CALIFORNIA
ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Late Stage Development and Product Launch of Cummins Westport 11.9 Liter Natural Gas Engine

Prepared for: California Energy Commission

Prepared by: Gas Technology Institute

Gavin Newsom, Governor

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued solicitation PON-08-010 for alternative fuel vehicle projects. The Gas Technology Institute and Cummins Westport, Inc. submitted an application that was proposed for funding in the Energy Commission's Notice of Proposed Awards on March 18, 2010. The agreement was executed as ARV-09-013 on April 12, 2011. The Energy Commission grant totaled $1,754,081, while the applicants committed $3,622,636 in match funding.

ABSTRACT

This report for the AB 118 Project entitled "*Late Stage Development, Demonstration and Product Launch of Cummins Westport 11.9 Liter Natural Gas Engine*" was funded under the CEC's Clean Transportation Program Grant ARV-09-013. Work under this grant commenced upon the completion of work performed under CEC Agreement PIR-08-044 from the Energy Commission's Research Division. PIR-08-044 supported ISX11.9 G engine concept development and creation of the "alpha" design. This report includes completion of the engine build-out, validation testing, emissions certification, demonstration tests, and manufacturing readiness tasks leading to commercial launch of a new low emission, high performance natural gas 11.9-liter engine for the heavy-duty Class 8 truck market.

Keywords: Natural Gas Engine, Cummins-Westport, 11.9-liter engine, heavy duty Class 8 truck, natural gas fueling, California Energy Commission, California, product launch, alpha design.

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EXECUTIVE SUMMARY

The goal of this Agreement is to complete the development process, then test, certify, and commercialize a heavy-duty spark ignited natural gas 11.9-liter engine with ultra- low emissions, high performance, and best in class fuel economy in specific vocational and regional haul Class 8 truck duty cycles. The emissions, performance, and fuel economy benefits will be achieved by applying Cummins Westport's spark ignited natural gas, cooled exhaust gas recirculation, three-way catalyst technology to a Cummins 11.9-liter diesel engine platform.

The objectives of this Agreement included:

- Validating, engineering, and further refining the Alpha engine design completed in a prior Energy Commission-sponsored project (partially funded under PIER Grant Agreement PIR-08-044), including extensive laboratory, rig, and engineering-vehicle testing,
- Demonstrating a number of engines in a variety of vocational and regional haul Class 8 truck/tractor customer vehicles with California-based fleet operators,
- Obtaining emissions certification at or below EPA/CARB 2010 emission standards (g/bhp-hr.): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO,
- Demonstrating improved fuel economy of 5 to 10% when compared to current spark ignited natural gas-powered trucks in specific vocational and regional haul Class 8 truck/tractor duty cycles,
- Demonstrating and quantifying engine greenhouse gas (GHG) emission reductions (i.e. measured on a tank-to-wheels basis) vs. diesel engines when operated on the EPA emission certification duty cycle,
- Validating production manufacturing and testing capability for the new natural gas engine,
- Identifying and qualifying production suppliers for all new components required to build the proposed engine,
- Launching the new engine into limited commercial production by April 2013 and full production by July 2013, making the engine product available directly from the factory of multiple North American heavy-duty Class 8 truck and tractor manufacturers, and
- Demonstrating the engine in California fleet operations, gathering six months of data, and reporting project results to the California Energy Commission.

Benefits to California

This project directly supports California's climate change policies by introducing a low-GHG engine technology to a high-impact vehicle market segment. It is estimated there are 167,000 Class 8 heavy duty trucks on the roads in California on any given day. Although Class 8 trucks represent only 4 percent of vehicles on the road nationwide, they consume 20 percent of the nation's transportation fuel. Adopting this engine technology in Class 8 trucks will reduce emissions of GHG by at least 20-25 percent. This is a significant reduction, virtually double California's Low Carbon Fuel Standard (LCFS) goal of 10 percent reduction by 2020. Compared to diesel engines, the emissions control technology on the 11.9-liter gas engine 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.

The project result is the commercial availability of a high-performance natural gas engine ideally suited for a wide variety of high-fuel use Class 8 truck applications in California and throughout North America. Availability of the 11.9-liter gas engine will enable Class 8 truck fleets and owner-operators to realize significant operational cost savings without compromising vehicle performance and operational efficiency.

Californians will also benefit from reduced consumption of diesel fuel as the 11.9-liter natural gas engine displaces diesels in the target market application. 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.

CHAPTER 1: Introduction

Product Development

The goal for this development project is to complete all product development activities resulting in a "ready-to-launch", fully engineered and fabricated, pre-commercial, beta engine product. These activities include mechanical development of engine and fuel system hardware, engine control and ignition system design, calibration development for performance and emissions, component design optimization, design validation/verification, controlled field testing, production readiness/beta engine build-out, and design finalization, structure, and release.

Cummins Westport shall:

Prepare the Product Development Implementation Report. The Product Development Implementation Report shall include:

- A description of the electronic control systems meeting the requirements for heavy-duty vehicle operation,
- Summaries of engine calibration and engine testing in an engine dynamometer test cell,
- Summary of fuel "maps" modeling the fuel economy benefits of the ISX 11.9 G engine against existing SI natural gas engines,
- Quantification of GHG advantages of this engine product for the intended application,
- Endurance test data summary from thermal, vibration, reliability testing performed on a "shaker rig" and another with Cummins Westport Inc. (CWI) test equipment.
- Prepare the Design Optimization, Structure and Release Report. The Design Optimization, Structure, and Release Report shall include, but is not limited to:
- Final drawings, diagrams, and component lists of the engine design,
- Summary of key findings from a Design Failure Mode and Effect Analysis.
- Prepare a Design Verification and Validation Report. The Design Verification and Validation Report shall include:
    - Photographs and drawings of the final engine product,
    - An engineering evaluation of the engine after installation in a single test vehicle.
- Prepare the Field Test Engines Report. The Field Test Engines Report shall include:
    - Identification of initial test sites for end-user customer trucks,
    - Operational assessments and review of component performance.
- Prepare the Production Readiness Report. The Production Readiness Report shall include:
    - Photographs and drawings of beta engine models,
    - Status update on identifying and validating production suppliers for engine components,
    - Description of the order entry, manufacturing and test processes implemented and validated at the Cummins Jamestown Engine Plant.
- Prepare the Design Finalization, Structure, and Release Report. The Design Finalization, Structure, and Release Report shall include:

    - A final assessment of all components and subsystem designs by a CWI engineering team,
    - Final engine specifications and structure components for the new engine configuration at limited production status.

Recipient Products:

- Final Product Development Implementation Report
- Final Design Optimization, Structure, and Release Report
- Final Design Verification and Validation Report
- Final Field Test Engines Report
- Final Production Readiness Report
- Final Design Finalization, Structure, and Release Report

Emissions Certification

The goal of this task is to build a certification engine, equip it with production intent software and hardware to complete emission certification testing in accordance with EPA/CARB on-highway emission testing procedures. Final test data will be submitted to EPA and CARB to obtain the required documents. This task also includes operating a production-intent engine and three-way catalyst system in a test cell over an extended period of time, with emission tests at prescribed intervals. This is to demonstrate emissions stability and quantify the emissions deterioration, if any, throughout the 435,000-mile useful life prescribed by EPA and CARB for heavy-heavy duty certified engines.

The Recipient shall prepare:

- An Emissions Certification Report. The Emissions Certification Report will include, but is not limited to:
    - Engine Emissions test data submitted to both EPA and CARB,
- Verification documents from EPA and CARB confirming the engine has met all certification requirements.
- Final Emissions Certification Report

Reliability Assessment and Product Launch

The goal of this task is to review the results of the design verification process and the test data generated in Task 2 in order to assess the reliability and readiness of the engine prior to product launch. After a review by a CWI engineering team, any items identified that require modification will be made. A successful assessment will enable the engine to be released for production and commercialization.

The Recipient shall prepare:

- A Reliability Assessment and Product Launch Report. The Reliability Assessment and Product Launch Report will include, but is not limited to:
- A summary of findings during the engineering review of the engine reliability and overall Product Development process outlined in Task 2.
- Final Reliability Assessment and Product Launch Report

Field Demonstration and Data Collection

The goal of this task is to conduct a six-month field demonstration program in California to collect data from vehicles operated in commercial applications. Due to the time lag associated with engine manufacturing, shipment, assembly, and delivery of this new natural gas engine product, and to allow the demonstration period to begin immediately after product launch, this task will be performed using the test vehicles described in Task 2.

The Recipient shall prepare:

- The Field Demonstration and Data Collection Report. The Field Demonstration and Data Collection Report will include, but is not limited to:
  - Identification of test vehicles, locations, vehicle operators, and applications,
  - Test data from the vehicle operations, including miles traveled, hours of operation, engine performance and durability under extreme operating conditions (e.g. high and low ambient temperatures, high altitude, high loads, varying duty cycles), vehicle fuel consumption and other performance, reliability, and cost information,
  - Photographs of test vehicles, locations, and operating environment.
- Final Field Demonstration and Data Collection Report Task 1 Administration

CHAPTER 2: Technical Development of the 11.9 Liter Natural Gas Engine

Team Composition

For this project, GTI teamed with CWI, a joint venture company between Cummins Inc. and Westport Innovations Inc. Under a subcontract to GTI, CWI was responsible for Tasks 2 through 5. CWI owns the natural gas engine intellectual property developed in this project and is the commercialization entity responsible for bringing the technology to the marketplace.

The Products (Reports) required under each of the technical tasks (as listed in Section 1) were all submitted to the Grant Manager. In the sections to follow of this report, a summary of work performed in each task, including key accomplishments, will be documented. For more detailed information about the work and results under each task, the reader can refer to the individual Task Reports.

Product Development

The goal of the Product Development task is to complete all product development activities resulting in a "ready-to-launch", fully engineered and fabricated, pre-commercial, "Beta" engine product. These activities include mechanical development of engine and fuel system hardware, engine control and ignition system design, calibration development for performance and emissions, component design optimization, design validation/verification, controlled field testing, production readiness/beta engine build-out, and design finalization, structure, and release.

The various activities within this task are categorized as follows:

- Product development implementation
- Design optimization, structure and release
- Design verification and validation
- Field test site selection
- Design finalization, structure and release

The product development work under this project dovetails into the initial Concept demonstration and Alpha design work conducted for the Cummins Westport 11.9-liter natural gas engine under a prior PIER-funded program (PIER Grant Agreement PIR-08-044). Product development included building 23 "Alpha" engines at the Cummins Jamestown Engine Plant (JEP) in Jamestown, New York. These engines were manufactured on the production line and tested in end-of-line engine dynamometer test cells at JEP. A number of these engines were shipped from JEP to the Cummins Technical Center in Columbus Indiana to support product development testing by Cummins Westport Engineering. A significant number of these engines were shipped to various locations to support on-road field testing in trucks, including new trucks factory-built by original equipment manufacturers (OEMs) as well as re-powering existing diesel-powered trucks to enable on-road natural gas testing.

Key engine components and subsystems addressed during the "Beta" engine product design and the associated product development activities included:

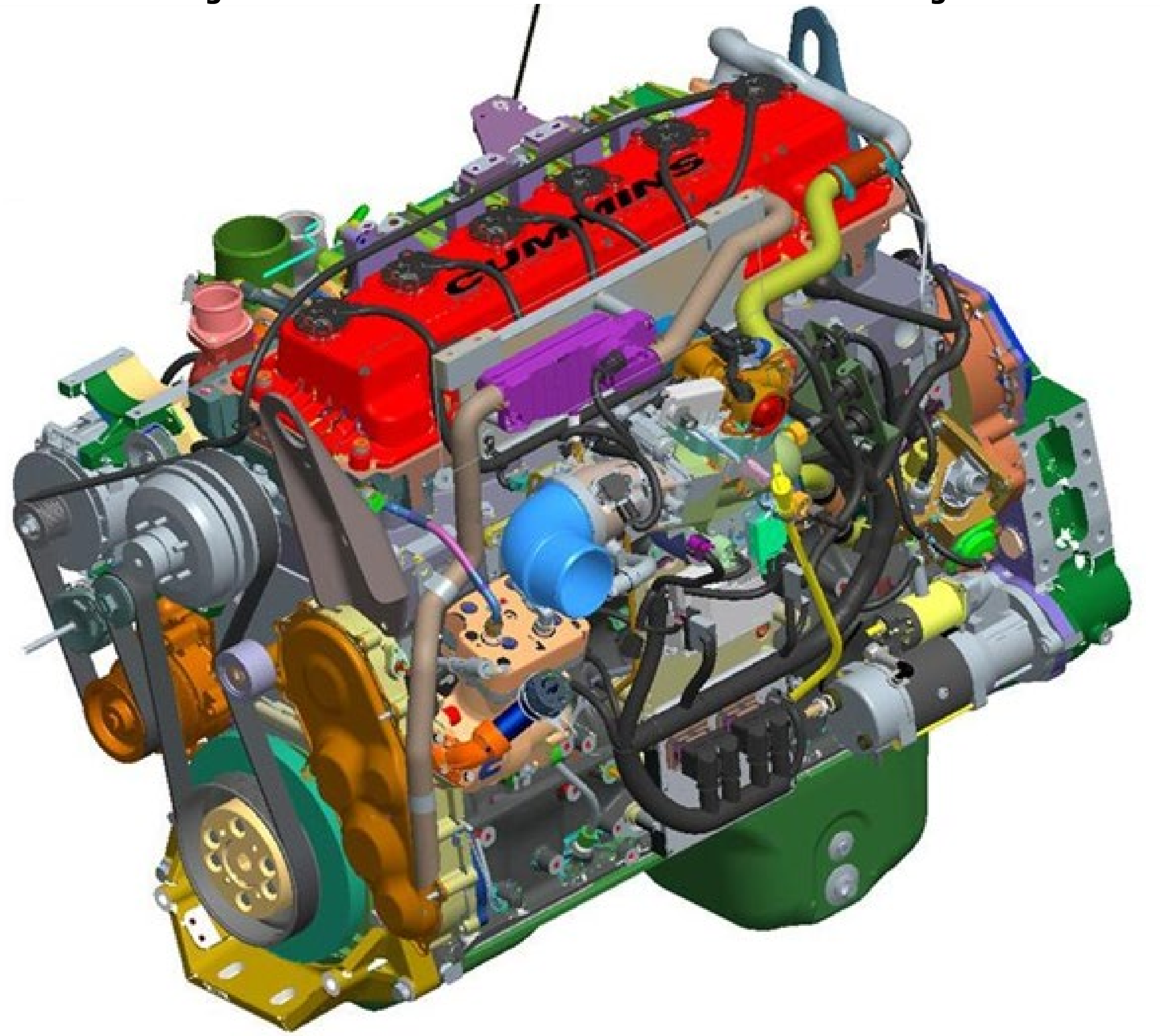
- Electronic Control System
- Sensors
- Actuators
- Wire harness
- Software and calibrations

For the electronic control module (ECM), Cummins Westport used the same ECM model as used on Cummins Westport's existing 8.9-liter ISL G natural gas engine. Unique software and calibrations are required to enable certain electronic features that have not previously been developed for Cummins Westport's natural gas engines, including:

- Compression release braking, which is required for the 11.9-liter natural gas target market but is not used elsewhere within Cummins Westport's product line.
- 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 Cummins Westport's development program;
- Gear-down protection, an electronic feature commonly used in highway tractors to encourage drivers to remain in the upper gear range by derating available vehicle speed in lower gears;
- Load-based speed control, an electronic feature that limits engine speed based on the commanded load as a function of which gear the transmission is in. This feature promotes "progressive shifting" or shifting to a higher gear in order to optimize fuel economy, rather than operating the engine at unnecessarily high engine speeds in a lower gear.

The ignition system architecture for the Beta engine consists of “coil-on-plug” technology, consistent with Cummins Westport’s ISL G engine, and a unique ignition control module (ICM) incorporating additional diagnostic capability not currently supported by the ISL G ICM. Figure 1 and Figure 2 illustrate the location of the ECM, ICM, and ignition coils in the Beta engine design.

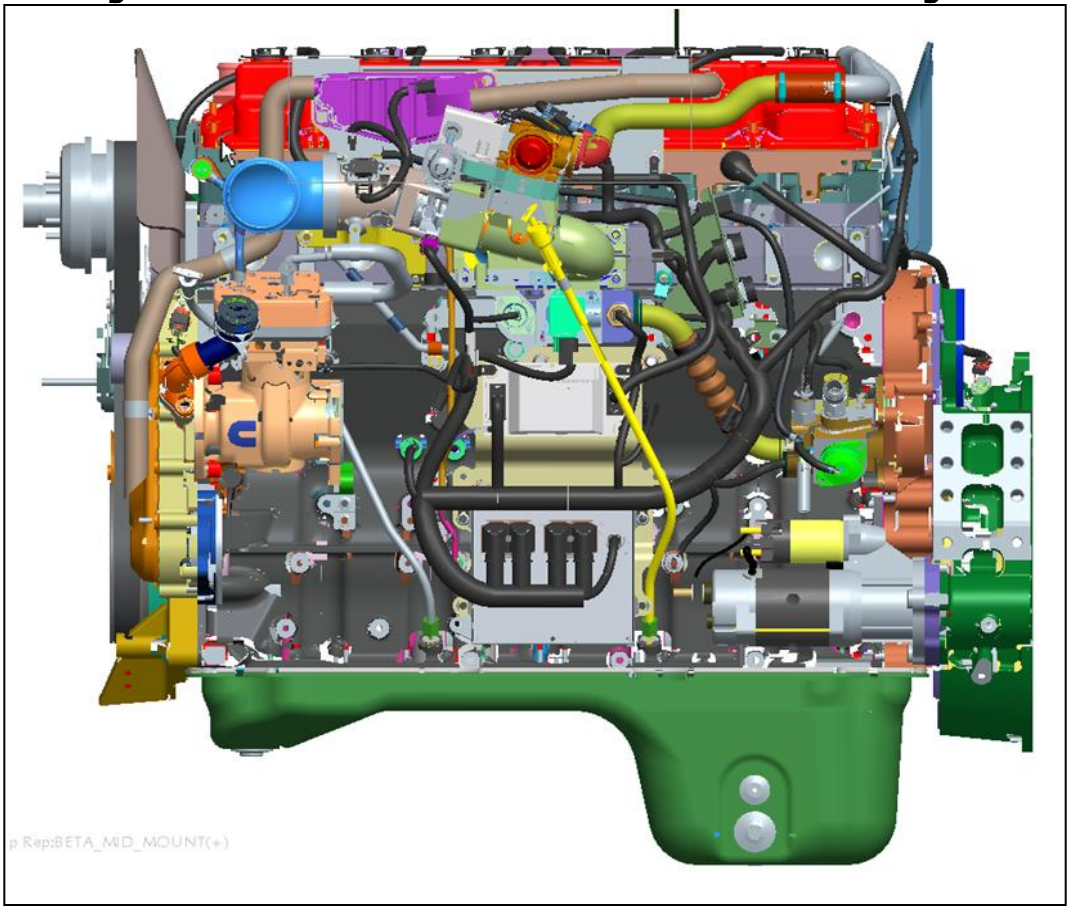
Figure 1: Isometric View of 11.9 Liter Natural Gas Engine



Source: Cummins Westport, Inc.

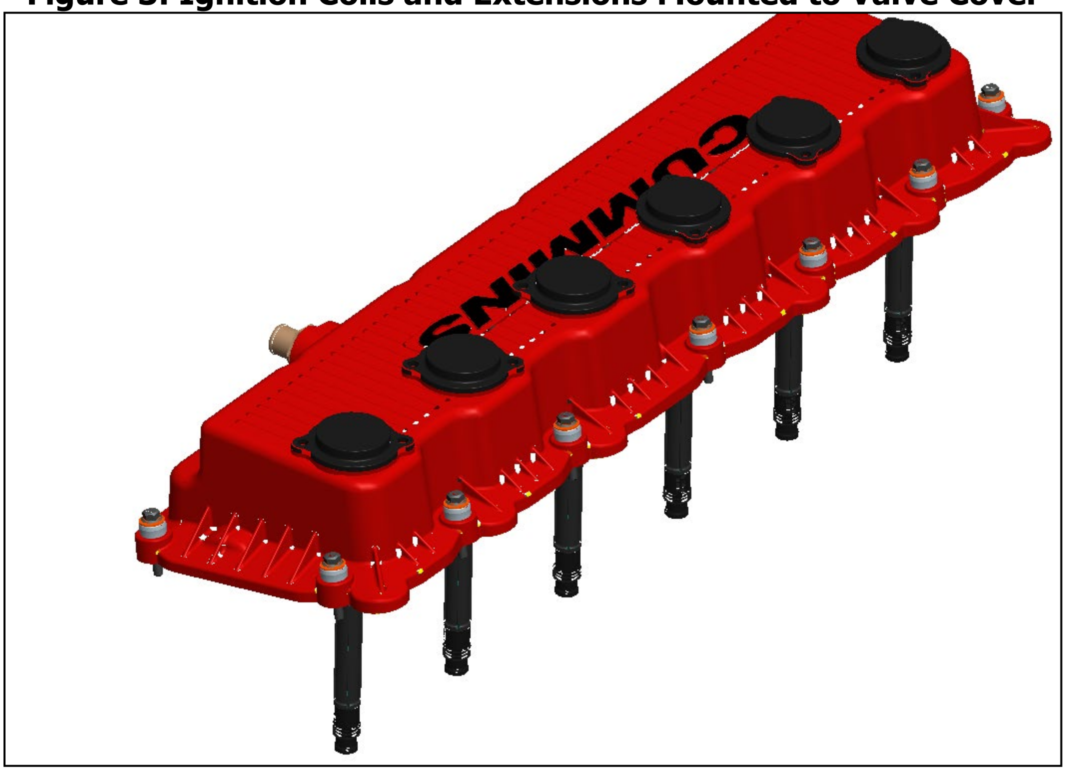
While the ignition system architecture is identical to Cummins Westport's existing ISL G engine, the design requires unique elements imposed by the packaging limitations in the target Class 8 truck/ tractor applications. Many Class 8 tractors used in regional haul applications feature air cleaner assemblies 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. In the design for the 11.9-liter natural gas engine, the 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. Figure 3 and Figure 4 identify the ignition system components and their mounting configuration.

Figure 2: Elevation View of 11.9 Liter Natural Gas Engine



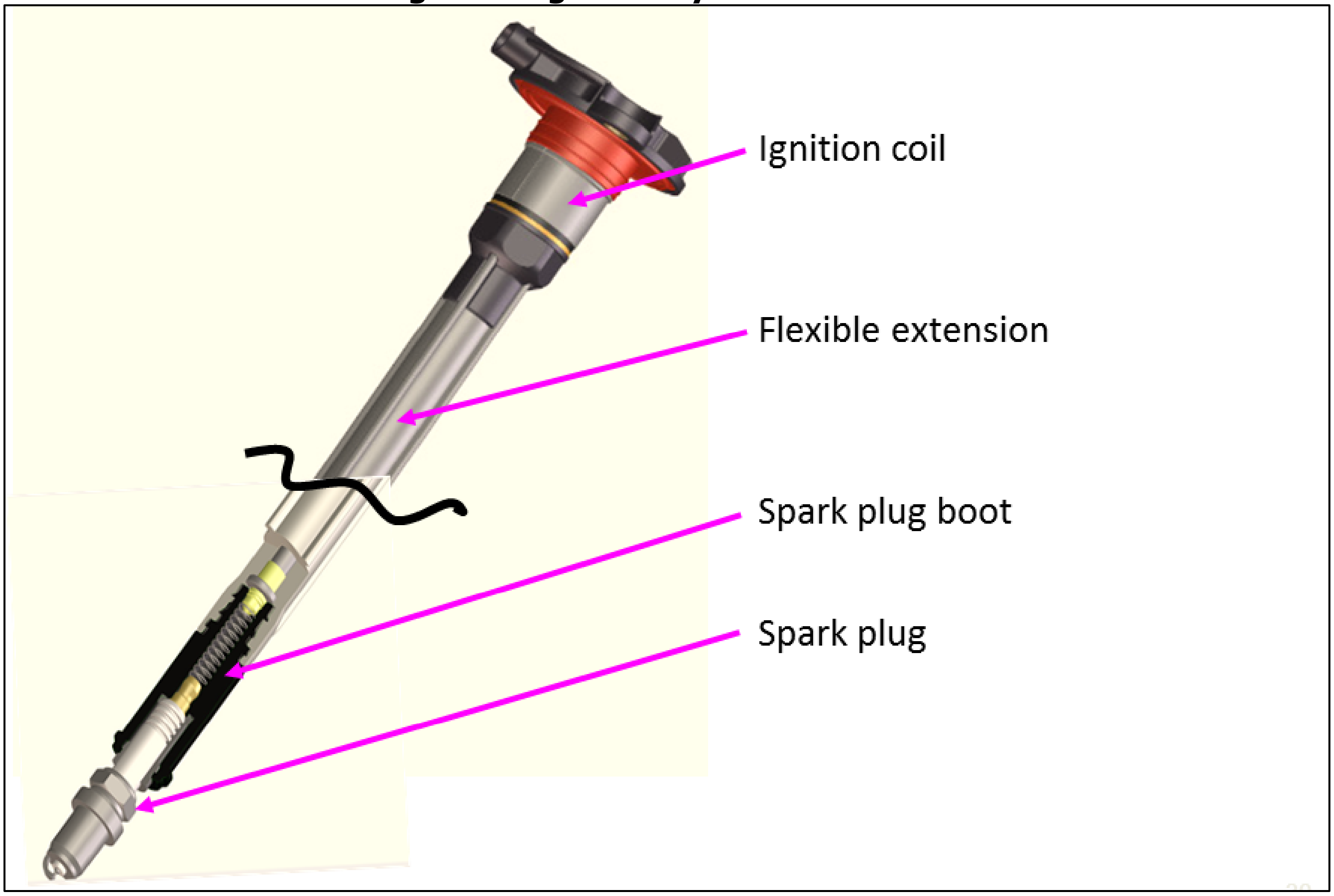
Source: Cummins Westport, Inc.

Figure 3: Ignition Coils and Extensions Mounted to Valve Cover



Source: Cummins Westport, Inc.

Figure 4: Ignition System Hardware



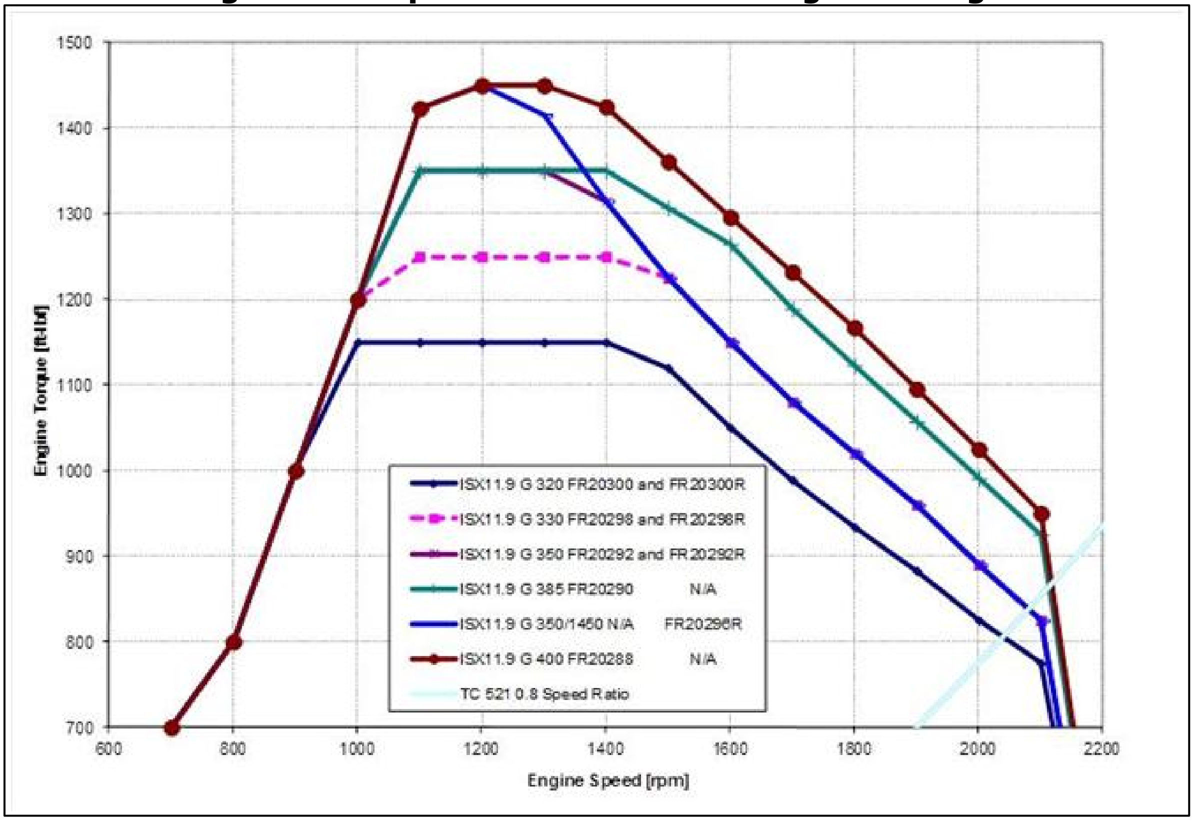
Source: Cummins Westport, Inc.

