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FINAL PROJECT REPORT

Ultra-Low Emission Natural Gas 12-Liter Engine for On-Road Heavy-Duty Vehicles

Edmund G. Brown Jr., Governor

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PREFACE

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

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

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

Ultra-Low Emission Natural Gas 12-Liter Engine for On-Road Heavy-Duty Vehicles is the final report for the Low NOx 12-Liter Natural Gas Engine Development project (Contract Number 500-16-002) conducted by the South Coast Air Quality Management District. The information from this project contributes to Energy Research and Development Division's Natural Gas-Related Transportation Program.

All figures and tables are the work of the authors for this project unless otherwise cited or credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's research website (www.energy.ca.gov/research/) or contact the Energy Commission at 916-327-1551.

ABSTRACT

Heavy-duty on-road diesel vehicles are currently among the top ten sources of NOx (oxides of nitrogen) emissions in the South Coast Air Basin. The development of ultra-low emission natural gas engines would significantly reduce emissions from this category of vehicles and assist the region in meeting federal ambient air quality standards in the coming years.

The project team designed, developed, demonstrated, and achieved California Air Resources Board and United States Environmental Protection Agency certification of an ultra-low emission 11.9-liter natural gas engine, named the “ISX12N”. The ISX12N represents an upgrade to the current ISX12 G production engine, with an improved three-way catalyst, a closed crankcase ventilation system, and optimized engine controls that improve upon the base design and meet state engine certification goals. The project team also developed heavy-duty on-board diagnostics to meet California Air Resources Board requirements.

The project proved the technical and commercial viability of the ISX12N engine, and the engine was able to meet the certification requirements for the California Air Resources Board’s most stringent Optional Low NOx standard as well as the United States Environmental Protection Agency’s current criteria pollutant and greenhouse gas emissions standards.

The project successfully demonstrated the ISX12N engine in on-road heavy-duty vehicle applications including regional haul truck and refuse truck applications. Fifteen field test units supplemented the rigorous engine testing by accumulating mileage in real-world operation and addressing unforeseen issues prior to the engine entering commercial production, thereby improving product reliability. The engine moved to commercial production in February 2018.

Keywords: ultra-low emissions, heavy-duty engine, Class 8, near zero, ISX12 G, ISX12N

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EXECUTIVE SUMMARY

Introduction

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

According to the California Air Resources Board, around 80 percent of NOx emissions in California come from cars, trucks, and other mobile sources powered by fossil fuels. In the South Coast Air Basin, considered one of the worst areas for smog in the nation, heavy-duty on-road diesel vehicles are currently among the top ten sources of NOx. This source category is projected to continue to be one of the largest contributors to NOx emissions, even though the legacy fleet of older and higher-polluting vehicles is gradually being replaced by vehicles meeting newer and more stringent emission standards.

One way to help address this problem is to develop ultra-low emission natural gas engines that can significantly reduce emissions from this on-road source category and assist the region in meeting federal ambient air quality standards in the coming years. The emissions from an internal combustion engine that emits 90 percent fewer NOx emissions relative to current standards for heavy-duty vehicles could be roughly comparable to emissions from an equivalent all-electric heavy-duty vehicle, if the emissions associated with the electricity production are taken into account.

Ultra-low emission natural gas engines are already being used in the transit, refuse, regional haul truck, and school bus markets. Cummins Westport Inc., which conducted the project described in this report, designs, engineers, and markets natural gas engines for commercial applications including trucks and buses. More than 80,000 Cummins Westport natural gas engines based on Cummins diesel engines are in service worldwide and are designed to meet the most stringent emissions regulations. Cummins Westport Inc. released the first heavy-duty engine certified to 2010 United States Environmental Protection Agency emissions standards – the 8.9-liter ISL G – in 2007, three years before the standards took effect. The ISL G engine quickly gained favor in the transit and refuse market segments, and was followed by other engines targeted toward the regional haul truck and school bus markets. In 2016, Cummins Westport Inc. released an ultra-low emissions version of the ISL G, called the ISL G Near Zero, which was certified to the California Air Resources Board's lowest optional NOx standard.

Project Purpose

The specific objectives of this project were to:

- Design, develop, and demonstrate a commercially viable, ultra-low emission 12-liter natural gas engine suitable for on-road heavy heavy-duty vehicle applications such as Class 8 trucks and buses. In California, heavy-duty trucks are defined as those more than 14,000 pounds gross vehicle weight, divided into light heavy-duty (14,000 pounds to 19,500 pounds, Class 4 and Class 5), medium heavy-duty (19,501 pounds to 26,000 pounds, Class 6), and heavy heavy-duty (26,001 pounds to 33,000-plus pounds, Class 7 and Class 8).
- Support the pathway to certifying the engine to the California Air Resources Board's lowest Optional Low NOx standard and to United States Environmental Protection Agency standards.
- Keep exhaust ammonia emissions from the engine as low as achievable.
- Achieve minimal fuel economy penalties relative to 2010 United States Environmental Protection Agency and California Air Resources Board certified diesel engines under similar operating conditions.

Project Approach

The early stages of product development in this project focused on "paper design," including simulations and calculations to identify design changes needed to existing production engines to meet the project's emission reduction, fuel economy, and commercial viability objectives. The design progressed with actual prototypes that were built based on the early design. The team tested Alpha (preliminary design phase) prototype engines in "test cells" to address specific performance characteristics in an environment that allowed precise control of operation and accurate measurement of engine performance. The aftertreatment technologies (devices for reducing harmful emissions from internal combustion engines) underwent a similar design and testing process.

During the Beta (secondary and final design phase) prototype phase of the project, the team revised the engine designs and identified changes to the aftertreatment system needed to address issues detected in the Alpha phase. The Cummins engine plant built prototype engines and aftertreatment systems that were installed in 13 Class 8 vehicles operated by UPS, FedEx Freight, Dillon Transport, Waste Management, TTSI, Sheehy, Thatcher Chemical, and Frito Lay. Testing the engines and aftertreatment systems during actual vehicle operation confirmed overall performance in a real world environment and accumulated mileage to prove reliability and durability.

In parallel with the engine design process, the team conducted work in other areas of the overall engine development to address commercialization aspects including supply chain, manufacturing, marketing, and customer care. All of these areas were addressed, resulting in a quality engine and after-treatment system ready for production and commercial sales to vehicle manufacturers.

Project Results

The project team developed and demonstrated a production-ready (generally beyond a prototype, with a stable design to enter production), 11.9-liter (ISX12N), heavy-duty natural gas engine, certified to the California Air Resources Board's lowest Optional Low NOx standard and United States Environmental Protection Agency's emissions standards. The engine met the project objectives by:

- Demonstrating a peak rating of 400 horsepower and 1,450 foot pounds of torque.
- Reducing ammonia emissions by more than 50 percent compared to the base ISX12 G natural gas engine, to just under 40 parts per million measured in the Cold/Hot Emission Test cycle.
- Achieving approximately 15 percent more fuel efficiency than a similar model year 2010 ISX12 diesel engine, based on analysis of carbon dioxide emissions during the Federal Test Procedure cycle.
- Meeting the NOx emissions target of 0.02 grams per brake horsepower-hour, and reducing other gaseous, particulate matter, and certain non-regulated emissions below previous levels.
- Receiving emissions certification from the California Air Resources Board and United States Environmental Protection Agency with more than 90 percent lower NOx emissions than the current federal standard.

Cummins began production of the ISX12N engine in February 2018. Going forward, existing vehicle manufacturers that offer the prior Cummins engine (ISX12 G) will integrate the ISX12N into their vehicle chassis for commercial availability. Vehicle manufacturers will have the engine available in their product offerings following the engine production launch, with the exact timing varying by manufacturer and vehicle model.

Technology Transfer

Cummins Westport Inc. plans to make the knowledge gained in the project publicly available, and will promote the technical and economic benefits of the project in the following ways:

- Continue commercial production of the ISX12N and work with existing vehicle original equipment manufacturers to offer their vehicles with the new engine. All existing vehicle original equipment manufacturers that currently offer the ISX12 G will transition to offer the same vehicles with the ISX12N.
- Going forward, offer only the ultra-low NOx ISX12N engine over the prior ISX12 G engine.

- Publicly provide engine and aftertreatment emissions results, including real-world emission test results from the University of California, Riverside.
- Continue presenting information about near zero technology and the ISX12N product at technology forums, tradeshows, and industry events.
- Provide new technology and product presentations for original equipment manufacturers to use internally within their companies as well as with their customers.
- Provide training on engines through the Cummins dealer network that includes information on the ISX12N engine.
- Provide current information on the Cummins Westport Inc. public website.

Benefits to California

Various industry stakeholders, including consultants, government agencies, and original equipment manufacturers, project continued natural gas vehicle penetration in the North American heavy-duty commercial vehicle market. The technical achievements in this project will help support that penetration.

This project successfully produced an ultra-low emissions natural gas engine for use in heavy-duty on-road vehicles, which are some of the largest contributors to NOx emissions in California. Emissions of NOx and particulate matter have been linked to health problems like asthma, bronchitis, lung cancer, and heart disease. Adoption of these engines will provide significant air quality improvements over time as older, more polluting vehicles are replaced.

Using these engines with renewable natural gas will provide significant greenhouse gas reductions. Renewable natural gas is acquired from renewable organic material such as food and animal waste. Left unused, these sources typically decay and emit potent greenhouse gases to the atmosphere. If collected and processed, however, the resulting gases can be used as a renewable vehicle fuel to displace fossil fuels and thereby reduce greenhouse gases, in some scenarios resulting in "near zero" or even negative emissions. Reducing greenhouse gas emissions is important for addressing climate change and its associated negative public health, environmental, and economic effects on California and its residents.

Finally, this project will support California state and regional regulatory policy to implement lower emissions technologies by proving heavy-duty natural gas engines are able to cost effectively achieve ultra-low emissions. Incentive funding and public fleet mandates will help accelerate deployment of the ISX12N engine to quickly realize emission reductions from the heavy-duty on-road vehicle sector.

Recommendations

Cummins Westport Inc. suggests the following activities to implement low NOx technologies, engines, and vehicles:

- Promote awareness of ultra-low NOx engine and vehicle availability through outreach to government agencies, policy makers, air districts, commercial fleets, and the general public.
- Support regulatory and incentive programs, such as the California Air Resources Board's Sustainable Freight Transport Initiative, and execution of programs such as the Clean Air Action Plan for the Port of Los Angeles and Port of Long Beach.
- Offer assistance with low NOx technology development and commercialization by expanding low NOx engine offerings. Continue advancements in natural gas engine and vehicle development to reduce emissions and improve fuel efficiency.

CHAPTER 1: Introduction

Background

Cummins Westport Inc. (CWI) – a joint venture company between Cummins Inc. and Westport Fuel Systems Inc. – develops and markets the world's widest range of high-performance low-emission engines for transit and commercial vehicles. The company has established broad vehicle original equipment manufacturer (OEM) availability of its engines.

CWI originally proposed to develop and demonstrate an advanced, commercially ready version of its 11.9-liter spark ignited natural gas engine and exhaust aftertreatment system that could achieve an oxides of nitrogen (NOx) level of 0.02 grams per brake horsepower-hour (g/bhp-hr), reduced ammonia (NH_3) emissions (targeting 10 parts per million NH_3), and minimal fuel economy penalties.

CWI assembled a comprehensive team comprised of internal CWI engineers, supporting engineers within the Cummins family (Cummins Emission Solutions, Cummins Filtration, and Cummins Distributors), and vehicle OEM partners such as PACCAR, DTNA, Autocar, Volvo, and Mack. In addition, a number of commercial fleets assisted with the testing of prototype engine systems, including UPS, FedEx Freight, TTSI, Sheehy, Waste Management, Thatcher Chemical, Dillon Transport, and Frito Lay.

This project builds on prior work funded by the South Coast Air Quality Management District, California Energy Commission, and Southern California Gas Company. In that project, CWI developed the technology to reach ultra-low NOx (0.02g/bhp-hr) levels which resulted in the commercially available ISL G Near Zero 8.9-liter engine. The technology was very effective at achieving California Air Resources Board (CARB) Optional Low-NOx emissions certification. Compared to the existing line of spark-ignited engines, the technology added little new hardware, and built on the reliability and durability improvements achieved since the ISL G was first introduced in 2007.

The success of the ISL G Near Zero project led to CWI's decision to use the same architecture – adding a closed crankcase ventilation system (CCV), improved aftertreatment, and optimized controls to an existing ISX12 G stoichiometric spark ignited natural gas engine – for the development of a new ultra-low NOx engine, named the "ISX12N." Using a proven architecture avoided lengthy and costly development of other possible technologies and allowed a short commercial development process, thereby delivering a commercial product which could cost effectively improve air quality in the near term. Common architecture across multiple engines will also provide cost and time advantages for future engineering work, such as issue correction and performance improvements.

CWI developed the ISX12N engine and enhanced aftertreatment system using established CWI and Cummins product development procedures that validate engine performance, emissions, reliability, durability, and manufacturability. CWI worked with existing ISX12 G vehicle OEMs to have them integrate the advanced ISX12N into at least five vehicle models. CWI then installed prototype ISX12N engines and aftertreatment systems into 2 engineering and 13 customer vehicles (12 Class 8 tractors and 1 Class 8 refuse truck) for customer vehicle demonstrations and field trials. CWI secured the support of leading industry vehicle OEMs in the Class 8 tractor and refuse truck markets, and leveraged their expertise and design guidance for the pre-commercial, production-intent[1] engine and aftertreatment system. CWI demonstrated the engine and aftertreatment system in these vehicles for at least six months each, with some demonstration vehicles operating for more than a year.

By the end of the project, CWI completed development and commercialization of the engine; production of the ISX12N engine began at the Cummins engine plant in Jamestown, New York in February 2018.

Project Objectives

The goal of this project was to have a commercially available 12-liter natural gas engine certified to CARB's lowest Optional Low NOx standard. The availability of such an engine in the market will help improve California's air quality and its ability to meet ambient air quality standards.

Specific project objectives were:

- Achieve emissions targets of 0.02 g/bhp-hr NOx, 0.01 g/bhp-hr particulate matter, 0.14 g/bhp-hr non-methane hydrocarbons, and 15.5 g/bhp-hr carbon monoxide or lower as determined by the heavy-duty engine Federal Test Procedure.
- Keep exhaust ammonia emissions as low as achievable while targeting ammonia emissions at 10 parts per million or less.
- Achieve minimal, fuel economy penalties relative to 2010 United States Environmental Protection Agency (USEPA) and CARB -certified diesel engines on a similar duty cycles.
- Support the pathway to certifying the engine to the California Air Resources Board's lowest Optional Low NOx standard and to United States Environmental Protection Agency standards.

[1] Generally speaking, production-intent indicates a product that is more than a prototype but not yet a full commercial product.

CHAPTER 2: Project Approach

Work Plan Development

At the start of the project, Cummins Westport Inc. (CWI) developed a detailed work-plan for the design, analysis and development of the proposed natural gas engine and aftertreatment technologies.

The project team completed a system technical profile which was then reviewed and approved by CWI management. Based on the project objectives, the system technical profile identified the following requirements for the model year 2018 engine project:

- Attainment of Near Zero (0.02 grams per brake horsepower-hour [g/bhp-hr]) NOx (oxides of nitrogen), which required:
    - New exhaust aftertreatment catalyst with changes to formulation, volume, oxygen sensor location, and packaging.
    - New engine control strategies.
- Improved exhaust gas recirculation (EGR) system (higher fidelity sensing and control).
- Improved fuel system (higher fidelity control and field reliability improvement).
- Closed crankcase ventilation system (CCV).
- Power cylinder changes to improve oil consumption.
- Heavy Duty On-Board Diagnostic (HD-OBD) compliance, requiring:
    - New engine control module (CM2380) with increased memory, throughput and input/output with new engine electrical harness.
    - Society of Automotive Engineers (SAE) J1939 compliant on-board diagnostic (OBD) Scan Tool Interface @500k baud.
    - Additional and enhanced diagnostic algorithms to meet California Code of Regulations 1971.1 requirements.
    - OBD-compliant fault management (malfunction indicator lamp), data logging and reporting).
    - Additional or enhanced sensors (exhaust manifold pressure, EGR delta-P, intake manifold pressure and temperature, CCV pressure, and exhaust gas oxygen).

The team then analyzed the requirements and proposed design using an Integrated Design, Failure Modes and Effects Analysis (iDFMEA) process[2] to identify high risk areas and actions needed to quantify and reduce those risks (Table 1).

Table 1: Integrated Design, Failure Modes and Effects Analysis Process Steps

Step	Status
Complete Statement of Work	Complete
Gather existing system level data	Complete
Update boundary diagram	Complete
Update function analysis	Complete
Identify new, unique, or difficult design functions	Complete
Identify update/creation needs	Complete
Complete failure modes and effects analysis creation and ranking	Complete
Enter high Risk Priority Number items into Design Verification Plan & Report database (Risk Priority Number = Severity x Occurrence x Detection, and is used to set the priority of a specific failure mode.)	Complete
Track Design Verification Plan & Report progress versus plan	Complete

Source: Cummins Westport Inc.

The process used to ascertain risk identifies each new, unique, or difficult (NUD) design function that is critical to program success and whether the following characteristics are unknown, not understood, or undefined:

- Process Performance Index (a measure of manufacturing process performance in meeting a specification).
- Sources of variation.
- Key parameters.
- Impact on other functions.
- Transfer function (ratio of output to input).

Table 2 shows the NUD functions identified for this project.

[2] An Integrated Design, Failure Modes and Effects Analysis process identifies potential failure modes and effects of a component or system and assesses possible design changes or mitigation steps fed back through the design process.

Table 2: Identified New, Unique, or Difficult Functions

NUD Function	NUD Item
Transfer Torque	Fuel system capability Spark plug durability Power cylinder updates
Transfers Data	On-board diagnostics New sensors (exhaust gas recirculation delta-P, lambda sensors, inlet manifold pressure temperature sensor) New electronic control module introduction with higher speed datalink for on-board diagnostics compliance
Transfers Exhaust Gas	Catalyst degradation Catalyst configuration changes
Transfers Fuel	New fuel system
Transfers Blowby Gas	Closed crankcase ventilation introduction

Source: Cummins Westport Inc.

