin at high engine speeds. Due to the time associated with iteratively designing, prototyping and testing candidate piston designs, a significant portion of the time spent on this task was dedicated to optimizing the combustion margin at rated power. By the conclusion of this task, CWI Engineering demonstrated adequate operating margin at rated power and throughout the full load range of the engine. This was achieved via optimization of the piston bowl design, and by altering the swirl c characteristics of the cylinder head via valve port design modifications.

During this task, CWI obtained transient emissions data based on the Pre-Alpha engine design with the prototype three-way catalyst. NOx, CO and NMHC values for the combined Cold and Hot engine tests (CHET) showed good margin compared to the target 2010 emission standard levels as shown in Figure 20. Particulate emissions were also below target levels.

In addition to demonstrating the performance and emissions capabilities of the ISX11.9 G engine, an important objective of this task was to characterize the fuel inlet pressure capability of the engine. The ISX11.9 G will offer higher power and torque than existing spark-ignition engines in the North American commercial vehicle market, and will therefore require higher fuel delivery rates from compressed natural gas (CNG) and liquefied natural gas (LNG) vehicle fuel delivery systems. Higher fuel flow rates will lead to increased pressure drop through off-engine, OEM-supplied CNG and LNG fuel delivery components, which may require re-design of the off-engine fuel supply systems to ensure that delivered fuel pressure is within the engine's specifications. In order to ease the design burden for off-engine CNG and LNG fuel system suppliers and installers, CWI recognized the need to develop the ISX11.9 G engine to accept a lower range of fuel inlet pressures than current engines.

Figure 19: Preliminary Torque and Power Curves for ISX11.9 G Peak Rating

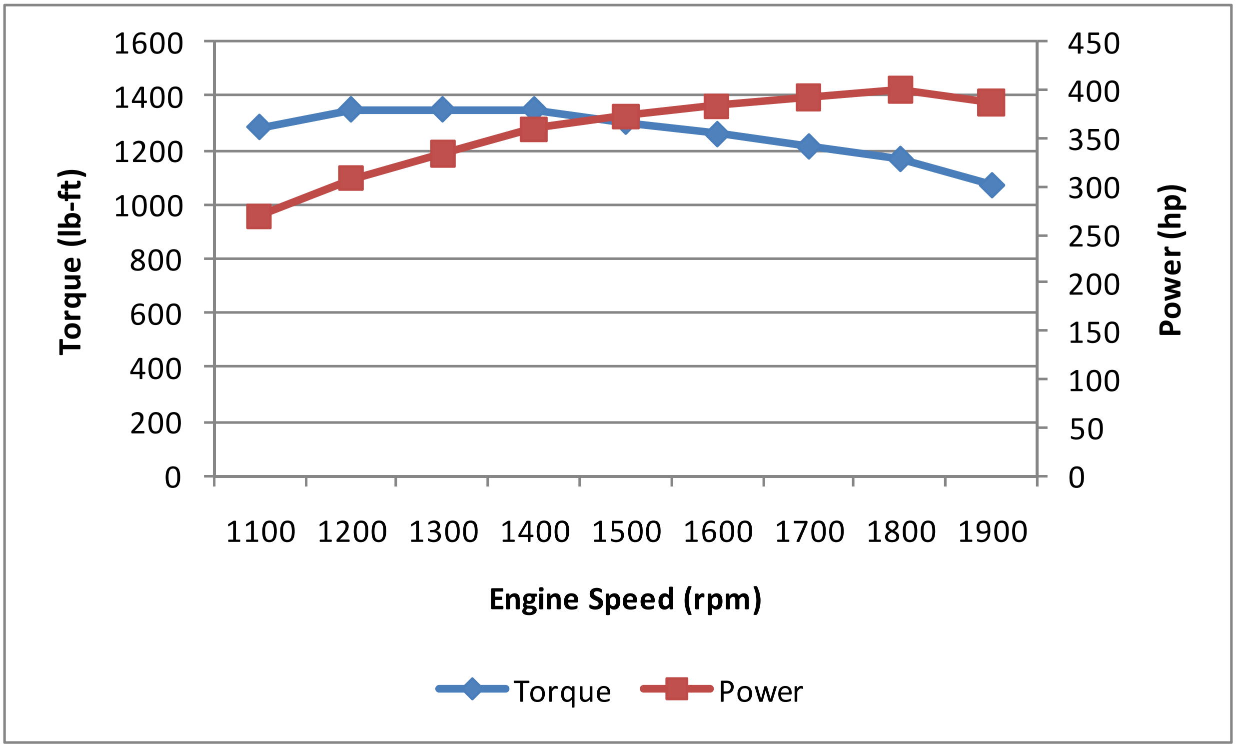
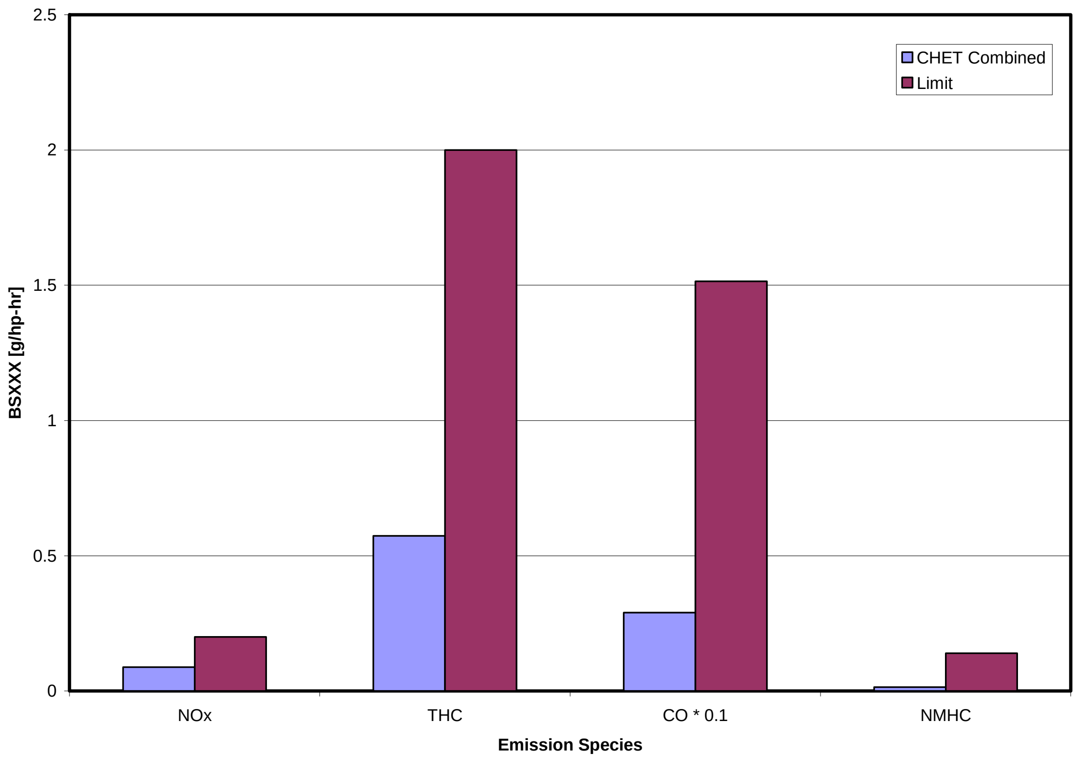


Figure 20: Preliminary ISX11.9 G Emission Data



Whereas CWI's 8.9 liter ISL G engine requires a minimum fuel inlet pressure of 70 psig to maintain advertised performance, CWI established a design target of 60 psig minimum allowable inlet pressure for the ISX11.9 G engine. During this task, CWI measured the pressure drop across the Alpha fuel module, and tested the engine at reduced fuel inlet pressures in a test cell. This testing confirmed that the Alpha engine design is capable of operating with significantly lower fuel inlet pressures than the ISL G engine. Based on testing to-date, achieving the design target of 60 psig minimum allowable inlet pressure appears to be achievable. The ISX11.9 G fuel inlet pressure specification will be finalized prior to production launch after additional testing, including field demonstrations, under a range of operating conditions and with various CNG and LNG fuel compositions.

2.5.2 Fuel Consumption

One of the objectives of this task was to model the fuel economy benefits of the engine versus existing spark-ignited natural gas engines, with a target of achieving a 5 to 10 percent benefit in the target heavy-duty truck applications. CWI's ISL G engine is used in similar Class 8 truck duty cycles today, despite the ISL G engine offering significantly lower peak torque (1000 lb-ft) than larger displacement engines typically used in Class 8 vocational and regional haul trucks. To optimize vehicle performance with the ISL G engine, most Class 8 trucks OEMs specify a "deeper" (for example, numerically higher) rear axle ratio for ISL G-powered trucks than typically used with diesel-powered trucks. This has the effect of multiplying the torque available at the drive wheels to diesel-like levels despite the lower engine torque. However, the deeper rear axle ratio requires the ISL G engine to operate at a significantly higher engine speed than a diesel engine for a given vehicle operating speed. Therefore, the consequence of altering vehicle driveline specifications to improve vehicle drivability is an increase in engine operating speed and a corresponding increase in fuel consumption.

CWI used a Cummins fuel economy model to quantify the fuel impact of variations in the rear-axle ratio for a diesel-powered truck. Table 3 shows the impact on engine speed and fuel economy by altering the rear axle ratio of an ISX 400 hp diesel-powered truck, which is the rating in the Cummins fuel economy model that most closely matches the ISX11.9 G peak rating.