Engine Calibration and Testing

Whereas the original target peak rating was 400 hp, and 1350 lb.-ft of peak torque, the team has determined that 400 hp and 1450 lb.-ft of torque is achievable. This is a significant achievement, as 400 hp/ 1450 lb.-ft is a key node with significant customer demand in the Class 8 truck market. While the peak rating is expected to be the most common rating selected for highway tractors, additional sub-ratings are required for non-tractor applications, including refuse collection trucks and other vocational trucks (e.g. dump trucks, snowplows, concrete mixers). Cummins Westport has developed a range of ratings from 320 hp/ 1150 lb.-ft through 400 hp/ 1450 lb.-ft. The torque curves for the full range of ratings are shown in Figure 5.

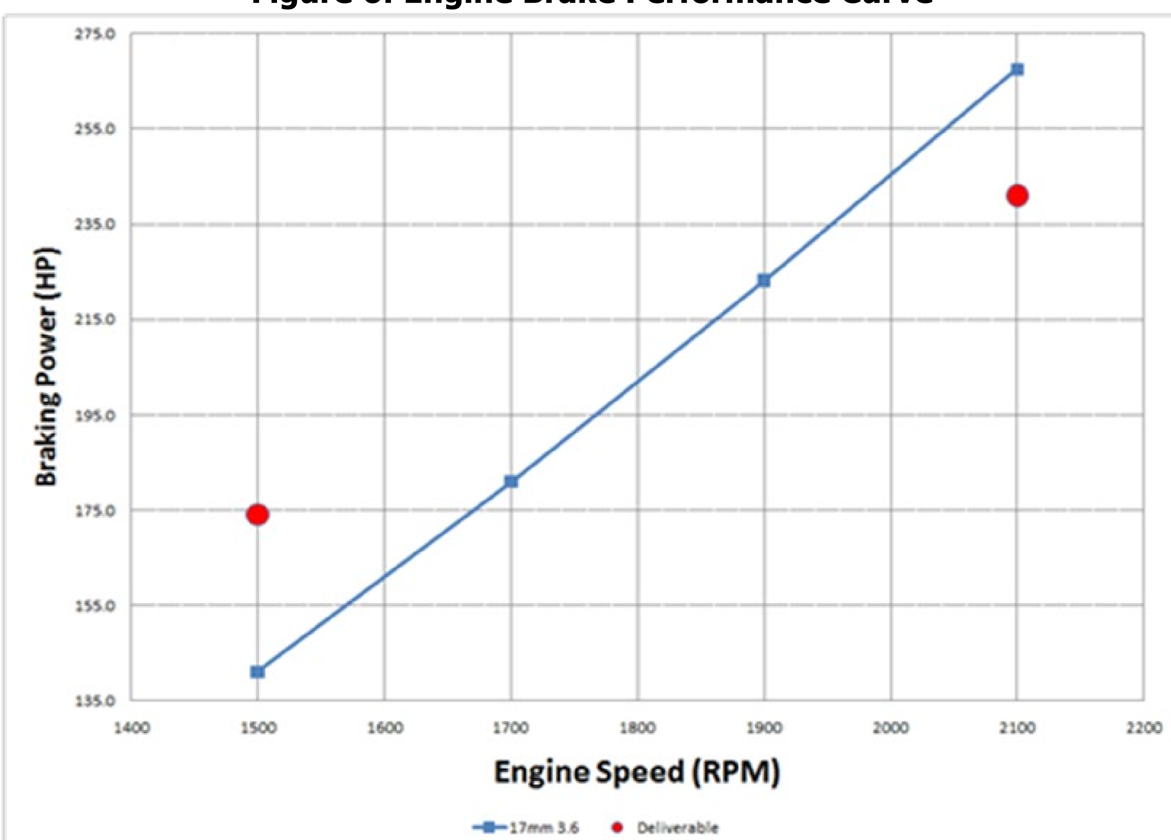
The compression release engine brake design was finalized, and validation tests completed. The performance, as shown in Figure 6, is above target at high engine speed but drops below target at 1500 rpm. This was deemed acceptable and no further development will be undertaken. The engine brake design is unique to the natural gas engine, and braking performance is lower than for a diesel engine of similar displacement due to the lower compression ratio employed with spark ignition technology than with diesel engines.

Figure 5: Torque Curves for the Six Engine Ratings



Source: Cummins Westport, Inc.

Figure 6: Engine Brake Performance Curve



Source: Cummins Westport, Inc.

Fuel Economy

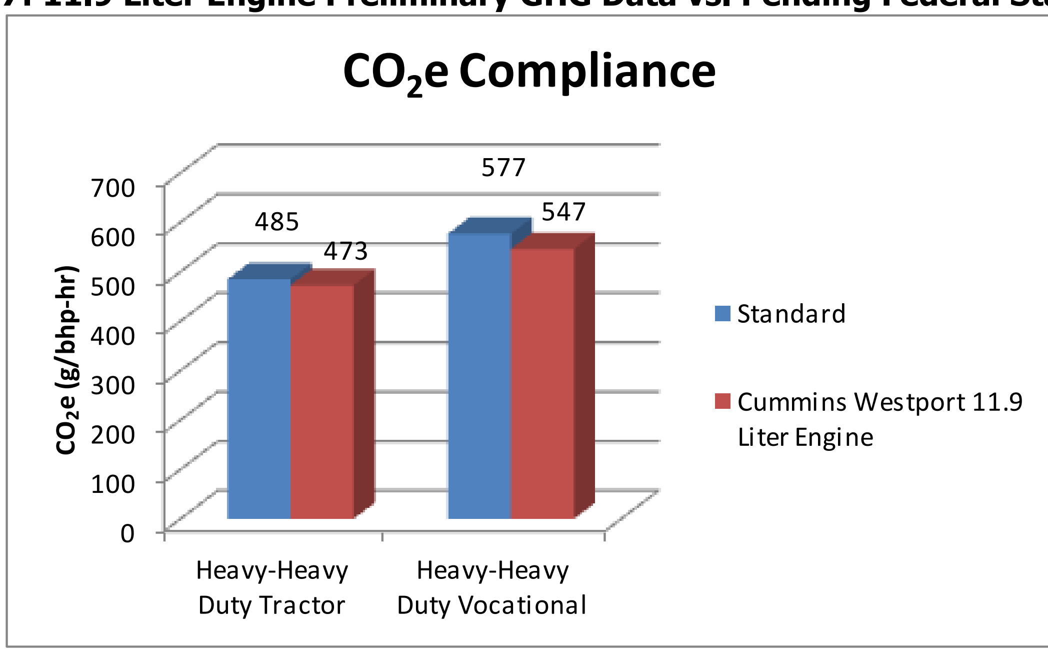
Cummins Westport's experience in the Class 8 truck market suggests that ISL G fuel economy is approximately 20 percent lower than diesel-powered trucks operating in Class 8 regional haul duty cycles. On this basis, Cummins Westport Engineering translated the task objective (5 to 10 percent fuel economy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

Cummins Westport mapped the fuel consumption of the 11.9-liter engine throughout the engine speed and load operating range during engine dynamometer testing. Cummins Westport Engineering then loaded these fuel maps into the Cummins Vehicle Mission Simulation analytical model, which is used to predict vehicle fuel consumption based on specific vehicle, load, route and load factor input data. Cummins Westport modeled the fuel consumption from comparable Cummins diesel engines using the same input criteria, in order to evaluate the fuel consumption of the 11.9-liter natural gas engine vs. the fuel economy target. This modeling was conducted for a variety of simulated Class 8 trucks routes and vehicle types, including highway tractors operating on interstate highways, tractor operation in a stop-and-go delivery duty cycle, and refuse collection truck operation in an urban environment. This analysis concluded that the fuel consumption of the 11.9-liter natural gas engine currently ranges from 13.7 percent to 15 percent lower than comparable Cummins diesel engines in the same duty cycles, and therefore meets the program target. Further evaluation and optimization of fuel economy took place throughout the remainder of the program.

Greenhouse Gas Emissions

Preliminary GHG emissions data indicated that the 11.9-liter engine would achieve the first phase of GHG emission standards based on the current design, as shown in Figure 7. Additional emissions testing throughout the duration of the engine development program was used to confirm that the launch design will achieve the first phase of GHG regulations.

Figure 7: 11.9 Liter Engine Preliminary GHG Data vs. Pending Federal Standards



Source: Cummins Westport, Inc.

Endurance Testing

Oil consumption testing initially revealed unacceptably high oil consumption at low idle speed when there was little or no torque demand upon the engine. While the oil consumption during loaded operation meets design targets, oil consumption during low speed / low load operation (when the throttle plate is closed, and the power cylinder is subject to vacuum conditions) did not meet target. Extensive investigation and analysis, conducted in conjunction with the suppliers for power cylinder and cylinder head components, revealed that the valve stem seals were the primary contributor to high oil consumption at idle. A revised valve stem seal design, along with a revised valve stem seal installation procedure, have been proven to greatly reduce oil consumption at idle conditions. Further development continued with the piston ring design and engine control strategy to investigate potential incremental improvements in idle oil consumption.

Summary

The Alpha engine design generated prior to the start of this Grant Agreement was implemented, and a number of engines were built and tested at JEP and deployed for testing in vehicles and in numerous engine development test cells. Preliminary emissions, fuel consumption, and GHG data show that the engine design achieves the design targets for the program. Additional development work continued throughout the program to further validate the engine design in preparation for emission certification and commercial launch.

CHAPTER 3: Design Optimization, Structure and Release

Design Optimization

The 11.9-liter natural gas engine is based on the 11.9-liter Cummins ISX diesel engine platform. The Beta 11.9-liter natural gas engine design retains the majority of the components from the diesel engine. The list of components that are common between the diesel and natural gas engine designs includes the engine block, exhaust manifold, exhaust gas recirculation (EGR) cooler, crankshaft, oil pan, flywheel, flywheel housing, fan drive pulleys, customer-selectable accessories such as starter motors and alternators, and numerous other items.

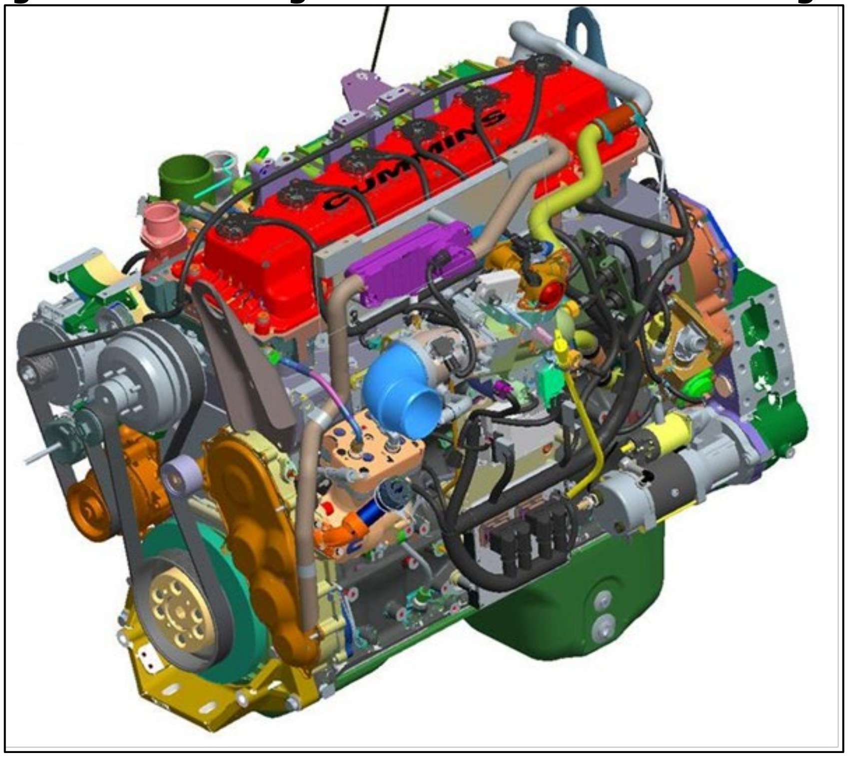
The components and sub-systems that are unique to the 11.9-liter natural gas engine include the following:

- Electronic control system
- Ignition system
- Power cylinder
- Cylinder head
- Fuel supply module
- Air handling system (i.e. turbo-charger and EGR piping)
- Engine brake
- Three-way catalyst

When designing the natural gas-specific components for each of these sub-systems, Cummins Westport's objective was to maintain the engine envelope as near as possible to the ISX11.9 diesel engine. Minimizing engine envelope differences versus the diesel engine will ease the vehicle integration burden for the truck OEMs, most of which have already engineered the Cummins ISX11.9 diesel engine into their truck models.

Figure 8 depicts the Beta design for the 11.9-liter natural gas engine. Figure 9 and Figure 10 show this Beta design overlaid on the design models for the Cummins ISX11.9 diesel engine. These figures illustrate the few areas where the natural gas engine envelope extends beyond the envelope of the diesel engine.

Figure 8: Beta Design for 11.9 Liter Natural Gas Engine



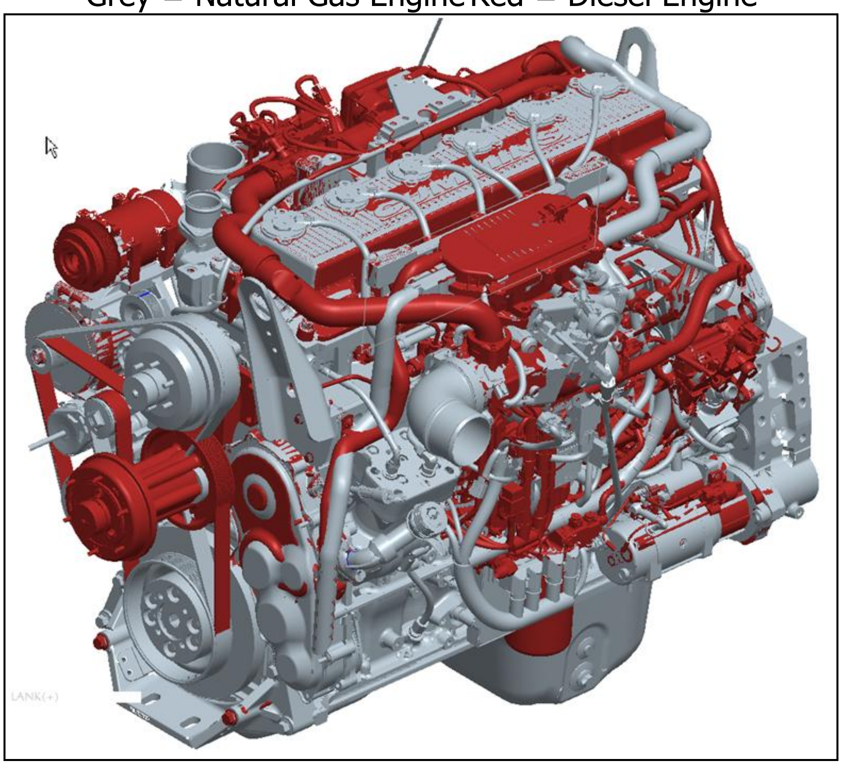
Source: Cummins Westport, Inc.

Alpha to Beta Engine Development

The following sections describe the design improvements from Alpha to Beta for the components and sub-systems that are unique to the 11.9-liter natural gas engine.

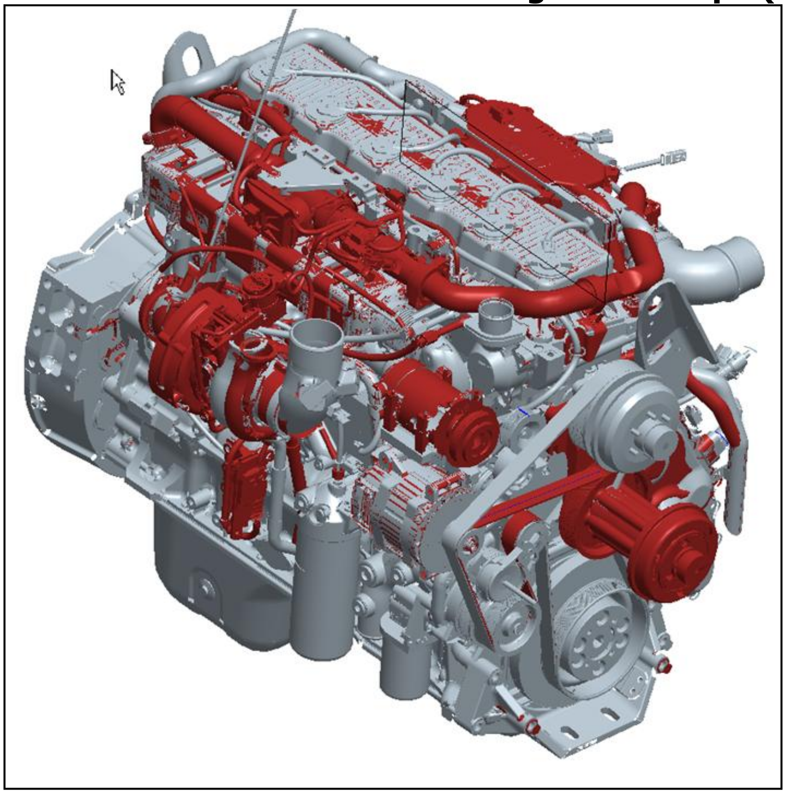
Figure 9: 11.9 Liter Natural Gas vs. Diesel Engine Envelope (Intake Side)

Grey = Natural Gas Engine Red = Diesel Engine



Source: Cummins Westport, Inc.

Figure 10: 11.9 Liter Natural Gas vs. Diesel Engine Envelope (Exhaust Side)

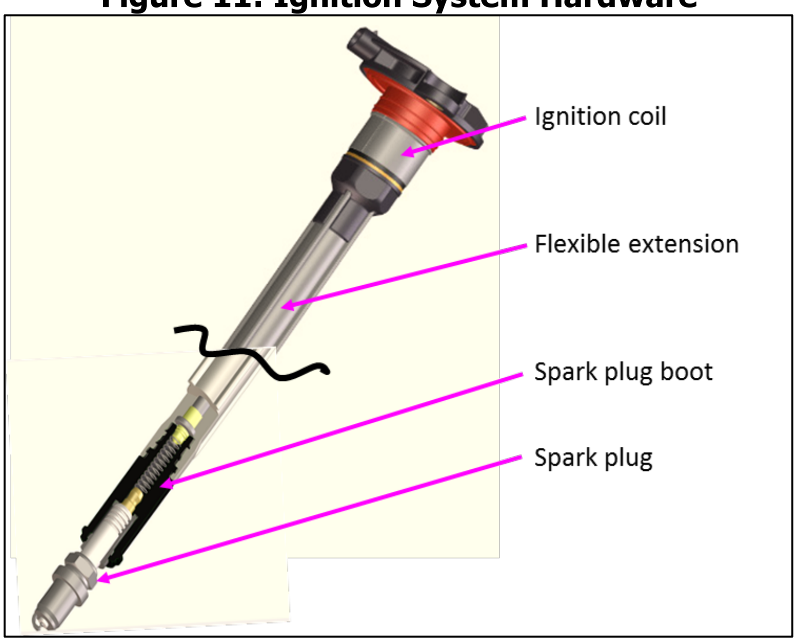


Source: Cummins Westport, Inc.

Spark Plug Boot

Testing and development of the Alpha design revealed the need to improve the durability of the spark plug boot, which connects the coil extension to the spark plug as shown in Figure 11. The Alpha spark plug boot was subject to tearing at the spark plug connection during spark plug replacements. This issue has been addressed with a design change that is included in the Beta design.

Figure 11: Ignition System Hardware



Source: Cummins Westport, Inc.

Power Cylinder

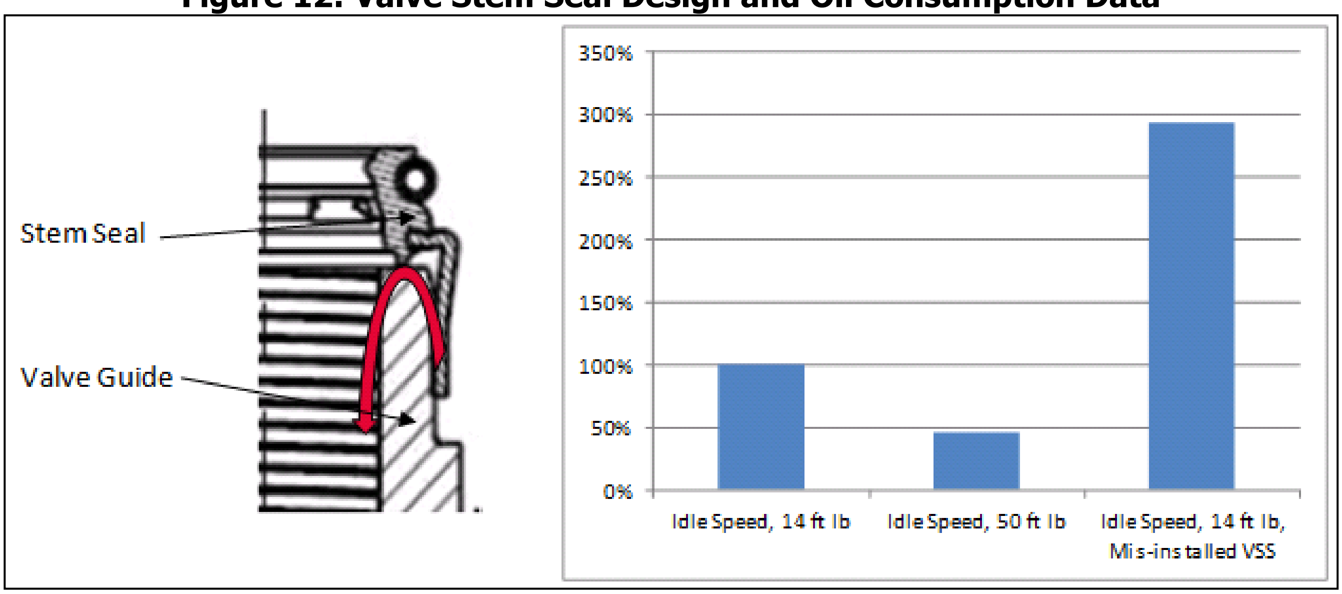
Testing of the Alpha design confirmed that the piston bowl geometry meets the design targets for combustion stability, engine performance, and emissions. Test data with instrumented engines to establish a temperature profile of the piston during combustion concluded that the piston design operates within the required temperature thresholds.

Oil consumption testing initially revealed that oil consumption was unacceptably high at low idle speed when there was little or no torque demand upon the engine. While the oil consumption during loaded operation meets design targets, oil consumption during low speed/ low load operation (when the throttle plate is closed, and the power cylinder is subject to vacuum conditions) did not meet target. Cummins Westport conducted extensive investigation and analysis of power cylinder and cylinder head components, and ultimately determined that no power cylinder design changes are required for the Beta design to achieve the program's idle oil consumption target. Further development continues with the piston ring design to investigate potential incremental improvements in idle oil consumption. Piston ring design changes, if any, were implemented for product launch.

Cylinder Head

The cylinder head for the program is based on the ISX11.9 diesel cylinder head but is machined to accommodate spark plugs. As explained above, Cummins Westport's analysis of the idle oil consumption issue included evaluation of the cylinder head. This investigation and analysis concluded that the valve stem seals were the primary contributor to high oil consumption at idle. The function of the stem seal is to seal the oil path between the valve stem and the valve guide. Compromising this connection allows oil to be sucked through the valve guide into the cylinder under vacuum conditions, which is a typical condition at idle speed. Figure 12 illustrates the impact of load (i.e. reduced vacuum) and poor installation. A revised valve stem seal design, along with a revised valve stem seal installation procedure, have been proven to greatly reduce oil consumption at idle conditions. The revised valve stem seal design and installation procedure were implemented in the program's Beta build later that year.

Figure 12: Valve Stem Seal Design and Oil Consumption Data



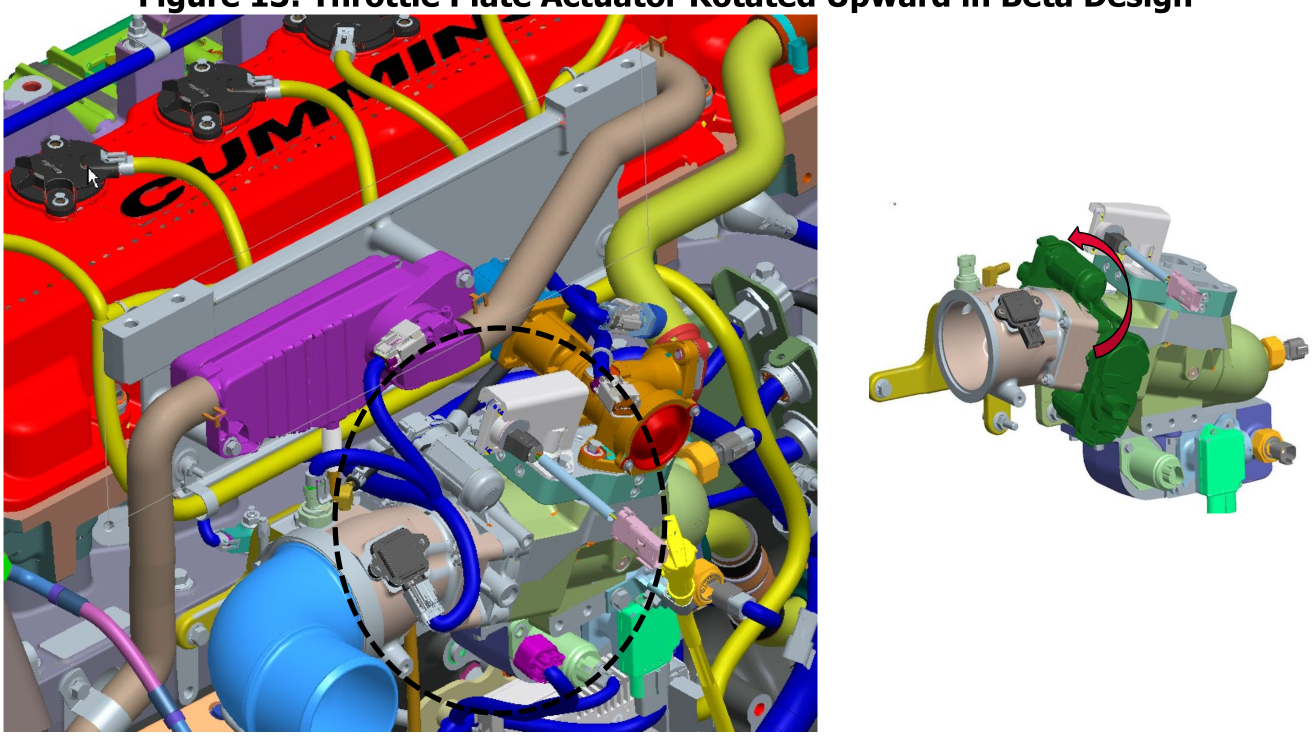
Source: Cummins Westport, Inc.

Fuel Supply Module

A design target established at the start of the engine development program was to enable low fuel inlet pressures, in order to mitigate the anticipated increased fuel pressure, drop through the off-engine fuel supply components on Class 8 trucks. Pressure drop from the fuel storage tanks on the vehicle to the engine inlet is particularly important for vehicles fueled with liquefied natural gas (LNG), which rely on a relatively small fuel pressure differential to drive the fuel supply to the engine. With the increased peak fuel flow rates for the 11.9-liter natural gas engine versus existing, lower powered natural gas engines for which conventional LNG fuel supply systems have been designed, Cummins Westport anticipated lower fuel supply pressures due to increased pressure loss from the LNG tanks to the engine inlet. During this phase of the development program, Cummins Westport determined that the 11.9-liter natural gas engine can achieve full rated power and torque with a minimum fuel supply pressure of 60 psig, which is 10 psi lower than the minimum pressure required for Cummins Westport's 8.9-liter ISL G engine. This satisfies Cummins Westport's design target for the engine; therefore, no further pressure loss optimization or internal orifice sizing is required for the fuel supply module.