Once the team determined the NUDs, they identified lower-level risks and issues, which fell into four broad categories:

- Performance Risks:
  - Spark plug life.
  - Emissions performance.
  - Oil consumption.
  - Fuel consumption and thermal efficiency transparency.
  - Aftertreatment capability.
  - Cooling system top tank temperature limits.
- Software/Controls/OBD Risks:
  - Electronic Service, Engineering and Manufacturing tool support schedule.
  - OBD emissions threshold monitor development.
  - OBD comprehensive component monitor development.
  - OBD infrastructure development.
  - OBD algorithm calibration.
  - OBD algorithm validation.
  - CM2380 control module development and validation.
- Mechanical Hardware Development Risks:
  - Fuel system development and integration.
  - EGR system development and integration.
  - Closed Crankcase Ventilation system development and integration.

- Exhaust Aftertreatment Development Risks:
    - Accelerated aging process development and validation.
    - Catalyst sintering from high temperature.

The team then developed and reviewed the Design Verification Plan & Report (DVP&R)[3] and entered the planned tasks into a database to allow tracking of the progress against the plan. Cummins Engineering Standard Work, Functional Excellence Practices, and CWI's past experience were used to develop the plan. Each sub-system and component was then reviewed to ensure the plan was sufficient. The breakdown of the number of detailed task elements required to complete the design validation plan for each major subsystem is shown in Table 3.

Typical DVP&R tasks included analysis to determine stress and strain levels, durability tests to subject the subsystem or components to environmental stresses they will experience in an expected product lifetime, electromagnetic interference and compatibility tests to determine susceptibility to external interference and quantify the amount electrical noise generated by the engine, and performance tests to validate that technical profile requirements are being met.

Table 3: Key Product Target Specifications

Subsystem	Task Quantity
Aftertreatment	310
Air Handling	164
Closed Crankcase Ventilation	27
Electronics & Controls	35
Fuel System	44
Ignition System	1
Performance Development	65
Power Cylinder	42
Total	688

Source: Cummins Westport Inc.

Product Validation Matrix

The team created a product validation matrix (Table 4) to show the progress of various engine areas throughout the product design and development process. Typically, engine product design starts with developing the technology architecture followed by validating the technology to provide a stable system architecture. The technology architecture for the ISX12N project was based on a previous project on the ISL G Near Zero engine that was funded by the South Coast Air Quality Management District, the

[3] The Design Verification Plan & Report is a plan of the activities which will verify the technical requirements of a component or system, followed by a report to document the results of these activities.

California Energy Commission, and Southern California Gas Company on the ISL G Near Zero engine. In that project, the technology architecture consisted of:

- Stoichiometric spark ignited combustion with cooled exhaust gas recirculation.
- Closed crankcase ventilation system.
- Three-way catalyst aftertreatment.
- Wastegate turbocharger.
- Throttle controlled intake air.
- Central natural gas injection into the air intake downstream of the throttle.

The project team completed initial component design during the Alpha design phase, and validated the Alpha design through further analysis and testing of prototype parts. Alpha prototypes are typically manufactured with prototype manufacturing processes and tooling. Completion of this portion of the project provided a stable engine design.

After incorporating feedback from Alpha validation, the project moved to the Beta design phase. The team validated the Beta design through upgrades of some Alpha test units as well as newly built Beta prototype test engines and field demonstrations. Beta prototypes are production-intent designs made through production-intent manufacturing processes. The outcome of Beta testing was stable performance.

After manufacturing the Beta prototypes, the team addressed any issues with the manufacturing process during the preparation for limited production. Although the design was theoretically stable after Beta design, deficiencies were expected in both Alpha and Beta prototype testing but could be corrected prior to the launch of limited production.

Alpha Heavy Duty Natural Gas Engine

Appendix A provides a detailed description of the design, build, testing, and evaluation process for the Alpha prototype engine, which is summarized below.

Conceptual Modeling, Testing, Analysis, and Simulation

Before beginning the Alpha design phase, the project team modified existing production engines with prototypes of the parts that would be altered to create the new engine. Engine testing emphasized emissions, on-board diagnostics, and performance requirements. The team then used data from experimental testing to refine the Alpha design.

After developing drawings and the engine configuration, the team created plans for the Alpha engine builds. Cummins engineering staff and the pilot manufacturing plant then conducted a virtual build in March 2016 to review key features of the new engine.

Throughout the process, the team met regularly with CWI management to review the Alpha design for various systems and components, and captured issued identified at each design review in a design review database to allow tracking as they were resolved.

Table 4: Product Validation Matrix

Hardware/Software	Stable Architecture (parented from ISL G NZ Project)	Stable Design Alpha Design	Stable Design Alpha Testing	Stable Performance Beta Design	Stable Performance Beta Testing	Stable Process
EM: Base Engine	✓	✓	✓	✓	✓	✓
EM: Power Cylinder	✓	✓	✓	✓	✓	✓
EM: Intake Manifold	✓	✓	✓	✓	✓	✓
EM: Exhaust Manifold	✓	✓	✓	✓	✓	✓
EM: Cylinder Head	✓	✓	✓	✓	✓	✓
EM: Turbo	✓	✓	✓	✓	✓	✓
EM: Fuel System	✓	✓	✓	✓	✓	✓
EM: Crankcase Ventilation	✓	✓	✓	✓	✓	✓
EM: Exhaust Gas Recirculation	✓	✓	✓	✓	✓	✓
ECS: Engine Control Module	✓	✓	✓	✓	✓	✓
ECS: Ignition Control Module	✓	✓	✓	✓	✓	✓
ECS: Sensors	✓	✓	✓	✓	✓	✓
ECS: Actuators/Valves	✓	✓	✓	✓	✓	✓
ECS: Ignition System	✓	✓	✓	✓	✓	✓
ECS: Engine Control Software	✓	✓	✓	✓	✓	✓
ECS: Diagnostics	✓	✓	✓	✓	✓	✓
ECS: Chassis Electronic Interface	✓	✓	✓	✓	✓	✓
Aftertreatment	✓	✓	✓	✓	✓	✓

EM = Engine Mechanical; ECS = Engine ControlSystem

Source: Cummins Westport Inc.

Alpha Engine Build

Thirty-four Alpha engines were then built and, after undergoing standard production in-plant tests, were approved for shipment to engineering, field test, and original equipment manufacturer (OEM) customers for further validation testing. Alpha emission aftertreatment systems went through the same process. Figure 1 shows an Alpha ISX12N engine and highlights key differences from the then-current production ISX12 G engine.

Figure 1: Alpha Prototype ISX12N Engine

Source: Cummins Westport Inc.

Alpha Engine Testing and Evaluation

The project team then completed testing on the Alpha engine in test cells[4] to characterize or "map" the performance of the engine and various systems under different operating conditions. The goal was to identify issues early in the development process to allow sufficient time to address them prior to production. Many of these tests were subsequently repeated when Beta level hardware became available. All tests were completed successfully with the exception of a knock test that was later determined to have been improperly conducted and was later completed on Beta level hardware further along in the project.

High-Speed Mechanical Test

A high-speed test of the Alpha level engine included 500 hours of steady-state operation at higher-than-rated power and an engine speed of 2,300 revolutions per

[4] Test cells are essentially an isolated space where engineers, technicians, and technologists can run batteries of tests and record the findings with highly sophisticated technology.

minute to expose the engine to high vibration and knock level conditions. The test was successfully completed and validated the performance of the new fuel system, CCV, EGR, sensors, power cylinder, and compressor bypass systems.

Mechanical System Cyclic Test

The Mechanical System Cyclic Test operated the engine at high speed, peak torque abuse (including high knock, over-power and over-torque modes), high idle, shutdown and oil system blowdown, and shift ramp conditions for 750 hours. The test was completed successfully and validated the operation and durability of the engine and controls.

Peak Power Over-fuel Test

This 1,000 hour peak power over-fuel test operated the engine at a steady state of peak power plus 10 percent, or 440 horsepower, and at 1,800 revolutions per minute. The procedure also tested other components for proper operation and durability. This test was not completed successfully after an exhaust valve failed. Investigation suggested the failure was not directly related to design changes, and the test was later completed successfully on a Beta engine.

Winter Testing

The team tested multiple vehicles on a winter testing trip, including a prototype model year 2018 ISX12N powered truck. The trip originated in Columbus, Indiana and ended near Mountain Iron, Minnesota where temperatures were below -20 degrees Fahrenheit. The test included 2,072 miles of travel, periods of idling, and cold starts. Overall performance of the truck exceeded expectations.

The ISX12N experienced ice formation in the EGR crossover tube that occurred after an extended idle period. Although no significant degradation in performance was detected, later calibrations of the engine implemented actions to reduce ice formation. These calibration changes increased EGR flow to warm the system and keep water from collecting and freezing.

Emissions and Fuel Economy Testing

The project team then performed emissions tests on the Alpha engines and aftertreatment technologies. Assessments were done on new, degreened[5] systems as well as end-of-useful-life aftertreatment systems. The team created end-of-useful-life catalysts using industry-accepted accelerated aging practices. Test results were not official emissions certification results, but did indicate expected performance within the 0.02 g/bhp-hr NOx emission target.

The team used test cell fuel economy data to map brake specific fuel consumption across the Alpha engine's speed and torque map. The mapping data was used to model

[5] DE greening is a term for a brief period of use needed for emissions control hardware to achieve a stable emissions reduction to allow representative testing.

fuel consumption in vehicles under specific customer duty cycles and evaluate the fuel economy relative to 2010 United States Environmental Protection Agency (USEPA) and California Air Resources Board (CARB) certified diesel engines.

Beta Heavy Duty Natural Gas Engine

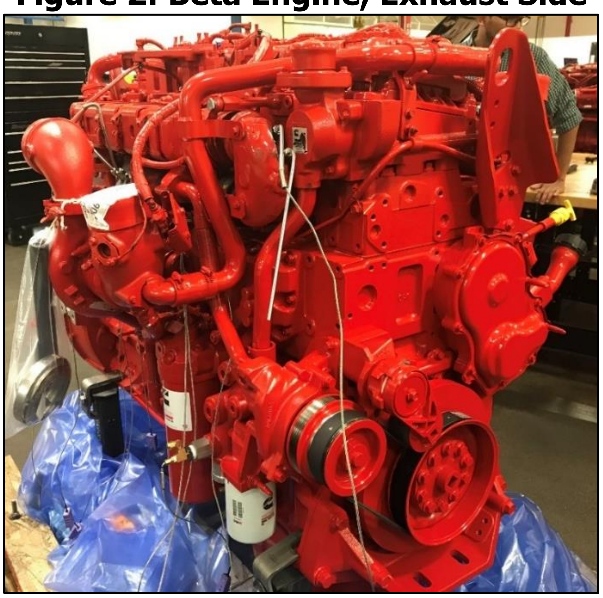
Beta Engine Design

The project team then revised the engine designs to correct issues detected during the Alpha phase in anticipation of the December 2016 Beta design freeze (the point at which no further changes to the Beta design would be contemplated or accepted). Primary reasons for Beta design changes include routing and packaging challenges, manufacturability and serviceability improvements, interference issues with certain vehicle chassis, and electrical harness redesigns to accommodate changes in part locations. Changes to catalyst volume and sensor location were also required for the after-treatment system to support lower NOx emissions and on-board diagnostics. During the Beta design phase, the team also completed the remaining outstanding Alpha design reviews. Appendix B provides a detailed description of the Beta design and testing process.

Beta Engine and Aftertreatment Build

Beta prototype ISX12N engines and aftertreatment systems were built for engineering development, field testing, and checking the fit for original equipment manufacturer (OEM) customers. The team created the specifications for the engines using the standard Cummins "On-Line Specification" system which ensures creation of a complete and workable engine. Figure 2 shows a Beta engine from the exhaust side.

Figure 2: Beta Engine, Exhaust Side



Source: Cummins Westport Inc.

Beta Engine Emissions, Fuel Consumption, and Performance Testing

The team performed transient dynamometer tests per the USEPA heavy-duty on-highway FTP duty cycle to determine the brake-specific fuel consumption and emissions of non-methane hydrocarbons, oxides of nitrogen, carbon monoxide, particulate matter, ammonia, nitrous oxide, nitrogen dioxide, carbon dioxide, and ultrafine emissions from the production-intent engine. In adherence to the California Code of Regulations Title 13 Section 2292.5, the team used laboratory tested natural gas within the CARB certification fuel specification. The team submitted the results to the USEPA and CARB, and received USEPA Certificates of Conformity and CARB executive orders certifying the ISX12N engine to the CARB Optional NOx level for model year 2018.

Original Equipment Manufacturer Engine-Vehicle Integration

CWI worked closely with existing ISX12 G vehicle OEM customers during the development of the new ISX12N engine to determine which design changes would affect them. The vehicle OEMs made alterations to their chassis designs as needed to resolve changes made to the engine's mechanical hardware, electronic hardware, and software interfaces. Cummins Installation Quality Audit process also required OEMs to prove that the vehicle design met all required installation requirements. Appendix C details the design changes and alterations made to address them, and provides the status of vehicle OEM progress on the required Installation Quality Audit process.

Field Testing

Appendix D provides detailed information about the field testing process, which is summarized below.

Rapid Truck Testing

Two Rapid truck test vehicles operated in December of 2016 and February 2017 using prototype ISX12N engines with the main goal of accumulating on-road mileage quickly. These vehicles were not driven for commercial operation. Each truck accumulated approximately 100,000 miles, and the team tracked issues observed during operation from when they were reported until issue resolution using the Failure Incident Reporting Group process.

Field Testing

The purpose of field testing was to integrate and implement at least five vehicles with Alpha and Beta engines and operate these vehicles for at least six months, with one of the vehicles located within the South Coast Air Basin. From an engineering standpoint, the goal of these vehicles was to perform daily commercial service just as they did prior to this project, and to accumulate mileage to identify issues prior to the commercial launch of the product. This field testing supplemented the rigorous performance testing done on the individual engine parts, the complete engines, and the aftertreatment systems in the test cells.

CWI approached UPS, FedEx Freight, Dillon Transport, and Waste Management to be the demonstrating customers for this project because of their experience with the ISX12 G engine and their history of environmental leadership in their industries. Other fleets that participated, were TTSI, Sheehy, Thatcher Chemical, and Frito Lay, for a total of 13 vehicles (not including the two Rapid trucks).

Due to the complexity of required changes to the vehicle engines and the tight timeline for the project, the most cost-effective option for installing the ultra-low NOx technology and after-treatment unit was to repower existing vehicles. This involved removing the original ISX12 G engines and replacing them with new prototype ISX12N engines. Fabrication of the mounting components for the new aftertreatment system and significant re-plumbing and rewiring was needed to properly install the prototype ISX12Ns to the field test vehicles. The installations included telemetry equipment to monitor, collect, and send data to the field test team. The field test fleet, including the two Rapid trucks, accumulated a combined 1.25 million miles during this project.

CWI Service Engineering recorded all reported product issues and tracked each issue's progress to resolution using a formalized Cummins reporting and issue management process. CWI also installed upgraded hardware and electronic calibrations on the engines as products improved throughout the program.

Chassis Dynamometer Testing

To test real world ISX12N emissions, the project team conducted chassis dynamometer testing of one field test vehicle to evaluate real world emissions from the ISX12N engine. Testing was done at the University of California, Riverside (UCR) College of Engineering Center for Environmental Research and Technology emission test facility. Data was collected over drive cycles chosen by the South Coast Air Quality Management District to represent vehicle operation in the South Coast Air Basin. UCR conducted the testing in early 2018. Details of the testing and results are included in Appendix D and in UCR's published report[6].

[6] Johnson, Kent and George K. Ultra-Low NOx Near-Zero Natural Gas Vehicle Evaluation ISX12N 400. April 2018. https://ucrtoday.ucr.edu/wp-content/uploads/2018/08/CWI-LowNOx-12L-NG_v03.pdf

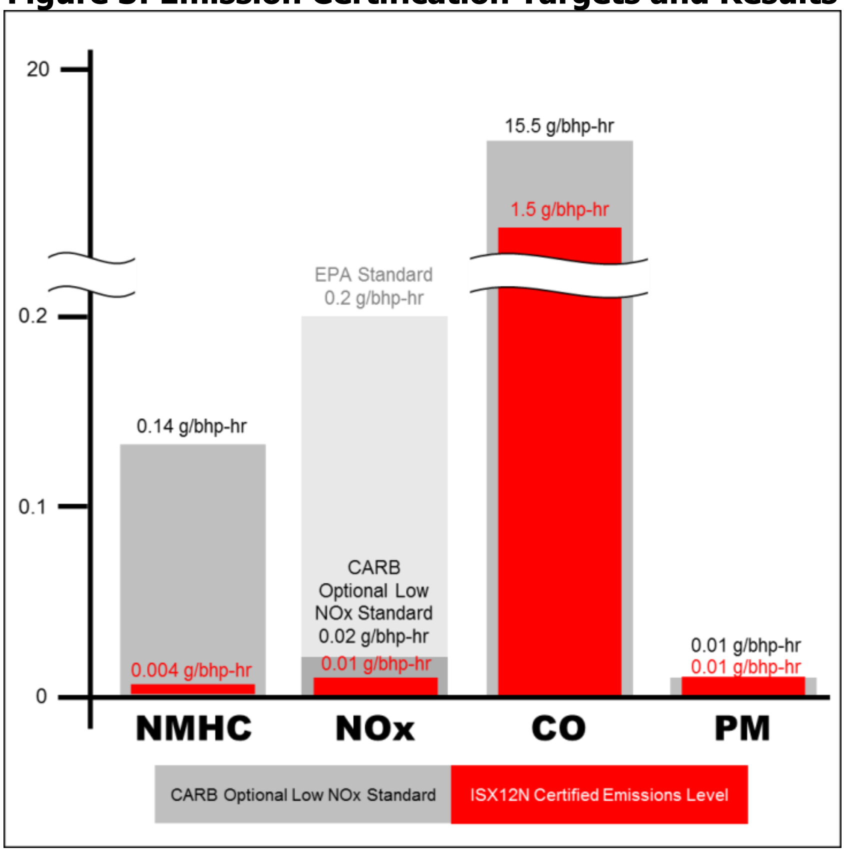
CHAPTER 3: Project Results

Objectives

This project successfully achieved each of the project objectives, with the results described below.

- Develop and demonstrate a 12-liter natural gas engine and associated exhaust aftertreatment technologies that are (1) suitable for on-road heavy heavy-duty vehicle applications such as Class 8 trucks and buses; and (2) commercially viable:
    - Cummins Westport Inc. (CWI) developed an ultra-low emission engine, called the ISX12N, which was certified to United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) Optional Low NOx 0.02 grams per brake horsepower-hour (g/bhp-hr) standards. Figure 3 shows the certified emissions of the ISX12N compared to the standards.