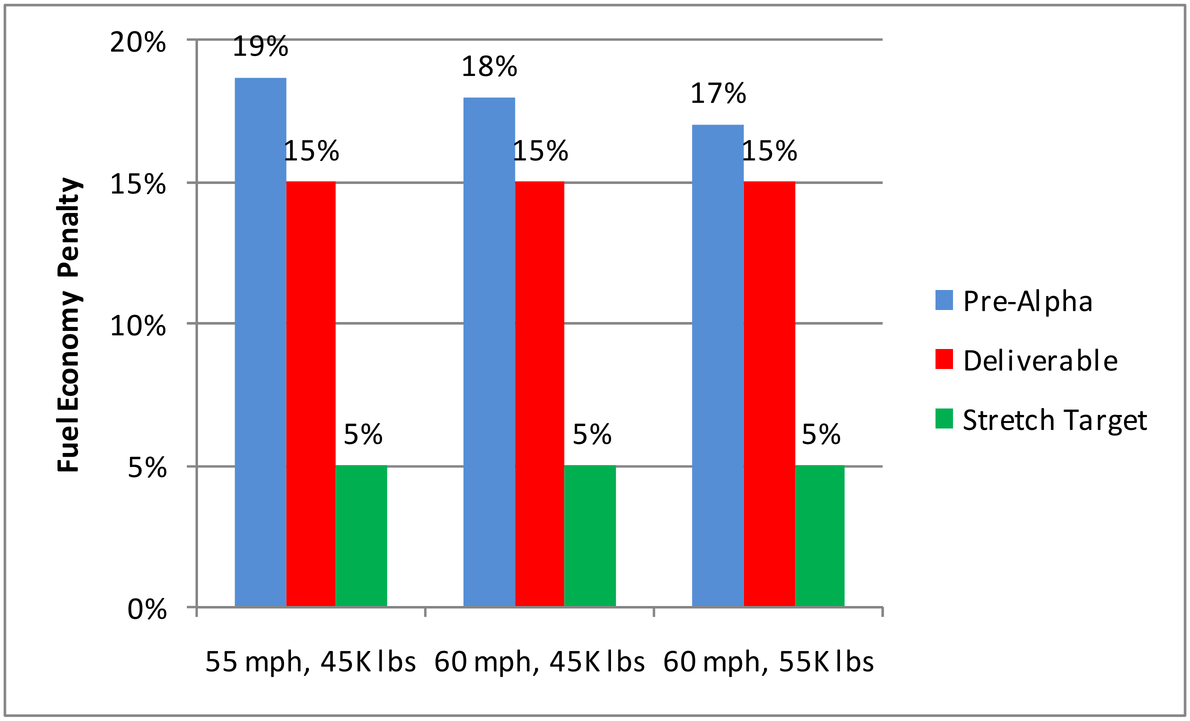
Table 3: Predicted Fuel Economy as a Function of Rear Axle Ratio

Engine	ISX 400	ISX 400
Transmission	Eaton 10 Speed	Eaton 10 Speed
Axle Ratio	3.55	4.9
Route Cruise Speed (mph)	65	65
Trip Time (minutes)	20:57	20:41
Average Engine Speed (rpm)	1425	1842
Predicted Fuel Economy (mpg)	4.95	4.42

CWI's experience in the Class 8 truck market suggests that ISL G fuel economy is approximately 20 percent lower than diesel-powered trucks operating in Class 8 regional haul duty cycles. On this basis, CWI Engineering has translated the task objective (5 to 10 percent fuel economy improvement versus existing spark-ignited natural gas engines) into a technical deliverable of achieving fuel economy within 15 percent of diesel vehicles in various Class 8 truck duty cycles. CWI Engineering has also established a more aggressive "stretch target" of achieving fuel economy within 5 percent of diesel vehicles in the same Class 8 truck duty cycles.

CWI has mapped the fuel consumption of the Pre-Alpha ISX11.9 G engine throughout the engine speed and load operating range during engine dynamometer testing. CWI Engineering then loaded these fuel maps into a Cummins analytical model used to predict vehicle fuel consumption based on specific vehicle, load, route and load factor input data. CWI modeled the fuel consumption from comparable Cummins diesel engines using the same input criteria, to evaluate ISX11.9 G Pre-Alpha fuel consumption versus the technical fuel economy target. The results of this analysis are presented in Figure 21, which shows that the fuel economy at this stage of the program doesn't yet meet target.

Figure 21: Preliminary Fuel Economy Assessment



As described above, CWI's primary development focus within this task to-date has been to achieve sufficient combustion margin throughout the speed and load range of the engine. Fuel economy improvements will primarily be obtained via detailed optimization of the engine's electronic control calibrations, involving spark timing, exhaust gas recirculation (EGR) rates, and fuel control. This level of detailed calibration optimization occurs following confirmation of the power cylinder design and demonstration of adequate combustion margin. Therefore, the numerous power cylinder design and testing iterations to achieve the required combustion margin have prevented fuel consumption optimization at this stage of the engine development cycle. Fuel economy optimization will resume once adequate operating margin has been established throughout the engine operating map. Based on CWI's prior experience applying this combustion technology to a smaller engine platform, we are confident that the commercialized version of the engine will achieve the fuel economy deliverable stated above, and may approach the stretch target. This work will continue in the next phase of the ISX11.9 G development program.

2.5.3 Greenhouse Gas Emissions

Natural gas offers significant GHG benefits versus petroleum fuels, as documented in CARB's Low Carbon Fuel Standard (LCFS) analysis. Table 4 summarizes the full fuel cycle, or "well-to-wheel" (WTW) GHG emissions of ultra low sulfur diesel fuel (ULSD) along with CNG and LNG from a variety of conventional and renewable fuel sources[1].

Table 4: Summary of CARB Low Carbon Fuel Standard Analysis

Fuel	Fuel Pathway	WTW Emissions (g CO2e/MJ)	% GHG Reduction vs. ULSD	Date of ARB Analysis	Version
ULSD	California ULSD	94.7	-	28-Feb-09	Ver 2.1
Conventional Natural Gas Pathways					
CNG	North America NG	68.0	28.2%	28-Feb-09	Ver 2.1
LNG	North America NG	83.1	12.3%	23-Sep-09	Ver 2.0
Renewable Natural Gas Pathways					
CNG	Landfill Gas	11.3	88.1%	28-Feb-09	Ver 2.1
CNG	Dairy Digester Biogas	13.5	85.8%	20-Jul-09	Ver 1.0
LNG	Landfill Gas	26.3	72.2%	23-Sep-09	Ver 2.0
LNG	Dairy Digester Biogas	28.5	69.9%	23-Sep-09	Ver 2.0

In addition to fuel type, GHG emissions are a function of vehicle fuel efficiency. As explained above, the ISX11.9 G engine fuel economy demonstrated to-date does not yet meet the program target. With further development, CWI expects to achieve the program deliverable of fuel economy 5 percent better than existing natural gas engines in Class 8 truck duty cycles, which corresponds to a fuel economy penalty of 15 percent relative to diesel engines. However, even at Pre-Alpha efficiency levels the ISX11.9 G engine enables significant GHG benefits versus diesel-powered vehicles, and the ISX11.9 G GHG profile will improve as fuel economy is optimized during the next stage of development.

The CARB analysis was used to forecast the GHG reductions associated with future ISX 11.9 G-powered trucks. Based upon the CARB data in Table 4 and the assumptions listed in Table 5, full fuel cycle GHG emissions were calculated, and are shown in Tables 6 and 7 on a "per vehicle per year" basis, for Pre-Alpha fuel economy and anticipated launch fuel economy,

[1] CWI summary of CARB GHG analysis, http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

respectively. Note that the ISX11.9 G fuel economy at launch is assumed to be 10 percent lower than diesel, which is midway between the program deliverable and the stretch target.

Sample calculation:

70,000 miles per truck per year / 6.5 mpg = 10,769 gallons per truck per year

x 130,000 BTU per gallon = 1400 MMBTU per truck per year

x 1055 = 1,477,000 MJ per truck per year

1,477,000 MJ per truck per year x 94.7 g CO_2e / MJ (from Table 4) = 139.9 x 106 grams CO_2e per truck per year

Table 5: Assumptions for "Per Vehicle" Emissions Calculations

Average Annual Mileage for ISX11.9 G Target Market	70,000	miles/truck/year
Average fuel economy for diesel truck in ISX11.9 G target market	6.5	miles / gallon
ISX11.9 G Engine Fuel Economy Differential vs. Diesel (Pre-Alpha)	18%	lower than diesel
ISX11.9 G Engine Fuel Economy Differential vs. Diesel (Launch)	10%	lower than diesel
Diesel Fuel Energy Content	127,500	BTU/gallon
Joules per BTU	1055	

Table 6: Annual GHG Emissions per Vehicle (Pre-Alpha ISX11.9 G)

Fuel Type	Fuel Consumption(Gal or DGE /Truck / yr)	Energy Content of Fuel(mmBTU/ truck / yr)	Energy Content of Fuel(MJ/truck/yr)	GHG Emissions(Mg CO_2e / Truck/yr)	GHG Reduction vs Diesel
Diesel (ULSD)	10,769	1400	1,477,000	137.2	-
CNG (conventional fuel pathway)	13,133	1707	1,801,220	120.1	12.4%
LNG (conventional fuel pathway)	13,133	1707	1,801,220	146.8	-7.0%
CNG (landfill gas)	13,133	1707	1,801,220	19.9	85.5%
CNG (digester gas)	13,133	1707	1,801,220	23.8	82.7%
LNG (landfill gas)	13,133	1707	1,801,220	46.5	66.1%
LNG (digester)	13,133	1707	1,801,220	50.4	63.3%