Preliminary vehicle integration work with the truck manufacturers revealed a physical interference between an electrical connector in the Alpha fuel module and the truck frame in one of the target chassis. Cummins Westport addressed this issue in the Beta design by rotating the throttle plate actuator assembly, which required design changes to two major castings in the fuel module assembly. The throttle plate actuator and the affected area of the engine are shown in Figure 13.

Figure 13: Throttle Plate Actuator Rotated Upward in Beta Design



Source: Cummins Westport, Inc.

Air Handling System

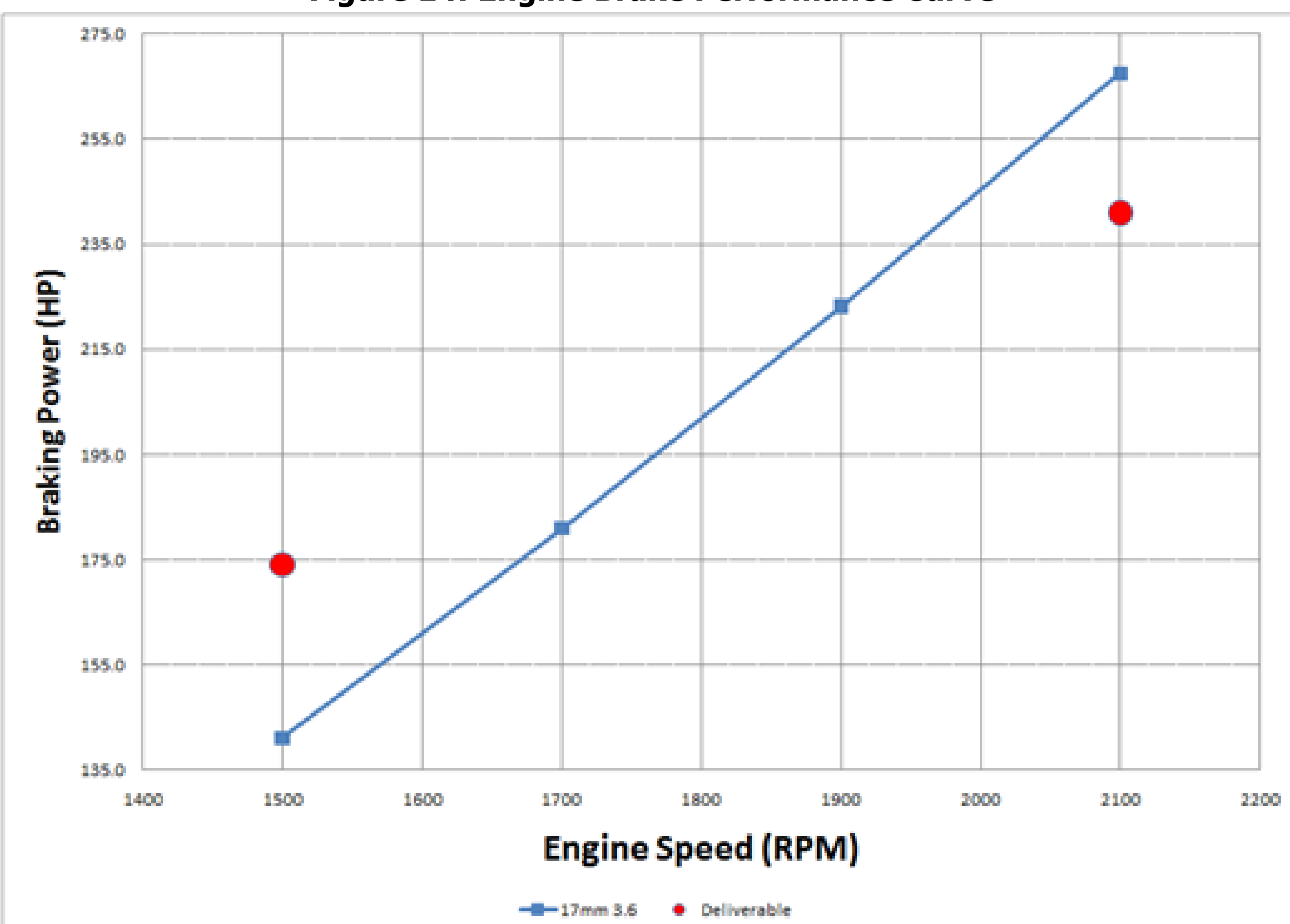
The air handling system includes the turbo-charger, and EGR components. The Beta design continues to use a waste-gated turbo-charger, which is less expensive than the variable geometry turbo-chargers used with modern diesel engines. The turbo-charger for the 11.9-liter natural gas engine is also smaller and lighter than the turbo-charger for the ISX11.9 diesel engine, due to the lower charge air flows required to maintain the stoichiometric conditions required for spark ignited combustion.

Alpha engine testing revealed a progressive decrease in the turbo-charger boost under certain test conditions, which was ultimately attributed to high temperature exposure of the waste-gate canister in the turbo-charger assembly. Extended high temperature exposure (due to the proximity to the exhaust manifold) affected the spring rate and therefore the pre-load force within the waste gate actuator. As a result, the waste gate began to open prematurely, with a resulting loss of charge air boost. A heat shield has been added to the Beta design to mitigate the high temperature exposure of the waste gate actuator.

Engine Brake

The compression release engine brake design has been finalized as part of the overall Beta design for the 11.9-liter natural gas engine. Validation testing of the brake design concluded that the engine brake performance, as shown in Figure 14, is above target at high engine speed but drops below target at 1500 rpm. This has been deemed acceptable and no further development will be undertaken. The engine brake design is unique to the natural gas engine, and braking performance is lower than for a diesel engine of similar displacement due to the lower compression ratio employed with spark ignition technology than with diesel engines.

Figure 14: Engine Brake Performance Curve



Source: Cummins Westport, Inc.

Three-Way Catalyst

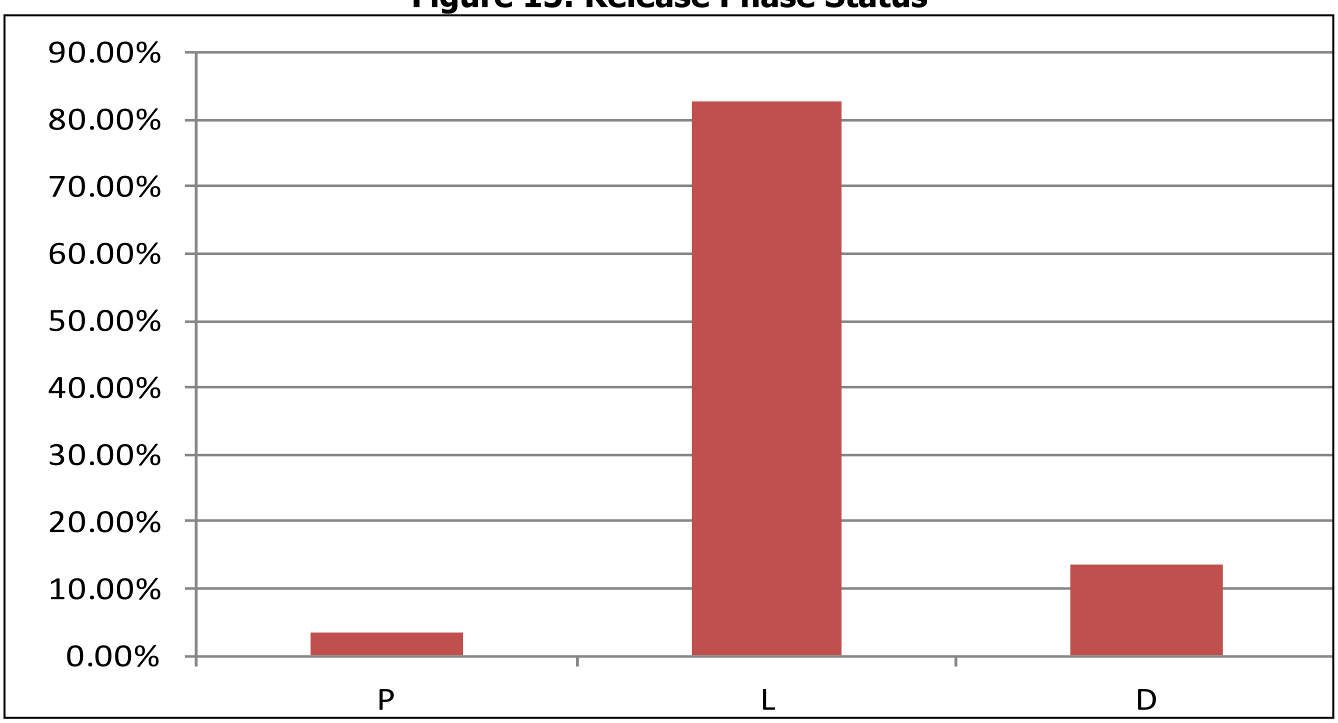
The 11.9-liter natural gas engine uses a three-way catalyst to treat NOx, CO and hydrocarbon (HC) emissions. Cummins Westport's 8.9-liter ISL G engine also uses a TWC for exhaust treatment. Early in the Alpha design Cummins Westport investigated the feasibility of using the existing ISL G catalyst with the 11.9-liter engine. However, analysis and measurements confirmed unacceptably high pressure drop across the ISL G catalyst with 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.

Through the Alpha engine installation numerous truck manufacturers have successfully installed the larger catalyst designed for the 11.9-liter natural gas engine. In parallel, engine development work has demonstrated that the Alpha catalyst formulation can achieve the emission targets for the program. Therefore, no changes to the catalyst substrate geometry or wash coat formulation are required for the Beta design, and no changes are required to the external mounting dimensions or envelope of the catalyst.

Structure and Release

Cummins Westport structures all engine components in the Cummins online database that is used for engine order entry and supply chain management. Each component is assigned a release phase code, which represent progressively increasing levels of design maturity. As component designs mature throughout the engine development program, each component progresses from Developmental "D" phase to Limited Production Intent "L" phase and ultimately to Production "P" phase. As shown in Figure 15, at this stage of product development, 14% of the new, natural gas-unique parts were released at "D" status. Prior to the Beta build later that year (2012), all hardware was released at "L" status. All parts eventually move to Production "P" status during the launch phase of the program.

Figure 15: Release Phase Status



Source: Cummins Westport, Inc.

Summary

The engine, sub-system, and component designs were finalized for the program's Beta build, based on extensive testing of the Alpha engines and components. All components were released in the Cummins specification database, and all designs were at an appropriate level of maturity to enable the Beta build late 2012.

CHAPTER 4: Design Verification and Validation

Extensive design verification activities that were conducted included engine, sub-system and component endurance tests totaling 7000 hrs. Depending upon test cell availability, multiple design verification tests were executed in parallel for the duration of this phase of product development.

Oil Consumption Endurance Testing

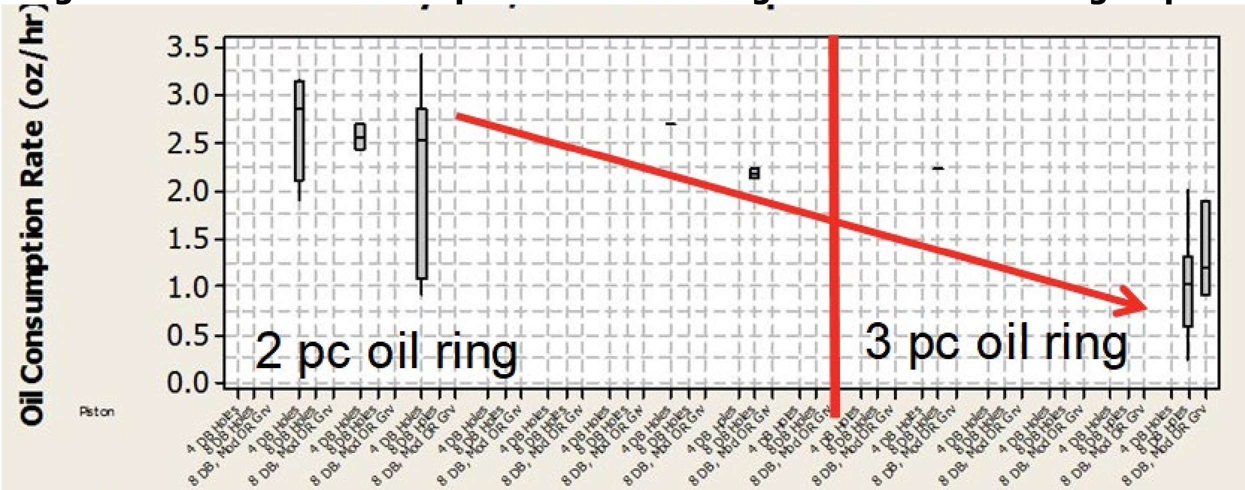
Based upon engine tests, high oil consumption at idle conditions was of concern. Significant variation was seen with oil consumption. Values as high as 15 ounces/hour were measured, which is extremely high. An investigation was undertaken to isolate the possible root cause(s). It was concluded that some of the variability was linked to hardware and installation issues with critical oil control parts. However, fundamental piston ring dynamics at idle speed and very low load conditions was identified as the major contributor to the higher-than-target oil consumption. An extensive investigation resulted in a re-design of the oil ring to reduce the oil consumption to an acceptable level by using a three-piece oil ring design (Figure 16).

Figure 16: Three-Piece Oil Ring

Source: Cummins Westport, Inc.

This design had proven effective in controlling oil consumption in Cummins Westport's other engines for medium-duty and light-heavy duty vehicle applications. Cummins has not historically used three-piece oil rings in large bore, heavy-heavy duty engines, which is the reason that the 11.9-liter gas engine development program originally planned to use two-piece oil rings. Due to the significant reduction in oil consumption at idle with this design as shown in Figure 17, the three-piece oil ring was pursued for production and installed in the endurance validation engines to demonstrate long term durability in heavy-heavy duty applications.

Figure 17: Idle Oil Consumption Data Showing Three-Piece Oil Ring Impact



Source: Cummins Westport, Inc.

An oil emulsion was also found in the engine overhead area that, in some cases, resulted in component corrosion. An investigation revealed that the emulsion was a water and oil mixture that can be formed when water vapor in the (piston) blow-by gas condenses on cold surfaces and is held in the oil by the dispersants used in the lubricating oil additive package (Figure 18). Heating the overhead area, and using oil without the dispersants, were found to be effective in controlling the amount of emulsion formation. The oil recommended for use with the engine (with much less dispersants) is consistent with oil used in all other Cummins Westport engines. Additionally, special coatings were added to critical overhead components to improve robustness against moisture related corrosion. Based on test data, it was also decided to add thermal insulation to the valve cover to retain heat in the overhead, particularly under cold and intermittent operation. Figure 19 is an illustration of that insulation design used for validation in development engines.

Figure 18: Picture Showing Emulsion inside Valve Cover

Source: Cummins Westport, Inc.

Figure 19: Valve Cover Insulation Design

Source: Cummins Westport, Inc.

Figure 20: Production Part: Insulated Valve Cover Assembly

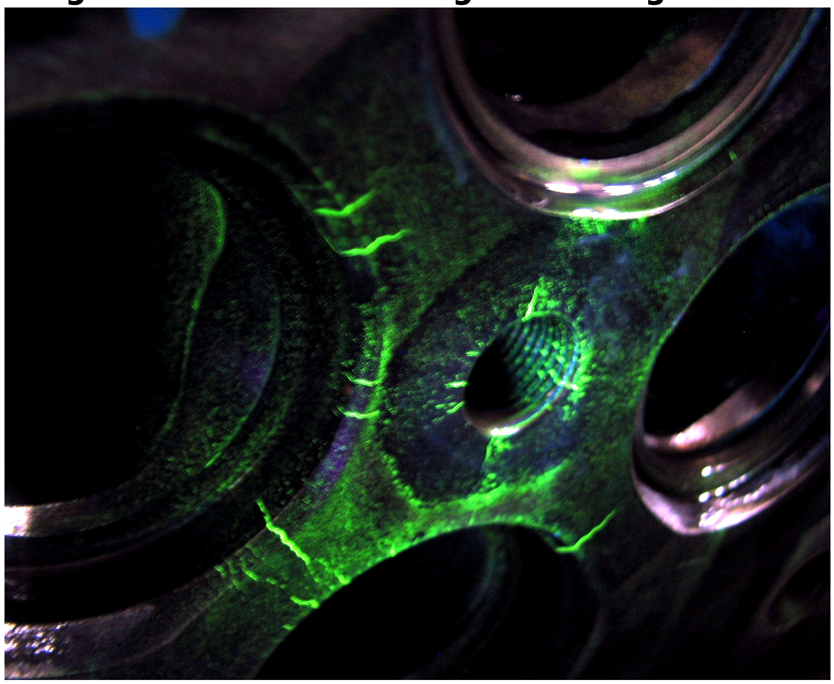
Source: Cummins Westport, Inc.

The insulated valve cover successfully met design validation and manufacturing requirements. Figure 20 below shows the insulated valve cover as delivered from production tooling from the supplier. The insulation is sent pre-assembled to the cover and therefore eliminates assembly concerns that the Jamestown Engine Plant identified with a prototype valve cover insulation design. The insulated valve cover is part of a series of steps to improve over-head corrosion mitigation. The over-head now contains permanently coated rocker levers, spark plug adapter tubes, and compression brake assemblies. Additionally, the production application documentation requires the use of engine oil formulated for natural gas engines. Finally, the production manufacturing process now requires the use of heated water during the end of production test, to avoid condensation in the overhead assembly.

Cylinder Head

The "Production" validation endurance test for the cylinder head revealed valve bridge cracks (Figure 21) at the midpoint inspection (750 hours). The test was run at an outside facility where natural gas methane number (MN) is sometimes relatively low relative to recommended minimum. An examination of the cylinder head for the test engine showed evidence of excessive temperature and deposits on the coolant passage side. An investigation was undertaken to identify root cause of the issue and alternative designs to alleviate the temperature concern.

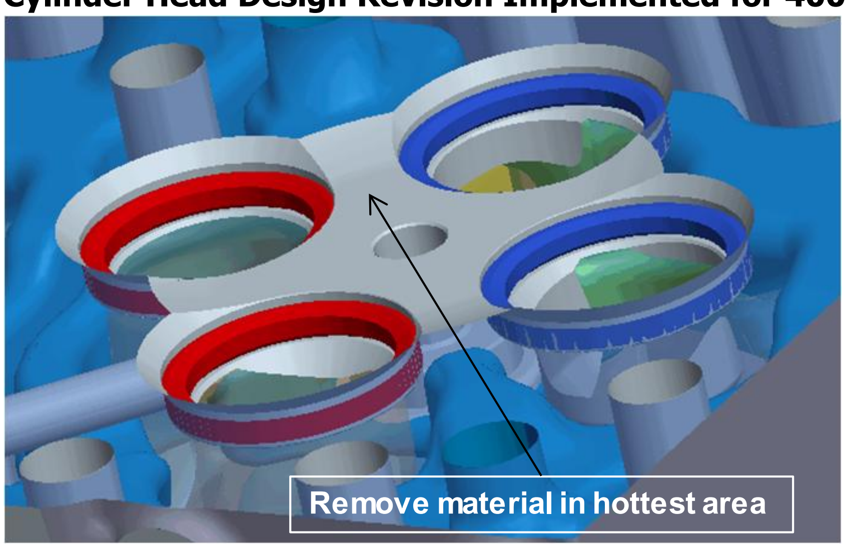
Figure 21: Picture Showing Valve Bridge Cracks



Source: Cummins Westport, Inc

The valve bridge cracking issue was linked to combustion surface temperature in the vicinity of the valve bridges. Analysis indicated that the temperature could be reduced by thinning the head deck in the critical regions extending through the valve bridge. For reference, Figure 22 below shows the analysis-led design solution necessary to reduce temperatures on the peak rating (400 hp).

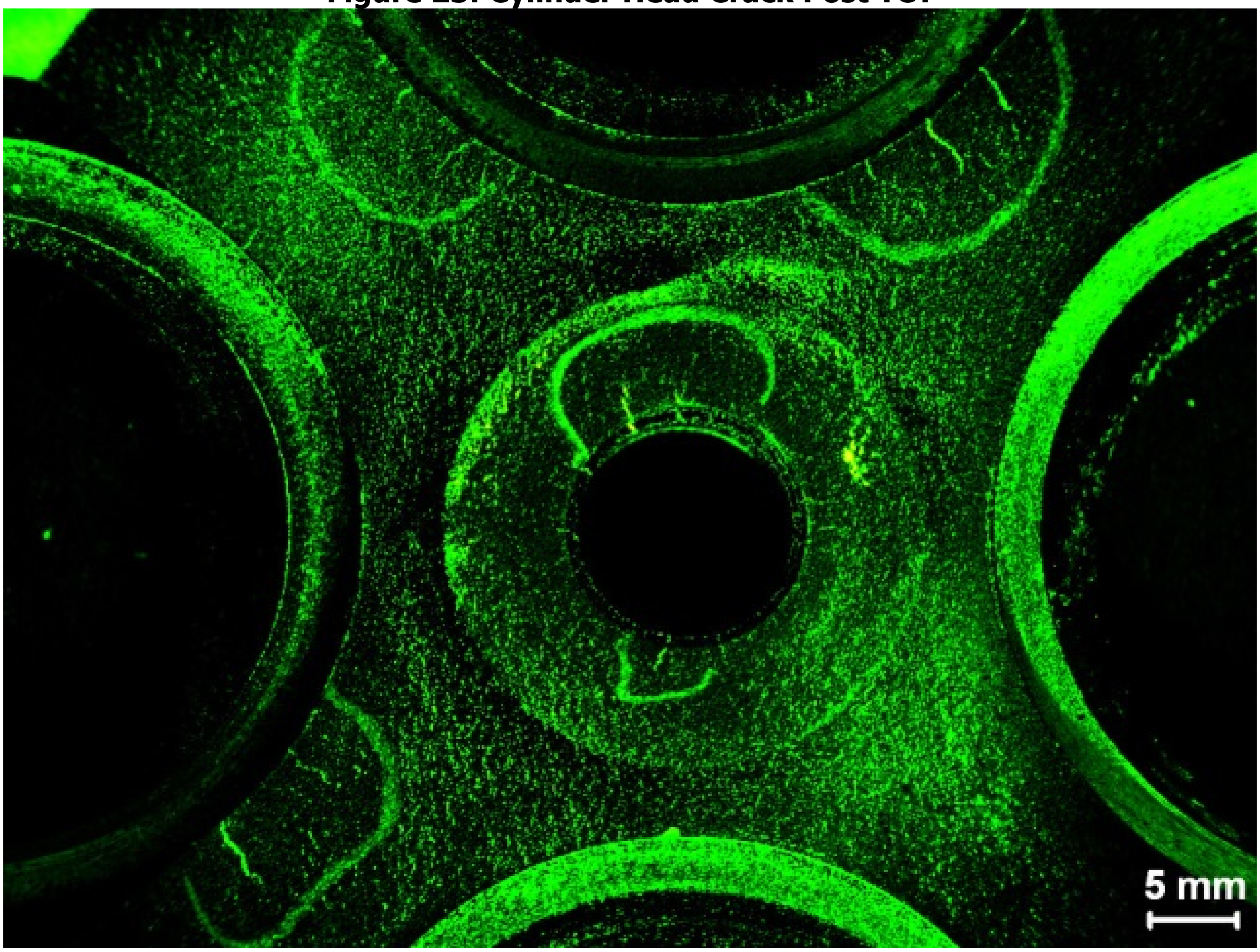
Figure 22: Cylinder Head Design Revision Implemented for 400 HP Rating



Source: Cummins Westport, Inc

Following redesign, CWI completed the required Thermal Cycle Test as dictated by Cummins Engineering Standard Work (ESW). Typical results of the Thermal Cycle Test are shown in Figure 23, where the combustion face is painted with MagnaGlo and illuminated with a black light. As can be seen in Figure 23, cracking features were still present at the completion of the Thermal Cycle Test, resulting in a marginal, non-passing score of the ESW (note, the semi-circular loops shown surrounding the small cracks on the combustion face are pencil marks made to highlight the crack regions). The ISX12 G technical review committee recognized the non-passing score but granted the program permission to proceed to production based upon a parenting assessment made to similar cracks witnessed on a different production product with acceptably low reliability risk.

Figure 23: Cylinder Head Crack Post TCT

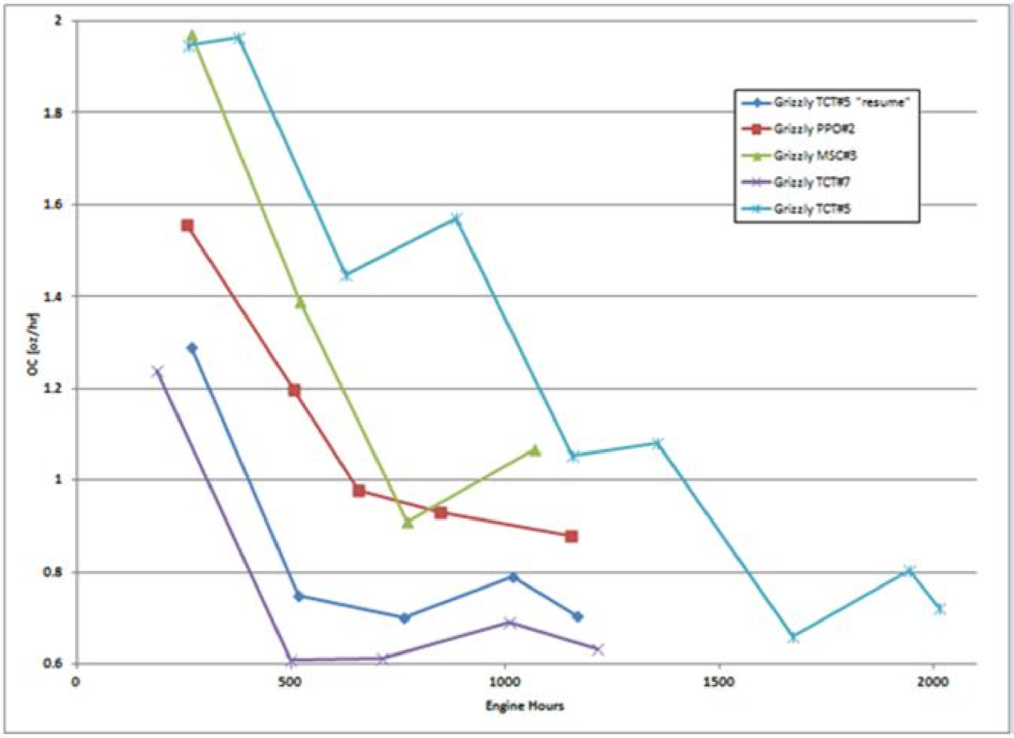


Source: Cummins Westport, Inc

Oil Consumption- ESW Abuse Testing

The evaluation of oil consumption measured over the duration of the various ESW long hour test cycles was completed. It can be seen from Figure 24 below that in all engines the oil consumption continued to improve markedly over the duration of each test. While acceptable oil consumption has been achieved on all "abuse tests", design modifications were developed for post-launch implementation to further reduce engine to engine variation, reduce run-in time, and improve long term durability of the power cylinder.

Figure 24: Oil Consumption Results of ESW Abuse Tests

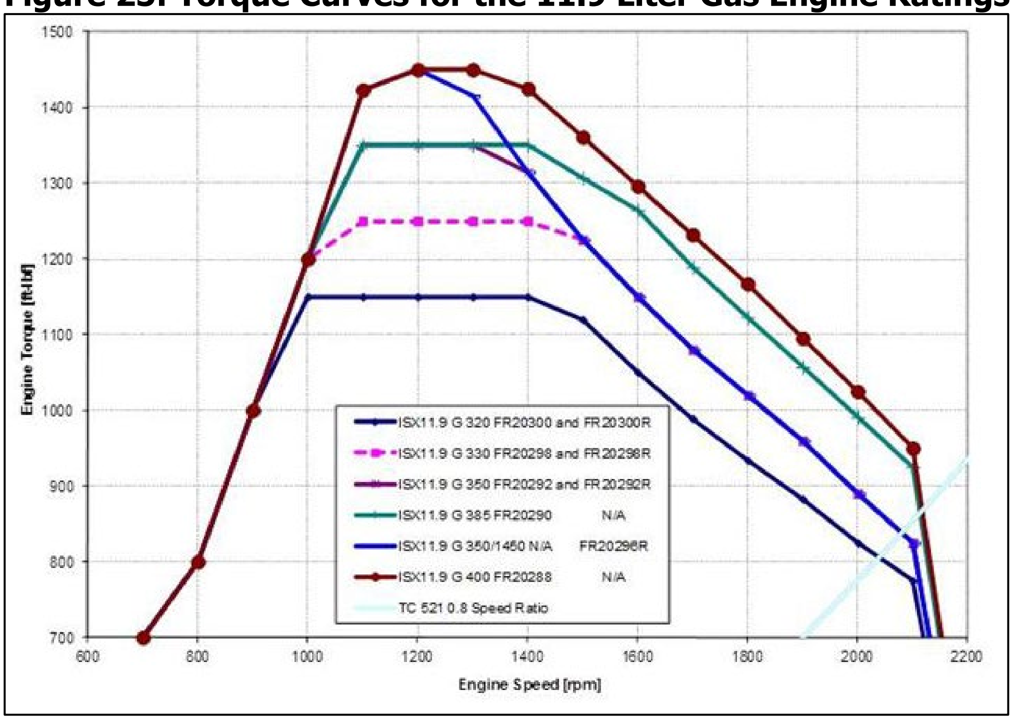


Source: Cummins Westport, Inc

Engine Calibrations/Ratings

Calibrations have been developed for all the planned ratings. Six different ratings were developed (Figure 25) to be offered to match the market and customer requirements for the intended applications. A peak torque of 1450 lb.-ft will be offered with the maximum power output of 400 hp.