Figure 3: Emission Certification Targets and Results



Source: Cummins Westport Inc.

    - Demonstrated a peak rating of 400 horsepower and 1,450 foot-pounds of torque.
    - The Cummins Jamestown, New York engine plant built prototype ISX12N engines and aftertreatment systems that were installed in 15 Class 8 vehicles operated by various fleets across the United States, with two units operating in the South Coast Basin in California. These field test vehicles accumulated a combined 1.25 million test miles, with 13 of the 15 vehicles operating in commercial service.
- Achieve emissions targets of 0.02 g/bhp-hr NOx, 0.01 g/bhp-hr particulate matter (PM), 0.14 g/bhp-hr non-methane hydrocarbons (NMHC), and 15.5 g/bhp-hr carbon monoxide (CO) or lower as determined by the heavy duty engine Federal Test Procedure (FTP):
    - The ISX12N received Heavy Duty engine certification from CARB and USEPA with FTP test certification values of 0.01 g/bhp-hr NOx, 0.001 g/bhp-hr PM, 0.01 g/bhp-hr NMHC, and 1.5 g/bhp-hr CO, shown in Figure 3.
- Keep exhaust ammonia (NH_3) emissions as low as achievable while targeting NH_3 emissions at 10 parts per million (ppm) or lower:
    - Although the ISX12N engine was unable to meet the NH_3 emissions stretch target of 10 ppm, it did reduce NH_3 emissions by more than 50 percent compared to the current ISX12 G engine, to just under 40 ppm measured in the Cold/Hot Emission Test cycle.
- Achieve minimal fuel economy penalties relative to 2010 USEPA- and CARB-certified diesel engines on similar duty cycles:
    - The Alpha prototype engine fuel economy assessment indicated a small improvement of 2 percent to 9 percent compared to model year 2017 ISX12 G in various duty cycles.
    - Fuel economy analysis based on CO_2 emissions from the FTP cycle suggest the ISX12N is approximately 15 percent more fuel efficient than a similar model year 2010 ISX12 diesel engine.
    - Based on CO_2 emissions, University of California, Riverside chassis dynamometer testing found the "fuel economy also appeared to be similar to previous versions where the Urban Dynamometer Driving Schedule (UDDS) cycle showed the lowest CO_2 emissions and were below the current FTP standard of 555 g/bhp-hr for both the cold start and hot start tests."
- United States Environmental Protection Agency and California Air Resources Board:

- Cummins Westport Inc. received the USEPA Certificate of Conformity JCEXH0729XBC-014 and the CARB Executive Order A-021-0674 (for Optional Low NOx 0.02 g/bhp-hr standard) for model year 2018 ISX12N.

Conclusions

Based on the results of this project and the data presented in this report, the project team's primary conclusion is that by using stoichiometric, cooled exhaust recirculation, and spark ignition technology with the addition of a closed crankcase ventilation system, an improved three-way catalyst, and optimized engine controls, a 12-liter natural gas engine suitable for on-road heavy heavy-duty applications can achieve ultra-low emissions in a commercially viable way. The project demonstrated the ability to design, build, and demonstrate a 12-liter natural gas engine that could achieve USEPA and CARB emission standards, keep ammonia levels low, be thermally and fuel efficient, and be suitable for Class 8 trucks and buses.

Recommendations

CWI recommends the following activities to continue with implementation of low NOx technology, engines, and vehicles:

- Conduct outreach to promote and bring awareness of ultra-low NOx engine and vehicle availability to government agencies, policy makers, air districts, commercial fleets, and the general public.
- Support regulatory and incentive programs such as CARB's Sustainable Freight Transport and the execution of programs such as the Clean Air Action Plan for the Ports of Los Angeles and Long Beach, in achieving their air quality goals through the implementation of near zero and zero emissions vehicles. The ISX12N engine offers an immediate cost-effective near-zero emission solution for these clean air plans, especially in port drayage use.
- Continue to offer assistance with low NOx technology development and commercialization by expanding low NOx engine offerings in other engine sizes and vehicle applications.
- Continue to advance natural gas engine and vehicle development in the areas of emissions reductions, including fuel efficiency improvements.

CHAPTER 4: Technology Transfer Activities

Cummins Westport Inc. (CWI) plans to make the knowledge gained in this project available to the public and promote the technical and economic benefits of this project through a number of technology transfer activities:

- Commercial Product: The commercial ISX12N, certified to California Air Resources Board (CARB) Optional Low NOx 0.02 level, went into production in mid first quarter of 2018. CWI has worked with existing vehicle original equipment manufacturers (OEMs) that currently offer the model year 2017 ISX12 G to offer these vehicles with the ISX12N. The ISX12N (0.02g/bhp-hr NOx) has replaced the ISX12 G (0.20g/bhp-hr NOx) and CWI is only offering the ultra-low NOx ISX12N going forward.
- Emissions Results: The ISX12N engine and aftertreatment emissions results are publicly available as shown on CARB's Executive Order and the United States Environmental Protection Agency Certificate of Conformity. In addition, the University of California, Riverside (UCR) has publicly released the results of their chassis dynamometer testing (Appendix D) which includes real world emission test results.
- CWI Presentations: CWI regularly attends and presents at technology forums, tradeshows and industry events. CWI plans to include the details of the near zero technology as well as ISX12N product information at these events. These presentations include PowerPoint presentations with results conveyed in various pictures, charts, graphs and tables. Table 5 lists events where CWI presentations have occurred.
- OEM Product Information Sessions: New technology and product presentations were created for the Cummins OEM Account teams. These teams interface directly with each of the vehicle OEMs (for example, Peterbilt, Kenworth, Freightliner, Volvo, Mack, Autocar). Variations of these presentations were created for the OEMs to use internally within their company and also with their customers – the end user of the vehicle and engine system. Integration information was also provided to vehicle OEMs through Cummins Global Customer Engineering website. Information included, but was not limited to, engine and aftertreatment installation requirements, engine option information, and performance information.
- Maintenance Training: Training on CWI engines is provided to service providers through the Cummins dealer network. Information was updated to include the improved ISX12N engine. Additional service information on the ISX12N is

available through Cummins Quick Serve which conveys service and parts information.

Table 5: CWI Planned Presentations and Event Participation

Event	Approximate Date
Game Changer 2.0 Summit, Long Beach, CA	May 2017
ACT Expo (Alternative Clean Transportation Expo), Long Beach, CA	May 2017
Waste Expo, New Orleans, LA	May 2017
Energy Vision & NW RNG Workshop, Portland, OR	September, 2017
Wastecon, Baltimore, MD	September, 2017
NA Commercial Vehicle Show, Atlanta, GA	September, 2017
NGVA Annual Meeting & Summit, Atlanta, GA	September, 2017
CWI/Cummins/Gain Clean Fuel Industry Shippers Forum, Indianapolis, IN	October, 2017
The Power of Waste: Renewable Natural Gas (RNG) for California, Sacramento, CA	October, 2017
Sustainable Fleet Technology Conference & Expo, Raleigh, NC	October, 2017
American Trucking Association (ATA) Management Conference & Expo, Orlando FL	October, 2017
Calstart 2th Anniversary Symposium, Pasadena, CA	October, 2017
CWRE (Canadian Waste and Recycling Expo), Niagara Falls, ON	October, 2017
Natural Gas Vehicle Technology Forum (NGVTF), Downy, CA	February 21, 2018
ACT Expo (Alternative Clean Transportation Expo), Long Beach, CA	May 2018

Source: Cummins Westport Inc.

- CWI Website Information: CWI's public website (http://www.cumminswestport.com) hosts a section titled "Natural Gas Academy" where technology and industry information is available. This includes written information on natural gas and vehicle systems, videos on natural gas and CWI engine walk-arounds where the engine is presented at a high level.

The results of this project presented in the final report and disseminated through technology transfer activities could be used in the following ways:

- Government emission regulators will be able to use the results in the final report for this project to confirm that natural gas internal combustion engines in heavy duty vehicle applications are capable of reaching "near zero" NOx and PM emissions. This will provide valuable insight into the capability of current technology as well as the potential capability of future technology and related costs. With that data, regulators will be able to make better informed decisions for the content and timing of both state and federal emission regulations.
- Air quality policy makers will be able to use the information from the final report to confirm that natural gas engine technology is a viable option to reach near

zero emissions levels. Confirmation of this technology’s capability allows policy makers to substantiate air quality improvement roadmaps with higher confidence both from a technical capability standpoint and a cost standpoint as they have a more accurate view of the vehicle and infrastructure implementation requirements. This same view is not as clear with future technologies that have not been proven technically and are not currently widely integrated by vehicle manufacturers.

- Although CWI is already well engaged with all major vehicle OEMs in the on-road heavy-duty vehicle market and has regularly shared product information, the information in the final report will provide additional information on the process CWI used to achieve these results. Those OEMs not familiar with CWI products will be informed of the engine and aftertreatment technology architecture used to achieve near zero emissions and the durability testing conducted on real world vehicles.
- Engine manufacturers can use the final report results to better understand the engine and aftertreatment architecture used in the project to achieve near zero emissions. This may alter their research and development plans for achieving lower emissions, thereby affecting their technology architecture decisions or changing their planned completion dates. The report results could spur competitors to accelerate commercial plans for near zero engines. The report will also provide a clear picture of CWI’s chosen near term architecture which will indicate mid-term and possibly long term technology direction.

The information in the final report will also provide heavy-duty fleets that are evaluating new engine technology with a technical assessment of the complexity and emission performance of CWI’s Near Zero technology. These fleets face significant investment costs in vehicle and infrastructure capital purchases as well as personnel training for future low emissions technology. This report will aid with their evaluation of low emissions technology. The report will also provide a better understanding for the expected range of heavy-duty vehicle availability for the new ultra-low emission engine and the applications that can make use of the engine.

CHAPTER 5: Benefits to California

Various industry stakeholders, including consultants, government agencies, and OEMs, are projecting continued natural gas vehicle penetration in the North American heavy-duty commercial vehicle market. The technical achievements in this project further support California's state and regional regulatory policies for implementing lower emissions technology by proving natural gas heavy-duty engines are able to cost effectively achieve ultra-low emissions.

Heavy-duty on-road vehicles contribute heavily to oxides of nitrogen (NOx) emissions in California, particularly in the South Coast Air Basin which faces many air quality challenges.[7] This situation is projected to continue despite the ongoing replacement of older vehicles with new vehicles that meet current air quality standards imposed by the United States Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB). According to the USEPA, NOx reacts with other chemicals in the air to form particulate matter and ozone, both of which are harmful when inhaled. NOx can also affect the environment by reacting in the atmosphere to form acid rain, which harms sensitive ecosystems like lakes and forests, as well as tropospheric ozone which is the primary constituent of smog.

States such as California that have air districts in nonattainment of the National Ambient Air Quality Standards are required by the Clean Air Act to develop and implement state implementation plans that outline policies and strategies for achieving attainment. Failure to do so may lead to withholding of federal transportation funding. CARB's 2016 State Strategy for the State Implementation Plan[8] includes initiatives for deploying near-zero emission heavy-duty vehicles and developing a future mandatory low NOx standard for heavy-duty on-road engines. The development of the ISX12N is an important milestone that opens up the heavy-duty on-road vehicle sector to a commercial near-zero emission option. Incentive funding and public fleet mandates will help accelerate deployment of the ISX12N engine to quickly realize emission reductions.

The South Coast Air Basin requires a 45 percent reduction in NOx by 2023 to meet USEPA ambient ozone standards. With NOx reductions of more than 90 percent from the current federal standard, the emissions from 10 trucks powered with the ISX12N engine would be the equivalent to the emissions of a single truck that uses a 2010

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[7] South Coast Air Quality Management District. *2016 Air Quality Management Plan for the South Coast Air Basin and Coachella Valley*.

[8] California Air Resources Board. *Revised Proposed 2016 State Strategy for the State Implementation Plan*.

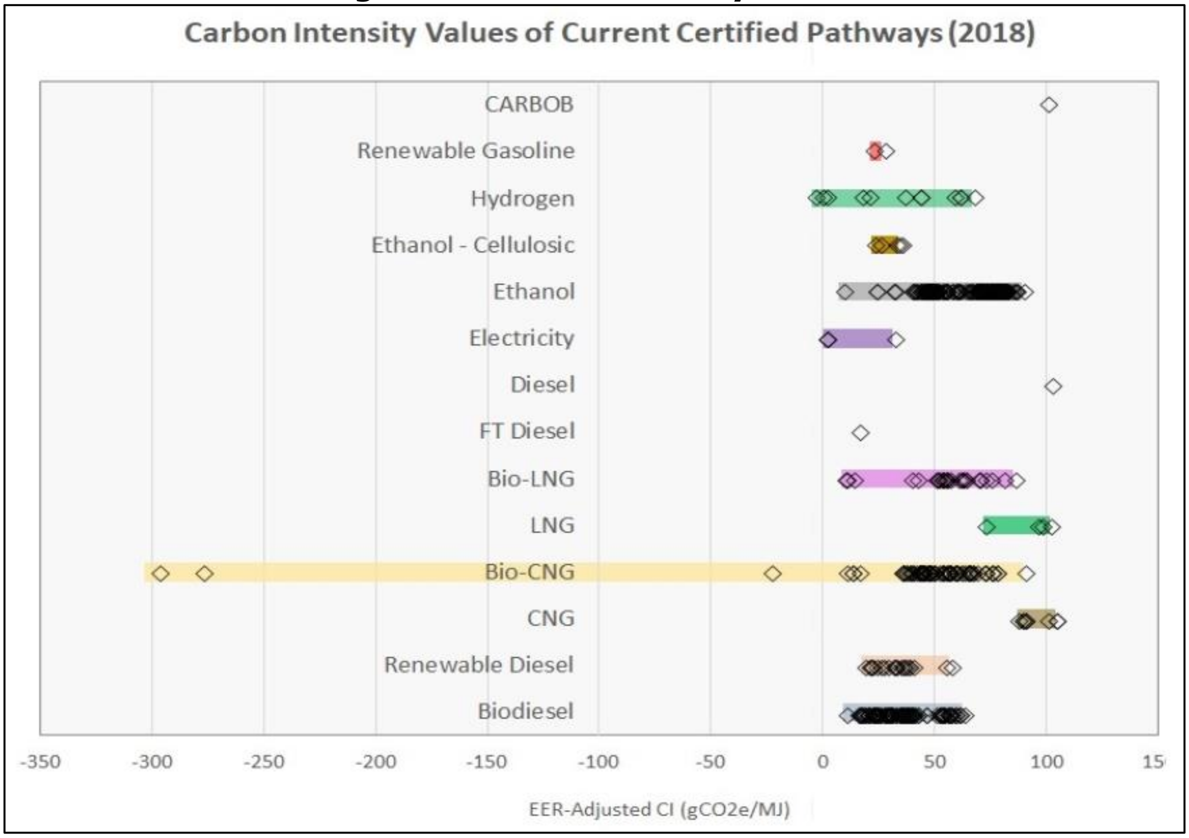
USEPA certified engine. As the largest commercially available near-zero emission engine option for on-road heavy-duty vehicles, the ISX12N can play a major role in cost effectively achieving the region's aggressive NOx reduction targets ahead of the development of a mandatory low NOx engine standard.

Widespread adoption of the ISX12N ultra-low emission natural gas engine would help reduce NOx emissions and improve California's air quality over time as vehicles are replaced. Reduced emissions would provide a wide array of benefits to California's citizens including improved health, reduced health care costs from hospital and emergency room visits, better visibility, and fewer impacts on the environment.

When combined with renewable natural gas (RNG), the ISX12N engine can provide even larger greenhouse gas emissions reductions by reducing the emissions from renewable waste sources. CARB's Low Carbon Fuel Standard aims to decrease greenhouse gas emissions by encouraging the use of low-carbon fuels. CARB assesses the lifecycle greenhouse gas emissions of various fuels, expressed as a fuel's carbon intensity (CI), and incentivizes adoption of fuels with lower CI than the standard. The CI value considers the direct emissions from the production, transportation, and use of the fuel but also includes significant indirect effects such as uncontained emissions from organic waste as it decomposes.

Figure 4 compares various alternative fuels and conventional diesel fuel. RNG falls under the Bio-CNG pathway and offers a range of feedstock sources and CI reductions compared to diesel.

Figure 4: Carbon Intensity Values



Source: California Air Resources Board (CARB). *LCFS Pathway Certified Carbon Intensities*. Retrieved from https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm.

The feedstocks with the greatest CI reduction are both from animal wastes: CN056, with a CI value of -272.97, and CNGDD201, with a CI value of -254.94. In both of these pathways, methane emissions from the animal waste would normally be uncontained and directly impact the atmosphere because methane is a far more potent greenhouse gas than carbon dioxide. However, by capturing the methane and converting it to a useful transportation fuel, that fuel now has a negative CI value, and a greater than 100 percent greenhouse gas reduction is realized.