Table 7: Annual GHG Emissions per Vehicle (ISX11.9 G at Launch)

Fuel Type	Fuel Consumption(Gal or DGE /Truck / yr)	Energy Content of Fuel(mmBTU / truck / yr)	Energy Content of Fuel(MJ / truck / yr)	GHG Emissions(Mg CO_2e / Truck/yr)	GHG Reduction vs Diesel
Diesel (ULSD)	10,769	1400	1,477,000	137.2	-
CNG (conventional fuel pathway)	11,966	1556	1,641,111	109.4	20.2%
LNG (conventional fuel pathway)	11,966	1556	1,641,111	133.8	2.5%
CNG (landfill gas)	11,966	1556	1,641,111	18.1	86.8%
CNG (digester gas)	11,966	1556	1,641,111	21.6	84.2%
LNG (landfill gas)	11,966	1556	1,641,111	42.3	69.1%
LNG (digester)	11,966	1556	1,641,111	45.9	66.5%

The ISX11.9 G engine will be capable of consuming either CNG or LNG. The CARB LCFS full fuel cycle GHG emissions data summarized in Table 4 yields the average GHG emissions (reported in Table 8) for the various natural gas fuel pathways considered by CARB:

Table 8: Average Full Fuel Cycle GHG Emissions for Various Fuel Pathways

Average GHG Emissions (Mg CO2e / truck / year)	Conventional Fuel Pathways	Renewable Fuel Pathways
Pre-Alpha Efficiency	133.5	35.1
Launch Target Efficiency	121.6	32.0

For example, the average GHG emissions corresponding to pre-alpha efficiency and conventional fuel pathways is calculated as follows, based on the values in Table 6:

Average GHG emissions = (120.1 + 146.8) / 2 = 133.5 Mg CO2e / truck / year

The average GHG emissions corresponding to launch target efficiency and renewable fuel pathways is calculated as follows, based on the values shown in Table 7:

Average GHG emissions = (18.1 + 21.6 + 42.3 + 45.9) / 4 = 32.0 Mg CO2e / truck / year

For the purpose of calculating total GHG emissions, CWI identified a "base case" for natural gas fuel supply, assuming that 90 percent of the natural gas fuel consumed by the ISX11.9 G fleet will be derived from conventional natural gas fuel pathways, and 10 percent from bio-methane pathways. CWI has also identified an "upside case" whereby 50 percent of the fuel consumed by the ISX11.9 G fleet will be derived from bio-methane pathways. Table 9 quantifies the anticipated full fuel cycle GHG emissions for ISX11.9 G-powered trucks, as a function of fuel source and engine efficiency.

Table 9: Average Full Fuel Cycle GHG Emissions with Varying Renewable Fuel Content

Average GHG Emissions (Mg CO2e / truck / year)	Base Case (10% Renewable Fuel)	Upside Case (50% Renewable Fuel)
Pre-Alpha Efficiency	123.7	84.3
Launch Target Efficiency	112.6	76.8

For example, the average GHG emissions corresponding to pre-alpha efficiency and the base case fuel supply is calculated as follows, based on the values in Table 8:

Average GHG emissions = 133.5 x 0.9 + 35.1 x 0.1 = 123.7 Mg CO2e / truck / year

Table 10 summarizes the predicted full fuel cycle GHG benefits for the ISX11.9 G engine versus diesel-powered Class 8 trucks.

Table 10: Predicted Full Fuel Cycle GHG Emission Reductions vs. Diesel Trucks

GHG Emission Reduction vs. Diesel	Base Case (10% Renewable Fuel)	Upside Case (50% Renewable Fuel)
Pre-Alpha Efficiency	9.9%	38.6%
Launch Target Efficiency	17.9%	44.0%

For example, the GHG emission reduction corresponding to pre-alpha efficiency and the base case fuel supply is calculated as follows based on the values in Tables 6 & 10:

GHG emission reduction = (Diesel emissions – ISX11. 9 emissions) / Diesel emissions

= (137.2 – 123.7) / 137.2 = 9.9%

2.6 Task 3.2 Alpha Design

The goal of this task was to apply the learning from the Concept engine operation to begin optimizing the engine and engine component designs based on modeling analysis, bench tests and engine laboratory experience. This will also lead to build of representative engines to further assess the design capability to meet targets.

Whereas the Concept design uses existing components where possible, the Alpha design strives for "purpose-designed" components, and is the first design phase that focuses on creating component and sub-system designs that will enable high-volume manufacturing. This section of the report describes the Alpha design for the various major sub-systems that comprise the ISX11.9 G engine, as well as photos and CAD models of the overall Alpha engine design.

2.6.1 Base Engine

The Cummins ISX11.9 diesel engine is the base engine platform for CWI's engine development program. Cummins initiated commercial availability of the ISX11.9 diesel engine in July, 2010. See Figure 22 for a photo of the diesel engine.

Figure 22: Cummins ISX11.9 Diesel Engine

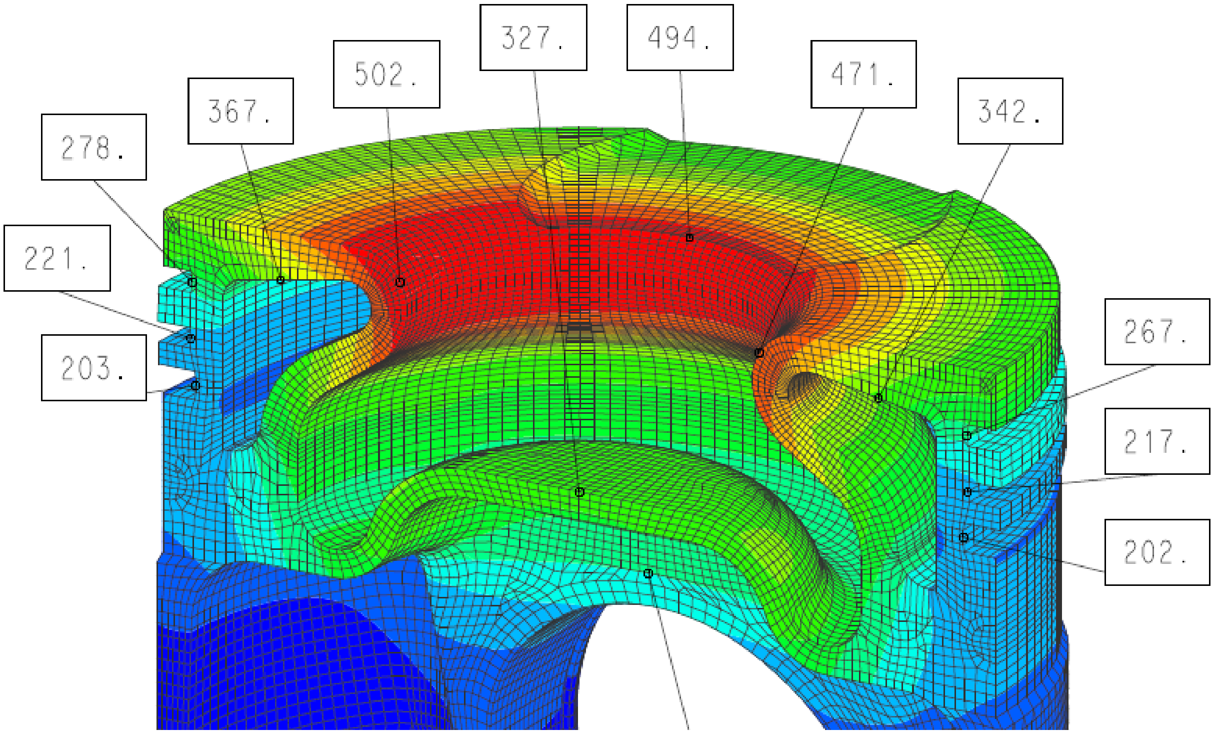
CWI will retain the majority of the base engine for the ISX11.9 G Alpha design, including the cylinder block, crankshaft, connecting rods, main bearings, engine mounts, external accessories (such as air compressors, alternators, starting motors, fan hubs, and so forth), and customer selectable options such as flywheel housing, oil pan, oil level gauge, and so forth.

CWI's design and development of the ISX11.9 G engine focused on unique designs for major engine subsystems, which are summarized below.

2.6.2 Power Cylinder

The ISX11.9 G engine requires a unique piston design, to provide the required compression ratio and to optimize in-cylinder conditions for spark ignition combustion. CWI identified a number of candidate piston designs based on analytical modeling, and assessed those designs based on Concept engine testing. During the Alpha design process, the piston design was refined based on test data and further analytical modeling. The piston design was selected based on the best combustion rate predicted from combustion models, while ensuring that the design yields acceptable maximum piston temperatures. Throughout the design process, finite element analysis and in-cylinder temperature measurements were used to quantify the piston's peak operating temperatures. Design iterations, including increasing the size of the piston oil cooling gallery, were required to reduce peak piston temperatures while maintaining good combustion characteristics. The resulting Alpha piston design and associated peak temperature distribution are shown in Figure 23.

Figure 23: Piston Temperature Distribution



2.6.3 Electronic Control system

The electronic control system design is described at length in the preceding section documenting Task 2.3.

2.6.4 Ignition System

The ignition system design is described at length in the preceding section documenting Task 2.3. Figures 10 through 12 describe the ignition system elements that comprise the Alpha ignition system design.