Figure 25: Torque Curves for the 11.9 Liter Gas Engine Ratings

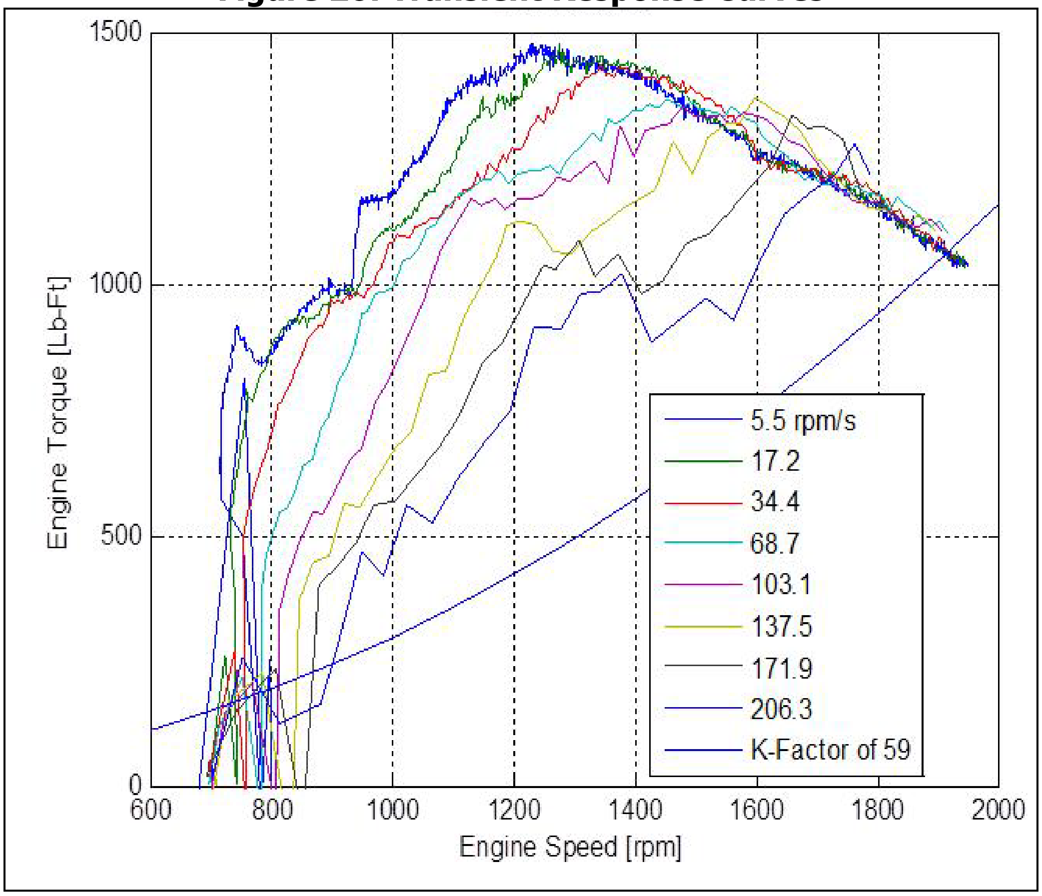


Source: Cummins Westport, Inc

Engine Transient Response

The transient response of the engine was improved by further development of the control system. As shown in Figure 26, the "lug up" response to load application slows as the rate of speed demand increases (rpm/s). However, the engine performance is sufficient to meet the target requirement of reaching full torque at lower speed than the match speed of the representative torque convertor (indicated in Figure 26 as "K-factor of 59" where the K-factor is a metric of the resistance that a particular torque curve design imposes on an engine). Maintaining transient response rates above the relevant torque convertor load absorption curve ensures acceptable vehicle transient response for vehicles equipped with automatic transmissions or manual transmissions.

Figure 26: Transient Response Curves

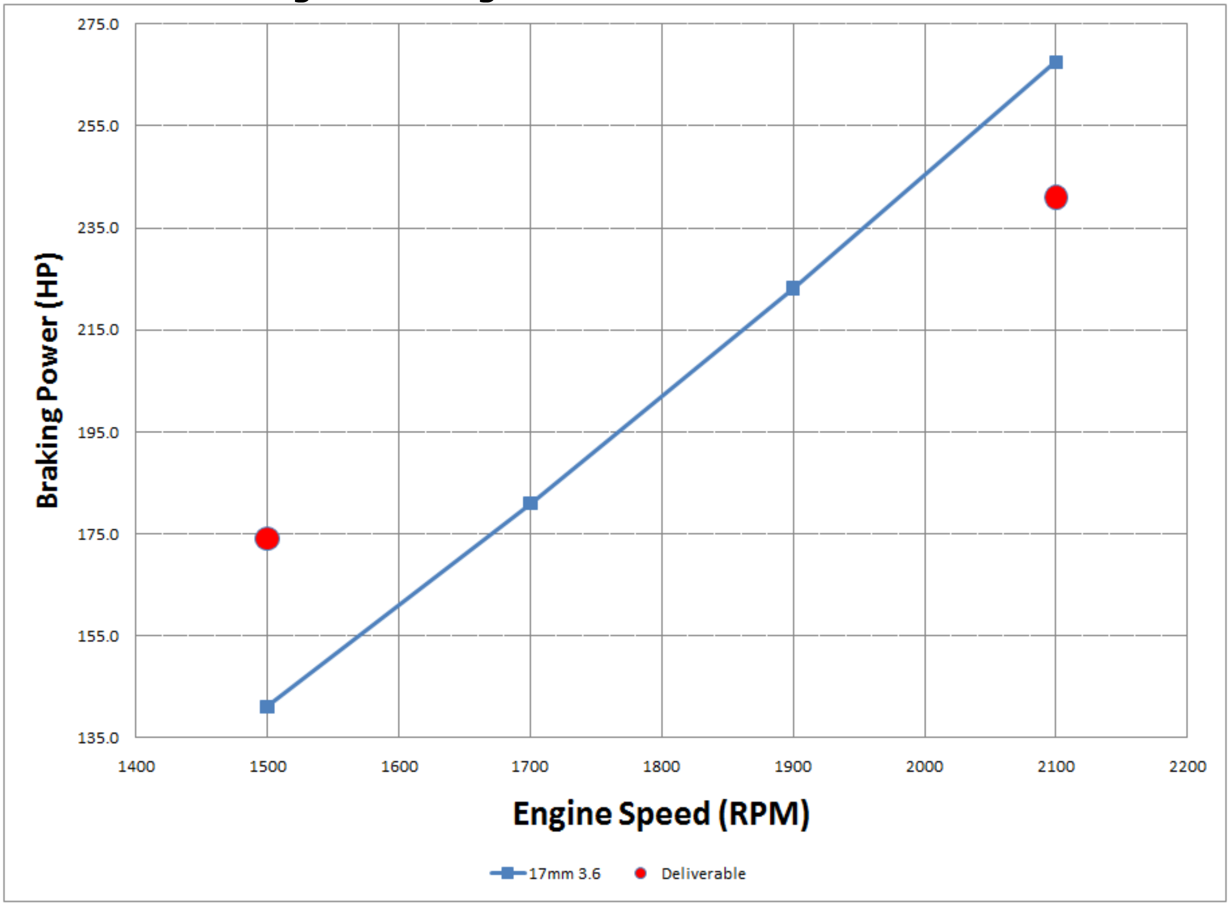


Source: Cummins Westport, Inc

Engine Brake

The compression release engine brake design was finalized, and the validation test was completed. The performance shown in Figure 27 is above target at high engine speed but drops below target at 1500 rpm. This was deemed acceptable and no further development was undertaken. The engine brake design employed is unique and a first for the spark-ignited natural gas engine industry. The braking performance is lower than that for a diesel engine of similar displacement due to the lower compression ratio employed with the SI-EGR technology than with diesel engines. The lower compression ratio results in lower motoring cylinder pressure and hence the energy absorbed by the compression process that can be utilized for vehicle braking is reduced. Field testing has demonstrated that engine braking performance is sufficient.

Figure 27: Engine Brake Performance Curve



Source: Cummins Westport, Inc

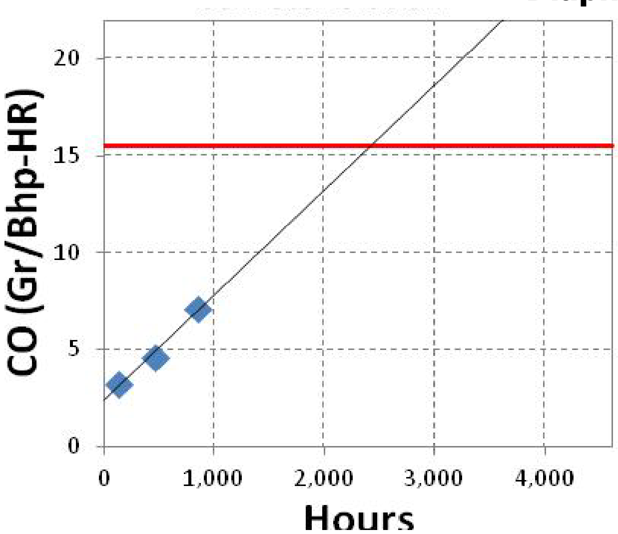
Engine Surge

A surge issue was reported from some field trucks during mid-speed operation. The problem was duplicated on CWI's Engineering truck and two sources were identified: transient boost pressure and coupled engine fueling issue, and turbocharger surge. Improvements were made to the control system to resolve the issue with transient behavior of boost and fueling resulting in a considerable reduction in the surge. However, the phenomenon of turbocharger surge under sudden throttle closing maneuvers was not resolved. This can result in noise associated with some of these events, but there is no impact on engine performance. A boost relief system would reduce the audible surge at throttle closing events. It is being considered for development and implementation in the future.

Emissions Deterioration Factor (DF)

Several obstacles were encountered when conducting the emissions deterioration factor (DF) test. The test includes a 1615-hour endurance cycle that simulates and accelerates the field duty cycle. Emissions data is gathered at several intervals during the test to quantify the extent of emissions deterioration compared to EPA-prescribed useful engine life (435,000 miles for heavy-heavy duty emission certification). The resulting deterioration factors for the regulated emissions are used to determine the certification level of the engine for EPA and CARB approval. The first DF test was halted near the 800-hour test point due to unacceptably high engine-out CO emissions. The root cause was confirmed to be a result of deterioration of the turbocharger waste gate actuator, which controls the boost pressure and therefore the air flow to the engine. As seen in the picture in Figure 28, damage to the sealing surface of the waste gate actuator diaphragm is evident. This resulted in control system instability under some operating conditions which produced increased CO due to rich operation. Replacing the turbocharger corrected the issue and the CO emissions returned to normal levels. However, EPA requirements for DF testing dictated that there was no option to continue the test after this hardware change; therefore, the DF test was aborted, and a new engine was used for the second DF test.

Figure 28: CO Trend from Emission Deterioration Test and Waste gate Actuator Diaphragm



Source: Cummins Westport, Inc

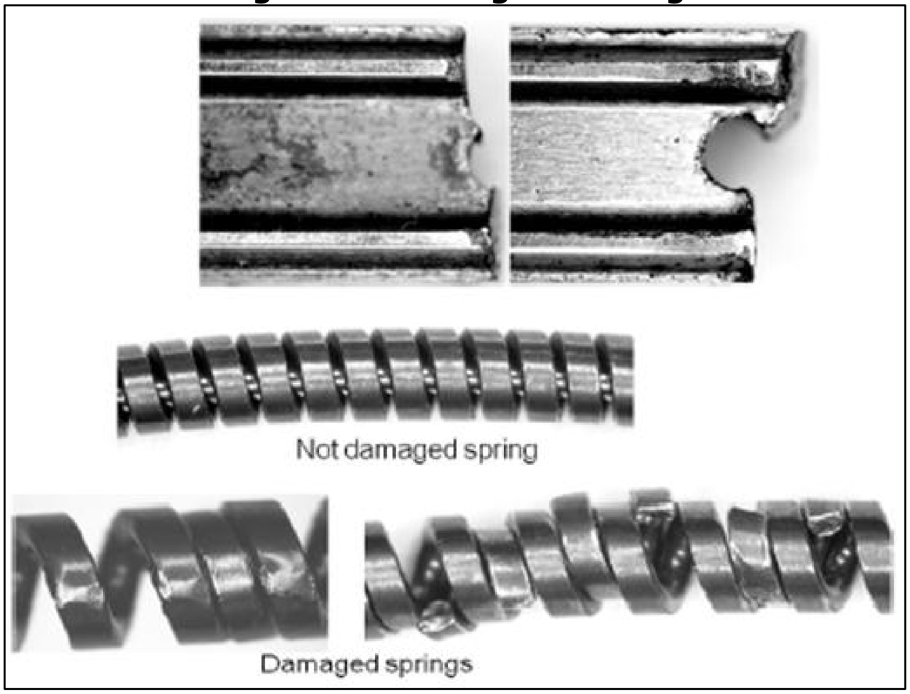
The second DF engine failed at the 1200-hour test point. As seen in Table 1, the particulate matter (PM) emissions were extremely high, which was expected due to the sharp increase in oil consumption in the last 200 hours of operation. Engine tear-down and inspection revealed broken oil control rings in three cylinders, which fully explains the high PM and oil consumption (Figure 29). In addition, excessive deposits were found on the piston and cylinder head surfaces (Figure 30) as a result of the very high oil consumption.

Table 1: Regulated Emissions from Emission Deterioration Test

Engine_Hrs	Nox	NMHC	CO	PM
120	0.135	0.037	2.036	0.009
550	0.130	0.042	2.103	0.013
800	0.186	0.043	2.557	0.013
810	0.140	0.051	2.658	0.010
1200	0.190	0.08	2.36	0.017

Source: Cummins Westport, Inc

Figure 29: Damaged Oil Ring



Source: Cummins Westport, Inc

Figure 30: Deposits on Pistons and Valves

Source: Cummins Westport, Inc

The third and final DF test was successfully completed, and the data is shown in Table 2. Due to an upward swing in NOx at the 1600 hours data point, the actual extrapolated DF for NOx was determined to be significantly larger at 1.8. Table 3 below shows the actual NOx DF results filed for certification on the ISX12 G1. The table also shows the final multiplicative DF values for NMHC, CO and PM. The DF factor for CO is typical for spark-ignited engines and is consistent with Cummins Westport's expectations prior to DF testing.

Table 2: Final Emissions DF Test Results

	ENG Hrs	NOx_CHET	NMHC_CHET	CO_CHET	PM_CHET
		Gr/Bhp-Hr	Gr/Bhp-Hr	Gr/Bhp-Hr	Gr/Bhp-Hr
	120	0.1093	0.0701	2.0538	0.004218
	448	0.0679	0.0449	2.4588	0.00367
	808	0.0887	0.0465	2.6114	0.00236
	820	0.1046	0.0359	2.3488	0.00166
	1211	0.0998	0.0412	2.9411	0.00493
	1615	0.1230	0.0364	3.8406	0.00233
0 hour	120	0.086799288	0.058984035	1.925268038	0.003646206
end of life	4614	0.162689311	-0.023499479	6.838279704	0.000812613
DF		**1.874**	**1.000**	**3.552**	**1.000**

Source: Cummins Westport, Inc

While the increases in NOx and CO emissions were believed to be attributable to variation in the emission control system, and were higher than anticipated, a decision was made to accept the DF as extrapolated and to recalibrate the engine control surfaces for reduced NOx when compared to the production-intent engine calibration that CWI had developed prior to completing the DF test. No further reduction in CO was necessary to maintain compliance of this criteria pollutant. Recalibration was completed, and the final emissions certification test results submitted to EPA and CARB are shown below in Table 3.

Table 3: Emissions Certification Test Results

Cycle	NOx	NMHC	CO	PM
EPA_Limit	0.2	0.14	15.5	0.01
CHET 1	0.078	0.033	2.374	0.003
CHET 2	0.074	0.031	2.45	0.003
RMCSET 1	0.011	0.009	1.645	0.001
RMCSET 2	0.014	0.011	1.801	0.001

Source: Cummins Westport, Inc

Table 4 below shows the CO2 and CH4 measured over the certification cycles. The column marked CO2_Eq represents the equivalent CO2 of this engine when accounting for the emissions of CH4 using the EPA-prescribed Global Warming Potential factor (25) for methane.

[1] Cummins Westport decided to market the 11.9 liter as the ISX12 G.

The CO2-equivalent values shown in Table 4 are below the applicable CO2 standards for heavy-heavy duty engines in the EPA Phase 1 GHG regulations.

Table 4: GHG Certification Test Results

Cycle	CO2	CH4	CO2_Eq
CHET 1	509.46	1.039	535.4
CHET 2	511.36	1.039	537.3
RMCSET 1	430.57	1.158	459.5
RMCSET 2	430.74	1.193	460.6

Source: Cummins Westport, Inc

Cold start testing was also completed in the Beta phase of development. An Engineering truck was used at a cold test facility at Baudette, MN to test cold start capability (Figure 31). At the onset of cold start testing, issues were encountered with the vehicle's on-board CNG fuel system and the ignition system. These issues were resolved, and the engine was successfully started (unaided) at 10F. The engine was also demonstrated to start at -20F with a block heater, thus meeting Cummins Westport's cold start operating recommendations.

Figure 31: Engineering Truck in Cold Test Room

Source: Cummins Westport, Inc

Valve Lash

An evaluation of the durability of the power cylinder and valve train identified that hot running valve lash was insufficient. Evaluation of cam lobes at the completion of the abuse tests showed markings on the base circle indicative of valve train loading when the cam should otherwise be unloaded. An increase in cold lash setting of 0.004 inches for both the intake and exhaust valves was evaluated under high speed mechanical abuse tests to monitor valve seat wear. Following ISX12 G commercial launch, CWI intends to continue optimizing valve lash settings and to conduct additional testing to ensure emissions and performance transparency. Upon successful completion of these tests, CWI may increase the production cold lash settings.

Summary

The ISX12 G engine design has been fully validated in accordance with a comprehensive battery of engineering verification and validation tests conducted by Cummins Westport. The ISX12 G design verification and validation results have been reviewed by Cummins and Cummins Westport technical experts. The engine design has been released into production at the Jamestown Engine Plant in Jamestown, New York, with ISX12 G Limited Production builds occurring from April through July 2013, and Full Production commencing in August 2013.

CHAPTER 5: Field Testing

Field Test Objectives

The primary objective of the field test and demonstration program is to obtain engine operating data from a variety of operational environments prior to commercial release of the 11.9-liter natural gas engine (the ISX12 G). Early in the ISX12 G development program, in addition to extensive laboratory-based engine, sub-system and component testing, CWI established a requirement to accumulate at least 10 warranty periods of on-road operational experience, which corresponds to approximately 1 million vehicle miles. In addition to a cumulative mileage goal, CWI established a target of four trucks exceeding 100,000 miles each, in order to assess potential engine issues in high-mileage applications.

A secondary objective is to provide key customers with the opportunity to operate the engine prior to commercial availability, in order to demonstrate the performance capabilities of the engine.

To satisfy these objectives, CWI worked with various OEM truck manufacturers to make field test trucks available to end users. Twelve new Class 8 trucks (nine tractors and three refuse collection trucks) were built during 2011, using engines from the ISX12 G Alpha build. The majority of these trucks were built on the production line at the OEMs' truck manufacturing facilities. In addition to these 12 new, OEM-built, fleet-operated field test trucks, CWI planned to install ISX12 G Alpha engines in existing Class 8 tractors purchased by Cummins. These re-powered tractors would serve as engineering test and development vehicles while also contributing vehicle miles to the ISX12 G field test program.

Field Test Issues

While the OEM truck build was successful and the OEMs were actively engaged in the program, significant delays were encountered placing these trucks in service, largely due to delays in the supply chain of non-engine components (e.g. chassis components, refuse packer bodies). These non-engine supply issues caused delays to the mileage accumulation rate of the field test program throughout 2011 and early 2012. To accelerate the rate of field test mileage accumulation and compensate for the late field test start, CWI enacted a recovery plan which included a repower program for several trucks using additional engines from the program's Alpha build. The Alpha repower program included six existing, customer-owned tractors plus adding another tractor to Cummins Westport's Engineering Department truck fleet. All 21 Alpha-powered field test vehicles were deployed and in field test operation by late 2011, which was considerably later than originally planned.

In addition to deploying more Alpha-powered field test vehicles, Cummins Westport elected to deploy four more field test trucks powered with Beta engines to further accelerate field test mileage accumulation. Rather than relying on OEMs to build new trucks after the Beta engine build, CWI worked with truck fleets and a 3rd-party natural gas fuel system installer to have the CNG or LNG fuel systems installed on existing trucks prior to engine availability. The Beta-powered ISX12 G field test trucks were deployed in mid-2012 with fleets in Nebraska and Oklahoma. After deploying the Beta-powered field test trucks, the total ISX12 G field test fleet consisted of 25 vehicles (22 tractors and 3 refuse collection trucks). Table 5 specifies the field test fleet by state, vehicle type, and engine vintage (Alpha vs. Beta).

During the field test program, field test customers operated the trucks in their regular revenue service. In the event of product issues that impacted or prevented normal vehicle operation, CWI's Service Engineering group and the local Cummins distributors provided parts and service support to the field test customers. All reported product issues were recorded by CWI Service Engineering, and each issue's progress to resolution was tracked following a formalized Cummins reporting and issue management process. CWI periodically installed upgraded engine hardware and/or electronic calibrations on the field test engines as product improvements were developed throughout the program.

In addition to identifying and resolving engine and component issues, CWI relied on the field test fleet to follow the appropriate maintenance intervals, including the scheduled timing for spark plug, filter and lubricating oil replacement. Prior to placing each field test vehicle in operation, CWI's Service Engineering group met with the field test fleet's operations department to specify the required maintenance intervals and to coordinate regular reports from the fleets regarding fuel consumption, oil consumption (if any), and driver feedback. At these meetings CWI also specified the mechanism for the fleets to return used spark plugs, filters and oil samples to CWI for analysis.

With the expanded field test fleet size, the rate of mileage accumulation accelerated sufficiently to meet and exceed the original cumulative mileage goal of the project. CWI commenced limited commercial production of the ISX12 G engine in April 2013, at which time the field test fleet had accumulated 1.6 million miles, thus surpassing the original 1-million-mile goal. Four trucks had each surpassed 100,000 miles of field test experience, with the highest mileage vehicle achieving approximately 170,000 miles by April 2013.

Following commercial release of the ISX12 G engine, CWI started de-commissioning a portion of the field test fleet. Two units operating in Arkansas were removed from service first, and the three refuse collection truck engines will be removed from service during late Q2 or early Q3, 2013. The remaining ISX12 G field test engines will be removed from service through the end of 2013. By the conclusion of the ISX12 G field test program, the cumulative mileage is expected to exceed 2 million miles. Upon removal of the Alpha and Beta-powered field test engines, CWI expects to install new, emission-certified, production-built ISX12 G engines in the vehicles, such that the field test fleets will continue operating ISX12 G-powered vehicles.

Table 5: ISX12 G Field Test Locations by State

State	ISX12 G Field Test Quantity	Type of Operation
California	7	4 x Tractor-trailer, Alpha, OEM installed 1 x Tractor-trailer, Alpha, repower 1 x Tractor-trailer, Beta, repower 1 x Refuse collection, Alpha, OEM installed
Arizona	4	2 x Tractor-trailer, Alpha repowers 1 x Tractor-trailer, Alpha, OEM installed 1 x Refuse collection, Alpha, OEM installed
Indiana	4	1 x Tractor-trailer, Alpha, OEM installed 3 x Tractor-trailer, Alpha repowers
Texas	2	1 x Tractor-trailer, Alpha, OEM installed 1 x Tractor-trailer, Alpha, repower
Arkansas	2	Tractor-trailer, Alpha repowers
Nebraska	2	Tractor-trailer, Beta repowers
New Jersey	1	Refuse collection, Alpha, OEM installed
Wisconsin	1	Tractor-trailer, Alpha, OEM installed
Oklahoma	1	Tractor-trailer, Beta repower
Various	1	Tractor-trailer, Alpha, OEM installed
Total	**25**	**21 x Alpha, 4 x Beta**

Summary

The ISX12 G field test fleet consisted of 22 Class 8 on-highway tractors and 3 Class 8 refuse collection trucks. The field test size enabled the project to significantly exceed the proposed (project) mileage accumulation goal and provided valuable operational experience to identify product issues, validate design solutions, and demonstrate the performance capabilities of the ISX12 G engine for prospective customers in preparation for ISX12 G product launch. The field test fleet also yielded important data to quantify the required scheduled maintenance intervals for spark plugs, fuel filters, and lubricating oil. The ISX12 G field test engines will be removed from service and replaced with new, factory-built, emission-certified ISX12 G engines through the end of 2013.

CHAPTER 6: Design Finalization, Structure and Release

The ISX12 G natural gas engine is based on the Cummins ISX12 diesel engine platform. Throughout Task 2, the ISX12 G engine design has evolved to incorporate fit and performance feedback from OEMs, CWI's validation testing, and the ISX12 G field test fleet. The engine design has been finalized in preparation for the start of commercial production of the ISX12 G engine at the Cummins Jamestown Engine Plant in Jamestown, NY. ISX12 G production began in April 2013, offering ratings from 320 hp and 1150 lb.-ft to 350 hp and 1450 lb.-ft. The start of commercial availability is referred to as "Limited Production" whereby monthly production volumes are constrained to approximately 120 engines per month in order to validate all supply chain, manufacturing, OEM installation, and product support functions before accelerating the rate of engine production. Limited Production is scheduled to occur from April through July 2013. Beginning in August 2013, CWI anticipates release of additional ratings up to 400 hp and 1450 lb.-ft and anticipates progressively increasing monthly production volumes throughout 2013.

Design Finalization

The ISX12 G engine design retains the majority of the components from the ISX12 diesel engine. The list of components that are common between the diesel and natural gas engine designs includes the engine block, exhaust manifold, and EGR cooler, crankshaft, oil pan, flywheel, flywheel housing, fan drive pulleys, customer-selectable accessories such as starter motors and alternators, and numerous other items.

The components and sub-systems that are unique to the ISX12 G engine include the following:

- Electronic control system
- Ignition system
- Power cylinder
- Cylinder head
- Fuel supply module
- Air handling system (i.e. turbo-charger and EGR piping)
- Engine brake
- Three-way catalyst

The following sections describe the final designs for these ISX12 G components and sub-systems.