LIST OF ACRONYMS

Term	Definition
BSFC	Brake specific fuel consumption
CARB	California Air Resources Board
CCR	California Code of Regulations
CCV	Closed crankcase ventilation system
CHET	Cold/hot emission test
CI	Carbon intensity
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CRV	Compressor recirculation valve
CWI	Cummins Westport Inc.
DVP&R	Design verification plan & report
EGR	Exhaust gas recirculation
EUL	End of useful life
FTP	Federal test procedure
g/bhp-hr	Grams per brake horsepower-hour
IAT	Intake air throttle
IQA	Installation quality audit
ICM	Ignition control module
iDFMEA	Integrated design, failure modes and effects analysis
HD-OBD	Heavy duty onboard diagnostics
HHDDT	CARB heavy heavy-duty diesel truck cycle
LCFS	Low Carbon Fuel Standard
LNG	Liquefied natural gas
MSC	Mechanical system cyclic test
MIL	Malfunction indicator lamp

Term	Definition
NDF:	Non-diagnostic feature list
NH_3	Ammonia
NMHC	Non methane hydrocarbons
NOx	Oxides of nitrogen
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
NUD	New unique, or difficult
OBD	Onboard diagnostics
OEM	Original equipment manufacturer
PM	Particulate matter
PN	Particulate number
RMC-SET	Ramp mode cycle supplemental emissions test
RNG	Renewable natural gas
SAE	Society of Automotive Engineers
UDDS	Urban dynamometer driving schedule
USEPA	United States Environmental Protection Agency
WCV	Wastegate control valve

APPENDIX A: Alpha Design and Testing

Alpha Design of Heavy Duty Natural Gas Engine

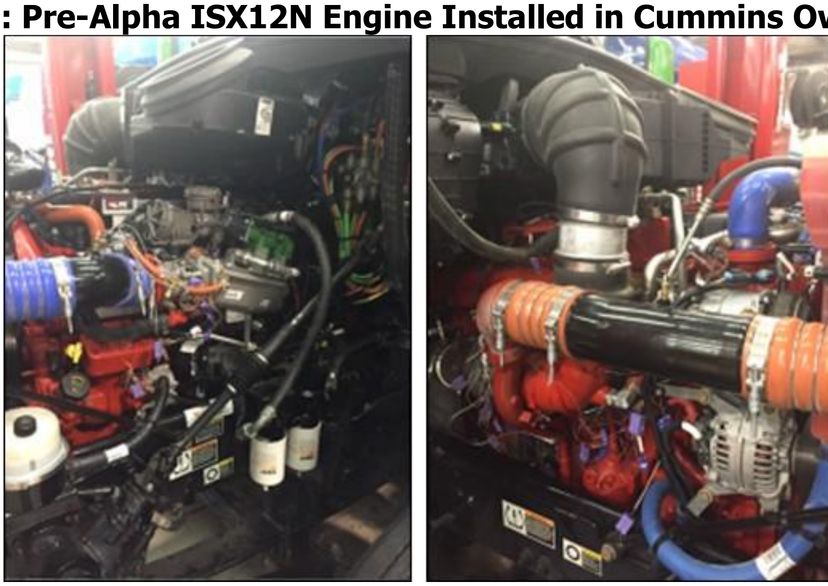
Conceptual Modeling, Testing, Analysis, and Simulation

Pre-Alpha component and subsystem designs were completed in accordance with the conceptual architecture developed to support the Cummins Westport Inc.'s (CWI) System Technical Profile requirements for emissions, performance, and diagnostics.

Pre-Alpha engines were created by modifying production engines with prototype versions of the parts to be modified. These engines were installed in test cells and experimental testing was conducted to validate the architecture and performance assumptions. This data was used to refine the Alpha design.

The focus of testing in the pre-Alpha was to demonstrate that key requirements could be achieved with the proposed architecture. The primary emphasis was on emissions, on-board diagnostics (OBD), and performance requirements. These were validated by running emissions test cycles (Federal Test Procedure [FTP] and ramped mode cycles-supplemental emissions test [RMC-SET]) as well as simulated real-world driving cycles. Tests were run in steady-state and transient test cells as well as on test trucks. Figure A-1 shows a pre-Alpha ISX12N engine installed in a Cummins-owned test truck.

Figure A-1: Pre-Alpha ISX12N Engine Installed in Cummins Owned Truck



Source: Cummins Westport Inc.

Examples of changes identified by testing the pre-Alpha design include:

- Moved aftertreatment sensor locations from the outlet of the catalyst to mid-bed in order to improve OBD algorithm performance.
- Revised the catalyst formulation to provide more robust emissions performance for the full useful life of the engine.
- Modified the compressor recirculation valve and crankcase breather flow paths because interactions between the combined flow paths resulted in undesirable transients in air flow.
- Modified OBD algorithm designs to provide acceptable probability of detection on real world and certification test cycles.

Detailed Alpha Design

Table A-1 lists the systems and components that were the subject of Alpha level design reviews held with CWI management.

Table A-1: Alpha System/Component Design Review Date Summary

System/Component Design Review	Review Date
Compressor Recirculation Valve	23 February 2016
Turbocharger Plumbing	1 March 2016
Oxygen Sensor	4 March 2016
Crankcase Breather System	8 March 2016
Wastegate Plumbing	8 March 2016
Wiring Harness	22 March 2016
Fuel Filter Option	15 April 2016
Intake Manifold Pressure/Temperature Sensor	10 May 2016
Exhaust Gas Recirculation System	27 May 2016
Plant Build Calibration and Software	21 June 2016
Catalyst System	8 July 2016
Ignition System	19 July 2016
Wastegate Control Housing	22 July 2016
Spark Plug	26 August 2016
Field Test Calibration and Software	8 September 2016
System Performance & Emissions	15 September 2016

Source: Cummins Westport Inc.

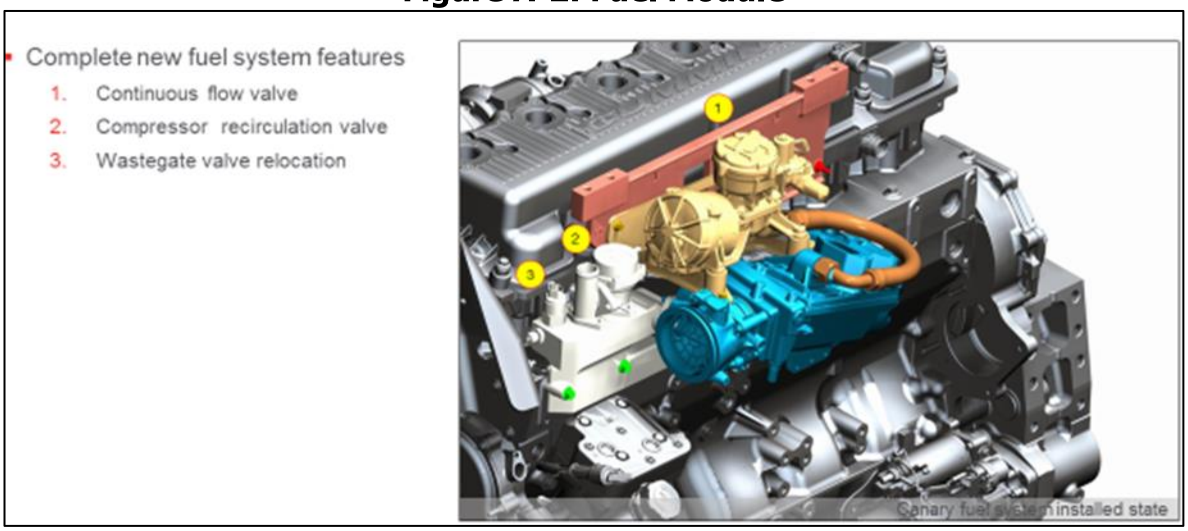
The project team captured issues at each design review and tracked them to resolution in a design review issue database.

The team developed drawings and engine configuration and created plans the Alpha engine builds. Cummins engineering staff and the pilot manufacturing plans conducted an Alpha Virtual Build on 24 March 2016 at the Jamestown Engine Plant. Key features of the new engine were reviewed, with some of the major subsystem designs illustrated in Figure A-2 through Figure A-6.

The Closed Crankcase breather chosen for the ISX12N engine differed from that used on the ISL G NZ engine. The team selected an electrically driven, rotating breather, developed by Cummins Filtration, for the ISX12N engine compared to the passive coalescing filter used on the ISL G NZ engine. The electrically driven filter rotates at high speed, which results in higher efficiency in separating aerosols from the crankcase gas. In addition, the electric drive offers an opportunity to implement heavy-duty on-board diagnostic (HD-OBD) to monitor performance aspects such as rotational speed.

Figure A-2 shows three key features of the Alpha ISX12N engine including: (1) the Continuous Flow Valve which is the key control element of the new fuel system selected to provide improved field reliability and control; (2) the Compressor Recirculation Valve (CRV) which was added to reduce turbo chuff[9] during transient operation; and (3) the Wastegate Control Valve (WCV) was relocated to accommodate the CRV integration.

Figure A-2: Fuel Module

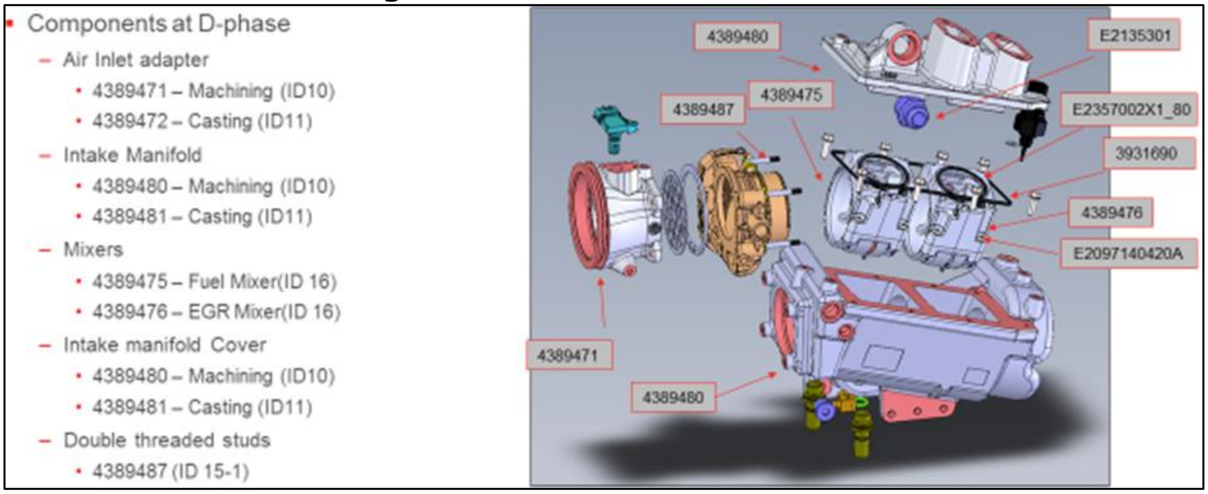


Source: Cummins Westport Inc.

The internal components of the fuel module are shown in Figure A-3. The Intake Air Throttle, part #4389487, was carried over from the existing ISX12 G product. All other parts were new to the ISX12N.

[9] Turbo chuff is a puffing sound that occurs when the throttle plate in a turbocharged engine is closed and boost is released through the wastegate.

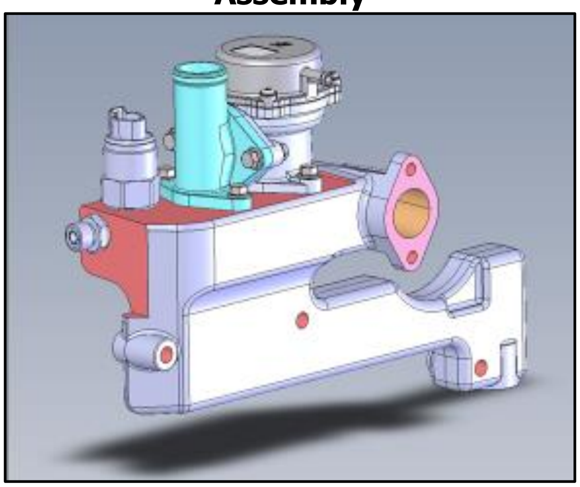
Figure A-3: Air Intake Manifold



Source: Cummins Westport Inc.

The WCV and CRV assemblies are shown in Figure A-4. This design was initially chosen to reduce the space claim for plumbing but was later shown to have undesirable interactions between the combined flows which resulted a Beta redesign to split the flows.

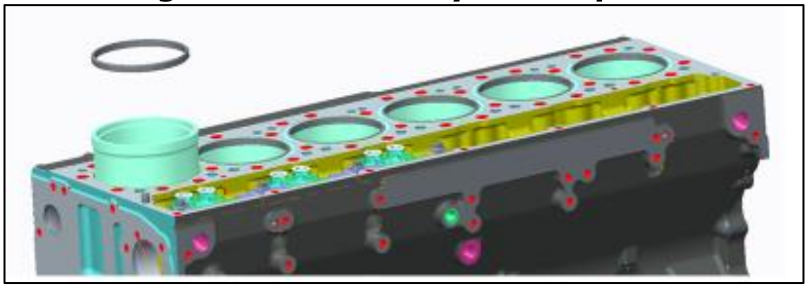
Figure A-4: Wastegate Control Valve/Compressor Recirculation Valve Assembly



Source: Cummins Westport Inc.

Figure A-5 shows the addition of an anti-polish ring to the cylinder liner to reduce top land carbon packing and improve oil consumption.

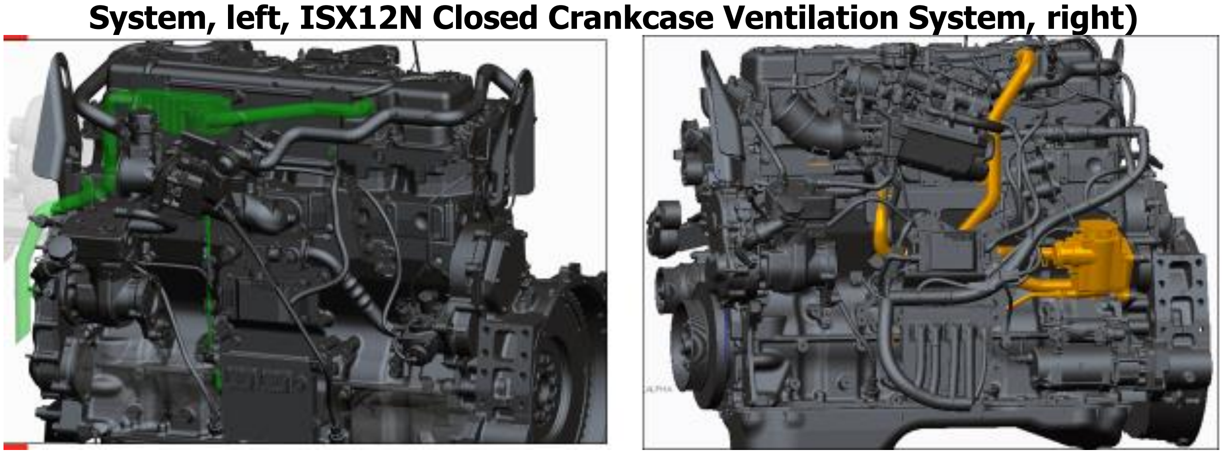
Figure A-5: Power Cylinder Option



Source: Cummins Westport Inc.

Figure A-6 shows the changes between the ISX12 G open crankcase ventilation system (OCV) on the left and the new ISX12N closed crankcase ventilation system (CCV) on the right. The closed system recirculates the blow by gasses to the compressor inlet rather than venting to the atmosphere, allowing reduction in total system emissions. The electrically operated rotating crankcase separator has higher efficiency in separating oil and other blowby gases from the flow before the gas is recirculated into the compressor inlet. This ensures the compressor efficiency is not degraded due to accumulation of deposits of blowby gas constituents over a long period.

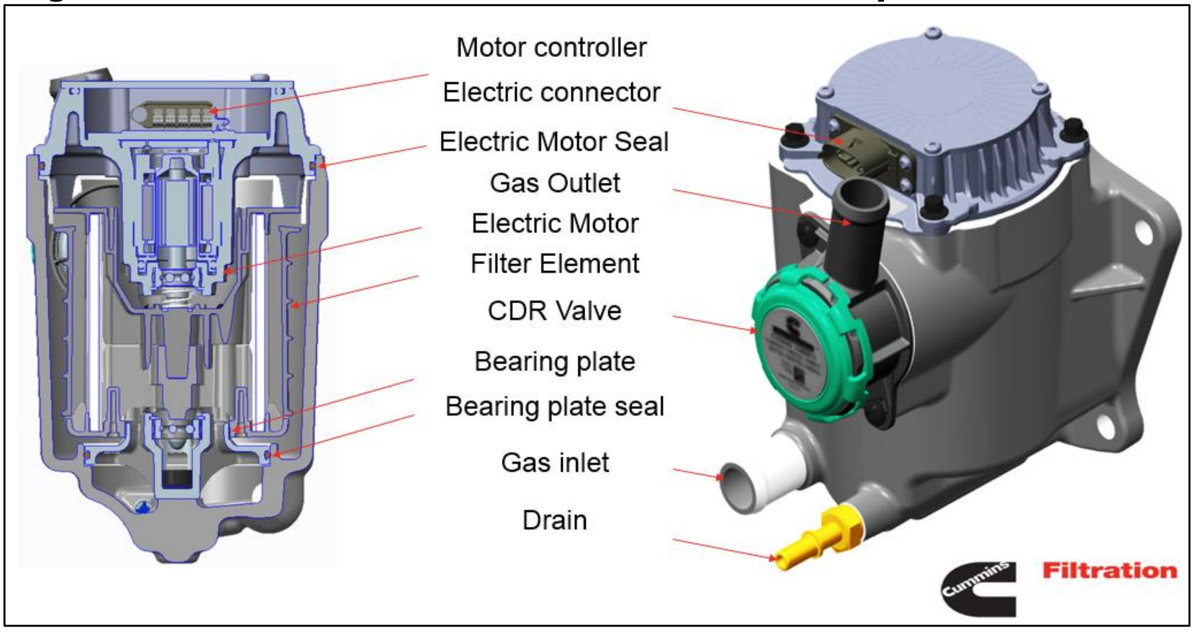
Figure A-6: Crankcase Breather Option (ISX12 G Open Crankcase Ventilation System, left, ISX12N Closed Crankcase Ventilation System, right)



Source: Cummins Westport Inc.

Figure A-7 shows the internal components of the electric CCV separator. The filter rotates at high speed to provide very high separation efficiency, ensuring minimal contaminants are passed back to the turbocharger compressor inlet.

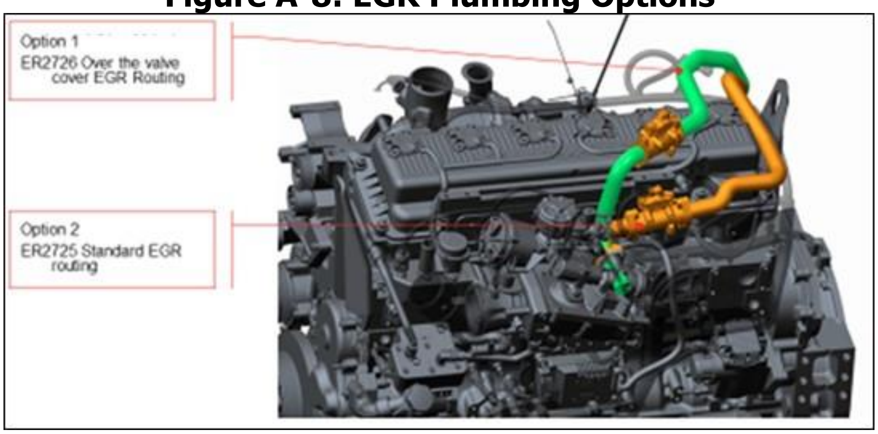
Figure A-7: Detailed and Sectioned View of Electrically Driven CCV Filter



Source: Cummins Westport Inc.