2.6.5 Cylinder Head

The ISX11.9 G cylinder head is modified from the base diesel head to accommodate spark plugs rather than diesel fuel injectors. Therefore, the major design change involves casting and machining differences to create a spark plug bore in place of the diesel injector bore. Due to different combustion dynamics between spark ignition and compression ignition combustion, the design team tailored the cylinder head design to provide optimal combustion conditions for natural gas spark ignition combustion. Specifically, the intake port design was altered from the base engine cylinder head design to increase swirl velocity, which is expected to improve combustion. The Alpha cylinder head design will be validated during additional engine testing following completion of this project.

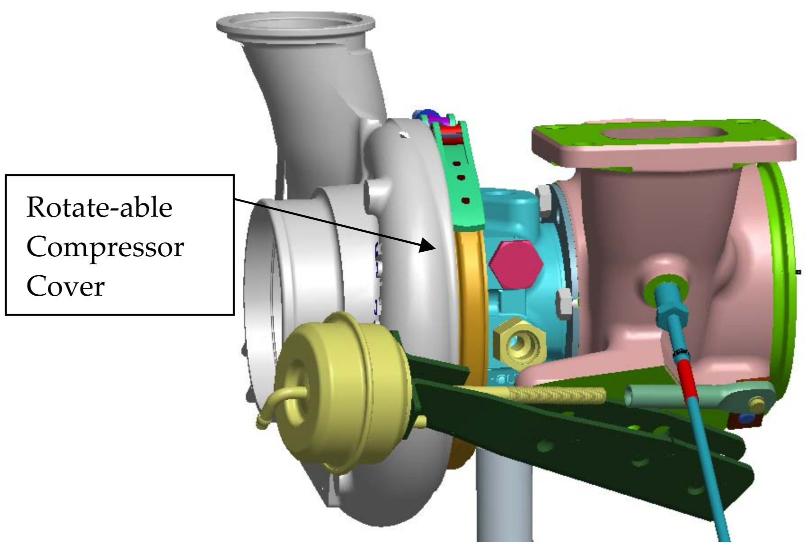
2.6.6 Air Handling System

Due to the lower air flow requirements associated with stoichiometric combustion the ISX11.9 G requires a much smaller turbo-charger than the base diesel engine. Therefore, the ISX11.9 G Alpha engine design required development of a unique turbo-charger.

Based on analytical modeling and Concept engine test results, an optimal turbine casing size was selected. Due to requirements for engine manufacturing and anticipated OEM needs for various orientations of the turbo-compressor, the turbo-charger requires a rotatable compressor cover.

This required a new design for the turbocharger bearing housing. The Alpha turbo-charger design was completed, including the rotatable compressor housing – see Figure 24.

Figure 24: Revised Turbocharger Design Enabling Compressor Cover Rotation

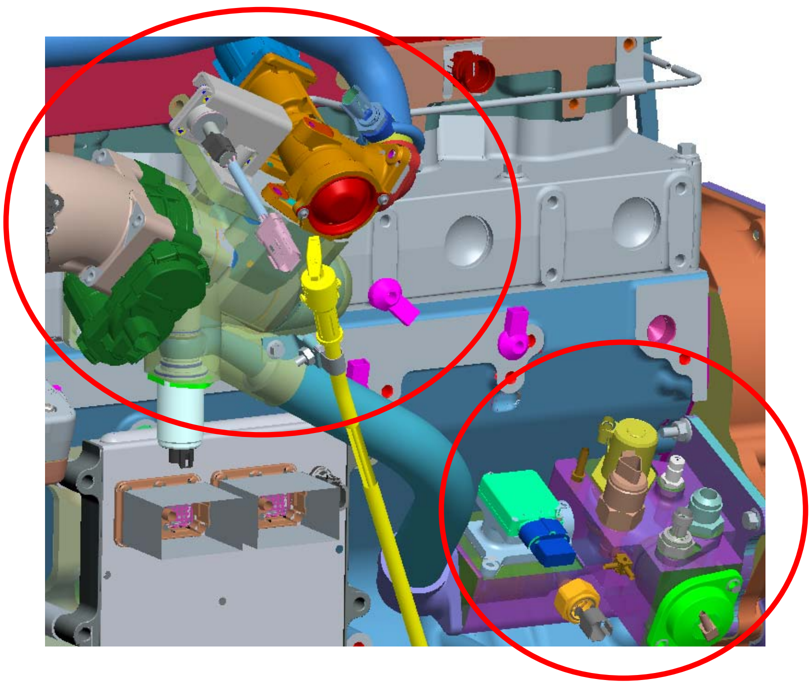


2.6.7 Fuel System

The ISX11.9 G fuel system includes natural gas fuel supply, pressure regulation, metering and control, along with charge air throttling and measurement, and EGR control and mixing functions. Many of these functions are either not required on the diesel base engine, or are handled elsewhere on the engine. As a result of combining all these critical functions into one module for the natural gas engine, the fuel supply module is inherently larger than the diesel fuel components that it replaces on the intake side of the engine. As a result of the larger space claim required for the natural gas fuel supply module, CWI performed numerous design iterations in conjunction with various Class 8 truck OEMs to arrive at a design that will fit in various truck chassis in the Class 8 regional haul and vocation truck target markets.

Whereas CWI's 8.9 liter ISL G engine uses an integrated, one-piece fuel supply module, CWI determined that an ISX11.9 G integrated fuel housing would create vehicle chassis interference issues. As a result the Alpha design focused on dividing this component into two separate housings mounted in two locations on the engine. See Figure 25.

Figure 25: Two-Piece Alpha Fuel Housing Design for ISX 11.9 G



Figures 26 and 27 provide additional details about the upper section of the Alpha fuel module, which is responsible for EGR, fuel and charge-air metering and mixing.

Figure 26: Alpha Fuel Module Mounted on Engine

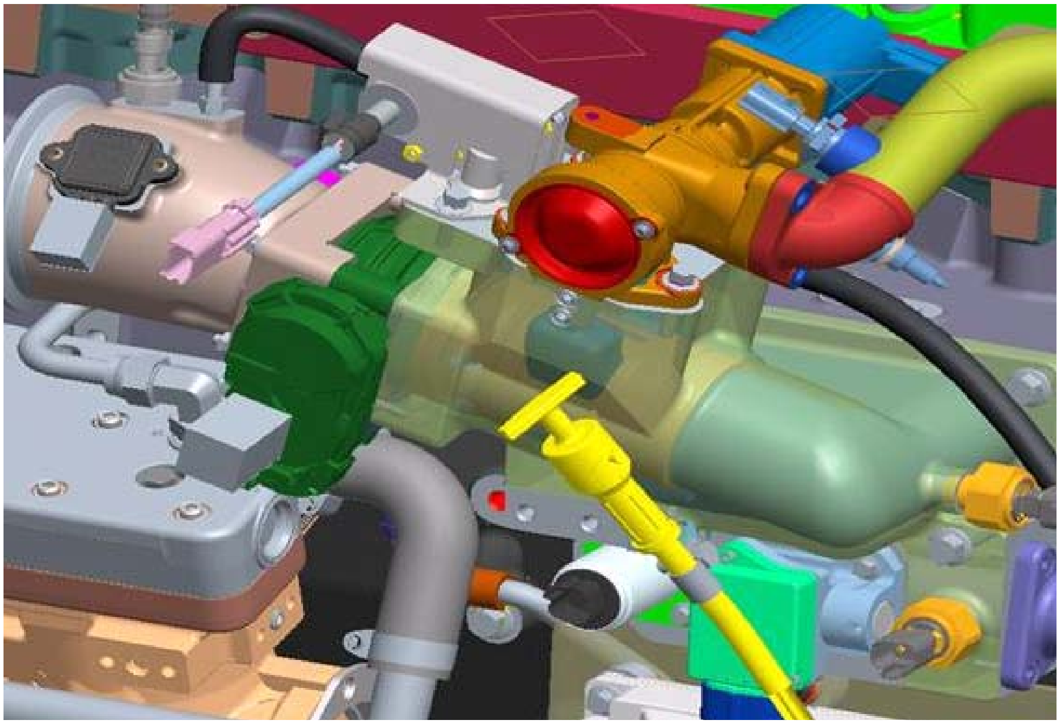
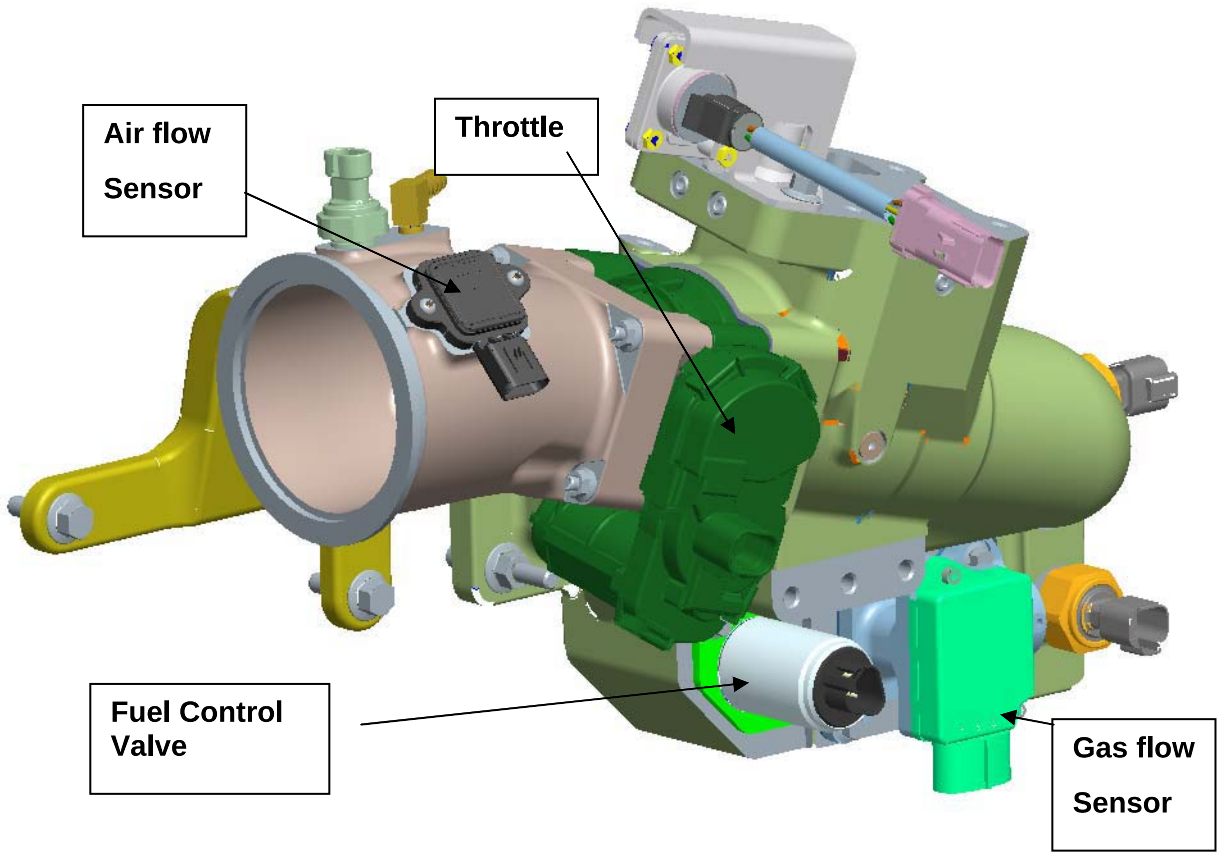
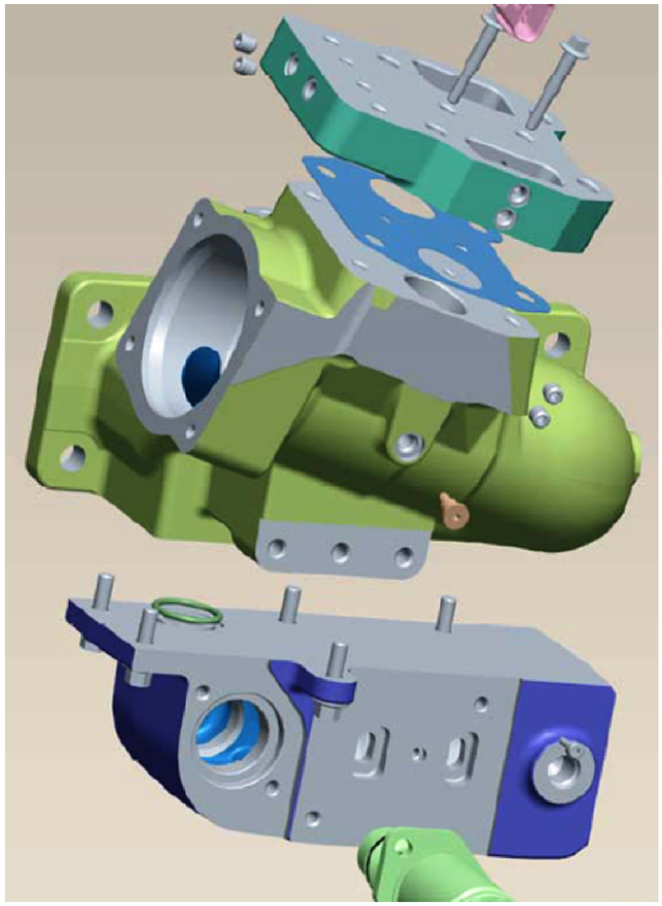