Electronic Control System

The electronic control system consists of the following components:

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

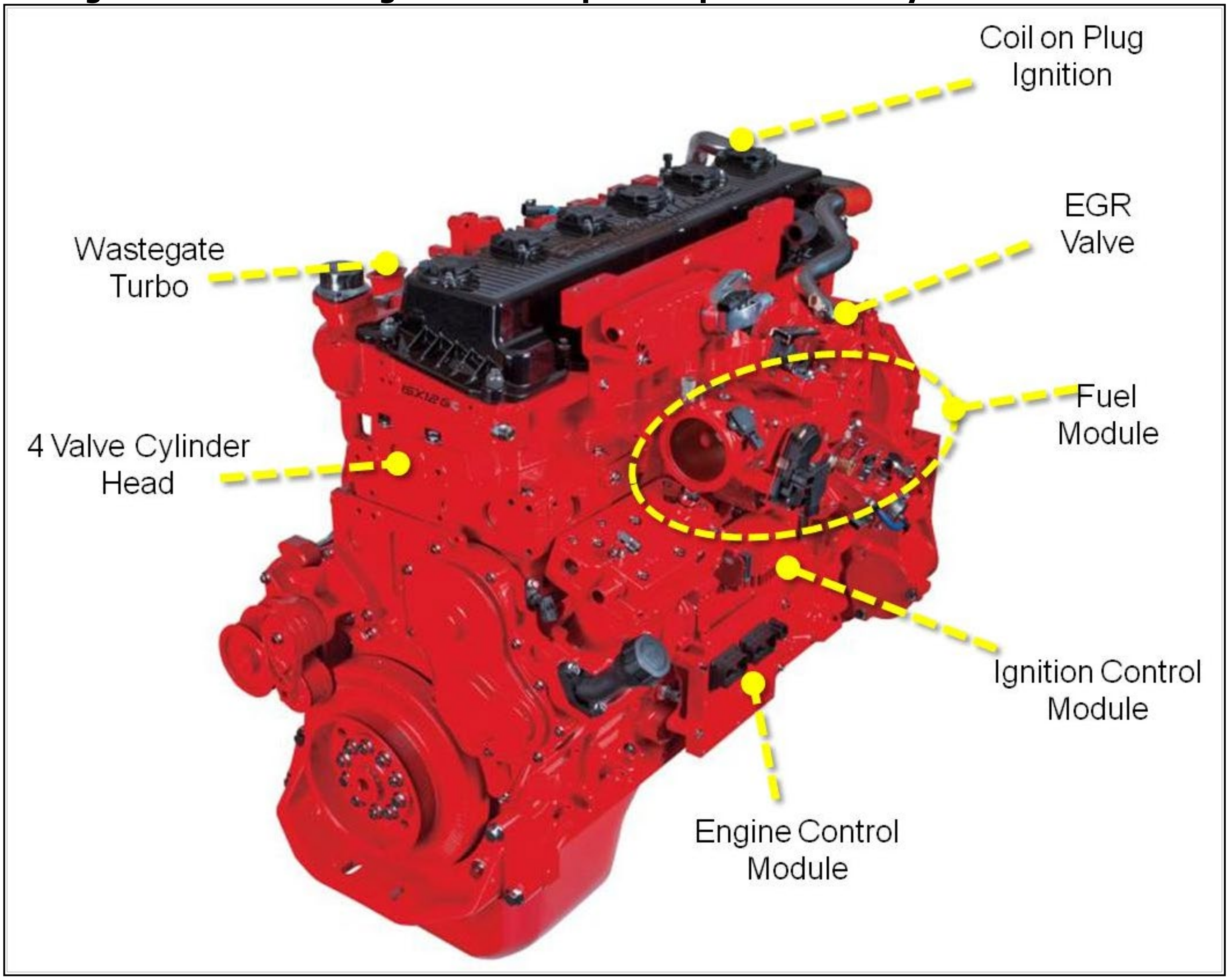
The ISX12 G engine uses the same ECM as used with CWI's 8.9-liter ISL G natural gas engine. This ECM is designated CM2180A and uses a Core2 based processor. No hardware design modifications were required to the CM2180A ECM during the ISX12 G development program. Figure 32 identifies the mounting location of the ECM.

Unique software and calibrations were developed during the ISX12 G program to enable certain electronic features that have not previously been developed for Cummins Westport's natural gas engines, including:

- Compression release braking, which is required for the 11.9-liter natural gas target market but is not used elsewhere within Cummins Westport's product line. Unique compression release brake hardware was developed for ISX12 G, along with software and calibrations to control the braking based on inputs from the vehicle operator;
- Gear-down protection, an electronic feature commonly used in highway tractors to encourage drivers to remain in the upper gear range by de-rating available vehicle speed in lower gears;
- Load-based speed control, an electronic feature that limits engine speed based on the commanded load as a function of which gear the transmission is in. This feature promotes "progressive shifting" or shifting to a higher gear in order to optimize fuel economy, rather than operating the engine at unnecessarily high engine speeds in a lower gear.
- Adaptive cruise control capability, to enable the ISX12 G engine to interface with and respond to vehicle-based collision avoidance systems employing forward-looking radar, such as the Eaton Vorad and Bendix Wingman systems.

The ISX12 G electronic control system includes software algorithms to comply with onboard diagnostic (OBD) requirements, which are mandated by EPA and CARB. EPA and CARB prescribe various levels of OBD regulations for heavy duty engines, including Engine Manufacturer Diagnostics (EMD+) and Heavy Duty OBD (HD OBD). Beginning in 2013, all diesel engines require HD OBD, but natural gas engines are subject to a different OBD compliance schedule than diesel engines, such that EMD+ is required beginning in 2013, and HD OBD is required beginning in 2018. CWI has developed ISX12 G for EMD+ compliance and has obtained EPA and CARB EMD+ certification.

Figure 32: ISX12 G Engine with Unique Components and Systems Identified



Source: Cummins Westport, Inc

Ignition System

The ignition system 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

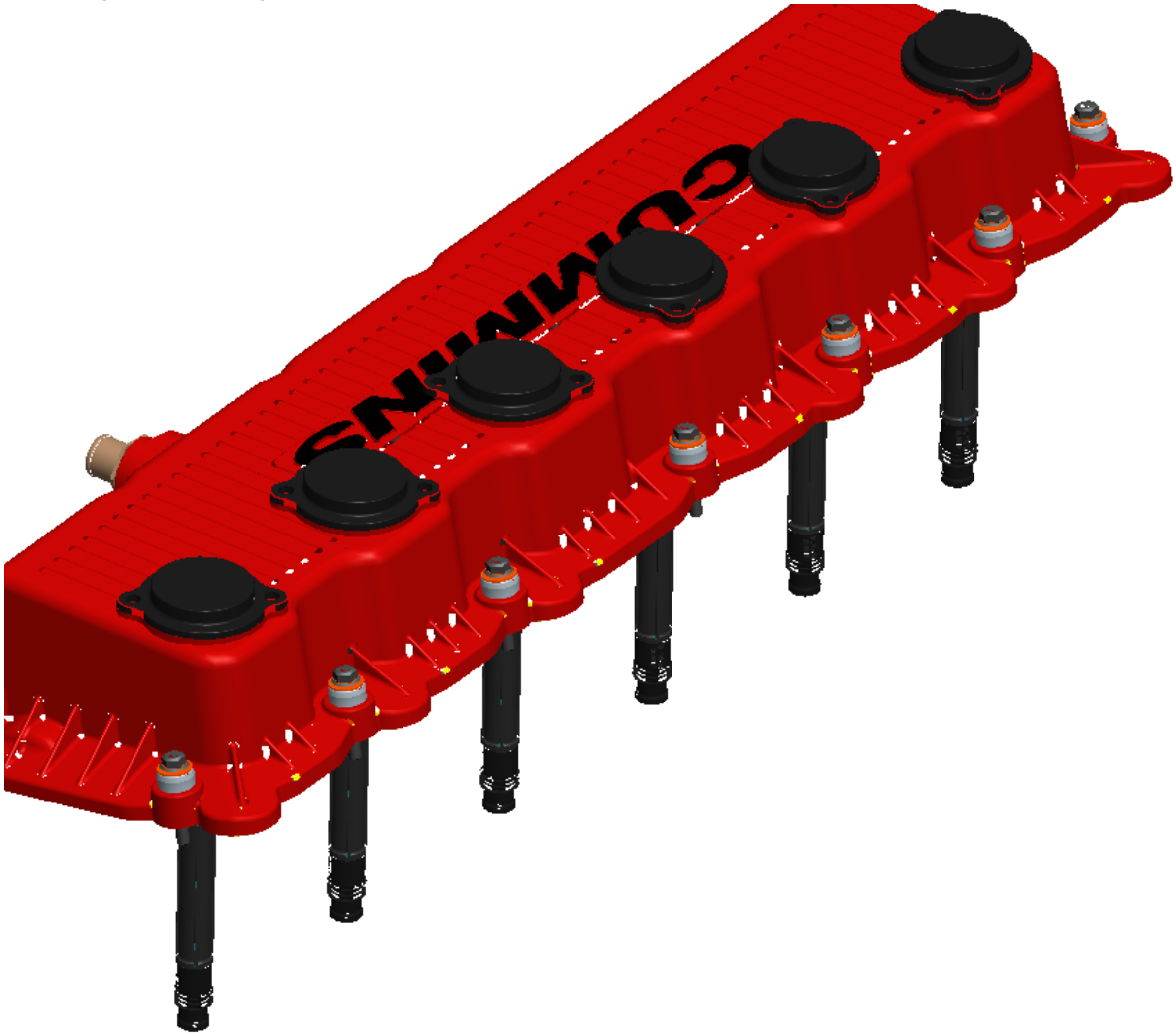
The ignition system architecture consists of "coil-on-plug" technology, consistent with Cummins Westport's ISL G engine, and a unique ICM incorporating additional diagnostic capability not currently supported by the ISL G ICM. While the ignition system architecture is identical to Cummins Westport's existing ISL G engine, the design requires 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. In the design for the ISX12 G engine, the 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. Figure 32 shows the location of the ICM and ignition coils in the ISX12 G engine design. Figure 33 shows the ignition coil and ignition coil extension. Figure 34 shows a CAD model of the ignition coils and coil extensions mounted to the ISX12 G valve cover.

Figure 33: Ignition Coil and Extension

Source: Cummins Westport, Inc

The spark plugs require periodic replacement in accordance with the engine's maintenance schedule. Through field testing and ignition system durability testing, the ISX12 G spark plug replacement interval has been set at 1500 hours of engine operation. The ignition system design must enable easy serviceability of the ignition coils, extensions, and spark plugs every 1500 hours. Many of the target chassis include a recessed firewall, such that the rear of the engine is surrounded by the engine bay above the valve cover and on both sides of the cylinder head. As a result, there can be limited vertical clearance above the valve cover to service the ignition system components in the rearmost cylinder of the engine. To enable spark plug replacement in cylinder 6, the ignition system design features a flexible ignition coil extension that enables removal in vehicle configurations that feature limited vertical clearance.

Figure 34: Ignition Coils and Extensions Mounted to Cylinder Head



Source: Cummins Westport, Inc

Power Cylinder

Spark ignited engines with pre-mixed air and fuel require a lower compression ratio than diesel engines to prevent pre-ignition during the compression stroke at high loads. Rather than modifying the cylinder head to incorporate a combustion bowl and to generate the required compression ratio, CWI elected to develop unique piston geometry vs. the ISX12 diesel engine. Early in the program CWI assessed numerous potential piston bowl geometries and compression ratios via analytical modeling. After evaluating numerous candidate designs through engine testing, CWI selected the preferred ISX12 G piston design, which consists of a symmetrical bowl incorporated into the piston. The final compression ratio has been confirmed as 12:1, whereas the ISX12 diesel engine compression ratio is 16.6:1.

ISX12 G power cylinder validation assessed the oil consumption rate of the engine under various operating conditions, including low speed, low load idling. Throttled engines are more susceptible to oil consumption than diesel engines due to partial vacuum conditions in the power cylinder of a throttled engine during the piston's intake stroke at low load, closed throttle conditions. In this operating condition, the pressure in the power cylinder can be lower than the engine crankcase and overhead pressures. The engine's piston rings and valve stem seals must be designed to prevent oil ingestion into the power cylinder. During the ISX12 G power cylinder testing, CWI identified excessive oil consumption rates while idling. This issue has been conclusively addressed by changing from a two-piece oil control ring design (common on heavy-duty diesel engines) to a three-piece oil control ring design (which is not common on heavy-duty diesel engines but has been successfully used on other CWI natural gas engines). Whereas a two-piece oil ring design includes a spring to energize the oil ring radially and ensure robust contact between the ring and cylinder liner, the three-piece oil ring is energized radially and axially to ensure a tight sealing surface to the upper and lower lands of the oil ring gland as well as to liner. In this manner, the three-piece ring controls oil consumption during partial vacuum conditions. Figure 35 shows a portion of the assembled three-piece oil ring used with the final ISX12 G power cylinder design.

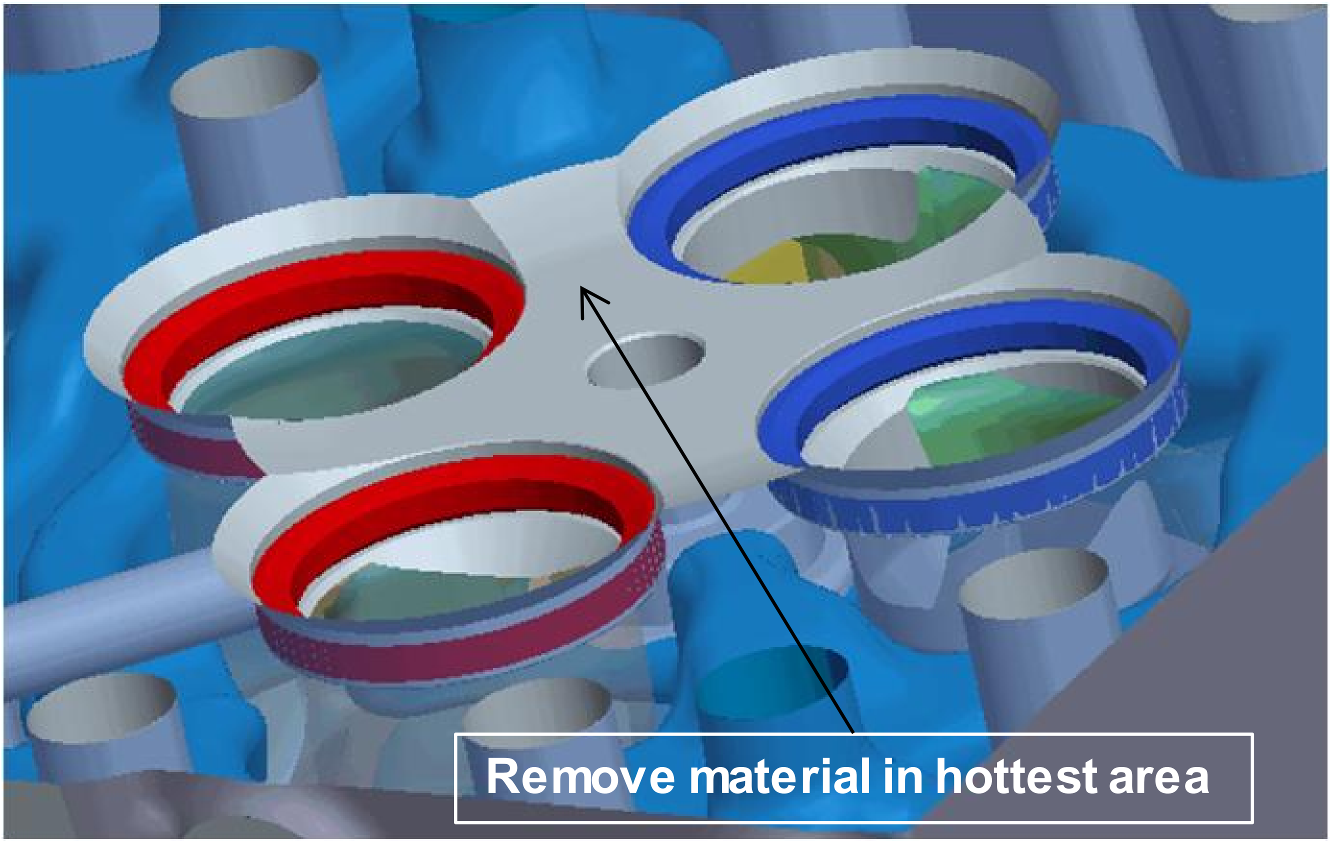
Figure 35: Three Piece Oil Ring

Source: Cummins Westport, Inc

Cylinder Head

While the cylinder head for the program is based on the ISX12 diesel cylinder head casting, it is machined to accommodate spark plugs and to increase heat transfer from the combustion face to the engine coolant passages inside the cylinder head. Following the ISX12 G Beta build, CWI Engineering identified a cylinder head design issue associated with high temperatures at the combustion face. While this operating mode has not yielded any engine performance or durability issues in the ISX12 G field test fleet, CWI elected to make a design change to the machining of the cylinder head's combustion face in order to improve heat transfer to the water jacket and reduce the peak combustion face temperature. This design change required additional cylinder head validation testing, which is described in the Design Verification and Validation Report for Task 2. Through extensive analysis and testing, CWI determined that the elevated cylinder head combustion face temperatures were an issue only for the ISX12 G engines at 400 hp and 385 hp ratings. Therefore, CWI elected to proceed with Limited Production using the original cylinder head design while restricting ISX12 G Limited Production to the 320 hp through 350 hp ratings. When the final cylinder head validation testing is complete, the revised cylinder head design will go into production for all ISX12 G engines throughout the range of available performance ratings. Figure 36 shows the revised cylinder head combustion face machining profiles for the Limited Production and final ISX12 G cylinder head designs.

Figure 36: Combustion Face Profile for the Final Cylinder Head Design



Source: Cummins Westport, Inc

Due to the low carbon content (and conversely high hydrogen content) of natural gas, the water concentration is higher in natural gas products of combustion than in diesel exhaust. Through validation testing, CWI determined that under certain operating conditions it was possible to form condensation in the overhead assembly of the ISX12 G engine. To minimize condensation, CWI identified a number of design solutions, including:

- Insulated valve cover;
- Permanently coated rocker levers, spark plug adapter tubes, and compression brake assemblies;
- Engine oil formulated specifically for natural gas engines;

The valve cover insulation is pre-assembled with the valve cover by the valve cover supplier and consists of a material that is already used for other engines components. The insulated valve cover, shown in Figure 37, has been validated to accept paint and to withstand repeated wash and environmental exposure cycles.

Figure 37: ISX12 G Insulted Valve Cover Assembly

Source: Cummins Westport, Inc

Fuel Supply Module

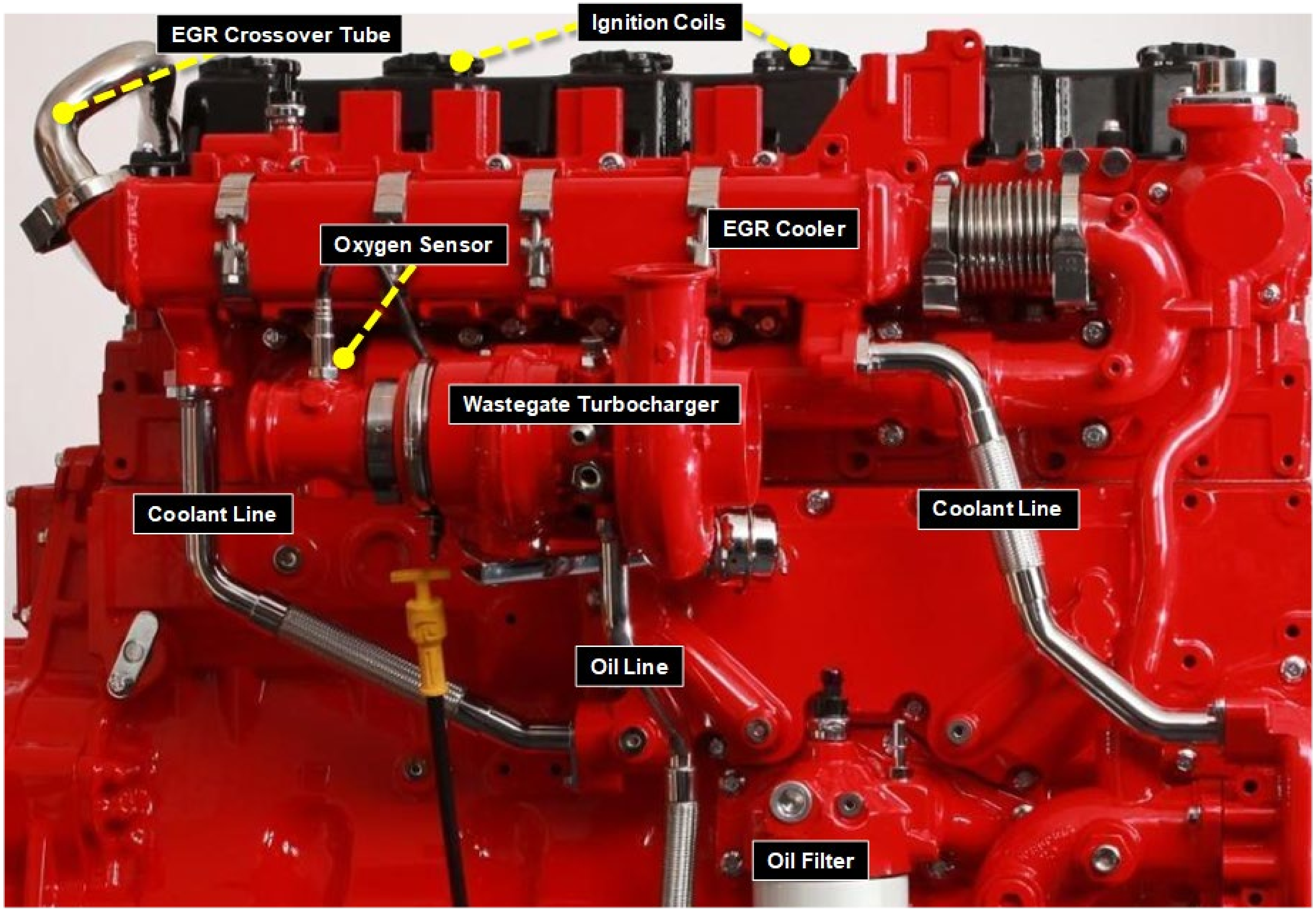
The fuel supply module's function is to regulate and deliver fuel, EGR, and charge-air to the engine. To avoid interference issues with OEM-supplied hardware in all of the various target truck models, the final design of the ISX12 G fuel supply module incorporates two separate housings, joined by a fuel transfer tube. The first-stage module is located near the lower rear corner of the engine when viewed from the cold-side of the engine, and incorporates a fuel pressure regulator, fuel pressure sensor, and fuel shutoff valve. The second-stage module is connected to the cylinder head and connects directly to the intake manifold, which is cast into the cylinder head. The second-stage module incorporates a gas flow sensor, fuel control valve, fuel sensors, EGR valve, throttle plate actuator, and the mixer housing where fuel, EGR and charge air are combined and directed to the intake manifold. Figure 31 shows the location of the fuel module on the engine.

At the outset of the ISX12 G development program, CWI established a design goal to enable low fuel inlet pressures without jeopardizing engine performance. CWI Engineering developed the ISX12 G fuel module with minimal pressure drop, such that the ISX12 G engine will generate peak power and torque (400 hp and 1450 lb.-ft, respectively) with fuel inlet pressures as low as 60 psig at the fuel inlet connection to the fuel module. By comparison, CWI's 8.9-liter engine requires 70 psig minimum inlet pressure for a peak rating of 320 hp and 1000 lb.-ft. Reducing the ISX12 G allowable fuel inlet pressure maximizes the vehicle's operating range by enabling the vehicle operator to use more of the fuel stored onboard the vehicle. Reducing the inlet pressure also allows LNG fuel storage tanks to operate at slightly lower fuel pressures than with other engines, thus extending the LNG tank "hold-time" before the tank pressure reaches the pressure relief valve setting and fuel is vented.

Air Handling System

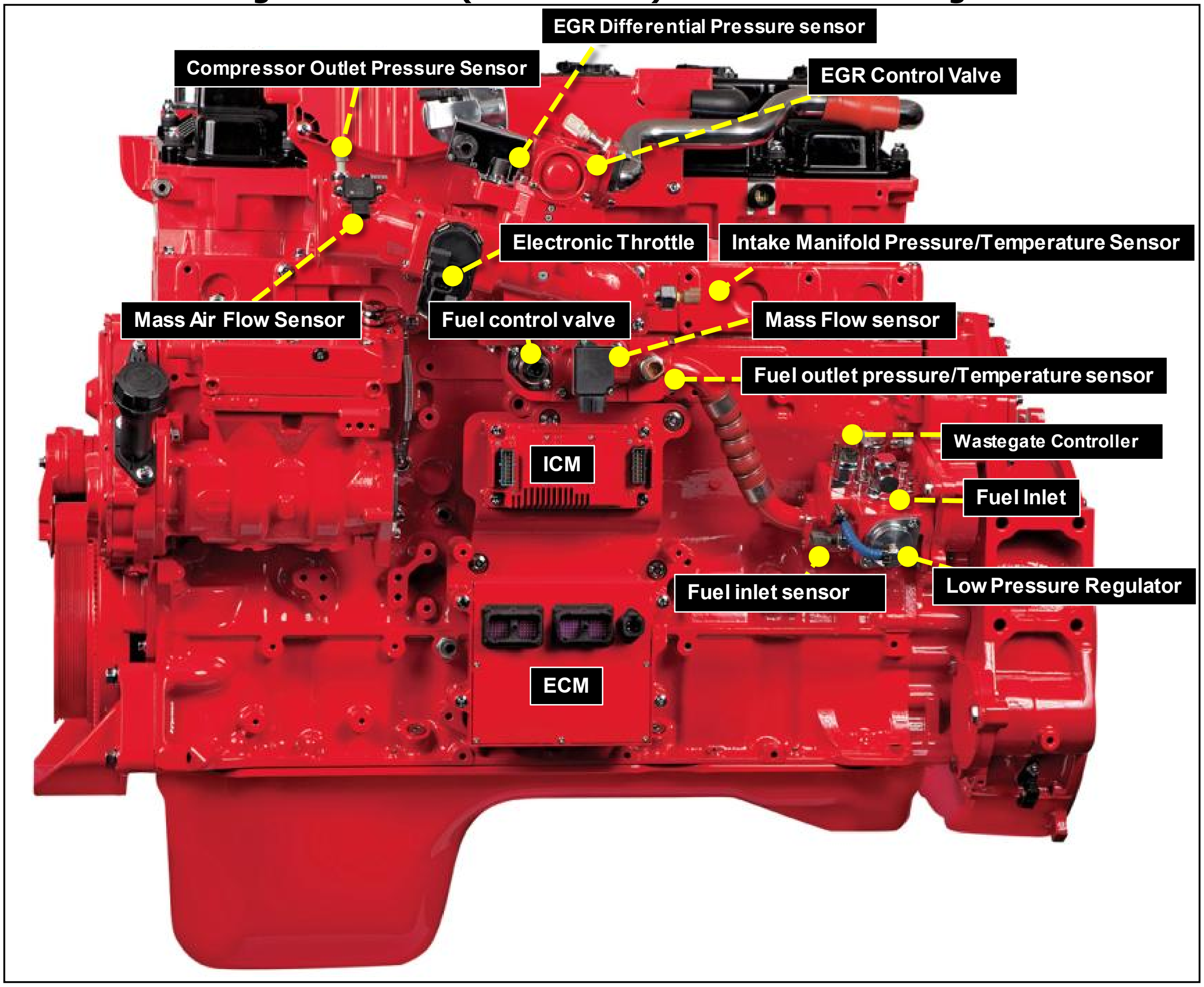
The air handling system includes the turbo-charger and EGR components. The final ISX12 G engine design uses a waste gated turbo-charger, whereas the Cummins ISX12 diesel engine uses a variable geometry turbo-charger in order to modulate exhaust pressures more precisely throughout the engine speed and load range in order to drive high EGR flow rates. CWI's stoichiometric EGR combustion technology does not rely on high EGR flow rates to meet the emission and performance targets; therefore, CWI has been able to eliminate the additional cost and complexity associated with variable geometry turbochargers. Also, whereas diesel engines inherently operate lean with high charge air flow rates, the ISX12 G combustion technology relies on maintaining stoichiometric conditions at all engine operating points, and therefore the required charge air flows are much lower than with the ISX12 diesel engine. Accordingly, the turbocharger used with ISX12 G is much smaller than the ISX12 diesel turbocharger. The final ISX12 G design uses the same EGR valve and EGR cooler as the ISX12 diesel engine. Figure 38 identifies the location of the turbo-charger and EGR components in the final ISX12 G engine design. Figure 39 shows the opposite side of the engine where many of the sensors for control of EGR, fuel, air are located.

Figure 38: Hot (Turbo) Side of ISX12 G Engine



Source: Cummins Westport, Inc

Figure 39: Cold (Fuel Module) Side of ISX12 G Engine



Source: Cummins Westport, Inc.

Engine Brake

Heavy-duty engines used in Class 8 tractor applications require a compression release brake (aka "Jake brake") to enable the engine to provide braking to the vehicle driveline. CWI's existing engines are not available with a compression release brake; therefore, the ISX12 G engine brake development was a first for CWI. The compression release brake hardware actuates the engine's exhaust valves near top-dead center of the compression stroke during zero-fueling events (e.g. when the vehicle is coasting) and holds the valves open during the expansion, or power, stroke. In this manner, the engine absorbs vehicle energy during the compression stroke but releases this energy through the exhaust valves and exhaust manifold rather than returning the compression energy to the piston during the expansion stroke. The compression release brake is an optional feature that may be specified by end-users when ordering an engine.