Two EGR plumbing options were created to allow the engine to fit into the maximum number of OEM cab configurations, shown in Figure A-8.

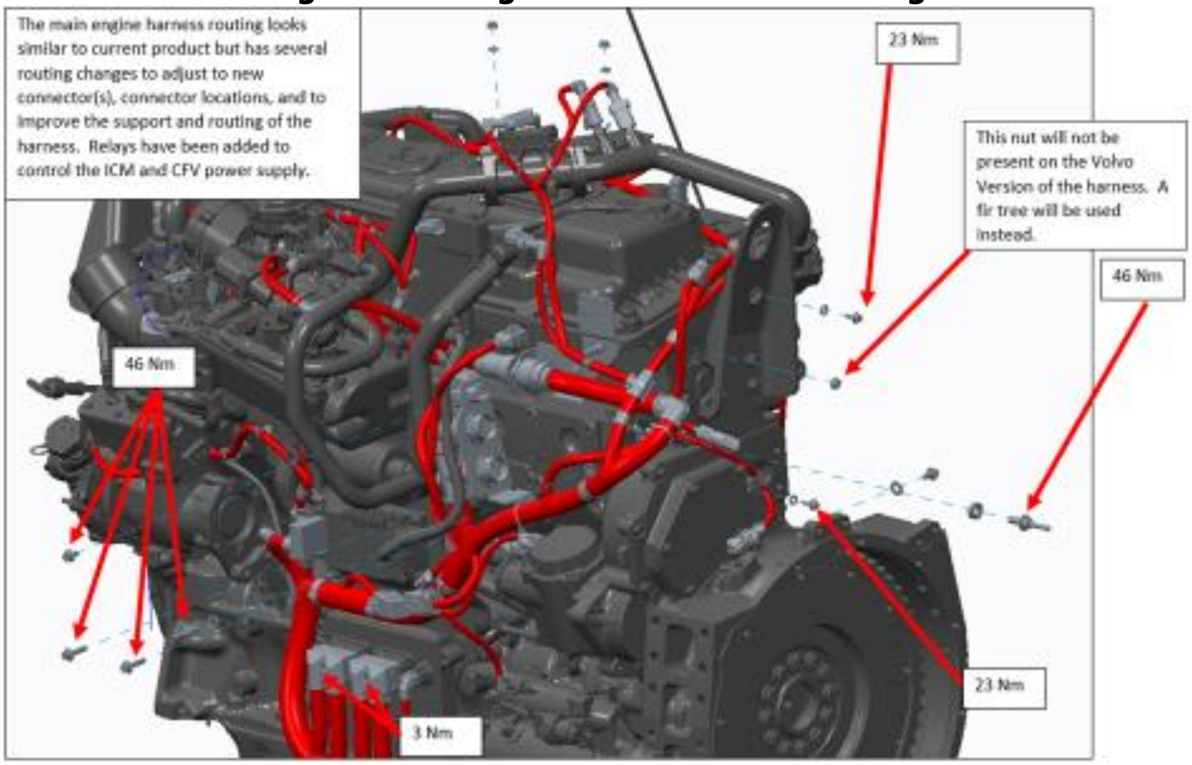
Figure A-8: EGR Plumbing Options



Source: Cummins Westport Inc.

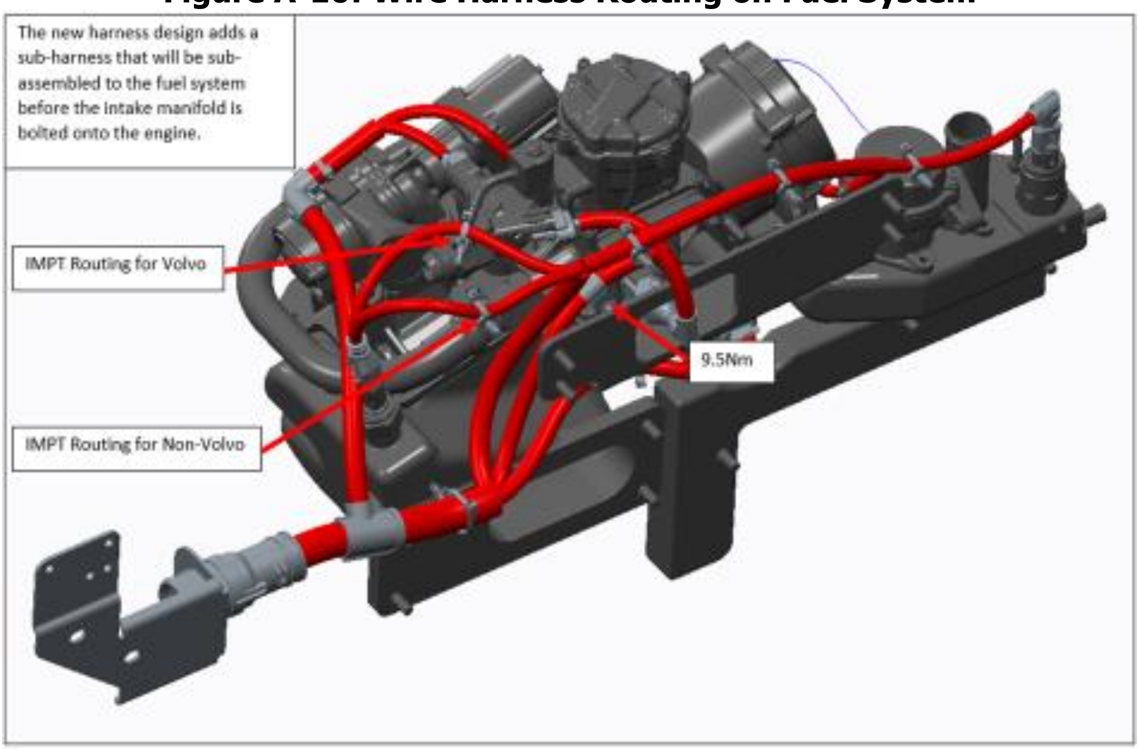
Figure A-9 and Figure A-10 show the wiring harness complexity with the ISX12N engine and fuel system.

Figure A-9: Engine Wire Harness Routing



Source: Cummins Westport Inc.

Figure A-10: Wire Harness Routing on Fuel System



Source: Cummins Westport Inc.

Alpha Engine Build

CWI built 34 Alpha engines, with the last engine built on August 30, 2016 and the last engine shipped on September 9, 2016. Engines were subjected to standard production in-plant tests and approved for shipment to engineering, field test and OEM customers for further validation testing. Figure A-11 shows an Alpha ISX12N engine at the Jamestown Engine Plan with key differences from the then current production ISX12 G highlighted.

The project team built the Alpha aftertreatment systems during August and September 2016. The aftertreatment systems were subjected to standard, production, and in-plant tests and approved for shipment to engineering, field test and OEM customers for further validation testing. Figure A-12 shows an "end-in/end-out" configured ISX12N alpha prototype three-way catalyst ready for shipment.

Figure A-11: Alpha Prototype ISX12N Engine at Jamestown Engine Plant

Source: Cummins Westport Inc.

Figure A-12: Alpha Prototype Three Way Catalyst

Source: Cummins Westport Inc.

Alpha Engine Testing and Evaluation

The team completed significant testing on the Alpha level engine in test cells. The tests included mapping or characterizing the engine and the various system performance at various operating conditions, and evaluating reliability and durability to prove out the integrity of the engine and components during harsh conditions. The intention with these tests was to uncover issues early in the development program which allowed time to address them prior to production rather than see these issues uncovered by customers once in commercial operation.

Mapping Tests

A series of mapping or characterizing tests were conducted on the ISX12N engine in the test cell. Changes to the ISX12N over the previous version (ISX12 G) include a new fuel system, addition of a crankcase pressure sensor, new engine control module, and changes to the aftertreatment. These mapping tests provided valuable data on how the engine and more specifically, individual systems, perform during the range of expected engine operating conditions, typically over the torque curve and at a number of operating conditions.

These values were then evaluated to ensure they stayed within expected ranges and also could be used in subsequent evaluation of potential and actual component changes. Most of these tests were repeated when Beta level hardware was available to ensure any changes made did not negatively impact performance. Table A-2 summarizes the mapping tests performed on the Alpha level prototype of the ISX12N. All tests were completed successfully with the exception of the "Knock Test #2", where it was discovered the test was not conducted properly. This test was completed on Beta level hardware later in the project.

Table A-2: Alpha Mapping Tests Summary

Mapping Test name	Components validated	Result
Challenge Rate Test	CCV system	System characterized/pass
Vibration Mapping	All sensors, fuel system, major castings	Pass
Oil Carryover Test	CCV system	System characterized/pass
Blow by Mapping	CCV system/power cylinder	System characterized/pass
Fuel Line Pressure Mapping	Fuel system	Pass
Balanced CRV Mapping	Compressor recirculation valve	System characterized/pass
Breather Particle Size Mapping	Breather system	System characterized/pass
Pressure & Thermal Mapping	All systems	System characterized/pass
Knock Test #1	Power cylinder	Pass
Knock Test #2	Power cylinder	Fail - test not run properly

Source: Cummins Westport Inc.

High Speed Mechanical Test

A high speed test with an Alpha level engine consisted of 500 hours of steady state operation at higher than rated power and an engine speed of 2,300 revolutions per minute. This operation exposed the engine to high vibration and knock level conditions. This test was successful and provided validation specifically for the following parts and systems:

- New fuel system
- Closed crankcase ventilation system (CCV)
- Exhaust gas recirculation (EGR) system
- Sensors
- Power cylinder
- Compressor bypass system

Figure A-13 shows the instrumented alpha level engine in the test cell.

Figure A-13: Instrumented Alpha Prototype Engine for High Speed Mechanical Test

Source: Cummins Westport Inc.

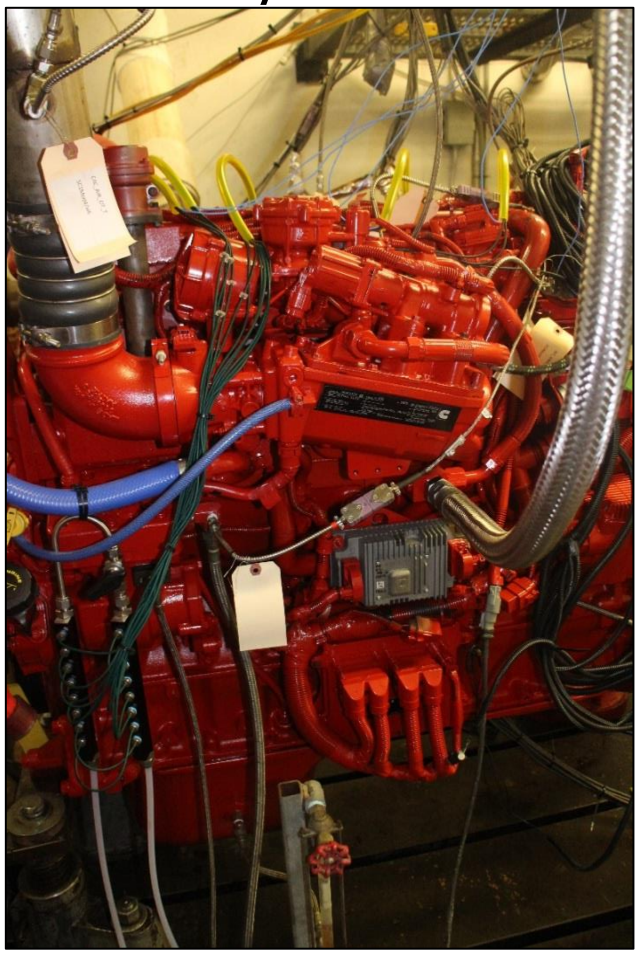
Mechanical System Cyclic Test

Another long-hour test conducted on an Alpha level engine was the mechanical system cyclic test which operated the engine at the following engine conditions for 750 hours:

- High speed mechanical test point
- Peak torque abuse point including high knock and over-power/over-torque modes
- Idle
- High Idle
- Shutdown and oil system blowdown
- Shift ramp simulation

This test successfully validated the operation and durability of the engine and controls. Figure A-14 shows the instrumented engine during the test.

Figure A-14: Instrumented Alpha Prototype Engine for Mechanical System Cyclic Test



Source: Cummins Westport Inc.

Peak Power Over-fuel Test

This 1,000 hour peak power over-fuel test on an Alpha level engine operated the engine at a steady state of peak power plus 10 percent, or 440 horsepower and at 1,800 revolutions per minute. The test is intended as an abuse test for the power cylinder and cylinder head with the high heat generated from the over power condition. Other components' operations were also tested at this peak temperature for proper operation and durability. The test also evaluated high blow-by conditions for the CCV system and exposed the engine to high knock levels. This test was not completed successfully because an exhaust valve failed and the test was stopped after 587 hours. The exhaust value was a component and design used in the current ISX12 G production engines and therefore was not expected to have issues with this test. The initial failure investigation suggested the failure was not directly related to the design changes made with the ISX12N, but was a combination of assembly error, existing design, and exacerbation by this abusive test. Further analysis is ongoing outside of this project to look at potential improvements. The test was rerun with a Beta engine and was completed successfully. There were no failures of any of the new components on this engine.

Winter Testing

Winter testing was conducted on a trip from January 28 to February 5, 2017. Multiple vehicles were on the trip, including a prototype model year 2018 ISX12N powered truck. The trip originated in Columbus, Indiana and the northern terminus was the area around Mountain Iron, Minnesota where the trucks faced temperatures below -20 degrees Fahrenheit. The prototype ISX12N engine ran 2,072 miles and also had many periods of extended idle in cold conditions and cold starts after cold soak periods (exposure to low temperatures for an extended period). Figure A-15 shows several trucks in Minnesota on the winter test after their overnight cold soak. The green truck on the right was the model year 2018 ISX12N truck.

Figure A-15: Model Year 2018 ISX12M Winter Test Truck (green truck on right)

Source: Cummins Westport Inc.

Overall performance of the truck exceeded expectations. Testers detected ice formation in the EGR and crankcase ventilation systems; however, there was no excessive impact on engine performance. Figure A-16 shows the ice formation in the EGR crossover tube that occurred after an extended idle of 8 hours to 9 hours in -20 degree Fahrenheit conditions. Although no significant degradation in performance was detected, later calibrations implemented actions to reduce ice formation. These calibration changes increased EGR flow to warm the system and keep water from collecting and freezing, more than would otherwise be necessary.

Figure A-16: Ice Formation in Exhaust Gas Recirculation Crossover Tube after Extended Idle in Minus 20 Degree Fahrenheit Conditions

Source: Cummins Westport Inc.

Emissions and Fuel Economy Testing

Emission development and testing was completed with Alpha level engines and aftertreatment. Assessments were done with new, degreened systems[10] as well as end-of-useful-life (EUL) aftertreatment systems. EUL catalysts were created using industry accepted accelerated aging practices. Tests were conducted to assess emissions performance on all regulated emissions on the Federal Test Procedure (FTP) and Ramp Mode Cycle Supplemental Emissions Test (RMC-SET) cycles. Typically, the most difficult test is the RMC-SET with an EUL catalyst against the 0.02 grams per brake horsepower-hour (g/bhp-hr) NOx emissions requirement.

Tests were run with two different EUL catalyst with multiple samples taken. These results were not official emissions certification results, but indicate expected performance. The results are summarized in Table A-3.

Table A-3: Alpha Engine NOx Emissions Results

RMC-SET Tests	EUL Cat #1	EUL Cat #2
Sample Runs:	17	16
Average NOx Emissions (g/bhp-hr):	0.016	0.011

Source: Cummins Westport Inc.

A fuel economy assessment was also completed on the Alpha engines. Fuel economy data was taken in a test cell to create a Brake Specific Fuel Consumption (BSFC) map which shows fuel consumption (g/bhp-hr) across the engines speed and torque map. This data was then used to model fuel consumption in vehicles running specific customer duty cycles. Table A-4 shows the specific vehicles and simulated duty cycles.

Table A-4: Vehicle Duty Cycle Simulation Summary

Project Name	Application	Vehicle
2018 ISX12N Linehaul	Linehaul	80,000 lb, 18 wheels
2017 ISX12 G Linehaul	Linehaul	80,000 lb, 18 wheels
2018 ISX12N Delivery Automatic	Step Van	17,000 lb, 6 wheels
2017 ISX12 G Delivery Automatic	Step Van	17,000 lb, 6 wheels
2018 ISX12N Delivery Manual	Step Van	17,000 lb, 6 wheels
2017 ISX12 G Delivery Manual	Step Van	17,000 lb, 6 wheels

Source: Cummins Westport Inc.

[10] DE greening is a term for a brief period of use needed for hardware to achieve a stable emissions reduction to allow representative testing (United States Environmental Protection Agency, https://archive.epa.gov/nrmrl/archive-etv/web/pdf/05_vp_emissions.pdf).

The results of this analysis showed a small improvement in fuel economy versus the current product ranging from roughly 2 percent to 9 percent.

One of the objectives of this project was to achieve "minimal, fuel economy penalties relative to 2010 USEPA and CARB certified diesel engines on similar duty cycles." The assessment compared CO_2 certification data from the ISX12N with USEPA certification data issued on July 2, 2010 for a model year 2010 ISX12 diesel (engine family ACEXH0729XAA, certificate number CEX-ONHWY-10-14). Test data for both engines were from the FTP test cycle. The ISX12 diesel had CO_2 emissions of 689 grams per horsepower-hour, and using the National Highway Traffic Safety Administration regulation conversion of 10,180 grams CO_2 per gallon and a diesel fuel density of 6.943 pounds per gallon suggests a BSFC of 0.47 pounds horsepower-hour. The ISX12N certification data shows a BSFC of 0.40 pounds per horsepower-hour over the FTP cycle. Therefore, the ISX12N was approximately 15 percent more fuel efficient than the similar 2010 ISX12 diesel engine.