Figure 27: Alpha Fuel Module



Manufacturability issues were highlighted by the intended suppliers for the Alpha design of the fuel housing. The design required a multi-core casting that would be difficult to manufacture with adequate quality control. To resolve the manufacturing concerns, the fuel housing design was sub-divided into three distinct sub-assemblies, which will be bolted together to create the overall fuel housing as shown in Figure 28.

Figure 28: Revised Fuel Housing Alpha Design



2.6.8 Engine Brake

Class 8 trucks in regional haul applications required an engine brake to maximize vehicle braking performance without relying excessively on the vehicle's foundation brakes. Accordingly, diesel engines for Class 8 truck applications are available with an optional compression release brake. CWI's existing natural gas engines are not available with compression release brakes; therefore, the ISX11.9 G engine development program represents the first engine brake development for CWI.

The ISX11.9 G diesel engine compression release brake is not compatible with CWI's ignition system design due to a space-claim interference with the spark plugs and ignition coil extensions. CWI was unable to resolve this interference with the ignition system design; therefore, CWI engaged the 3rd-party compression release brake supplier selected by Cummins for brake development, to design and develop a unique compression release brake for the ISX11.9 G engine.

Figure 29 shows the Alpha compression release brake design. Prototype hardware was received from the supplier and installed on a pre-Alpha ISX11.9 G engine with no interference issues. See Figure 30.

Figure 29: Compression Release Brake Design

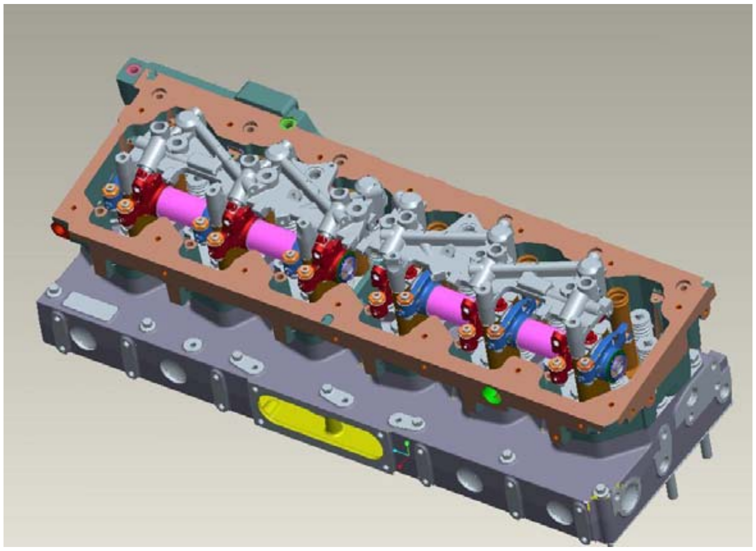
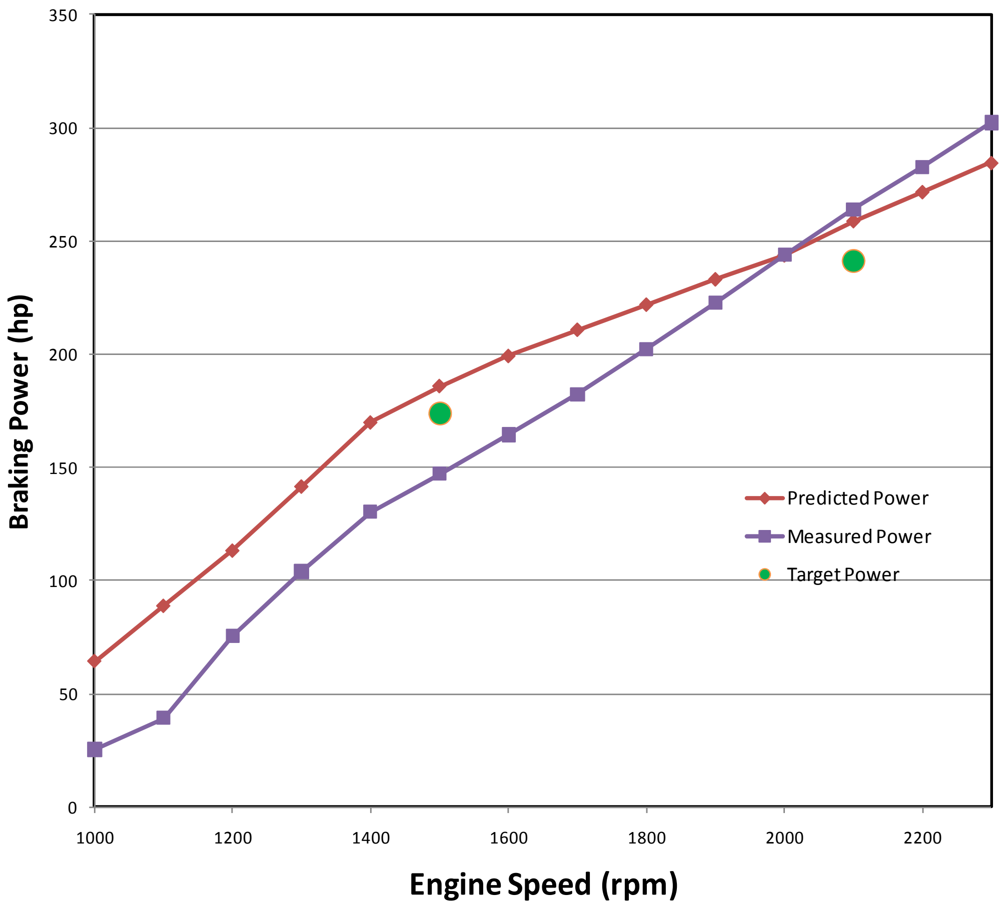


Figure 30: Compression Release Brake Hardware Installed in Cylinder Head

The prototype compression release brake was installed on an engine in a test cell that could motor the engine at the desired speed to demonstrate the braking power of the design. The prototype brake design produced lower braking performance than predicted by the braking supplier. The reduced performance was traced to a machining issue at the supplier. This was corrected and target braking power was demonstrated at rated engine speed. Performance at lower engine speed however was measured to be below target as well as below the predicted values, as shown in Figure 31. This is being investigated, and will be addressed via continued collaboration with the brake supplier during the next phase of engine development.