CWI evaluated the existing compression release brake developed by Cummins for the ISX12 diesel engine and determined that the ISX12 diesel brake would not fit the ISX12 G engine due to interference with the spark plug tubes and the ignition system in the engine's overhead assembly. CWI worked with Cummins's engine brake supplier to develop unique brake hardware to suit the ISX12 G engine. The ISX12 G compression release brake hardware has since been adopted by Cummins for the ISX12 diesel engine. Therefore, the ISX12 and ISX12 G engines use common compression release brake hardware, which will maximize production volumes and will optimize manufacturing costs and service inventories at Cummins distributors.

The braking power provided by a compression release brake is partially a function of the engine's compression ratio. ISX12 G uses a lower compression ratio than the ISX12 diesel engine (12:1 vs. 16.6:1, respectively). Therefore, ISX12 G engine braking performance is reduced versus ISX12 diesel. Table 6 shows the brake performance characteristics for ISX12 G and ISX12.

Table 6: ISX12 G vs. ISX12 Compression Release Brake Performance

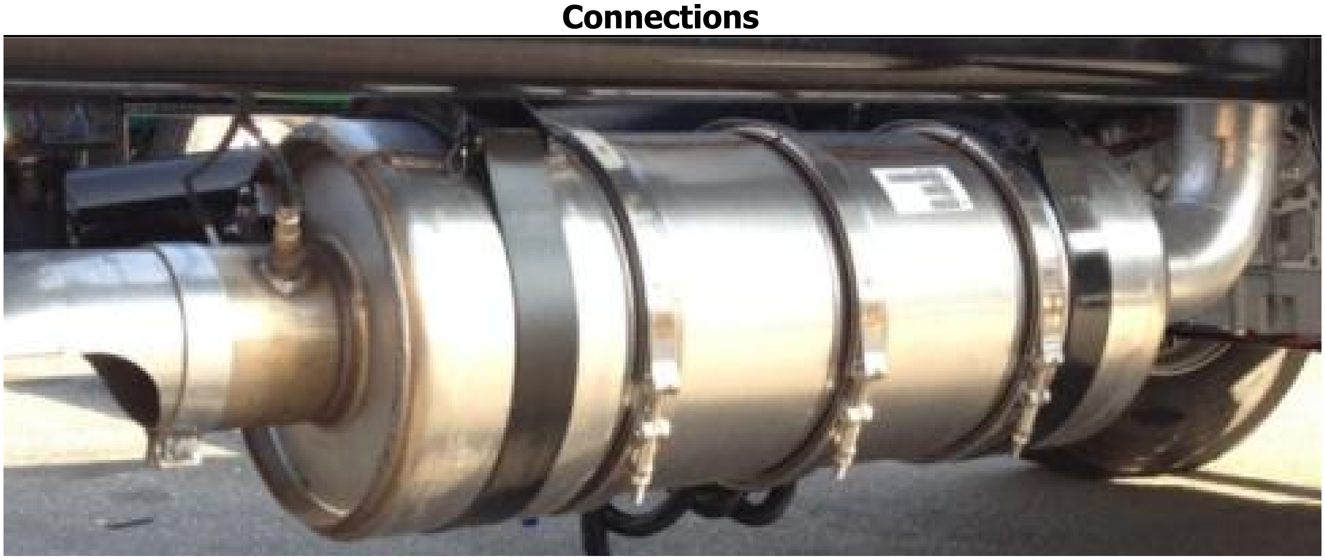
Engine Speed (rpm)	ISX12 G Braking Power (hp)	ISX12 Diesel Braking Power (hp)
1500	147	247
1700	182	292
1900	223	332
2100	264	366

Source: Cummins Westport, Inc.

Three Way Catalyst

The ISX12 G engine uses a three-way catalyst to limit NOx, CO and hydrocarbon (HC) emissions. The catalyst is packaged as an acoustic muffler (Figure 40) and is available in numerous geometries to suit a variety of vehicle installations. For example, the ISX12 G catalyst is available with options to support vertical or horizontal installations, whereby the vertical catalysts are longer as they include a rain-trap and drain in the outlet section of the catalyst. The catalyst is also available with varying inlet and outlet geometries, such as end-in/ end-out vs. side-in/ end-out. The catalyst diameter is 13", the overall length varies from 38" to 54" depending on the geometric configuration, and the weight varies from 93 to 130 lbs. The internal structure of the catalyst consists of two ceramic substrates with a proprietary wash coat consisting of precious metals (platinum, palladium, and rhodium).

Figure 40: Horizontal ISX12 G Three Way Catalyst with End-In / End-Out Connections

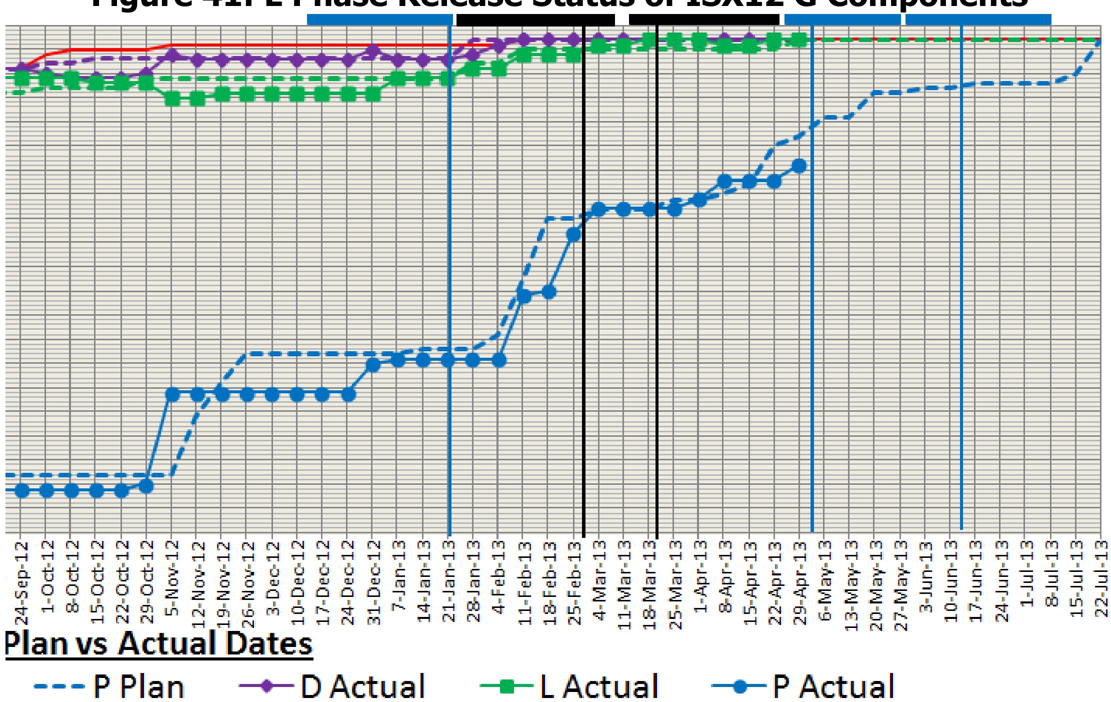


Source: Cummins Westport, Inc.

Structure and Release

Cummins Westport structures all engine components in the Cummins online database that is used for engine order entry and supply chain management. Each component is assigned a release phase code, which represents progressively increasing levels of design maturity. As component designs mature throughout the engine development program, each component progresses from Developmental "D" phase to Limited Production Intent "L" phase and ultimately to Production "P" phase. As shown in Figure 41, all ISX12 G components are released at "L" status, and the vast majority are released at "P" phase. The remaining components to be released at P phase are associated with the cylinder head, piston, and piston rings, for which P phase release is pending completion of the final component validation tests. The remaining validation tests are described in the Design Verification and Validation Report for Task 2.

Figure 41: L Phase Release Status of ISX12 G Components



Source: Cummins Westport, Inc.

Summary

The ISX12 G engine is based on the Cummins ISX12 diesel engine platform and is manufactured at the JEP in Jamestown, NY. The ISX12 G engine shares the vast majority of its components with the ISX12 diesel platform but uses certain unique, natural-gas specific components and sub-systems including electronic control and ignition systems, air handling hardware, fuel system, power cylinder, and after treatment. The unique ISX12 G sub-system and component designs have been finalized and released into the Cummins corporate and JEP databases to support pre-production and Limited Production engine builds. The vast majority of the components have been released at "P" phase, which corresponds to final release of fully validated components suitable for Full Production. A handful of components remain to be released at "P" phase pending successful completion of the final validation tests associated with the ISX12 G 400 hp rating, which is scheduled to go into production beginning in August 2013.

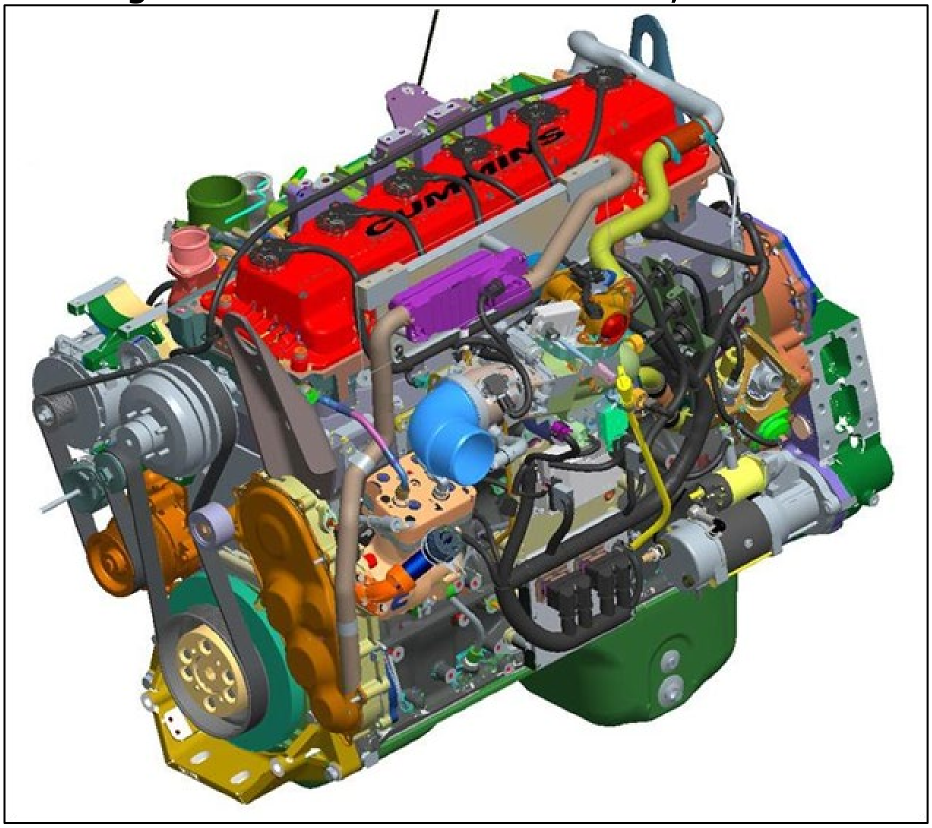
CHAPTER 7: Production Readiness

Along with engine design and development engineers, the ISX12 G team includes members from all Cummins and Cummins Westport functions that are required to support component procurement, engine production, and vehicle integration.

Throughout Task 2, Cummins and Cummins Westport Application Engineers worked directly with vehicle OEMs to ensure the engine will fit in a wide range of OEM chassis models, and to ensure that each OEM's design meets CWI's installation requirements and recommendations, such as electrical interface specifications, engine coolant and charge air cooling capability, and correct sizing and routing of fuel delivery hoses. Throughout Task 2, CWI worked with several truck OEMs including Autocar, Freightliner, Kenworth, Peterbilt and Volvo. The Application Engineers provided each OEM with CAD models for the Beta engines. The Beta engine design incorporated feedback from the OEMs to optimize the engine fit in their respective truck chassis. It was necessary to perform numerous iterations to the Beta design to accommodate the unique installation requirements and "engine fit" challenges for a range of Class 8 truck models. Figure 42 and Figure 43 illustrate the Beta design after extensive feedback from OEMs.

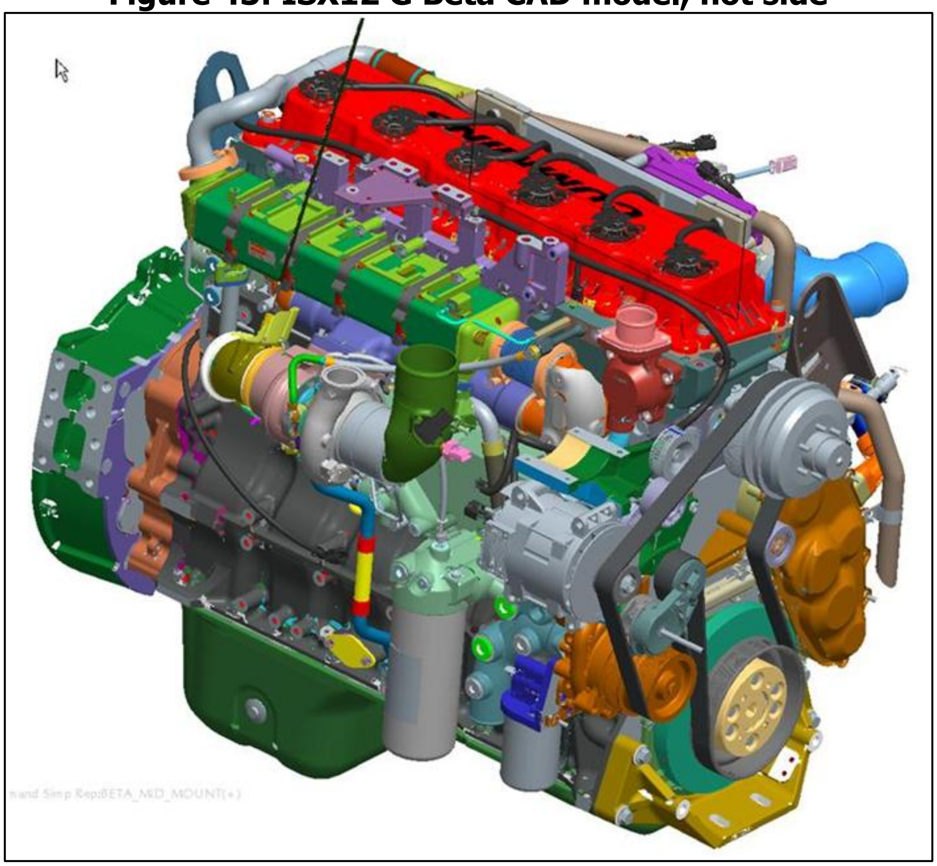
The ISX12 G Beta engine build was conducted in Q2 2012 and involved 30 engines. The OEMs continued to provide installation feedback and design change requests based on their Beta installation experience. CWI incorporated that feedback into a final design iteration and a final pre-production engine build during February and March 2013. CWI conducted this Quality Validation build to validate all production processes including order entry, JEP production processes and hot-test. The Quality Validation build consisted of 35 engines built and tested at JEP using production processes. These engines were then delivered to truck OEMs to validate each OEM's production readiness in their truck assembly plants.

Figure 42: ISX12 G Beta CAD model, cold side



Source: Cummins Westport, Inc.

Figure 43: ISX12 G Beta CAD model, hot side



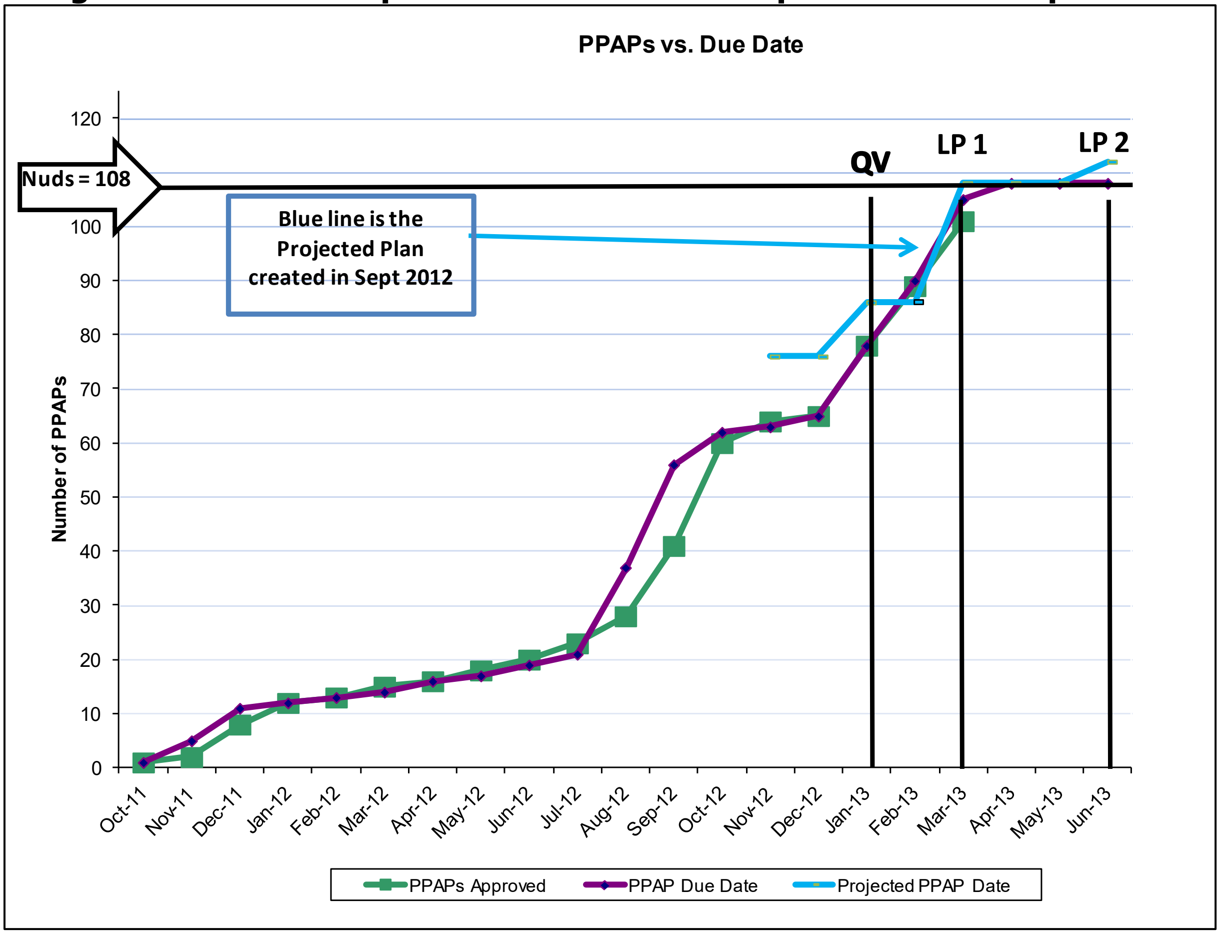
Source: Cummins Westport, Inc

Throughout Task 2, the Cummins Purchasing group identified and validated production suppliers for all-natural gas-unique components in the ISX12 G design. Greater than 80 percent of the individual components in the ISX12 G design are identical to the components used by Cummins for ISX12 diesel engine production. The components unique to ISX12 G include the cylinder head, pistons, turbo-charger, fuel module, ECM, ignition system, spark plugs, valve cover, and wire harness. For each of these unique components, the Purchasing group identified a production supplier with high volume production capability, then provided design specifications to the supplier. In many cases the production suppliers provided design input and feedback to optimize design for manufacturability and identified potential cost saving opportunities. In later stages of the program, the Purchasing group worked with suppliers to confirm high-volume production capability at negotiated cost targets, to ensure supplier adherence to CWI's component specifications, and to ensure that all suppliers were validated and approved in accordance with industry standard PPAP requirements (Production Part Approval Process).

The PPAP process required each supplier to produce a batch of components using production tooling and production processes, and to inspect each component to ensure compliance with the specified manufacturing tolerances and performance criteria. Figure 44 demonstrates the PPAP completion status for the ISX12 G components that are new, unique, or different (NUD) versus ISX12 diesel components. Figure 44 shows that all NUD components had completed PPAPs by April 2013 in order to support the start of Limited Production (LP1) engine builds at JEP. From April through June, incremental PPAP work continues to support final release of the unique hardware required for the 400 hp rating, which is scheduled to begin production in August 2013.

In production, ISX12 G engines will be ordered electronically by OEMs using the Cummins On-Line Specifications (COLS) order entry process that Cummins employs for diesel engine orders. The COLS order entry system is linked to the component and options database that is maintained by Cummins and CWI Engineering, whereby individual components are categorized into various option groupings (e.g. engine block vs. cylinder head vs. turbo-charger vs. exhaust manifold vs. fuel filter). Details of the ISX12 G option release status are described in the Task 2- Design Finalization, Structure and Release report for this project. All "Quality Validation" engines were ordered via the COLS online order entry process, thus validating the order entry process prior to initiating commercial launch of the ISX12 G engine.

Figure 44: PPAP Completion Schedule for Unique ISX12 G Components



Source: Cummins Westport, Inc.

ISX12 G will be built at the Cummins JEP in Jamestown, NY on the existing ISX12 diesel production line. Rather than building a batch of diesel engines followed by a large quantity of natural gas engines, ISX12 diesel and natural gas engines will be mixed into the production schedule throughout any given build day. Therefore, each installation station on the JEP ISX12 production line must be capable of accommodating diesel or NG engines without changing tooling or technicians. To accommodate ISX12 G production, JEP's operations staff undertook numerous equipment and process changes, including the following:

- Modifying ISX12 production line stations to accommodate unique ISX12 G installation operations, including unique cylinder head, fuel module, spark plugs, turbo-charger, pistons, ECM, ICM, wire harness. Along with training installation technicians and ensuring appropriate tooling, the JEP Operations staff used the Beta builds to assess the cycle-time to complete ISX12 G-unique installations, then determined which installation station should perform each operation in order to ensure the overall production line remained balanced and that no single installation station became the "choke point" for the production line during ISX12 diesel or ISX12 G production.
- Most OEMs specify that their engines be shipped pre-filled with oil. Consistent with other CWI engines, ISX12 G requires a unique oil formulation for natural gas engines, rather than diesel lubricating oil. Prior to the ISX12 G engine program, JEP only had provision for filling engines with diesel oil. JEP invested in equipment to fill ISX12 G engines with a unique oil formulation.

- In order to accommodate testing of ISX12 G engines, JEP also invested in adding natural gas supply to two of the engine dynamometer test cells at the end of the production line, JEP, in conjunction with CWI's combustion and performance engineering group, developed the appropriate hot-test cycle duration and established the necessary pass/fail criteria to validate each ISX12 G engine at the end of the production line.

All Beta and Quality Validation engines were built at JEP. All production line processes, including hot-test and filling engines with natural gas oil, were fully validated during the Quality Validation engine build. Figure 45 shows various members of the CWI and JEP ISX12 G team standing with the Quality Validation engines in the shipping area of JEP.

Figure 45: ISX12 G Quality Validation Engines Ready to Ship from JEP

Source: Cummins Westport, Inc.

The truck OEMs used ISX12 G Beta and Quality Validation engines to complete the final testing to validate that their engine installations meet their design specifications and also satisfy CWI's engine installation requirements and recommendations. Prior to production launch, CWI and the OEMs completed the Cummins Installation Quality Assurance (IQA) process, whereby the OEMs provide extensive data and design specifications documenting the engine installation in each vehicle model, along with data demonstrating compliance with critical vehicle performance requirements such as the ability to accommodate the engine coolant and charge air heat rejection rates with the engine operating at rated power in high ambient temperatures. Table 7 identifies the Class 8 truck makes and models in which the ISX12 G engine is commercially available during the Limited Production phase of the ISX12 G engine launch beginning in 2013.

Table 7: ISX12 G OEM Availability at Commercial Launch

OEM	Freightliner	Peterbilt	Kenworth	Volvo	Autocar
Model	Cascadia	320 384 365	W900S T660	VNL	Xpeditor
Engine	ISX12 G	ISX12 G	ISX12 G	ISX12 G	ISX12 G
Application	Tractor	Refuse Tractor Vocational	Tractor Vocational	Tractor	Refuse
Availability	2013 **Launch Partner**	2013 **Launch Partner**	2013 **Launch Partner**	2013 **Launch Partner**	2013 **Launch Partner**

Source: Cummins Westport, Inc.

Summary

In parallel with the ISX12 G design and development activities within Task 2, CWI worked extensively with OEMs, suppliers, and the JEP manufacturing staff to prepare for ISX12 G commercial production at JEP and to ensure that truck OEMs are ready to build ISX12 G-powered trucks. Through the Alpha, Beta, and Quality Validation phases of the ISX12 G program, all launch partner OEMs provided design feedback and finalized their vehicle installations in accordance with CWI's engine interface requirements and recommendations. ISX12 G is now commercially available in a wide range of Class 8 truck makes and models.

CHAPTER 8: Emissions Certification

Introduction

This section describes the emission certification activities conducted during the program, including emission certification test results, emission durability testing to demonstrate the ISX12 G emissions at the end of the EPA-prescribed useful life (435,000 miles) for heavy-heavy duty on-highway emission certification.

The goal of the Emissions Certification task is to build a certification engine, equip it with production intent software and hardware and complete emission certification testing in accordance with EPA/CARB on-highway emission testing procedures. The final test data was submitted to EPA and CARB to obtain the required emission certification approvals. This task also involves operating a production-intent engine and three-way catalyst emissions control system in a test cell over an extended period of time, with emission testing at prescribed intervals. This approach is used to demonstrate emissions stability and to quantify the emissions deterioration factor, if any, throughout the 435,000-mile useful life prescribed by EPA and CARB for heavy-heavy duty certified engines.

CWI successfully completed Task 3 and obtained EPA and CARB emission certification for the ISX12 G engine for model year 2013. CWI also elected to certify the ISX12 G engine to the new, optional EPA GHG emission standards. This section documents the emissions deterioration factor and emissions certification tests conducted and documents the final certified emission levels including EPA GHG certification.

Deterioration Factor (DF) Testing

Engines are emission certified at levels corresponding to the expected emissions at the end of the "useful life" period prescribed by EPA and CARB, rather than certified based on the emissions from new engines. Based on engine displacement and primary intended use applications (heavy-duty trucks), ISX12 G qualifies as a Heavy-Heavy Duty engine. For Heavy-Heavy Duty on-road applications, EPA and CARB prescribe a useful life of 435,000 miles for emission certification purposes. To quantify the anticipated end-of-useful-life emissions, it is well established that an engine manufacturer must operate an engine and after treatment system in an engine dynamometer test cell under a high load duty cycle that ages the engine and catalyst at an accelerated rate versus typical in-vehicle, on-road operation. At periodic intervals, the engine and after treatment system are subjected to emission certification testing in accordance with the EPA and CARB emission certification requirements. The purpose of these periodic emission tests is to quantify the emissions deterioration, if any, as the engine and after treatment system age through use. The ISX12 G emissions deterioration test plan specified 1600 hours of engine operation with emission tests at the 120, 400, 800, 1200- and 1600-hour points. For each regulated emissions constituent, the deterioration trend over the 1600-hour test is then extrapolated to 4600 hours, corresponding to the end of the EPA / CARB-prescribed useful life. For each emissions category, the extrapolated deterioration factor (DF) is multiplied by the emission certification test result, and the product is the certified emission level.