APPENDIX B: Beta Design and Testing

Beta Engine Design

Beta engine design work was required to support the December, 2016 Beta design freeze (accepted milestone that marks the end point of a product development stage where the design is finalized and moved to production). Alpha engine designs were revised to correct issues detected during the Alpha build and validation processes. Primary reasons for Beta design changes included:

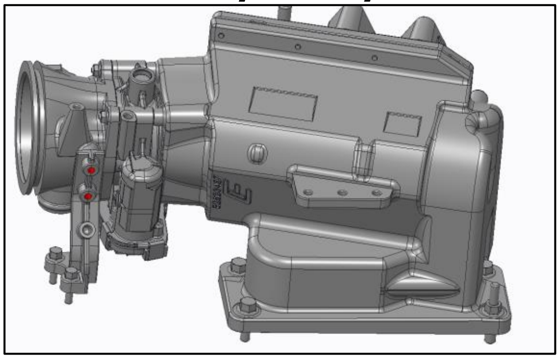
- Separating air flow from the closed crankcase ventilation system (CCV) and compressor recirculation valve (CRV). Flows were combined in the Alpha design to simplify routing of tubes and hoses, but Alpha engine testing showed that performance issues resulted from the combined flows. Separating the flows was determined to be the best solution although it created some routing and packaging challenges.
- Improving manufacturability and serviceability of the new systems. During Alpha assembly at the Jamestown Engine Plant, difficulties were encountered in fitting the exhaust gas recirculation (EGR) crossover tubes and flexible fuel lines. Changes were made to improve tolerances and allow increased flexibility in fitting the tubes.
- Resolving issues with interference with vehicle manufacturer chassis. Three-dimensional (3-D) Alpha models were provided to vehicle manufacturers to check for fit issues and some manufacturers were provided with Alpha engines for actual installs. Through this process, multiple issues with insufficient clearance were identified and corrections were included in the Beta design.
- Engine and ignition system electrical harness redesign was completed to accommodate component location changes, simplify harness design, and revise wiring for the electric rotating crankcase breather.

Some highlights of the Beta design activities are included below. Fit checks were performed with virtual 3-D modeling, with 3-D printed prototype parts and with actual prototype parts. Modal analysis and computational fluid dynamic modeling were also conducted to identify risks from vibration damage and ensure performance met requirements.

Fuel System and Air Handling Design Change Summary Design Review

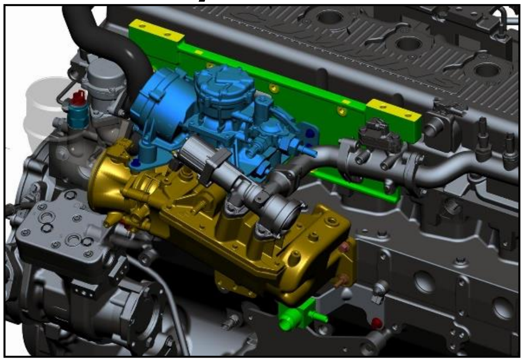
Dimensional variation analysis was completed which identified the allowable stack up for intake alignment as a critical issue. This ensured that the intake manifold can be installed after taking into account all the dimensional variation across the entire assembly. A fit check was conducted at the Jamestown Engine Plant with a combination of actual and 3-D printed parts to verify tolerances and assembly capability as shown in the following figures.

Figure B-1: Primary Fuel System Assembly



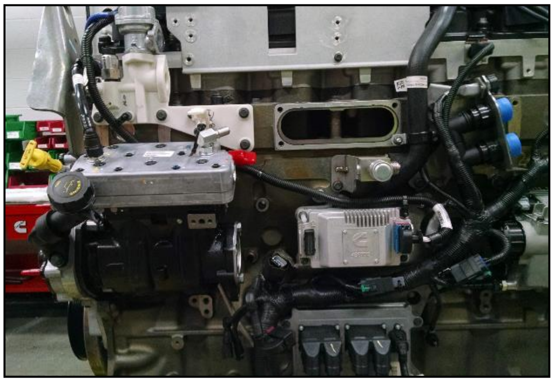
Source: Cummins Westport Inc.

Figure B-2: Fuel System Installed on Engine



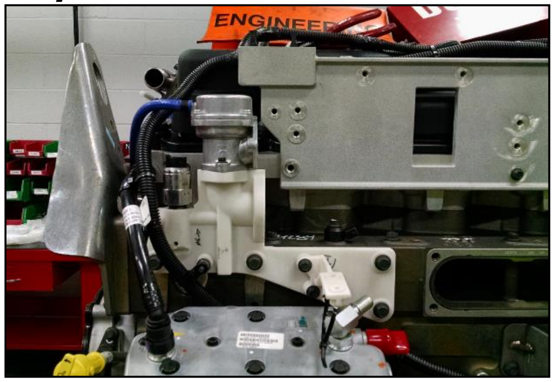
Source: Cummins Westport Inc.

Figure B-3: 3-D printed Parts Assembled on Engine Prior to Fuel Module Assembled



Source: Cummins Westport Inc.

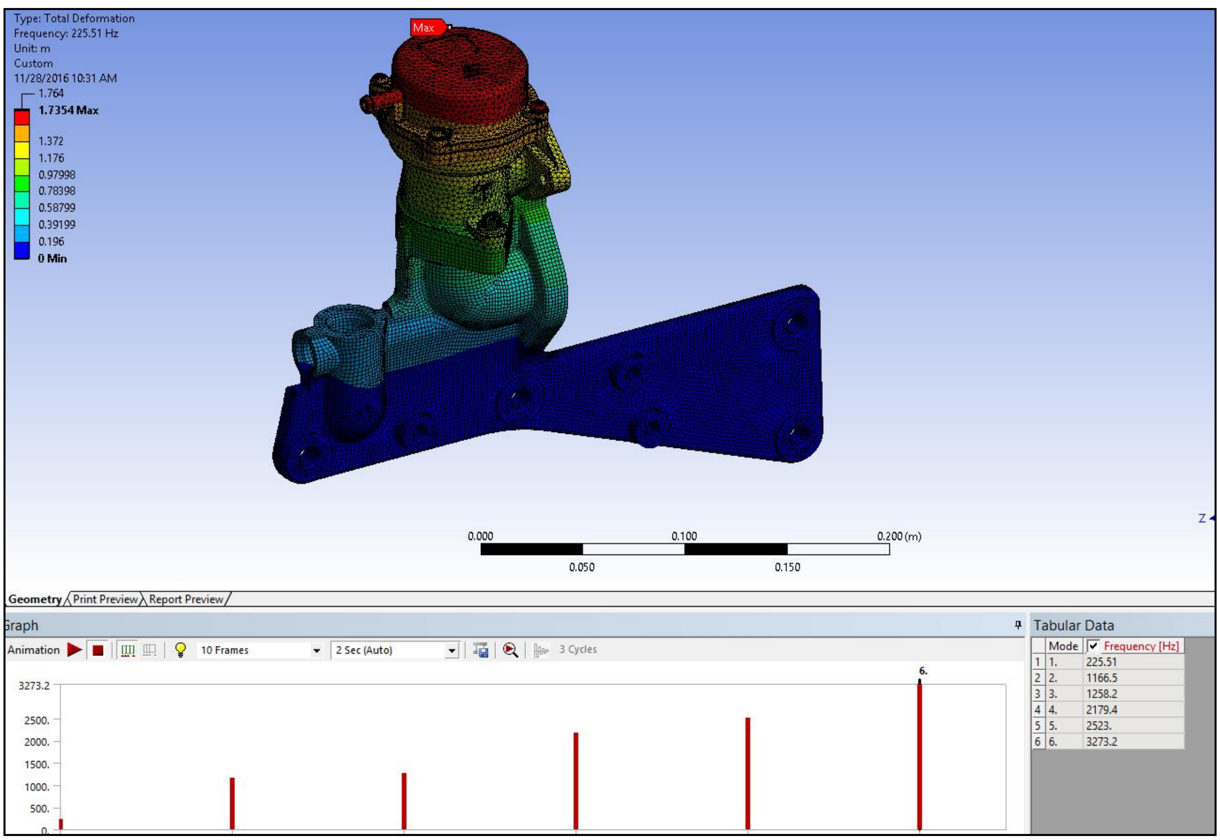
Figure B-4: Close-up of Wastegate Control Housing and Fuel Module Bracketry Prior to Installation of Fuel Module



Source: Cummins Westport Inc.

The wastegate control housing went through several design and modal analysis iterations before it met the vibration durability design criteria. Figure B-5 shows an example of the modal analysis results. The design changes included thickening the main bracket, adding a main support rib, and reshaping features based on lessons learned from the fit check. Tooling was kicked off and began at the supplier in December, 2016.

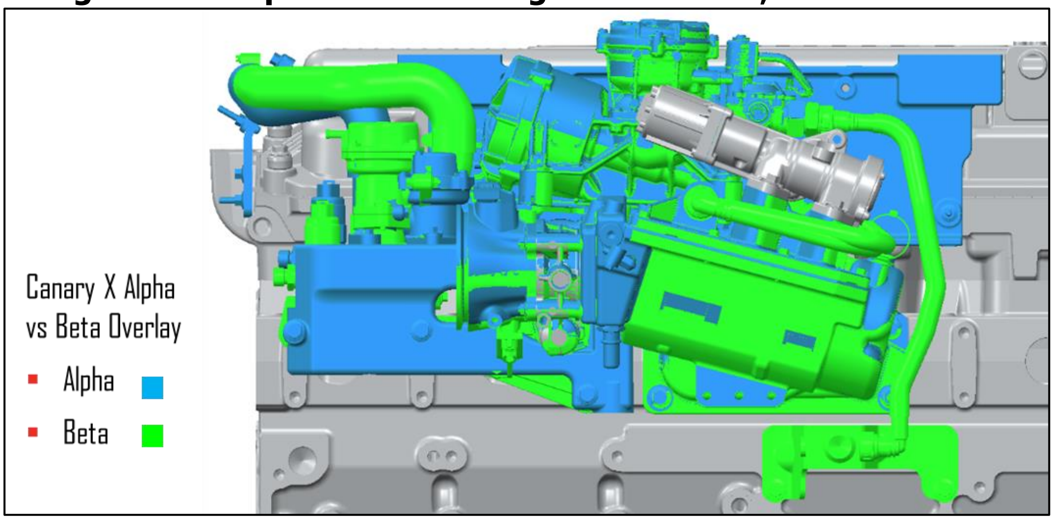
Figure B-5: Modal Analysis of Wastegate Control Housing and Fuel Module Bracket



Source: Cummins Westport Inc.

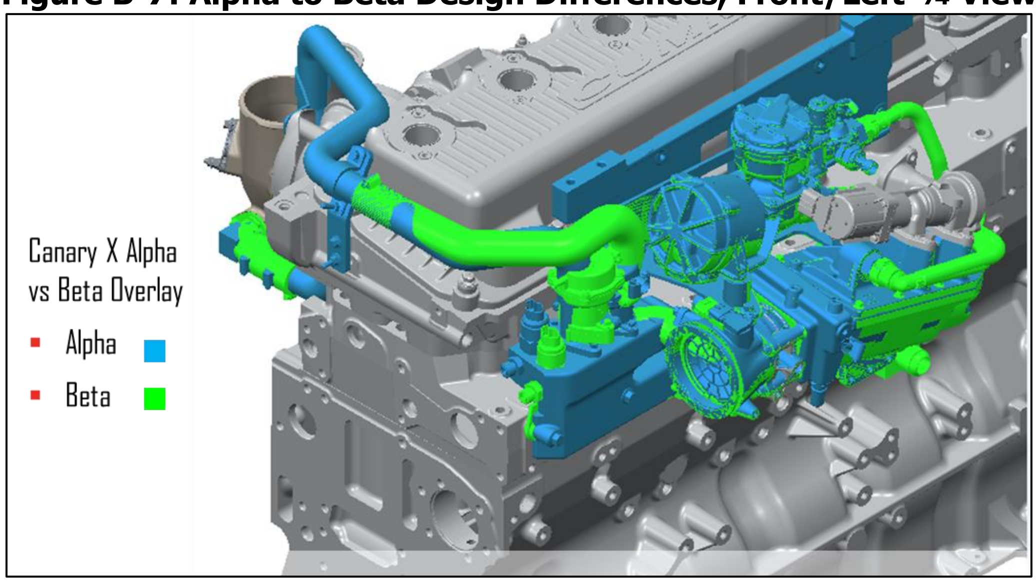
Additional images showing the changes from Alpha to Beta, including the plumbing for the fuel supply, wastegate control, and compressor recirculation valve plumbing, are shown in Figure B-6, Figure B-7, and Figure B-8. The reasons for these changes included engine performance, manufacturability and resolving interference with the many different truck chassis in which the engine will be installed. Note that "Canary" was a development name for the ISX12N.

Figure B-6: Alpha to Beta Design Differences, Left Side View



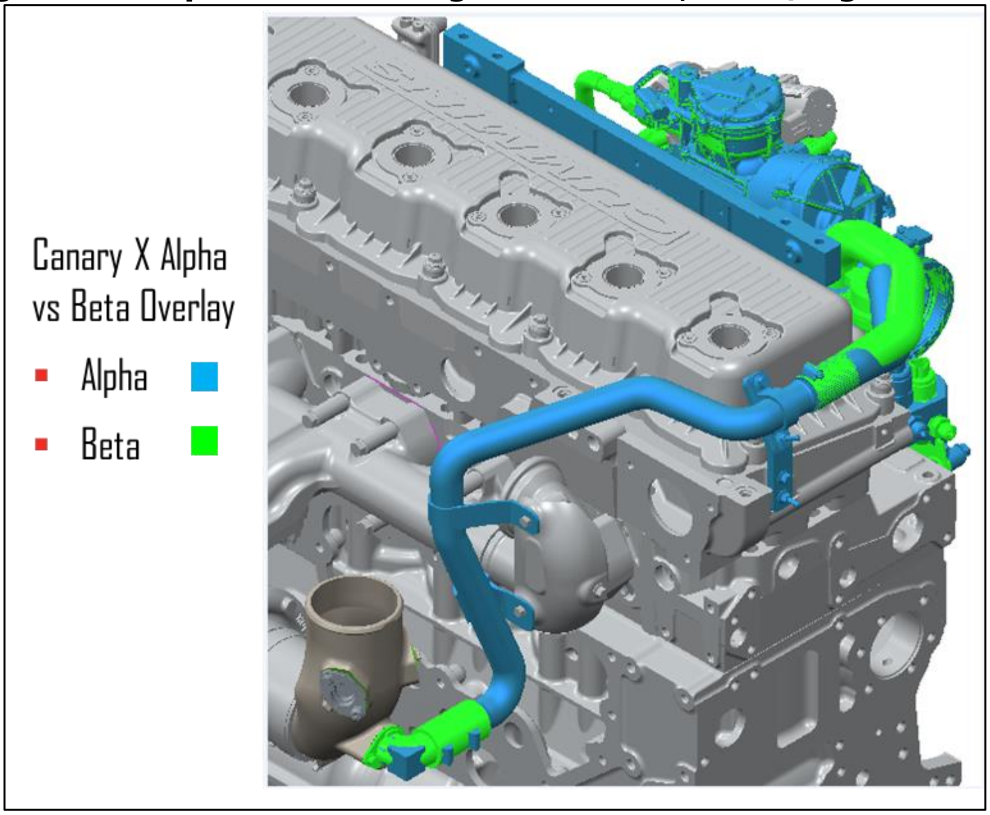
Source: Cummins Westport Inc.

Figure B-7: Alpha to Beta Design Differences, Front/Left ¾ View



Source: Cummins Westport Inc.

Figure B-8: Alpha to Beta Design Differences, Front/Right ¾ View

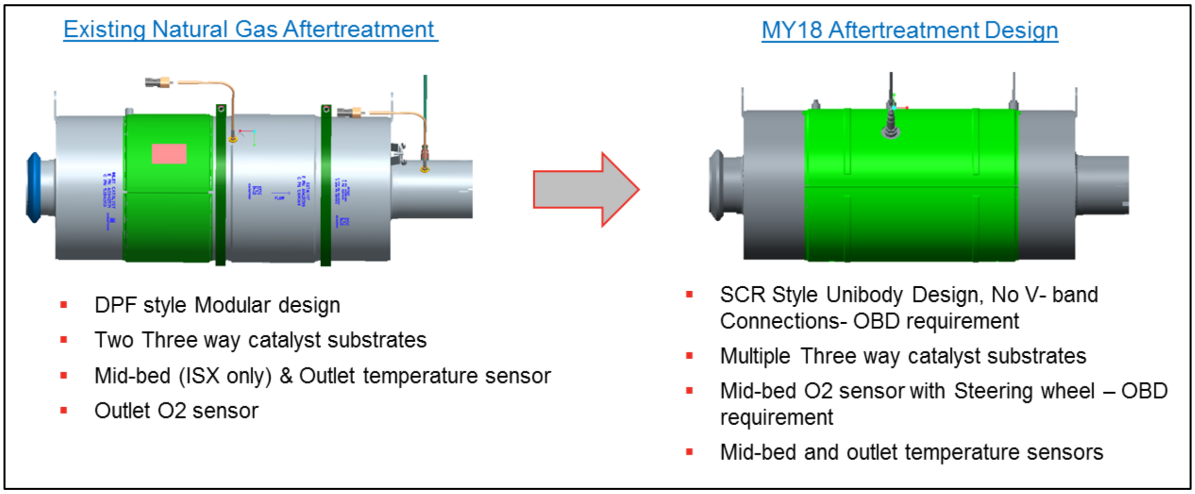


Source: Cummins Westport Inc.

Aftertreatment Design Summary

Significant changes were required for the aftertreatment system design to support the lower NOx emissions and on-board diagnostics (OBD) capability. These changes included increasing the volume of the catalyst and altering and relocating the sensors to improve control and OBD capability. The main body of the aftertreatment was changed due to a heavy-duty OBD requirement to be tamperproof. The previous design utilized multiple sections held together with band-clamps. The new design consisted of a welded unibody. The changes to the aftertreatment system design are shown in Figure B-9.