Figure 31: Preliminary Compression Release Brake Performance Data



2.6.9 Three Way Catalyst

The ISX11.9 G engine uses a three way catalyst to treat NOx, CO and hydrocarbon (HC) emissions. CWI's 8.9 liter ISL G engine also uses a TWC for exhaust treatment. Early in the Alpha design CWI investigated the feasibility of using the existing ISL G TWC with the 11.9 liter engine. However, analysis and measurements confirmed unacceptably high pressure drop across the ISL G TWC at the higher exhaust flow of the larger engine. Further analysis concluded that a larger catalyst substrate diameter of 12" would provide acceptable pressure drop, and would also provide similarity in packaging and installation with existing diesel after treatment components. This should facilitate OEM installations in the target Class 8 truck chassis. The catalyst wash coat was also selected to be the same as the current ISL G, which has been successful in meeting emission targets.

2.6.10 Overall Engine Design

During this task, CWI assembled a small quantity of Pre-Alpha engines at the Cummins Jamestown Engine Plant (JEP) in Jamestown, New York. The Pre-Alpha engines incorporated some of the Alpha sub-system designs described above. See Figure 32.

Figure 32: Pre-Alpha Engine Built at JEP

Figures 33 and 34 show CAD models of the ISX11.9 G Alpha engine design incorporating all of the Alpha component and sub-system designs described above. The Alpha engine build at JEP will occur following the conclusion of this project, when all Alpha components and sub-systems will be available from the production-intent suppliers.

Figure 33: Alpha Engine Design Viewed from Exhaust Side of Engine

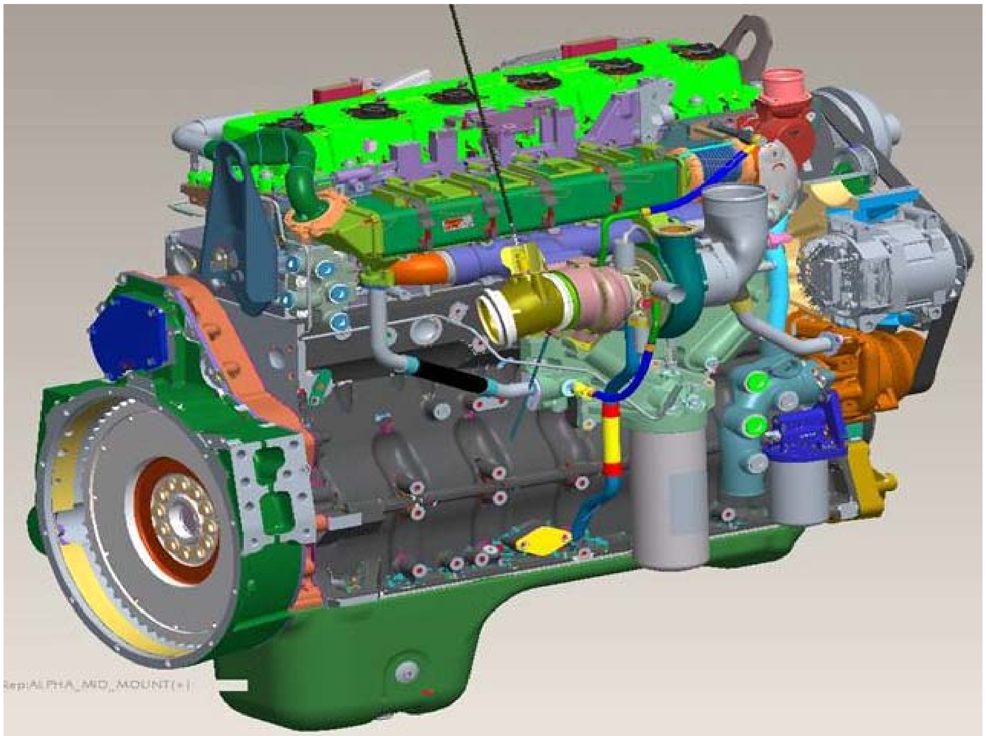
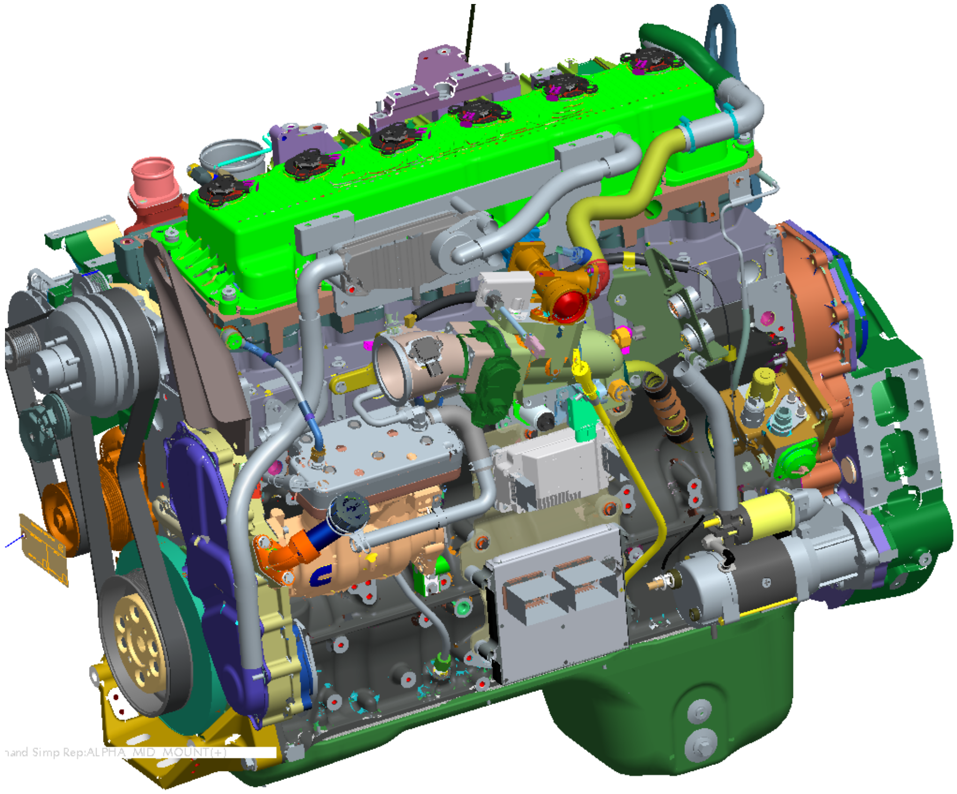


Figure 34: Alpha Engine Design Viewed from Intake Side of Engine



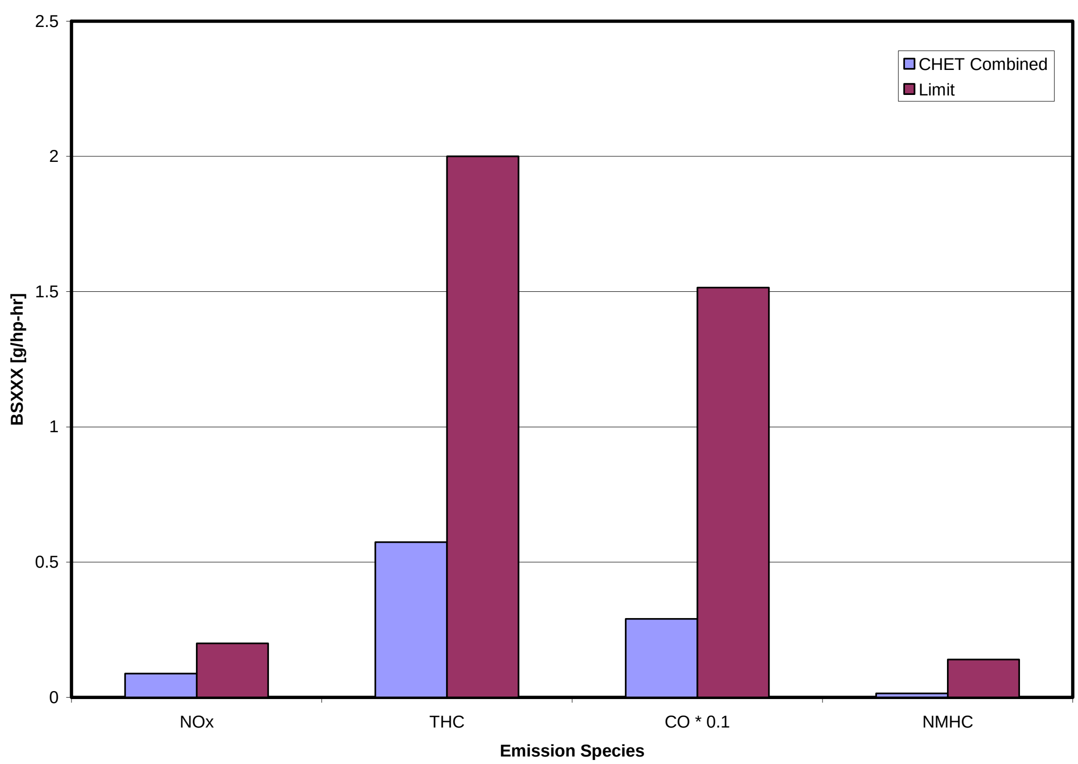
CHAPTER 3:
Project Results

The project successfully addressed each of the project objectives. The key project results are discussed in this section.