CWI started DF testing in 2011, and experienced numerous setbacks in the emission testing. The following is a chronology of the various DF tests and a summary of the various issues that arose during throughout Task 3:

- **DF Test #1:** Test commenced in June 2011. During unmanned operation over a weekend, the engine durability test cell monitoring system identified an abnormal operating condition. Instead of shutting down the engine, the test cell controller commanded the engine to operate at idle speed for an extended period of time. Extended idle operation is not included in the EPA-approved duty cycle for accelerated engine testing. As a result, CWI was forced to abandon this test, obtain a new engine and catalyst, and re-start the DF test.
- **DF Test #2:** Test commenced in 2nd half of 2011. This engine experienced a coolant leak due to a cylinder head porosity issue with the pre-production, prototype cylinder head. EPA would not approve continuation of the DF test following a cylinder head swap due to the potential impact on emissions deterioration; therefore, CWI was forced to abandon test #2 and re-start another DF test.
- **DF Test #3:** Test commenced by 4th Q of 2011. This test progressed well up to the 800-hour test point, when a significant increase in CO emissions was recorded. The root cause was identified as deterioration of the turbo-charger waste gate actuator, which controls the boost pressure and air flow to the engine. The waste gate actuator damage led to control system instability at certain operating conditions, causing high CO emissions due to rich operation. Replacing the turbocharger corrected the issue and the CO emissions returned to normal levels. However, EPA would not approve continuation of the DF test following the hardware change. Therefore, CWI was again forced to abandon the DF test.
- **DF Test #4:** Test commenced in Q1, 2012. This test proceeded as planned through the 800-hour test point. Beginning at approximately 1000 hours, the engine's oil consumption rate increased considerably. CWI elected to continue engine operation until 1200 hours, then inspect the engine to diagnose the oil consumption issue. At the 1200-hour emission test point, the PM emissions had increased considerably, and exceeded the 0.01 g/bhp-hr. emission standard. Engine tear-down and inspection revealed broken oil control rings in three cylinders, indicating a deficient piston ring design. The DF test was aborted during Q3, 2012.
- **DF Test #5:** Test commenced during Q3, 2012. This engine was equipped with the new piston rings, and immediately showed lower PM results at the 120-hour test point. This test proceeded as expected through the 1200-hour test point, with a slight increase in NOx emissions. However, at the 1600-hour test point conducted during Q1, 2013, the recorded NOx emissions increased more than expected. When extrapolated to the end of useful life, the resulting NOx DF was calculated to be 1.874, which is considerably higher than originally expected and much higher than the 1.000 (i.e. no deterioration) NOx DF obtained for CWI's 8.9-liter ISL G engine. The CO emissions also increased more than expected at the 1600-hour test point, resulting in a CO DF of 3.552. While the increase in NOx and CO was believed to be attributable to variation in the emission control system, CWI elected to accept the results rather than initiating another DF test.

Table 8 below shows the final multiplicative DF results filed for certification of the ISX12 G.

Table 8: Final Emissions DF Test Results

	ENG Hrs	NOx_CHET	NMHC_CHET	CO_CHET	PM_CHET
		Gr/Bhp-Hr	Gr/Bhp-Hr	Gr/Bhp-Hr	Gr/Bhp-Hr
	120	0.1093	0.0701	2.0538	0.004218
	448	0.0679	0.0449	2.4588	0.00367
	808	0.0887	0.0465	2.6114	0.00236
	820	0.1046	0.0359	2.3488	0.00166
	1211	0.0998	0.0412	2.9411	0.00493
	1615	0.1230	0.0364	3.8406	0.00233
0 hour	120	0.086799288	0.058984035	1.925268038	0.003646206
end of life	4614	0.162689311	-0.023499479	6.838279704	0.000812613
DF		**1.874**	**1.000**	**3.552**	**1.000**

Source: Cummins Westport, Inc.

All design issues experienced during DF testing have been addressed in the ISX12 G production design and are described in the Task 2 report (Section 3.1) for this project.

Emission Certification Testing

Emission certification testing consists of operating a new engine and catalyst in an emissions measurement test cell in accordance with transient and steady-state emission test procedures prescribed by EPA and CARB for on-highway, heavy-duty engines. All emission certification testing is conducted at the Cummins Technical Center in Columbus Indiana, using test cells and emissions measurement equipment that have been verified to meet the EPA and CARB certification requirements.

CWI built a new ISX12 G engine and conducted the emission certification tests during Q4, 2012. In December 2012, CWI submitted the certification test results to EPA along with interim DF results following the 1200-hour test point from DF Test #5. CWI submitted this data to EPA and CARB prior to completion of the DF test in order to obtain conditional emission certification during Q1 2013 in preparation for the start of commercial production of ISX12 G engines in April 2013.

As explained above, the NOx and CO DF factors increased unexpectedly upon completion of DF Test #5. As a result, the product of the NOx DF and the NOx certification result exceeded the 0.20 g/bhp-hr. NOx standard. Therefore, CWI Engineering needed to recalibrate the engine to reduce NOx. In parallel with the ISX12 G engine development program, CWI Engineering has been developing other natural gas engines to achieve Euro emission certifications, which require extremely low NOx emissions. The Euro development program revealed NOx control levers that CWI was able to apply to the ISX12 G calibration in order to reduce engine-out and catalyst-out NOx without noticeably impacting engine performance or vehicle drivability. The ISX12 G engine control calibration was revised to incrementally reduce the NOx emissions to 0.08 g/bhp-hr., thus enabling emission certification below the EPA / CARB standard in combination with the final NOx DF. CWI repeated the emission certification testing during Q1, 2013 and re-submitted the emission certification application to EPA and CARB. Table 9 shows the final emission certification test results submitted to EPA and CARB.

In Table 9, CHET refers to Cold and Hot Emissions Testing per the U.S. Federal Transient Protocol (FTP) emissions test cycle, and RMCSET refers to steady-state emissions testing prescribed by EPA and CARB.

Table 9: Emissions Certification Test Results (gm/bhp-hr.)

Cycle	NOx	NMHC	CO	PM
EPA_Limit	0.2	0.14	15.5	0.01
CHET 1	0.078	0.033	2.374	0.003
CHET 2	0.074	0.031	2.45	0.003
RMCSET 1	0.011	0.009	1.645	0.001
RMCSET 2	0.014	0.011	1.801	0.001

Source: Cummins Westport, Inc.

On March 14, 2013 EPA issued Certificate of Conformity CEX-ONHWY-13-14 certifying ISX12 G as a Heavy-Heavy Duty engine meeting EPA's on-highway emission regulations for model year 2013. On April 3, 2013, CARB issued Executive Order A-021-0591 certifying ISX12 G as a Heavy-Heavy Duty engine meeting CARB's on-highway emission regulations for model year 2013. Table 10 shows the certified emission levels and applicable emission standards as specified on the CARB ISX12 G Executive Order, whereby the certified emission levels are the product of the deterioration factors and emission certification test results specified in Table 8 and Table 9, respectively.

Table 10: Certified Emission Levels per CARB Executive Order

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
STD	0.14	0.14	0.20	0.20	*	*	15.5	15.5	0.01	0.01
FEL	*	*			*	*	*	*	*	*
CERT	0.03	0.01	0.15	0.03	*	*	8.7	6.4	0.003	0.01
NTE	0.21		0.30		*		19.4		0.02	

Source: Cummins Westport, Inc.

GHG Certification

EPA has adopted new GHG regulations that become mandatory in 2014, with a second phase of GHG regulations becoming mandatory in 2017. As part of the new GHG regulations, EPA also created a slightly less stringent optional set of standards effective in Model Year (MY) 2013, to align with the diagnostic regulations required for MY2013 heavy duty engines (Heavy Duty OBD for diesel engine families, Engine Manufacturers Diagnostics+ (EMD+) for alternate fuel engine families). In exchange for opting into the early compliance 2013 standards, manufacturers are required to meet the 2017 GHG standards beginning in 2016. Cummins and Cummins Westport elected to opt-in to the early compliance GHG standards for the entire diesel and natural gas engine product line, thus requiring ISX12 G to comply with the GHG standards applicable for MY2013 through MY2015.

EPA's GHG regulation specifies emission standards for CO_2, CH_4 and N_2O, and specifies unique emission standards depending on the intended end-use application of the engine (Tractor applications versus Vocational applications). EPA acknowledged that natural gas engines would not be able to comply with the CH_4 standards but specified an alternate compliance methodology whereby certified CO_2 emission levels below the applicable CO_2 standard can be used to offset CH_4 emissions that exceed the applicable CH_4 standard. The applicable 2013 standards for Heavy-Heavy Duty engines in Tractor and Vocational Applications are shown in Table 11. Table 12 identifies the CO_2 and CH_4 Family Certification Limits (FCLs) to which ISX12 G is certified in lieu of CO_2 and CH_4 standards, per EPA Certificate of Conformity CEX-ONHWY-13-14. The EPA certification document does not specify an emissions level for N_2O, thus implying that ISX12 G is certified to the applicable N_2O emission standard without specifying a N_2O FCL.

Table 11: EPA GHG Standards for Model Year 2013 Engines

Emissions (g/bhp-hr.)	**Tractor Applications**	**Vocational Applications**
CO_2	485	577
CH_4	0.10	0.10
N_2O	0.10	0.10

Source: Cummins Westport, Inc.

The EPA GHG regulation specifies that the transient (FTP) certification data is used to determine compliance with the Vocational standards, and the steady-state (Ramped modal) data is used to determine compliance with the Tractor standards. Further, the EPA regulation specifies a Global Warming Potential factor of 25 for CH_4. Table 11 – EPA GHG Standards for MY2013 Engines

The following sample calculation quantifies the ISX12 G compliance with the 2013 Tractor standard for Heavy-Heavy Duty engines:

$$
\begin{aligned}
\text{CO2 equivalent emissions} &= \text{CO2 FCL} + 25 \times (\text{CH4 FCL} - \text{CH4 standard}) \\
&= 427 + 25 \times (1.70 - 0.10) \\
&= 467 \text{ g/bhp-hr.}
\end{aligned}
$$

The applicable CO_2 standard for Tractor applications is 485 g/bhp-hr.; thus, ISX12 G is certified at a CO_2-equivalent level below the applicable standard.

Table 12: ISX12 G CO2 and CH4 Family Certification Limits

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF TRANSPORTATION AND AIR QUALITY
WASHINGTON, DC 20460

CERTIFICATE OF CONFORMITY
2013 MODEL YEAR

Manufacturer: **CUMMINS INC**

Engine Family:	**DCEXH0729XBA**		
Certificate Number:	**CEX-ONHWY-13-14**		
Intended Service Class:	**HHDD**		
Fuel Type:	**NATURAL GAS**		
FELs: **G/BHP**	NMHC +NOx:	N/A	
	NOx:	N/A	
	PM:	N/A	

Greenhouse Gas Info.

Primary Intended Service Class: **TRACTOR/VOCATIONAL**

Primary Test Configuration FTP (if applicable):

CO_2 FCL value	(g/hp-hr)	**506**
CO_2 FEL value	(g/hp-hr)	**521**
N_2O FEL value	(g/hp-hr)	
CH_4 FEL value	(g/hp-hr)	**1.70**

Primary Test Configuration Ramped-modal(if applicable):

CO_2 FCL value	(g/hp-hr)	**427**
CO_2 FEL value	(g/hp-hr)	**440**

Source: Cummins Westport, Inc.

Summary

ISX12 G is certified by EPA and CARB as a Heavy-Heavy-Duty on-highway engine for model year 2013, at emission levels below the applicable emission standards. ISX12 G is also certified to the new EPA GHG regulations at CO2-equivalent emission levels below the applicable CO2 standards. All work required under Task 3 has been successfully completed.

CHAPTER 9: Reliability Assessment and Product Launch

This section will describe the final results of the ISX12 G Reliability program vs. the original program reliability goals, specified in cumulative operating experience (miles and hours). This section will also describe the ISX12 G launch strategy, including an explanation of the Limited Production phase of the program prior to entering Full Production. Finally, this section will document the various Class 8 truck and tractor OEM models that are available with ISX12 G as a factory-installed option.

The goal of the Reliability Assessment and Product Launch task is to review the results of the design verification process and the test data generated in Task 2 in order to assess the reliability and readiness of the engine prior to product launch. Following a review of data, Cummins Westport Inc. (CWI) finalized design changes to various engine components to complete the ISX12 G engine validation tasks and proceeded to commercialization and launch of the ISX12 G engine. This report documents the reliability assessment and product launch activities within Task 4.

Reliability Assessment

Throughout the ISX12 G product development program, CWI conducted a series of reviews with senior Cummins and Cummins Westport personnel to assess the technical progress and reliability status of the ISX12 G engine. In preparation for the commercial release of the ISX12 G engine and the start of production at the JEP, detailed ISX12 G technical and reliability reviews were conducted in Q1 2013. As described in the Section 3.1.3 of this report - "Design Verification and Validation", a number of ISX12 G engine and component issues were discovered and addressed during the Beta Validation phase of the ISX12 G engine program. These issues included overhead corrosion, cylinder head cracking, and excessive oil consumption at idle. Resolving these issues became the primary focus of technical and management teams during the final production readiness reviews leading to commercial launch of the ISX12 G engine.

An over-head corrosion control strategy was finalized for production launch. A critical success factor to a manufacturing strategy was the development of an insulated valve cover. A review of data from the Cummins Purchasing and Manufacturing organizations, and CWI Engineering, led to the review group concluding that the insulated valve cover successfully met design validation and manufacturing requirements. Figure 46 below shows the insulated valve cover as delivered from production tooling by the supplier. The insulation is sent pre-assembled to the cover and therefore eliminates assembly concerns that JEP personnel identified with a prototype valve cover insulation design. The insulated valve cover is part of a series of steps to mitigate over-head corrosion. The production ISX12 G design also contains permanently coated rocker levers, spark plug adapter tubes, and compression brake assemblies. Additionally, the production application documentation requires the use of engine oil formulated for natural gas engines meeting Cummins Engineering Specification 20074. Finally, the production manufacturing process specifies the use of pre-heated engine cooling water during the end of production test, to avoid condensation in the overhead assembly.

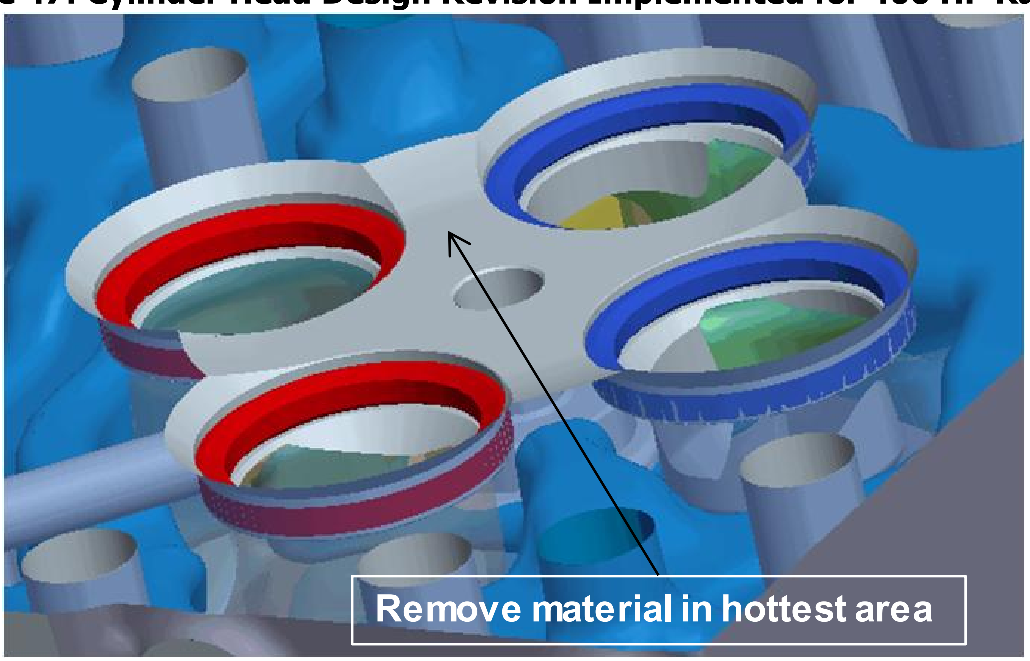
Figure 46: Production Insulated Valve Cover Assembly

Source: Cummins Westport, Inc.

As identified during the Alpha Verification and Beta Design stages of the program, the valve bridge cracking issue was linked to high combustion surface temperature in the vicinity of the valve bridges. Analysis showed that the excessive combustion surface temperatures occurred at high power conditions, in excess of 350 HP. Analysis showed that the temperature could be reduced by thinning the head deck in the critical regions extending through the valve bridge. For reference, Figure 47 below shows the analysis-led design solution necessary to reduce temperatures on the peak rating (400 HP).

Engine durability testing was required to confirm the cylinder head durability improvements yielded by the design change illustrated in Figure 47. At the final ISX12 G reliability review, CWI and Cummins senior management approved proceeding with ISX12 G production beginning in April 2013, but limiting the ratings to a maximum of 350 HP and 1450 lb.-ft. In parallel with this Limited Production release of the engine, CWI continued validation and durability testing of the 385 HP and 400 HP versions of the ISX12 G engine. This testing was performed to validate that the cylinder head design solution in Figure 47 would provide acceptable engine performance and durability.

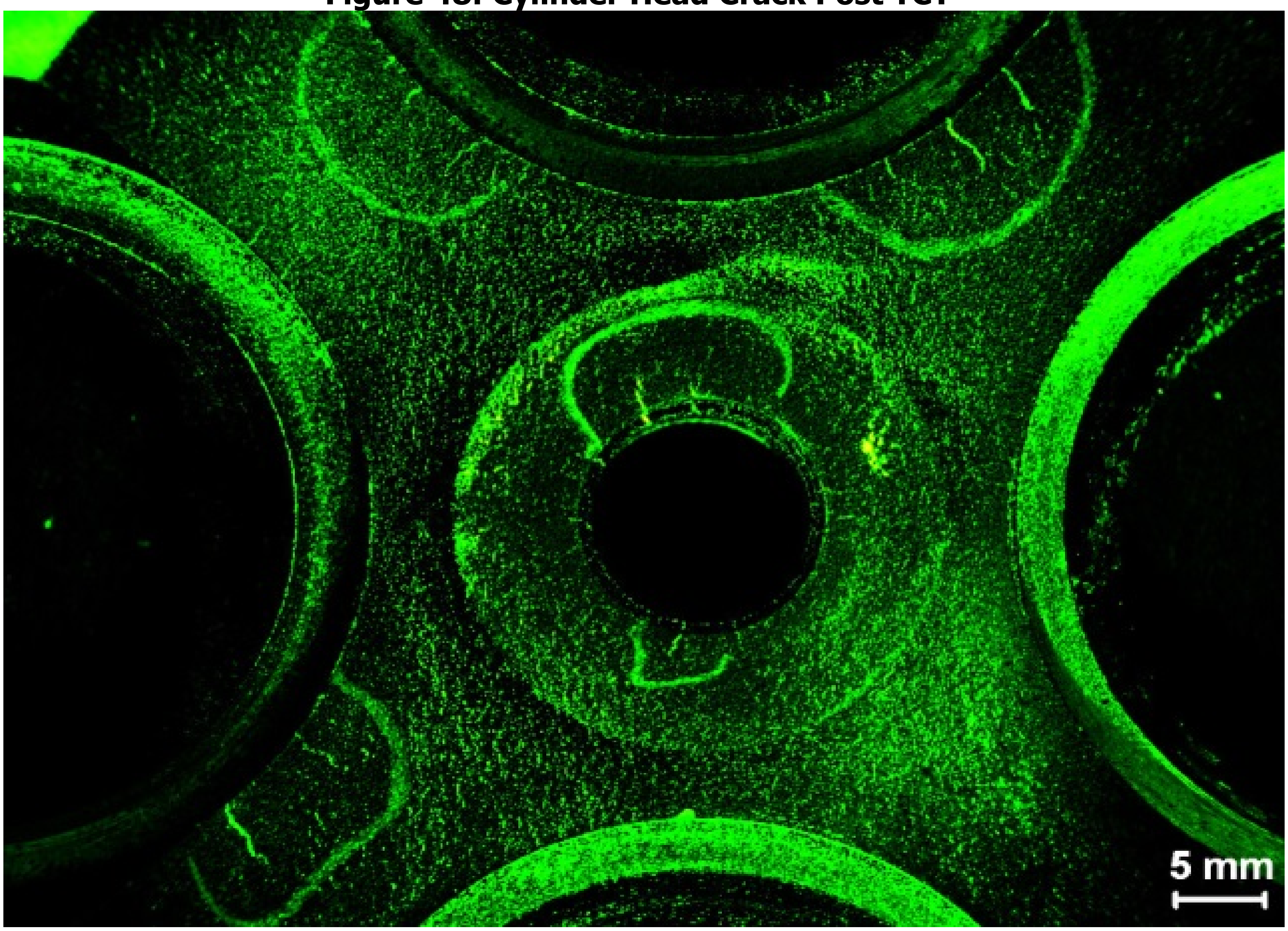
Figure 47: Cylinder Head Design Revision Implemented for 400 HP Rating



Source: Cummins Westport, Inc.

CWI subsequently completed the required Thermal Cycle Test as dictated by Cummins Engineering Standard Work (ESW). Typical results of the Thermal Cycle Test are shown in Figure 48, where the combustion face is painted with MagnaGlo and illuminated with a black light. As can be seen in Figure 48, cracking features were still present upon the completion of the Thermal Cycle Test, resulting in a marginal non-passing score of the ESW (note, the semi-circular loops shown surrounding the small cracks on the combustion face are pencil marks made to highlight the crack regions). The ISX12 G technical review committee, comprised of senior Cummins and Cummins Westport design, development, and manufacturing representatives, recognized the non-passing score but granted the program permission to proceed to production based upon a parenting assessment made to similar cracks witnessed on a different diesel production engine with negligible rates of cylinder head failures in customer applications. Therefore, the ISX12 G cylinder head cracking was deemed to pose an acceptably low reliability risk. The design solution illustrated in Figure 47 was applied to all ratings from 320 to 400 HP.

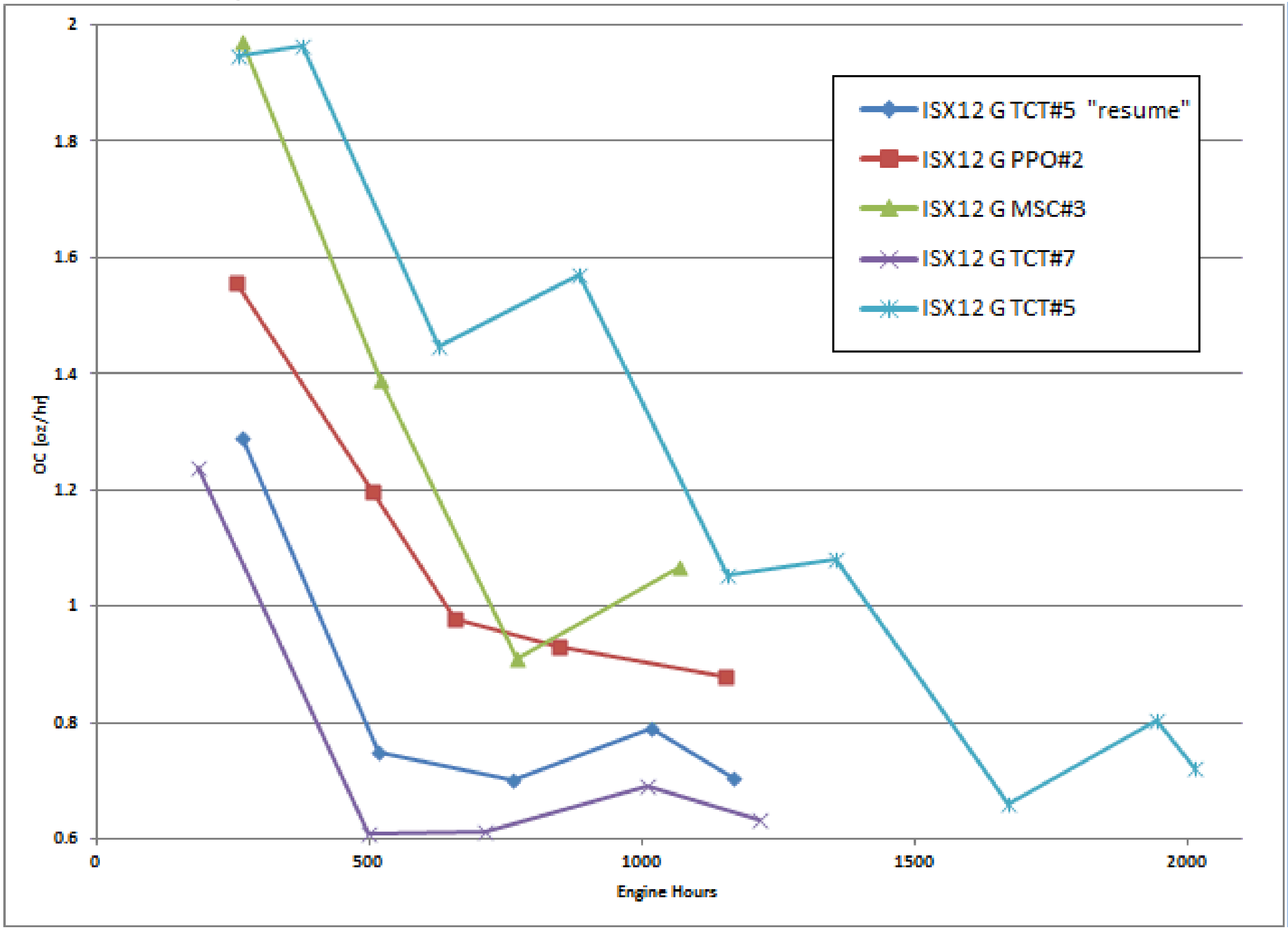
Figure 48: Cylinder Head Crack Post TCT



Source: Cummins Westport, Inc.

The technical review team evaluated data for oil consumption measured over the duration of the various ESW long hour test cycles. It can be seen from Figure 49 below that in all engines the oil consumption continued to improve markedly over the duration of each test. While acceptable oil consumption has been achieved on all abuse tests, design modifications are being developed for post-launch implementation to further reduce engine-to-engine variation, reduce run-in time, and improve long term durability of the power cylinder.

Figure 49: Oil Consumption Results of ESW Abuse Tests



Source: Cummins Westport, Inc.

Evaluation of the durability of the power cylinder and valve train identified that hot, running valve lash was insufficient in the Beta design. Evaluation of cam lobes at the completion of the abuse tests showed markings on the base circle indicative of valve train loading when the cam should otherwise be unloaded. An increase in cold lash setting of 0.004 inches for both the intake and exhaust valves was evaluated under high speed mechanical abuse tests to monitor valve seat wear. Following ISX12 G commercial launch, CWI intends to continue optimizing valve lash settings and to conduct additional testing to ensure emissions and performance transparency. Upon successful completion of these tests, CWI may increase the production cold lash settings.

In addition to component and sub-system level validation and durability tests conducted within Task 2 and referenced above, CWI conducted extensive vehicle testing throughout the ISX12 G development program. At the outset of the ISX12 G development program, CWI established the following field test goals within the broader ISX12 G Reliability Plan:

- 1.1 million miles, representing 10 warranty periods of operation prior to launch;

- At least four ISX12 G-powered trucks individually accumulating greater than 100,000 miles of operation prior to ISX12 G commercial launch.

Throughout the ISX12 G development program, CWI deployed 25 field test trucks throughout the United States equipped with Alpha or Beta ISX12 G engines. Following the Beta build and Beta field test deployment, the ISX12 G launch date was re-scheduled from late 2012 to mid-2013 in order to ensure sufficient time to address some of the technical challenges described above and described in the Task 2 reports. The change to the launch schedule extended the duration of the field-testing program. As a result, the field test fleet surpassed the original field test mileage accumulation goals prior to launch. The ISX12 G field test fleet achieved the original mileage accumulation goal (1.1 million miles of operating experience) during October 2012. By mid-2013 the ISX12 G field test fleet had significantly exceeded the original field test goals, with more than 2 million miles of operating experience, and 8 of 25 trucks surpassing the 100,000-mile threshold.

Taking into consideration the successful resolution of the overhead corrosion, cylinder head cracking, and oil consumption issues, and the proven reliability of the ISX12 G engine via extensive on-highway field testing, the ISX12 G technical review committee approved moving to production based on the results of the reliability assessment. The business review committee, comprised of senior business, sales, marketing and finance personnel from CWI, Westport Innovations, and Cummins, approved this recommendation, and production subsequently started on the ISX12 G higher ratings of 385 HP, 1350 lb.-ft and 400 HP, 1450 lb.-ft in mid-August 2013.

Product Launch

As described above, the ISX12 G engine entered commercial production at JEP in April 2013. This phase of the ISX12 G release was referred to as "Limited Production" as CWI constrained the engine availability to a subset of ratings, up to a maximum of 350 HP and 1450 lb.-ft peak torque. Limited Production continued through July 2013. In August 2013, CWI released the remaining ISX12 G ratings (400 HP, 1450 lb.-ft and 385 HP, 1350 lb.-ft) and commenced the Full Production phase of the ISX12 G commercial launch.

As of late 2013, the ISX12 G engine is available as a factory-installed option in a wide range of Class 8 truck and tractor models offered by leading commercial vehicle OEMs including Autocar, Freightliner, Kenworth, Mack, Peterbilt, and Volvo. A complete and current list of OEM makes and models available with the ISX12 G engine is located at Cummins website (www.cumminswestport.com).

Summary

The ISX12 G engine design has been released into production at the Jamestown Engine Plant in Jamestown, New York, with ISX12 G Limited Production builds occurring from April through July 2013, and Full Production commencing in August 2013. ISX12 G is available with a full range of ratings, from 320 HP, 1150 lb.-ft to 400 HP, 1450 lb.-ft, as a factory installed option from a broad range of Class 8 truck and tractor manufacturers. Following ISX12 G launch, CWI intends to continue developing and optimizing the ISX12 G to further reduce oil consumption and to optimize the overhead valve lash settings to maximize engine performance and durability.