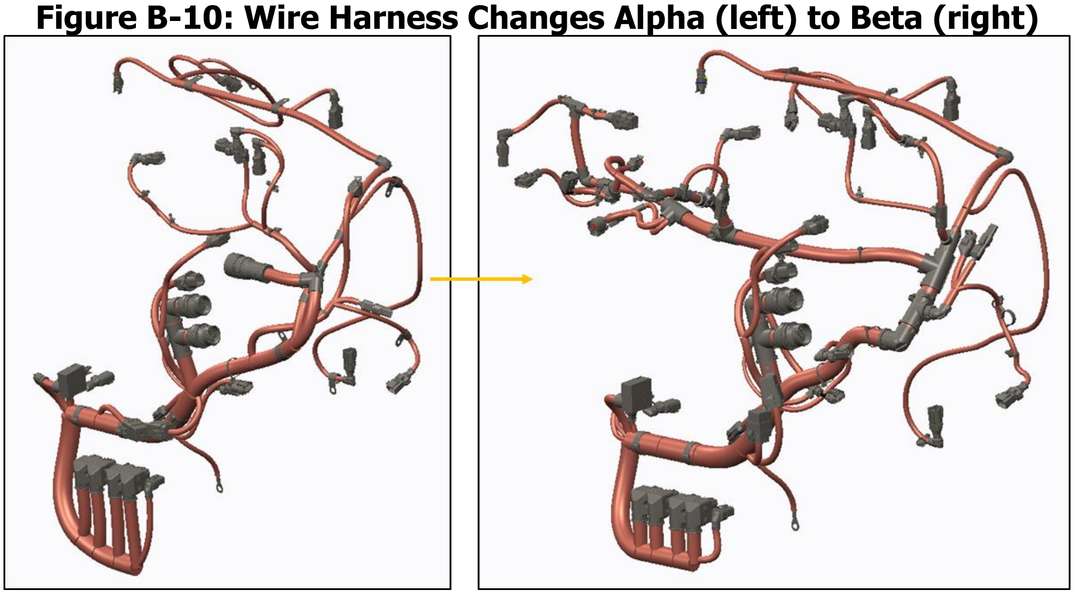
Figure B-9: Aftertreatment Design Changes from Current Product ISX12 G to New ISX12N



Source: Cummins Westport Inc.

The main engine and ignition harnesses required changes for the Beta engines and were reviewed on November 17, 2016. Changes were made to account for components that changed locations between Alpha and Beta, to improve routing and OEM interference issues that were discovered on the Alpha build, to improve assembly issues that were discovered during the Alpha build, and to provide adequate current carrying capacity for the electric rotary crankcase breather. One example of the main harness change from Alpha (left) to Beta (right) is shown in Figure B-10.

Figure B-10: Wire Harness Changes Alpha (left) to Beta (right)



Source: Cummins Westport Inc.

Although Beta design had commenced, the remaining outstanding Alpha design reviews were completed, which included a design review of the Ignition Control Module and the overall engine's stable performance review.

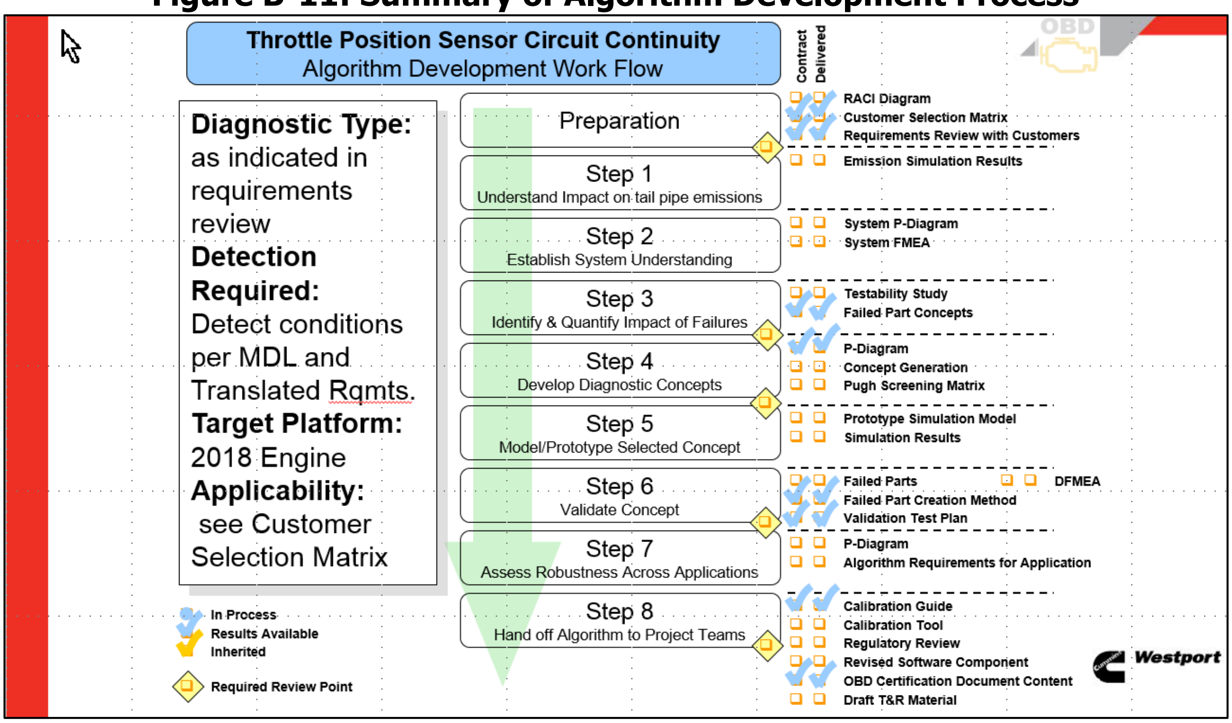
Significant work was completed on HD-OBD for the ISX12N in three areas: infrastructure development, diagnostics algorithm/software creation, and calibration.

The infrastructure and algorithm development established the software used to acquire and communicate data from the engine and aftertreatment, including the datalink communication to interface with generic scan tools and data log when engine or aftertreatment faults occur.

This infrastructure development was completed and validated. Testing of the standardized data logging, reporting and communication protocol capability was completed to the Society of Automotive Engineers J1939/84 standard. The Non-Diagnostic Feature List was used to track required software to support this capability and contained 164 specific items.

The diagnostics algorithm/software creation involved the development of monitors to detect and diagnose issues that will lead to emissions exceeding predetermined levels. Cummins has a proprietary process in place for the OBD algorithm and calibration developed. This process is defined in internal standards and requires reviews and documentation be completed prior to release of each algorithm. Figure B-11 shows a summary of the eight-step algorithm development process.

Figure B-11: Summary of Algorithm Development Process



Source: Cummins Westport Inc.

Reviews are imbedded within the process and each yellow diamond represents a potential review point. The tasks listed along the right side are selected based on the requirements and complexity of the diagnostic. This example shows the chart for the Intake Air Throttle position sensor out-of-range diagnostics.

An initial step was to review and analyze the requirements, both those from the OBD regulation and internal sources. Table B-1 and Table B-2 show the requirements applicable to this diagnostic.

Table B-1: Requirements for Intake Air Throttle Diagnostics (a)

MCID	Condition	Statement
82	Out of range high	The OBD system shall detect malfunctions of the sensor caused by an out-of-range high value
83	Out of range low	The OBD system shall detect malfunctions of the sensor caused by an out-of-range low value

Source: Cummins Westport Inc.

Table B-2: Requirements for Intake Air Throttle Diagnostics (b)

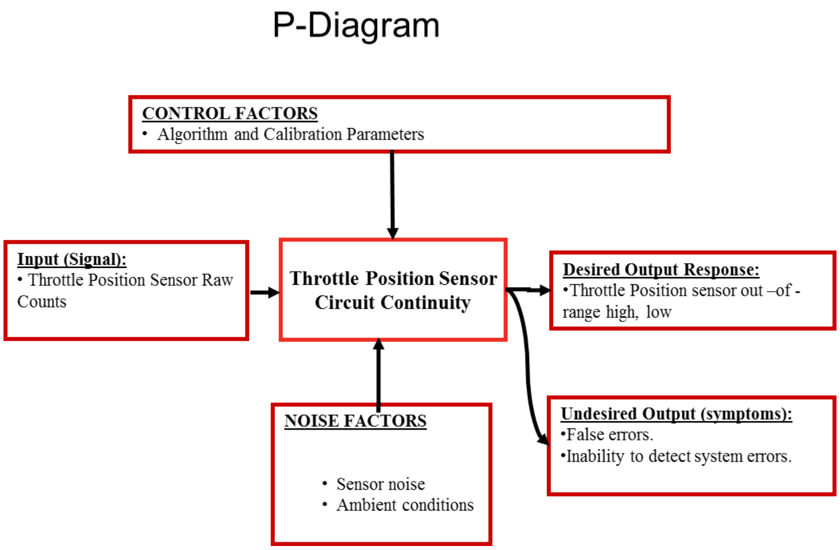
Cond	MCID 82	MCID 83	Description
MON001			Manufacturers shall define monitoring conditions to be technically necessary to ensure robust detection of malfunctions.
MON002			Manufacturers shall define monitoring conditions to ensure monitoring will occur under conditions that may reasonably be expected to be encountered in normal vehicle operation and use
MON003			Manufacturers shall define monitoring conditions and detection methods such that a malfunctioning system or component is detected before the end of the first engine start portion of the OBD Demonstration Cycle.
MON005			Manufacturers may request Regulatory Agency approval to define monitoring conditions that are not encountered during the OBD Demonstration Cycle.
MON006			Manufacturers may NOT use the calculated in-use ratio (or any element thereof) or any other indication of monitor frequency as a monitoring condition for a monitor.
MON008			Monitoring shall occur continuously for the malfunction criteria.
MON032			Manufacturers shall monitor for malfunctions of any electronic powertrain component/system that either provides input to (directly or indirectly) the on-board computer(s).
MON034			Manufacturers shall monitor for malfunctions of electronic powertrain input or output components/systems.
MON035			Manufacturers shall monitor for malfunction electronic powertrain input or output components/systems associated with components that only affect emissions by causing additional electrical load to the engine
MON040			OBD to run for actual running life of vehicle. (Should not disable for old /age vehicles)
MON041			If an input component is used only to derate fueling, it is not required to be in the OBD boundary if the derate does not disable other diagnostics or is severe enough to cause operator action
MON045			The stored fault code shall, to the fullest extent possible, isolate the likely cause of the malfunction.
MON053			A manufacturer may request Regulatory Agency approval to employ alternate statistical malfunction indicator lamp (MIL) illumination and fault code storage protocols to those specified in these requirements.
MON055			Manufacturers may request Regulatory Agency approval to disable an OBD system monitor at ambient engine start temperatures below -6.7 deg C (20 deg F)
MON056			Manufacturers may request Regulatory Agency approval to disable monitoring systems that can be affected by low fuel level.

Cond	MCID 82	MCID 83	Description
MON057			A manufacturer may request Regulatory Agency approval to disable monitors that can be affected by PTO activation on engines.
MON061			If the engine enters a default mode of operation, a manufacturer may request Regulatory Agency approval to be exempt from illuminating the MIL.
MON062			The OBD system shall be operational in specified operating range.
MON079			If the default or "limp home" mode of operation is recoverable the OBD system may delay illumination of the MIL until the condition is again detected before the end of the next driving cycle
MON080			The OBD system is not required to monitor an electronic powertrain component/system if specified conditions are met.
MON081			Diagnostics shall be operational down to or below a battery or system voltage of 11.0 Volts.
MON082	N/A	N/A	For input components that are used to activate alternate strategies that can affect emissions the OBD system shall detect input component rationality malfunctions that cause the system to erroneously activate or deactivate the alternate strategy.
MON083			Manufacturers may request approval to disable OBD system monitors if specified conditions exist.
MON100			Adequate monitoring during all modes of operation
SRV002			The in-mission diagnostic system, out of mission diagnostics and documented diagnostic procedures collectively shall isolate 100% of all failures to one FRU
SRV003			Employment of unique fault codes
SRV004			Surrogate diagnostic for out-of-mission
SRV005			The system shall be designed such that a technician can determine when a diagnostic has executed and rendered a decision (pass or fail)
SRV006			Product teams shall request Service approval of all monitoring conditions
SRV007			Detection when noticeable to operator
SRV008			Malfunction existence reassessment
SRV009	N/A	N/A	Production of excessive particulate matter
SRV010	N/A	N/A	DEF consumption too high
SRV011			The in-mission diagnostic system shall be operational during reasonable ambient and environmental conditions
SRV013			The monitoring method for input components shall be capable of detecting malfunctions which cause the engine control system to stop using the input component for emissions control
SRV015			Capability of failure detection
SRV016			Mean time to diagnose of 1 hour or less
SRV017			Maximum time to diagnose of 2 hours
IUPR002			ARB minimum IUPR of 0.100 (eng cert >14k)
IUPR003			ARB minimum IUPR of 0.336 (chassis cert, eng cert: 8.5k-14k)
IUPR011			EO approval of alternate Gen Denom
DOC008			OBD Certification Document content
DOC054			Failed part creation methodology
INT001			Diagnostic interfaces to the OBD Infrastructure
INT003			Diagnostic arbitration interface to the OBD Infrastructure
INT011			'Clear Faults' indication provided by the OBD Infrastructure
INT012			Diagnostic capability support
INT013			'Operation Cycle' provided by the OBD Infrastructure

Source: Cummins Westport Inc.

A P-diagram was created for each diagnostic that defines the inputs, control factors, noise factors, and desired/undesired outputs for the algorithm, as shown in Figure B-12.

Figure B-12: Example P-diagram



Source: Cummins Westport Inc.

A diagnostic design checklist was completed to show compliance with the process and the location of the outputs of the process (Table B-3).

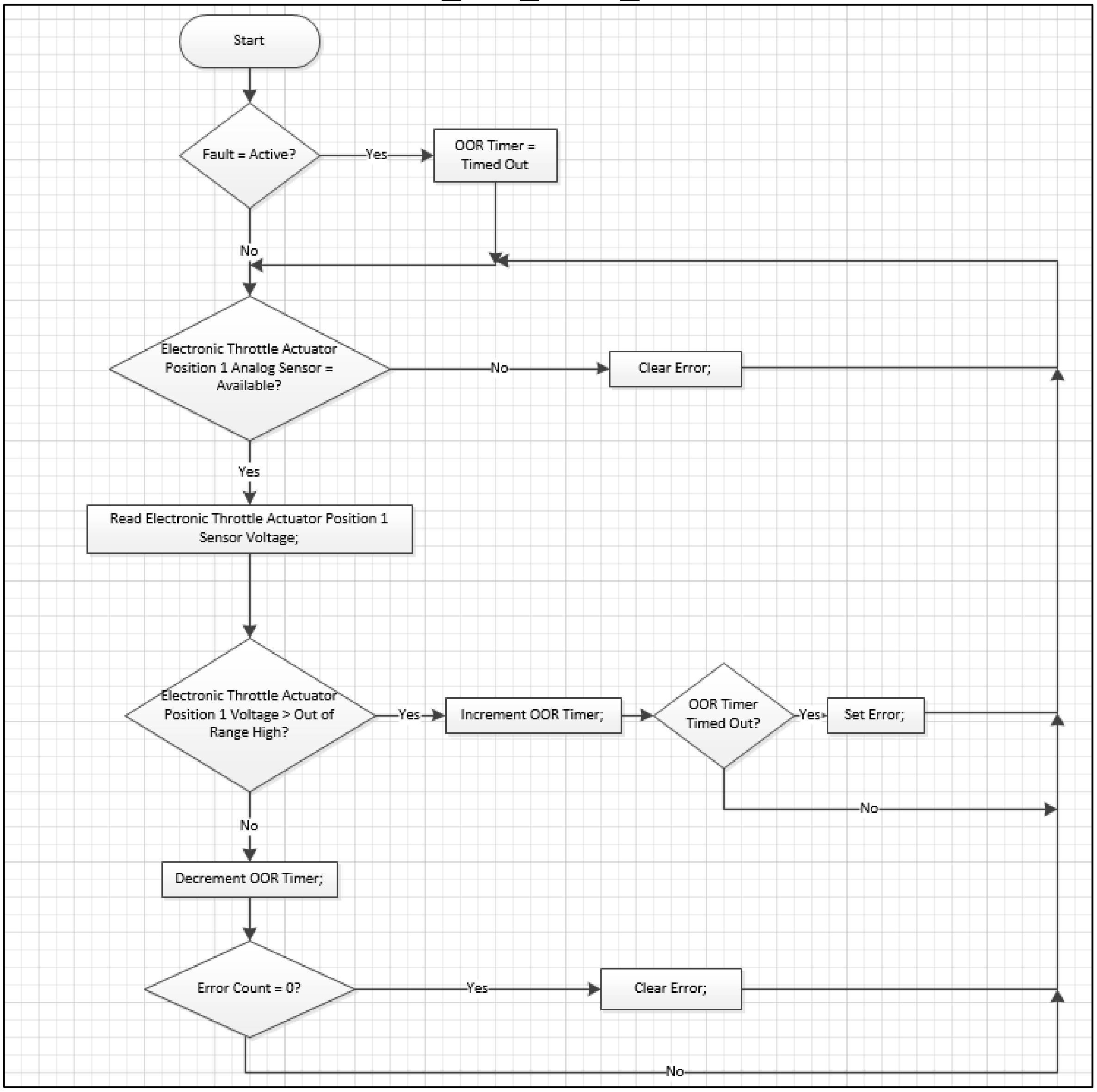
Table B-3: Diagnostic Design Checklist

Item	Status	Evidence/Location
Software component validated and released	Complete	Device Driver - ETC H bridge Alt Fuel 31.00.00.06
PRCR – System Errors update in MDL	Complete	Errors are correct
PRCR – Rules submitted for Rules Checker		Not Applicable
Application Tuning and Validation Guide updated and in latest template	Complete	H:\afp\HDOBD\8-Step_3-Step_Material\8-Step\2037.1_2038.1_2039.1_2040.1 - Throttle Position Sensors - Circuit Continuity\2037.1_2038.1_2039.1_2040.1- Throttle Position Sensor Circuit Continuity-CWI_Application Tuning and Validation Guide.doc
Cert Doc content	Complete	Device Driver - ETC H bridge Alt Fuel 31.00.00.06
Validation Test Plan (PVE Test Plan)	Complete	Slide 17
Failed Part Creation Method	Complete	Slide 16
Correct interface with OBD infrastructure implemented, reviewed (Set/Clear Errors, Operation cycle determination, Diagnostic Arbitration, Test results, Diagnostic Capability Metrics, Enable/Disable status)	Complete	Canary Build A04

Source: Cummins Westport Inc.

A flow chart was created describing the operation of the algorithm for submission in the OBD certification document to the regulatory agencies. Figure B-13 provides an example of one of the flow charts from this diagnostic.