- Designed, demonstrated, and conducted preliminary development of an "Alpha" stage 12 liter heavy duty natural gas engine, with emissions at or below U.S. EPA / CARB 2010 emission standards (g/bhp-hr): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO

As described in the preceding section of this report, CWI successfully demonstrated the feasibility of applying the SESI technology to an 11.9 liter heavy-duty engine via Concept engine testing. Based upon the data and experience gathered with the Concept engine, CWI proceeded to create an "Alpha" design comprise of existing diesel engine components where possible, and purpose-designed natural gas specific components and sub-systems where required. CWI obtained transient emissions data based from the engine coupled with a prototype three way catalyst design. NOx, CO and NMHC values for the combined Cold and Hot engine tests (CHET) showed good margin for all criteria pollutants versus the applicable U.S. EPA / CARB 2010 on-highway emission standard.

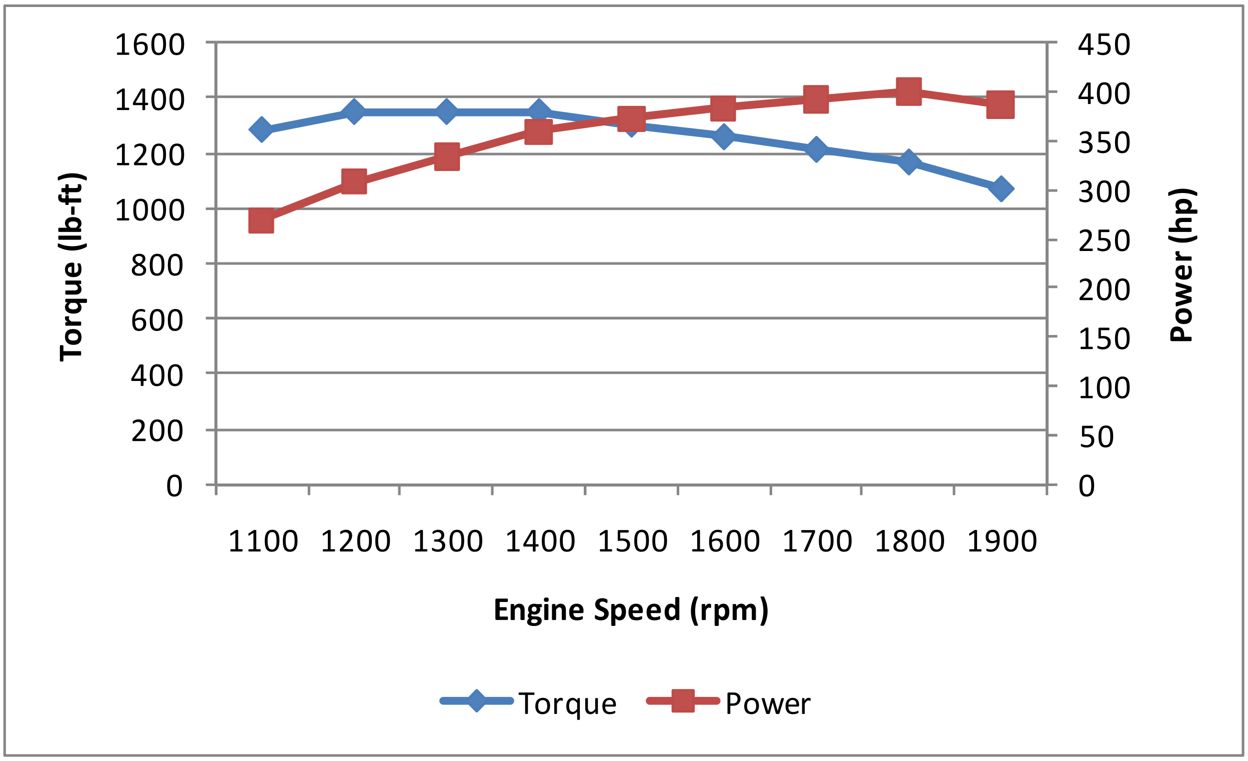
Figure 34: Preliminary ISX11.9 G Emission Data



3.1 Demonstrated 400 hp, 1350 lb-ft Peak Performance

CWI demonstrated the capability of the ISX11.9 G engine design to achieve the target peak rating of 400 hp and 1350 lb-ft. Figure 36 depicts the power and torque curves obtained from Pre-Alpha torque curve mapping in an engine dynamometer test cell. Initial test cell operation demonstrated acceptable combustion margin (for example, the margin between the engine's operating conditions at a given speed and load point, and various performance limits, including engine knocking, temperature, and turbo-machinery limitations) at peak torque speed (1200 rpm), but insufficient operating margin at rated (1800 rpm) and higher speeds. Through additional modeling, piston design, and extensive testing, CWI improved the combustion margin at high engine speeds, and demonstrated adequate operating margin throughout the full speed and load range of the engine.

Figure 35: Preliminary Torque and Power Curves for ISX11.9 G Peak Rating

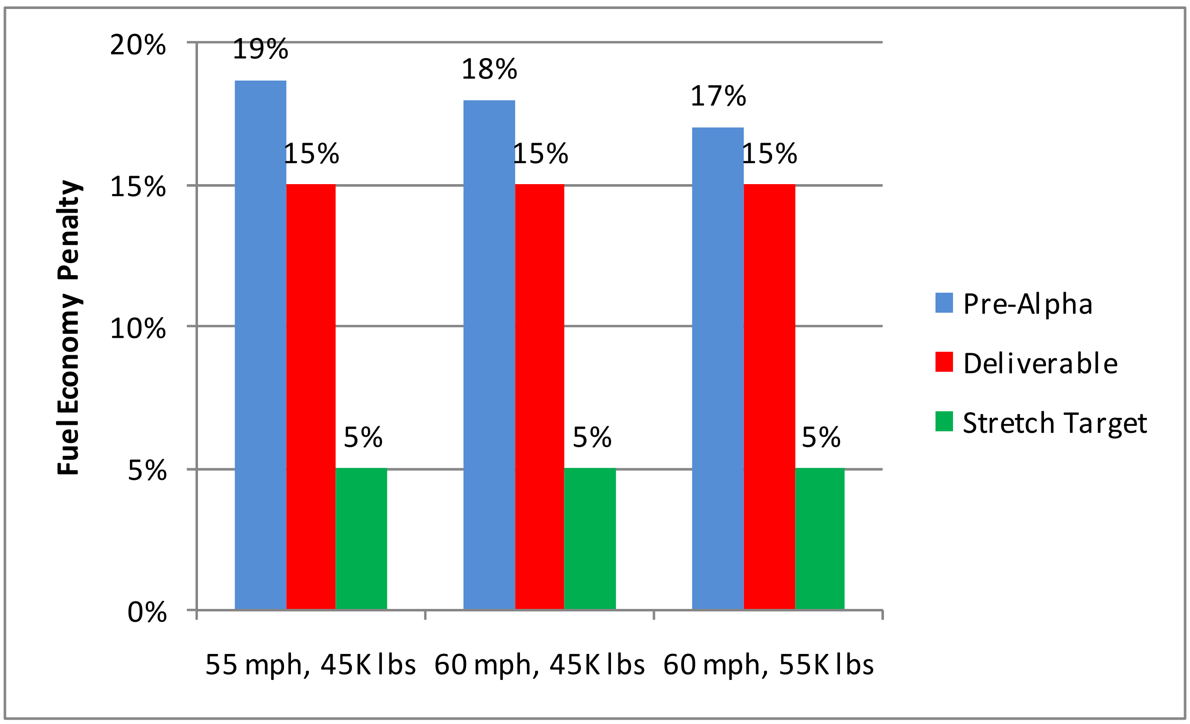


Demonstrated fuel economy improvement of approximately 2 percent versus existing spark-ignited natural gas current spark ignited natural gas powered trucks in specific vocational and regional haul Class 8 truck / tractor duty cycles.

CWI's experience in the Class 8 truck market suggests that ISL G fuel economy is approximately 20 percent lower than diesel-powered trucks operating in Class 8 regional haul duty cycles. On this basis, CWI Engineering has translated the task objective (5 to 10 percent fuel economy improvement versus existing spark-ignited natural gas engines) into a technical deliverable of achieving fuel economy within 15 percent of diesel vehicles in various Class 8 truck duty cycles. CWI Engineering has also established a more aggressive "stretch target" of achieving fuel economy within 5 percent of diesel vehicles in the same Class 8 truck duty cycles.

CWI has mapped the fuel consumption of the Pre-Alpha ISX11.9 G engine throughout the engine speed and load operating range during engine dynamometer testing. CWI Engineering then loaded these fuel maps into a Cummins analytical model used to predict vehicle fuel consumption based on specific vehicle, load, route and load factor input data. CWI modeled the fuel consumption from comparable Cummins diesel engines using the same input criteria, to evaluate ISX11.9 G Pre-Alpha fuel consumption versus the technical fuel economy target. The results of this analysis are presented in Figure 37, which shows that the fuel economy at this stage of the program doesn't yet meet target.

Figure 36: Preliminary Fuel Economy Assessment



Whereas ISL G-powered Class 8 trucks are estimated to have approximately 20 percent lower fuel economy than diesel trucks in Class 8 regional haul duty cycles, the data in Figure 37 indicates that the ISX11.9 G fuel economy demonstrated to-date is approximately 2 percent better than ISL G-powered trucks.