CHAPTER 10: Field Demonstration and Data Collection

This section summarizes the operating experience of the California-based vehicles within the overall ISX12 G field test program. Results presented in this section include cumulative mileage from the California fleet, in-use fuel economy data, and a summary of engine issues encountered and overcome during the field demonstration.

The goal of the Field Demonstration and Data Collection task is to conduct a six-month field demonstration program in California to collect data from vehicles operated in commercial applications. Due to the time lag associated with engine manufacturing, shipment, vehicle assembly, and delivery of new natural gas powered trucks, and to allow the demonstration period to begin immediately after product launch, this task was performed using the California-based field test trucks that Cummins Westport (CWI) used to validate the pre-production engines throughout Task 2. This report documents the field demonstration and data collection activities within Task 5.

Field Demonstration

CWI conducted extensive vehicle testing throughout the ISX12 G development program. At the outset of the ISX12 G development program, CWI established a reliability plan that included on-road vehicle testing with a series of Class 8 trucks and tractors operating in various end-use applications, geographic locations, duty cycles, and ambient conditions. Throughout the ISX12 G development program, CWI deployed 25 field test trucks throughout the United States equipped with Alpha or Beta ISX12 G engines, including seven trucks located in California. Table 13 identifies the California-based ISX12 G field test trucks.

The Ryder truck was leased to a Utah-based fleet in early 2013, and the truck was subsequently re-located from southern California to Salt Lake City. The vast majority of the mileage accumulated by this truck occurred outside California; therefore, the Ryder truck is not included in the scope of the Task 5 Field Demonstration.

The Agility Fuel Systems truck was used by Agility to evaluate and optimize CNG and LNG fuel system components in conjunction with the ISX12 G engine. This truck was instrumented by Agility to measure fuel pressure and temperature at various locations throughout the off-engine fuel system. Earlier in the ISX12 G development program, Agility operated this truck periodically, including on-road and chassis dynamometer testing, to measure and optimize the short-term performance of CNG and LNG fuel systems with the ISX12 G engine. The Agility truck was not intended to evaluate the long-term reliability and durability of the ISX12 G engine, and accordingly it

Table 13: California-based ISX12 G Field Test Trucks

Customer	Qty	Truck / Tractor	Alpha / Beta	New / Repower	Operating Location	Type of Application	Date in Service	OEM
Ecology	2	Tractor	Alpha	New	Los Angeles, CA	Refuse transfer	Nov-11	Kenworth
Waste Management	1	Tractor	Alpha	New	Oakland, CA	Refuse transfer	Dec-11	Freightliner
Walmart	1	Tractor	Alpha	New	Fontana, CA	Goods delivery	Jan-12	Freightliner
Agility Fuel Systems	1	Tractor	Alpha	Repower	Fontana, CA	CNG & LNG fuel system testing	Apr-12	Kenworth
Republic Waste	1	Truck	Alpha	New	Sun Valley, CA	Refuse collection (roll-off body)	Mar-12	Autocar
Ryder	1	Tractor	Beta	Repower	Fontana, CA	Goods delivery	Aug-12	Volvo

Source: Cummins Westport, Inc.

accumulated very few miles. The fuel system optimization work conducted with this truck is outside the scope of Energy Commission Grant ARV-09-013, and the limited mileage accumulated by this truck did not contribute meaningfully to CWI's Reliability Plan. Therefore, the Agility Fuel Systems truck is not included in the scope of the Task 5 Field Demonstration.

The remaining five California-based ISX12 G-powered field test trucks from Table 13 were operated in regular service by the respective fleets, and it is these five trucks that comprised the field demonstration fleet for the purpose of Task 5. Ecology operated two ISX12 G-powered Kenworth tractors in refuse transfer service in southern California (Figure 50). Republic Waste Services operated an Autocar low-cab forward truck in refuse collection service in Sun Valley. As shown in Figure 51, Republic's truck was equipped to deliver roll-on / roll-off refuse bins. Walmart operated a Freightliner tractor (Figure 52) delivering retail goods from Walmart distribution centers to Walmart stores throughout southern California. Walmart's truck was originally based at Walmart's Apple Valley facility, and also operated from Walmart's Fontana distribution center during 2013. Waste Management operated a Freightliner tractor in refuse transfer service in northern California, hauling trash from a transfer station in Oakland to the Altamont Pass landfill. Waste Management's truck is a Freightliner Cascadia equipped with CNG tanks and looks very similar to the Walmart truck shown in Figure 52.

As shown in Table 13, these trucks entered field test operation in late 2011 through early 2012. In late 2012, CWI upgraded these five trucks with production-intent software calibrations in order to yield production-representative ISX12 G-powered trucks for the purpose of Task 5. These calibration updates were completed in January 2013, which CWI considered to be the start of the Task 5 field demonstration task. The remainder of this section describes the mileage accumulation and demonstration data obtained from these five trucks from January through November 2013.

Figure 50: Ecology ISX12 G Refuse Transfer Tractor

Source: Cummins Westport, Inc.

Figure 51: Republic ISX12 G Refuse Collection Truck

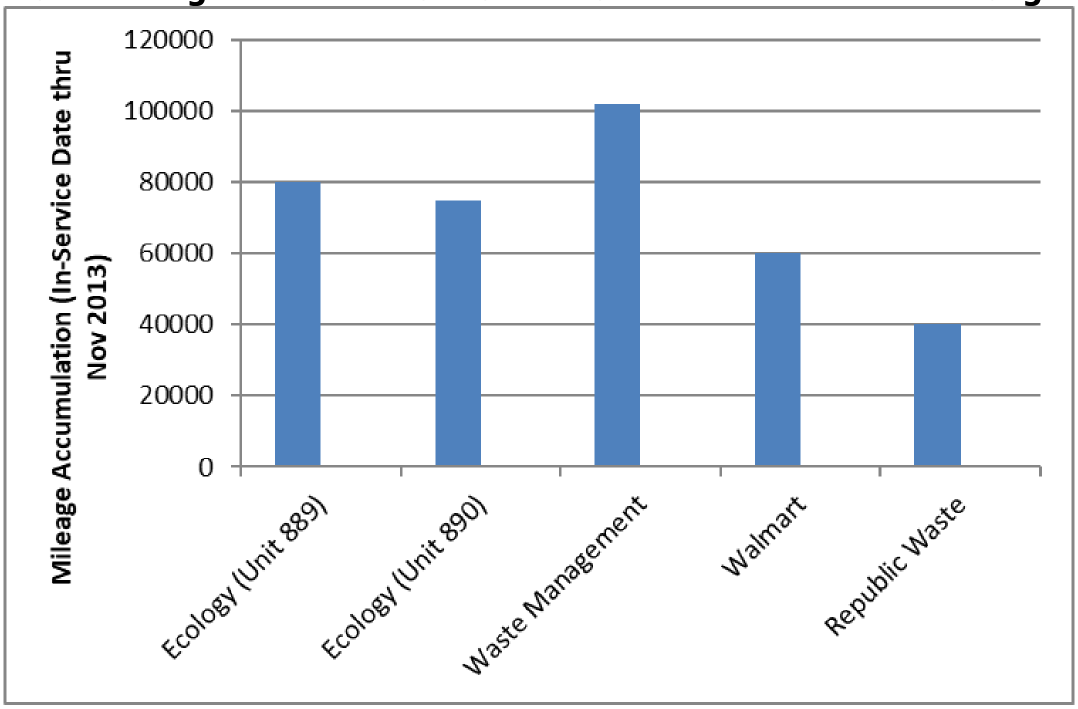
Source: Cummins Westport, Inc.

Figure 52: Walmart ISX12 G Tractor

Source: Cummins Westport, Inc.

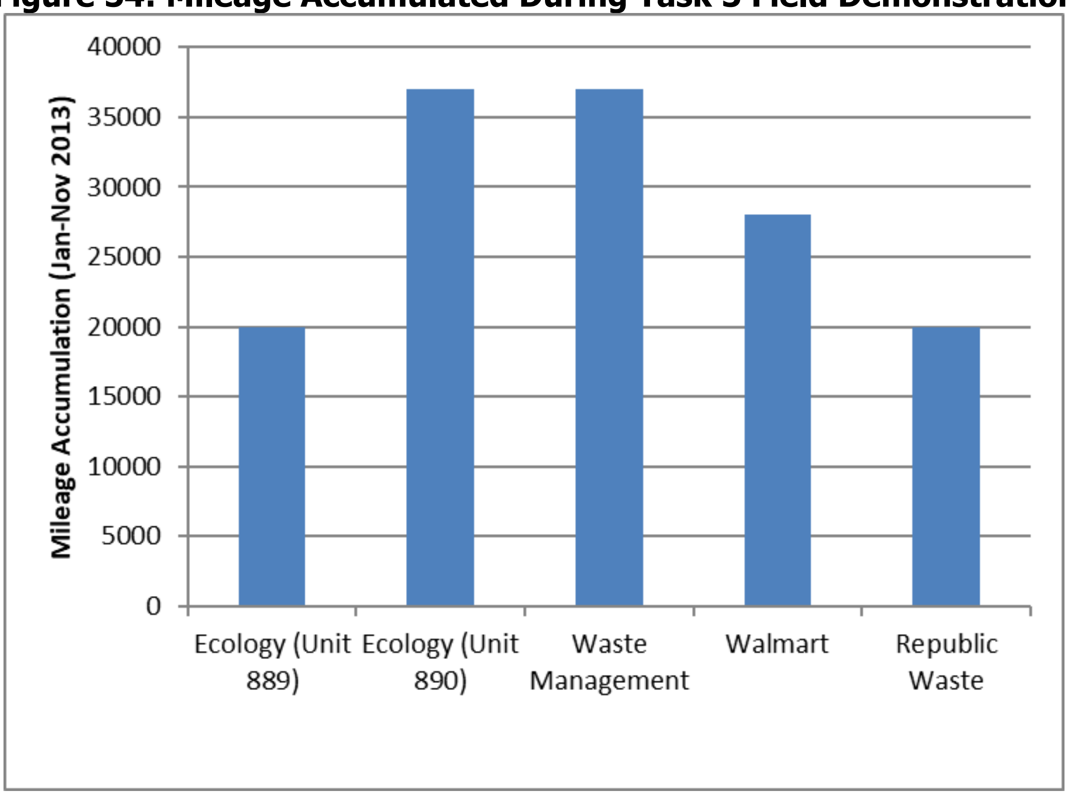
Figure 53 provides the total mileage accumulated by these five trucks throughout the ISX12 G development program (i.e. from each truck's respective in-service date through November 2013). Figure 54 provides the mileage accumulated by these five trucks specifically for the duration of the Task 5 field demonstration (January through November 2013).

Figure 53: Total Mileage Accumulation for California Field Test Fleet through Nov 2013



Source: Cummins Westport, Inc.

Figure 54: Mileage Accumulated During Task 5 Field Demonstration



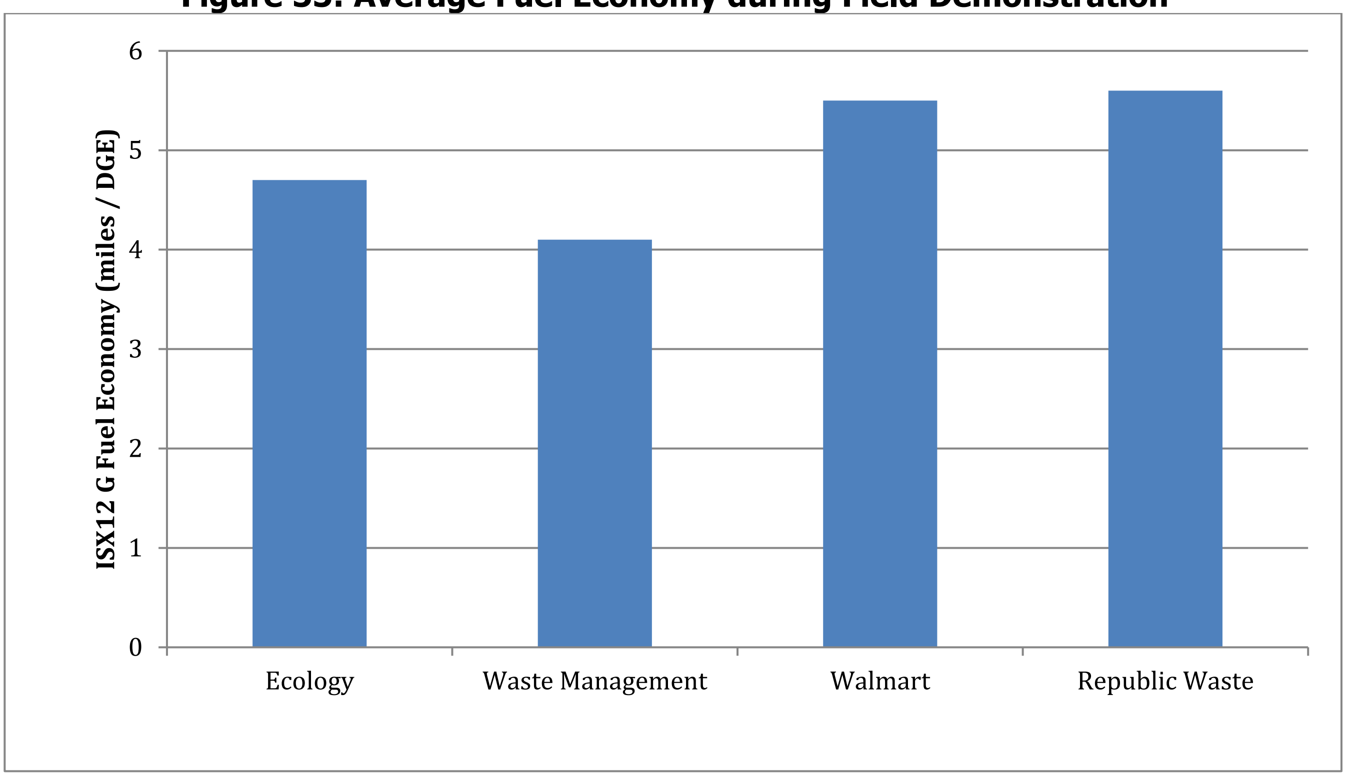
Source: Cummins Westport, Inc.

Figure 55 illustrates the average fuel economy from the customers operating the five trucks that comprise the Task 5 field demonstration fleet. The fuel economy in Figure 55 is reported in miles per diesel gallon equivalent (miles/DGE), as measured and reported by the ECM on the ISX12 G engine. Figure 55 clearly indicates lower fuel economy for the refuse transfer applications, which was expected and is well established in the Class 8 truck industry, for the following reasons:

- Refuse transfer trailers are loaded on a scale in order to maximize payload to the maximum allowable gross vehicle weight (GVW), which is 80,000 lbs. in California. Therefore, the refuse transfer tractors operate at 80,000 lbs. each and every trip from the transfer station to the landfill, then return empty. By contrast, the majority of on-highway Class 8 tractor fleets hauling retail goods in a van trailer (such as the Walmart truck) fill the trailer to its volumetric capacity (aka "cubing out") before reaching the maximum allowable GVW ("grossing out"). Further, the nature of Walmart's operation called for multiple deliveries per trip, thus the actual combined weight of the tractor and trailer progressively decreased throughout the shift as goods were removed from the trailer at each store.
- Refuse transfer trailers have no roof, in order to accommodate loading the trailer with trash through the open top. In order to ensure that the trailers have sufficient structural rigidity, the trailer sides have deep exterior ribs, as opposed to smooth sides for van trailers. Further, refuse transfer trailers are typically taller than conventional van trailers, in order to ensure sufficient trailer volume to enable maximum payload each trip. The resulting trailer aerodynamics are very poor in comparison with other trailer types, thus causing higher fuel consumption in comparison with typical on-highway Class 8 tractors.

The fuel economy data shown in Figure 55 is consistent with CWI's expectations prior to commencing the field demonstration.

Figure 55: Average Fuel Economy during Field Demonstration



Source: Cummins Westport, Inc.

As described in the Task 2 reports submitted previously for this project, late in the ISX12 G development program CWI revised the production-intent engine calibration in order to reduce the exhaust emissions, in response to achieving a NOx emission deterioration factor (DF) that was higher than originally expected. The new calibration was installed in the field demonstration trucks prior to commencing the Limited Production phase of the ISX12 G commercial launch in early 2013. Driver feedback from the fleets identified above indicated that the engine calibration changes resulted in noticeably different vehicle drivability versus prior versions of the ISX12 G field test calibrations. In particular, the field demonstration drivers reported that vehicle acceleration and throttle response had been compromised with the revised calibration. CWI Engineering used this field demonstration feedback to further refine the final production calibration, and successfully delivered a calibration that met the certified emission requirements while restoring vehicle drivability and responsiveness to the levels experienced throughout the overall field test program.

Throughout the on-road field test program, test drivers provided feedback regarding an audible turbocharger surge issue during mid-speed operation. The problem was duplicated on CWI's Engineering truck and two sources were identified: transient boost pressure and coupled fueling issue, and turbocharger surge. Improvements were made to the control system to resolve the issue with transient behavior of boost and fueling that resulted in considerable reduction in the surge. However, the phenomenon of turbocharger surge under sudden throttle closing maneuvers was not resolved, and results in possible noise associated with some of these events, although there is no impact to emissions or engine performance. The noise may be observable by the operator and is typically referred to as a "chuffing" sound. A boost relief system would reduce the audible surge at throttle closing events and is being considered for development and implementation through ongoing development and optimization of the ISX12 G engine post-launch.

Throughout the ISX12 G development program, CWI had planned to replace the prototype, emissions-exempt field test engines with new, production-built, emission certified engines. By late 2013, CWI had replaced the pre-production ISX12 G engines with new, production released ISX12 G engines in the two Ecology field demonstration trucks, and the Republic truck. The Walmart and Waste Management tractors are scheduled to be replaced with new, production released ISX12 G engines in early 2014.

Following production release of the ISX12 G engine, some of the field demonstration fleets placed orders for additional ISX12 G-powered trucks. Therefore, the Task 5 field demonstration provided value to end-users by informing their natural gas vehicle purchase decisions and accelerating the market adoption of the ISX12 G engine.

Summary

CWI successfully completed a field demonstration of five production-equivalent ISX12 G-powered trucks with various customers in California. The California-based field demonstration fleet accumulated significant mileage and contributed valuable data and driver feedback to enable CWI Engineering to finalize engine calibrations and confirm acceptable engine operation leading up to full production release of the ISX12 G in mid-2013. The field demonstration vehicles yielded fuel consumption data that was consistent with CWI's expectations. Perhaps most importantly, within the first few months following commercial production release of the ISX12 G engine, some of the Task 5 field demonstration customers had ordered new, ISX12 G-powered trucks.

CHAPTER 11: Conclusion

Summary of Agreement Objectives

- Validating, engineering, and further refining the Alpha engine design completed in a prior CEC-sponsored project (partially funded under PIER Grant Agreement PIR-08-044), including extensive laboratory, rig, and engineering-vehicle testing,
- Demonstrating a number of engines in a variety of vocational and regional haul Class 8 truck/tractor customer vehicles with California-based fleet operators,
- Obtaining emissions certification at or below EPA/CARB 2010 emission standards (g/bhp-hr.): 0.20 NOx, 0.14 NMHC, 0.01 PM, 15.5 CO,
- Demonstrating improved fuel economy of 5 to 10% when compared to current spark ignited natural gas-powered trucks in specific vocational and regional haul Class 8 truck/tractor duty cycles,
- Demonstrating and quantifying engine GHG emission reductions (i.e. measured on a tank-to-wheels basis) vs. diesel engines when operated on the EPA emission certification duty cycle,
- Validating production manufacturing and testing capability for the new natural gas engine,
- Identifying and qualifying production suppliers for all new components required to build the proposed engine,
- Launching the new engine into limited commercial production by April 2013 and full production by July 2013, making the engine product available directly from the factory of multiple North American heavy-duty Class 8 truck and tractor manufacturers, and
- Demonstrating the engine in California fleet operations, gathering six months of data, and reporting project results to the California Energy Commission.

All of the aforementioned objectives were achieved in this project. Full Production engine builds continue at the Jamestown Engine Plant. As anticipated, the Full Production engine orders are heavily weighted toward the peak rating (400 hp, 1450 lb.-ft), which entered production in July 2013. In excess of 2000 ISX12 G engines have been built since the start of Limited Production earlier in 2013. CWI replaced or is replacing field test engines with new, production-built, emission-certified engines.

CWI conducted, and successfully passed, the final ISX12 G development program review with the ISX12 G Management Review Group, which was comprised of senior management and functional experts from CWI, Cummins and Westport. The successful completion of this final program review formally marked the end of the ISX12 G development program. Technical, marketing, and customer service responsibility have now formally transitioned to CWI’s Current Product Support organization for ongoing product support.

GLOSSARY

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIRECT CURRENT (DC)—A charge of electricity that flows in one direction and is the type of power that comes from a battery.

CARBON MONOXIDE (CO)—A colorless, odorless, highly poisonous gas made up of carbon and oxygen molecules formed by the incomplete combustion of carbon or carbonaceous material, including gasoline. It is a major air pollutant on the basis of weight.

DIESEL GALLON-EQUIVALENT (DGE)—is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel gasoline.

DETERIORATION FACTOR (DF)—The relationship between emissions at the end of useful life and emissions at the low-hour test point, expressed in one of the following ways.

ELECTRONIC CONTROL MODULE (ECM)—A system that controls a series of actuators in the diesel engine to ensure optimal engine performance through electronic control. Modern diesel engines have a number of sensors within the engine and machine which provide readings to the ECU.7

EXHAUST GAS RECIRCULATION (EGR)—An emission control technology allowing significant NOx emission reductions from most types of diesel engines: from light-duty engines through medium- and heavy-duty engine applications right up to low-speed, two-stroke marine engines.[2]

ENGINE MANUFACTURER DIAGNOSTIC (EMD)—Requirements for light-duty vehicles and for heavy-duty engines used in vehicles up to 14,000 lbs. GVWR (medium-duty vehicles) have been introduced in two steps: OBD I—The first OBD regulation in the United States, which required manufacturers to monitor some of the emission control components on all 1991 and

[2] DieselNet Technology Guide. https://dieselnet.com/tech/engine_egr.php

newer vehicles sold in California.[3]OBD II—This more rigorous OBD regulation started to be phased-in in 1994. Since 1996, its implementation has been required on all new gasoline and alternate fuel passenger cars and trucks sold in California. All 1997 and newer diesel fueled passenger cars and trucks are also required to meet OBD II requirements.

GAS (GHG)—Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). (EPA)

GROSS VEHICLE WEIGHT (GVW)—The maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo but excluding that of any trailers.

HORSEPOWER (HP)—A unit for measuring the rate of doing work. One horsepower equals about three-fourths of a kilowatt (745.7 watts).

JAMESTOWN ENGINE PLANT (JEP)—one of Cummins' largest manufacturing facilities; accounted for 14.7 percent of Cummins total engine production in 2017. Cummins acquired the more than one million-square-foot facility in 1974, using it initially to manufacture engine components. Since building their first engine in 1981, production in recent years typically exceeds 100,000 engines annually. Jamestown is home to the production of Cummins heavy-duty engine technologies including the X15, ISX12, X12, ISM11 diesel engines and ISX12N natural gas engine as well as historically the ISX15 diesel engine and ISX12 G natural gas engine.[4]

LEAN BURN SPARK IGNITION (LBSI)—Lean burn gas engines produce NOx emissions as low as 0.5 g/bhp-hr. (250 mg/Nm^3) without the use of exhaust aftertreatment, versus 10 to 20 g/bhp-hr. (4,550 to 9,100 mg/Nm^3) for rich-burn engines not equipped with exhaust aftertreatment. Even lower emissions can be achieved through commercially available exhaust aftertreatment technologies such as oxidation catalysts, ureabased SCR catalysts, and three-way catalysts. This new generation of engines can operate for as long as 4,000 hours between spark plug and oil changes – some six months of continuous duty, more than double the intervals expected from traditional engine technology.[5]

LOW CARBON FUEL STANDARD (LCFS)—A set of standards designed to encourage the use of cleaner low-carbon fuels in California, encourage the production of those fuels, and therefore, reduce greenhouse gas (GHG) emissions. The LCFS standards are expressed in terms of the "carbon intensity" (CI) of gasoline and diesel fuel and their respective substitutes. The LCFS is a key part of a comprehensive set of programs in California to cut greenhouse gas emission

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[3] United States: On-Board Diagnostics, California OBD. DieselNet.com https://dieselnet.com/standards/us/obd_ca.php

[4] Cummins Inc. Cummins Newsroom. 2018. "Cummins Inc. Celebrates Production of Two Millionth Engine at Jamestown Engine Plant." https://www.cummins.com/news/releases/2018/07/26/cummins-inc-celebrates-production-two-millionth-engine-jamestown-engine

[5] Michael Devine, Caterpillar. "The Electronic Age of Engines: The Best of All Worlds." http://s7d2.scene7.com/is/content/Caterpillar/CM20160629-32522-02902

and other smog-forming and toxic air pollutants by improving vehicle technology, reducing fuel consumption, and increasing transportation mobility options.

LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

METHANE NUMBER (MN)—A measure of the resistance of the gaseous fuel to autoignition (knock) when used in an internal combustion engine. The relative merits of gaseous fuels from different sources and having different compositions can be compared readily on the basis of their methane numbers. Therefore, the calculated methane number (MN) is used as a parameter for determining the suitability of a gaseous fuel for internal combustion engines in both mobile and stationary applications.[6]

NATIONAL HIGHWAY TRANSPORTATION SAFETY ADMINISTRATION (NHTSA)—The agency within the U.S. Department of Transportation that works to reduce deaths and injuries and economic costs due to motor vehicle crashes. NHTSA works to deliver safer roads by encouraging Americans to make safer choices when they drive, ride, and walk; advancing lifesaving vehicle safety technologies; and supporting state and local police in their efforts to enforce the rules of the road that protect us all.[7]

ULTRA LOW SULFUR DIESEL (ULSD)—In parallel with the 1994 emission standards for heavy duty diesel engines, the EPA introduced new requirements for highway diesel fuel. Effective October 1, 1993, a new sulfur limit of 0.05% (500 ppm) superseded the earlier ASTM specification of 0.5%. The 0.05% sulfur fuel was termed "low sulfur" diesel. Further significant reductions of sulfur levels in highway diesel fuel were legislated by the EPA as a part of the 2007-2010 emission regulations for heavy-duty engines [66 FR 5135-5193, 18 January 2001]. Fuel of maximum sulfur content of 15 ppm (wt.)—called "ultra-low sulfur diesel" (ULSD)—was required to be available beginning in mid-2006. The ULSD fuel was legislated as a "technology enabler", to facilitate the use of sulfur-sensitive catalyst-based emission technologies on MY2007 and later heavy-duty engines, as well as on Tier 2 compliant light duty diesel vehicles.[8]

THREE-WAY CATALYST (TWC)—A three-way catalyst oxidizes exhaust gas pollutants -- both hydrocarbons (C_mH_n) and carbon monoxide (CO) -- and reduces nitrogen oxides (NOx) into the harmless components water (H_2O), nitrogen (N_2) and carbon dioxide (CO_2).

WELL TO WHEEL (WTW)—A specific LCA (Life-cycle Assessment) used for transport fuels and vehicles. The analysis is often broken down into stages entitled "well-to-station", or "well-to-tank", and "station-to-wheel" or "tank-to-wheel", or "plug-to-wheel". The first stage, which incorporates the feedstock or fuel production and processing and fuel delivery or energy

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[6] American Society for Testing and Materials. ASTM D8221. "Standard Practice for Determining the Calculated Methane Number (MNC) of Gaseous Fuels Used in Internal Combustion Engines." https://www.astm.org/Standards/D8221.htm

[7] U.S. Department of Transportation. https://www.transportation.gov/briefing-room/safetyfirst/national-highway-traffic-safety-administration

[8] DieselNet Fuel Regulations. Automotive Diesel Fuel. https://dieselnet.com/standards/us/fuel_automotive.php

transmission, and is called the "upstream" stage, while the stage that deals with vehicle operation itself is sometimes called the "downstream" stage. The well-to-wheel analysis is commonly used to assess total energy consumption, or the energy conversion efficiency and emissions impact of marine vessels, aircraft and motor vehicles, including their carbon footprint, and the fuels used in each of these transport modes. WTW analysis is useful for reflecting the different efficiencies and emissions of energy technologies and fuels at both the upstream and downstream stages, giving a more complete picture of real emissions.