Fuel economy improvements will primarily be obtained via detailed optimization of the engine's electronic control calibrations, involving spark timing, exhaust gas recirculation (EGR) rates, and fuel control. Detailed calibration optimization has not occurred to-date due to CWI's focus on confirming the power cylinder design and demonstrating adequate combustion margin. Fuel economy optimization will occur during the next phase of the ISX11.9 G development program. Based on CWI's prior experience applying this combustion technology to a smaller engine platform, the development team is confident that the commercialized version of the engine will achieve fuel economy that is 5 to 10 percent better than existing spark-ignited natural gas engines in Class 8 truck duty cycles.

- Quantified the GHG emission reductions of the proposed new engine versus diesel and existing SI natural gas engines in specific vocational and regional haul Class 8 truck / tractor duty cycles.

A portion of the natural gas fuel consumed in Class 8 truck applications in California today is derived from renewable fuel sources, including landfill gas. While the majority of the transportation fuel in the foreseeable future is likely to be derived from conventional natural gas fuel sources, CWI anticipates a progressive market share increase for renewable natural gas in the California transportation market. For the purpose of calculating total GHG emissions, CWI identified a "base case" for natural gas fuel supply, assuming that 90 percent of the natural gas fuel consumed by the ISX11.9 G fleet will be derived from conventional natural gas fuel pathways, and 10 percent from renewable biomethane pathways. CWI has also identified an "upside case" whereby 50 percent of the fuel consumed by the ISX11.9 G fleet will be derived from bio-methane pathways.

For each of these potential natural gas fuel distributions, CWI projected the GHG benefits of ISX11.9 G-powered Class 8 trucks versus diesel-fueled Class 8 trucks, based on CARB's Low Carbon Fuel Standard full fuel cycle GHG analysis for various fuel pathways. Based on the ISX11.9 G fuel economy demonstrated within this project, future ISX11.9 G-powered trucks are estimated to provide full fuel cycle GHG benefits ranging from 9.9 percent to 38.6 percent, depending on the proportion of renewable and conventional natural gas sources in the California transportation fuel supply. Based on the more probably scenario of achieving the program's fuel economy target (for example, 5 to 10 percent fuel economy improvement versus existing spark-ignited natural gas engines) by the time ISX11.9 G commercial availability begins, future ISX11.9 G-powered trucks are projected to provide full fuel cycle GHG benefits ranging from 17.9 percent to 44.0 percent versus comparable diesel-powered Class 8 trucks.

- Created technical data, including CAD models, bills of material, preliminary component design drawings, emissions data, detailed fuel maps, and vehicle mission simulations, to communicate the preliminary engine design and operating characteristics to enable continued product development and commercialization via a follow-on project.

The ISX11.9 G Concept demonstration and Alpha design project has been conducted in accordance with the first phase of a well-defined Cummins and Cummins Westport process for engine development, demonstration and commercialization. This process has been implemented and refined during multiple diesel and natural gas engine development programs, with a focus on ensuring cross-functional review and input on all major program decisions, to ensure that all required functions are engaged in the program and are simultaneously preparing for commercialization of the new engine. In accordance with this new product introduction process, CWI and Cummins staff representing an array of critical functions (such as engineering, manufacturing, purchasing, sales, marketing, customer service, and so forth) met weekly to review program progress, data, and deliverables. Through this process, all pertinent technical data, including CAD models, bills of material, design drawings, emissions data, fuel maps, and so forth, have been recorded in a Cummins internal database to facilitate sharing of information amongst the relevant program functions. Examples of relevant data are provided in the preceding sections of this report, documenting the specific work performed and results achieved for the various technical tasks within this project.

In addition to regular weekly cross-functional team meetings, CWI has also conducted regular reviews of the program status with designated senior management members from CWI, Cummins, and Westport Innovations. The intent is to ensure ongoing senior management commitment from each of the key program functional teams and to re-affirm plans to proceed toward commercial availability of the ISX11.9 G engine.

In accordance with this process, all the required data has been generated to enable the ISX11.9 G engine development program to proceed to the next phase, which will involve vehicle integration activities with Class 8 truck manufacturers and field demonstrations with end-user customers.

CHAPTER 4:
Conclusions and Recommendations

4.1 Conclusions

Based on the results of this project and the data presented in this report, the project team's primary conclusion is that the SESI technology can feasibly be applied to an 11.9 liter heavy-duty engine platform and can achieve the performance and emission targets established for the program. Further, the project team draws the following conclusions related to the specific objectives established for this project.

- The SESI technology, applied to an 11.9 liter heavy-duty engine platform, is capable of criteria pollutant emissions that are lower than the U.S. EPA / CARB 2010 on-highway emission standards (g/bhp-hr): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO.
- The ISX11.9 G engine can achieve a peak rating of 400 hp and 1350 lb-ft peak torque, with sufficient combustion margin to ensure robust operation in a variety of duty cycles and operating conditions.
- With limited emphasis on fuel economy optimization at this stage of the ISC11.9 G development program, the ISX11.9 G engine fuel economy data collected to-date indicates a marginal fuel economy improvement versus existing spark ignited natural gas engines used in Class 8 trucks. Based on CWI's experience with prior engine development programs, the project team is confident that the program goal of 5 to 10 percent improvement versus existing engines can be achieved.
- ISX11.9 G-powered Class 8 trucks, in comparison with diesel-fueled Class 8 trucks, are projected to deliver full fuel cycle GHG advantages ranging from 10 percent to 44 percent, depending on the proportion of renewable and conventional natural gas fuel sources in the future California transportation natural gas fuel supply and also depending on the ISX11.9 G fuel economy relative to diesel engines at launch.
- The ISX11.9 G development program has been conducted in accordance with the Cummins-prescribed process for new product introduction programs. In accordance with this process, all pertinent program technical data has been captured, recorded, and reviewed regularly by a cross-functional team that is responsible for directing the ISX11.9 G engine development and commercialization program.

4.2 Recommendations

CWI recommends proceeding with the next stage of the overall ISX11.9 G engine development, demonstration and commercialization, which will include the following activities:

- Field demonstrations with end-user customers to demonstrate engine reliability and durability, and to establish appropriate scheduled maintenance intervals
- Calibration development and optimization to achieve program fuel economy targets

- Accelerated testing to demonstrate component, sub-system and engine durability
- Identifying, validating and source-approving production suppliers for all components
- Volume-manufacturing of ISX11.9 G engines via scheduled Alpha and Beta builds at JEP
- Emission certification testing, including demonstrating emission durability over the EPA / CARB-prescribed useful life for heavy-heavy duty engines
- Vehicle integration activities with Class 8 truck manufacturers, installing Installation Quality Assurance (IQA) reviews to ensure that all engine installation requirements and recommendations are met

CWI intends to proceed with this next phase of work immediately, with an objective of initiating customer field demonstrations during the first half of 2011, leading to commercial availability of the ISX11.9 G engine in a broad range of Class 8 regional haul and vocational truck chassis by 2013. CWI anticipates that the total expense to enable ISX11.9 G commercial availability will be in the range of $6 million to $8 million.

4.3 Benefits to California

This project has successfully completed the first stage of an engine development program that is expected to lead to commercial availability of a more fuel efficient natural gas engine for heavy duty vehicle applications predominantly served by diesel engines. The limited market penetration of natural gas engines serving these applications are not considered optimized for fuel efficient performance. Accordingly, California natural gas ratepayers are expected to directly benefit by cost savings per mile traveled. This higher efficiency will also reduce the emissions of criteria pollutants and greenhouse gas emissions per mile traveled.

Natural gas ratepayers in California will also benefit from reduced consumption of diesel fuel as the ISX11.9 G natural gas engine will directly displace diesel fuel consumption in the target market applications. Natural gas use will lessen petroleum imports used for the heavy duty truck market. This reduced demand for diesel should enable gasoline production from capacity constrained refinery industry. This should help mitigate volatility in gasoline prices.

Emissions of greenhouse gases and particulate matter from natural gas engines will also be lowered compared to diesel engines. Compared to diesel engines, the emissions control technology on natural gas engines to meet the 2010 NOx requirements will not require the use of urea reagent. This will help California ratepayers as urea is used for fertilizer and increased demand for vehicles will put pressure on prices paid by farmers.

California ratepayers will also benefit from the ISX11.9 G engine following commercial launch as it is integrated with other technological advancements under development including advanced power trains, hybrid vehicle platforms and waste heat recovery. These improvements will result in further reductions in fossil energy used for transportation and emissions of greenhouse gases.

GLOSSARY

Acronym	Definition
CAD	Computer Aided Design
CES	Cummins Emission Solutions
CHET	Cold / Hot Emission Test
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2e	Carbon Dioxide Equivalent
CWI	Cummins Westport Inc.
ECM	Electronic Control Module
EGR	Exhaust Gas Recirculation
FEM	Finite Element Modeling
FMEA	Failure Modes and Effects Analysis
GHG	Greenhouse Gases
GTI	Gas Technology Institute
HC	Hydrocarbons
ICM	Ignition Control Module
JEP	Jamestown Engine Plant
LCFS	Low Carbon Fuel Standard
LNG	Liquefied Natural Gas
NMHC	Non Methane Hydrocarbons
NO_x	Oxides of Nitrogen
OBD	Onboard Diagnostics
OEM	Original Equipment Manufacturer
PM	Particulate Matter
SESI	Stoichiometric, EGR, Spark-Ignition
SI	Spark Ignition

TWC	Three-Way Catalyst
ULSD	Ultra Low Sulfur Diesel
WTW	Well to Wheels