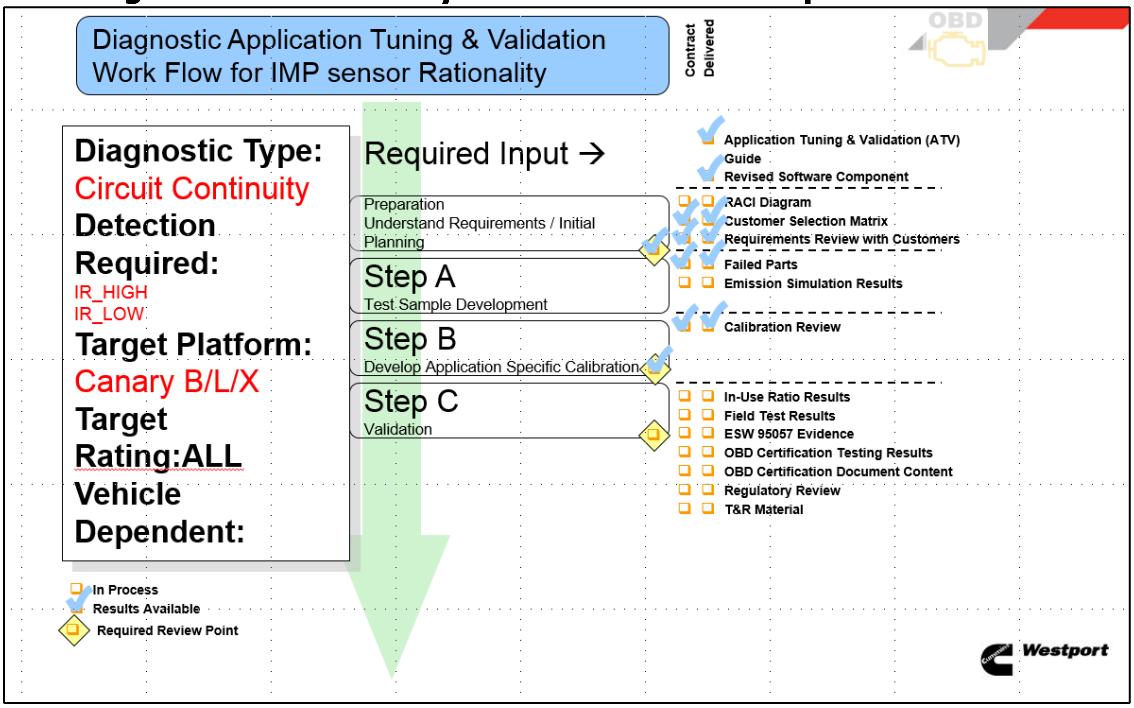
Figure B-13: Example Flow Chart for Diagnostic 2037.1 – TP1_00R_HIGH_ERROR



Source: Cummins Westport Inc.

As the algorithm development process was completed, the calibration development process started. The calibration portion consisted of tuning the previously developed algorithms so the monitor could detect accurately and repeatedly at the desired level. The calibrations may be unique to each power rating for the same engine platform. Figure B-14 shows a summary of the three-step calibration development process. Table B-4 provides a summary of the diagnostic strategy.

Figure B-14: Summary of Calibration Development Process



Source: Cummins Westport Inc.

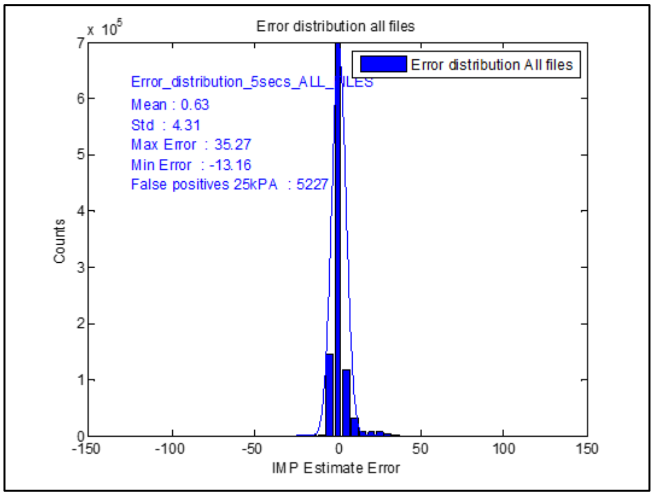
Table B-4: Diagnostic Strategy

Item	In-mission IMP In-range
Strategy	Compare IMP sensor reading to IMP estimate
Enable Conditions	Engine speed > 300 revolutions per minute
Disable/Pause conditions	Engine speed < 300 revolutions per minute, motoring (fuel cut off) bad input sensor status (COP, TPC)

Source: Cummins Westport Inc.

Data was collected to understand the system performance and build a statistical model of the component's behavior to identify abnormal behavior (Figure B-15). Following data collection and analysis, calibrations were created (Table B-5) and tested.

Figure B-15: Data Collected to Build Statistical Model



Source: Cummins Westport Inc.

Table B-5: Calibration Review Summary

Calterm Parameter Name	L	B	X	Unit	Description
C_IMPFT_IRDur	5	5	5	s	Fault duration
C_IMPFT_IRGapThreshold	30	30	30	kPa	In-range threshold
C_ThrotPR_Valid_RPMThd	300	300	300	RPM	Engine Speed RPM threshold
C_IMP_Diag_Offset_Table					See table in calibration
C_IMP_DiagThrot_PR_Table					See table in calibration

Source: Cummins Westport Inc.

Validation testing was completed with data taken to show compliance with the fault reporting, lamp illumination, and freeze frame data collection.

To track all the diagnostics required for full OBD compliance, a Master Diagnostic List was created for the ISX12N and progress was tracked against completion of algorithms and calibrations separately. There were 341 individual diagnostics required and tracked on the Master Diagnostic List.

With the infrastructure and algorithms developed and calibrated, the diagnostics were tested in both test cells and on vehicles. Based on California Code of Regulations (CCR) 1971.1, the Heavy Duty OBD regulation, engine and aftertreatment components were identified for diagnostic demonstration testing and the demonstration plan was reviewed and approved by California Air Resources Board (CARB). In accordance with this plan, fully failed or partially failed samples of these parts were installed on the engine. For specific parts identified by the regulation, the engine was operated in an emissions test cell to measure tailpipe emissions with the failed part installed. The OBD system was left to evaluate the engine operation with the expectation that the failed part would be detected and communicated to the operator through the activation of fault code(s) and the malfunction indicator lamp and that the required data was logged by the engine control module and reported properly over the required OBD datalink for communication to the service technician. The effect of the failed part on tailpipe emissions was also measured. The remainder of the diagnostics not requiring test cell emissions measurement were validated on a test vehicle, with nonworking parts installed on the engine and the vehicle operated to validate that the diagnostic system properly identified the fault(s).

Diagnostic development work continued as further tuning and validation was required. The validation of these diagnostics was completed when proven statistical confidence with the systems capability of detecting actual faults and not detecting false positives was achieved.

Product Validation Matrix

A product validation matrix was created to show the various engine areas and their progress through the product design/development process and is shown in Table B-6. The typical engine product design process starts with developing the technology architecture followed by validating this technology. The result of this process is a stable system architecture. The technology architecture for the ISX12N project was parented from the previous development project, funded by the South Coast Air Quality Management District, the California Energy Commission, and Southern California Gas Company on the ISL G Near Zero engine. The technology architecture consisted of:

- Stoichiometric spark ignited combustion with cooled exhaust gas recirculation.
- Closed crankcase ventilation system.
- Three-way catalyst aftertreatment.
- Wastegate turbocharger.
- Throttle controlled intake air.
- Central natural gas injection into the air intake downstream of the throttle.

Initial component design was the next step in the development process, which was completed during the Alpha design phase. Further analysis as well as testing of prototype parts validated the Alpha design. Alpha prototypes are typically manufactured with prototype manufacturing processes and tooling. Completion of this portion resulted in a stable engine design.

Following Alpha design and incorporating feedback from Alpha validation, the design was iterated with a Beta design, which typically uses production intent processes. The Beta design was validated through upgrades of some Alpha test units as well as newly built Beta prototype test engines and field demonstrations. Beta prototypes are production intent designs made through production intent manufacturing processes. The outcome of Beta testing was stable performance.

After Beta prototypes were manufactured, any issues with the manufacturing process were addressed during the preparation for limited production. Although the design is theoretically stable after Beta design, deficiencies are expected to be found in both Alpha and Beta prototype testing, which can be corrected prior to limited production launch. The ISX12N entered production in the first quarter of 2018.

Table B-6: Product Validation Matrix

		STABLE ARCHITECTURE	STABLE DESIGN		STABLE PERFORMANCE		STABLE PROCESS
	Hardware/Software	(parented from ISL G NZ Project)	Alpha Design	Alpha Testing	Beta Design	Beta Testing	
Engine Mechanical Components	Base Engine	✓	✓	✓	✓	✓	✓
	Power Cylinder	✓	✓	✓	✓	✓	✓
	Intake Manifold	✓	✓	✓	✓	✓	✓
	Exhaust Manifold	✓	✓	✓	✓	✓	✓
	Cylinder Head	✓	✓	✓	✓	✓	✓
	Turbo	✓	✓	✓	✓	✓	✓
	Fuel System	✓	✓	✓	✓	✓	✓
	Crankcase Ventilation	✓	✓	✓	✓	✓	✓
	Exhaust Gas Recirculation	✓	✓	✓	✓	✓	✓
Engine Control System	Engine Control Module	✓	✓	✓	✓	✓	✓
	Ignition Control Module	✓	✓	✓	✓	✓	✓
	Sensors	✓	✓	✓	✓	✓	✓
	Actuators/Valves	✓	✓	✓	✓	✓	✓
	Ignition System	✓	✓	✓	✓	✓	✓
	Engine Control Software	✓	✓	✓	✓	✓	✓
	Diagnostics (HD-OBD)	✓	✓	✓	✓	✓	✓
	Chassis Electronic Interface	✓	✓	✓	✓	✓	✓
	Aftertreatment	✓	✓	✓	✓	✓	✓

Source: Cummins Westport Inc.

The completion of HD-OBD shown in the table refers to the requirements set out as per the CARB Innovative Technology Regulation (ITR) approved under CARB Executive Order R-17-003. Under the ITR, a one year delay in implementing all OBD monitors was approved in exchange for reaching Near Zero NOx (0.02g/bhp-hr) in the second commercial engine (the first being the ISL G NZ/L9N). The ITR was utilized to accelerate the commercialization of the ISX12N and deliver a near zero NOx emissions engine a year early. The complete implementation of HD-OBD monitors is required for 2019.

Beta Engine and Aftertreatment Build

Beta prototype ISX12N engines and aftertreatment systems were built for engineering development, field test, and OEM customer fit check purposes. The build specifications for these engines were created using the standard Cummins "On-Line Specification" system which ensures a complete and workable engine is created. An engine specification is divided into engine options, which are a grouping of parts related to one function, such as the engine block, closed crankcase plumbing, turbocharger arrangement, etc. The system checks to see that the engine options chosen are compatible with each other and result in an engine that would operate.

Figure B-16, Figure B-17, Figure B-18, and Figure B-19 show a Beta engine including a close up of the data tag.[11]

[11] Note there is a typo in the data tag and the model should say "ISX12N", not "X12N".

Figure B-16: Beta Engine, Exhaust Side

Source: Cummins Westport Inc.

Figure B-17: Beta Engine, Intake Side

Source: Cummins Westport Inc.

Figure B-18: Beta Engine, Rear

Source: Cummins Westport Inc. Note:

Figure B-19: Engine Data Tag

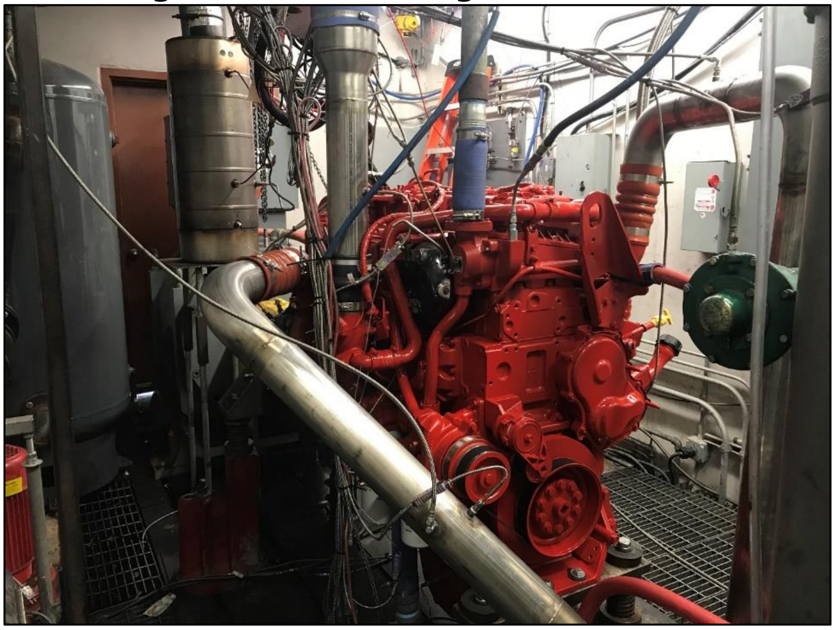
Source: Cummins Westport Inc.

In addition to the Beta engines, Beta three-way catalyst aftertreatment systems were also built. Figure B-20 through Figure B-23 show the Beta three-way catalyst mounted in the test cell along with the Beta engine.

Figure B-20: Beta Three Way Catalyst Mounted in Test Cell

Source: Cummins Westport Inc.

Figure B-21: Beta Engine in Test Cell



Source: Cummins Westport Inc.

Beta Engine Emissions, Fuel Consumption, and Performance Tests

Transient dynamometer tests per the United States Environmental Protection Agency (USEPA) heavy-duty on-highway Federal Test Procedure (FTP) duty cycle were performed to determine brake specific fuel consumption (BSFC), non-methane hydrocarbons, oxides of nitrogen (NOx), carbon monoxide, particulate matter, ammonia (NH_3), nitrous oxide, nitrogen dioxide, carbon dioxide, and ultrafine emissions from a production-intent engine. Both pre- and post-exhaust aftertreatment measurements were collected. The tests were the Cold/Hot Emission Test (CHET) which weights cold and hot FTP cycles by one and six, respectively.

The testing was conducted using natural gas that was laboratory tested to confirm its adherence to the certification fuel specifications in California Code of Regulations (CCR) Title 13 Section 2292.5. Bottled fuel was used for the certification test because the ethane concentration in natural gas pipeline fuel was not within the California Air Resources Board (CARB) natural gas certification fuel specification. The bottled fuel came in cylinders targeting CARB natural gas certification fuel specification as shown by the copies of certificate of analysis in Figure B-22. The last Ramped Mode Cycle Supplemental Emissions Test (RMC-SET) was run on house gas available at Cummins Technical Center, which met the USEPA natural gas certification fuel specifications.

The emissions certification test was carried out in late August 2017 and the results were submitted to CARB and USEPA in September 2017. The certification values submitted to USEPA and CARB (Table B-7) show NOx emissions meeting the program target of

0.02 g/hp-hr NOx. The 10 ppm NH_3 goal in the development project was not met by the certified configuration. However, a more than 50 percent reduction in NH_3 emissions on CHET and RMCSET cycles was demonstrated compared to the current production ISX12 G engine. BSFC was equivalent to current production engines. Pre-exhaust after-treatment emissions are summarized in Table B-8, without applying the deterioration factor. Note that this data was collected on a different engine serial number.

Ultrafine particulate emissions were not measured during the certification test but were measured in separate tests in mid-November 2017 using the Particle Number procedure described in the Euro 6 legislation. Over the CHET cycle, the particulate number (PN) was 5.732e12 PN/hp-hr and over the RMCSET cycle was 4.42e11 PN/hp-hr.

Figure B-22: Bottled Test Fuel Compositions

Airgas
an Air Liquide company

Airgas Specialty Gases
Airgas USA, LLC
24075 US Hwy 6
Stryker, OH 43557
Airgas.com

CERTIFICATE OF ANALYSIS

Grade of Product: PRIMARY HYDROCARBON

Part Number:	X08ME90P300C011	Reference Number:	141-124532063-2
Cylinder Number:	5445869Y	Cylinder Volume:	282.2 CF
Laboratory:	124 - Conley Stryker (SAP) - OH	Cylinder Pressure:	1800 PSIG
Analysis Date:	Feb 05, 2016	Valve Outlet:	350
Lot Number:	141-124532063-2		

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
HEXANE	950.0 PPM	948.0 PPM	+/- 1%
N PENTANE	0.1200 %	0.1200 %	+/- 1%
N BUTANE	0.3300 %	0.3302 %	+/- 1%
CARBON DIOXIDE	1.000 %	0.9995 %	+/- 1%
PROPANE	1.190 %	1.192 %	+/- 1%
NITROGEN	2.500 %	2.501 %	+/- 1%
ETHANE	4.200 %	4.201 %	+/- 1%
METHANE	90.57 %	90.5615 %	+/- 1%

CERTIFICATE OF ANALYSIS

Grade of Product: PRIMARY HYDROCARBON

Part Number:	X08ME90P300C011	Reference Number:	141-124532063-1
Cylinder Number:	5445883Y	Cylinder Volume:	282.2 CF
Laboratory:	124 - Conley Stryker (SAP) - OH	Cylinder Pressure:	1800 PSIG
Analysis Date:	Jan 20, 2016	Valve Outlet:	350
Lot Number:	141-124532063-1		

Traceability Statement: Hydrocarbon Process standards are NIST traceable either directly by weight or by comparison to Airgas laboratory standards that are directly NIST traceable by weight.

CERTIFIED CONCENTRATIONS

Component	Requested Concentration	Reported Mole %	Accuracy
HEXANE	950.0 PPM	947.0 PPM	+/- 1%
N PENTANE	0.1200 %	0.1199 %	+/- 1%
N BUTANE	0.3300 %	0.3299 %	+/- 1%
CARBON DIOXIDE	1.000 %	0.9994 %	+/- 1%
PROPANE	1.190 %	1.193 %	+/- 1%
NITROGEN	2.500 %	2.512 %	+/- 1%
ETHANE	4.200 %	4.201 %	+/- 1%
METHANE	90.57 %	90.5507 %	+/- 1%

Notes: Oxygen < 0.1%

Source: Cummins Westport Inc.

Table B-7: Summary of Emissions Submitted to EPA and CARB

Emissions Species		BSNOx	BSCO	BSPM	BSCO2	BSNMHC	N2O	NH3	BSFC	NO2
Units		(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(ppm)	(lbm/hp-hr)	(g/hp-hr)
DF Factor		1.3	1.6	1.6		2				
Results with DF Factor	CHET1	0.0133	1.511	0.0064	501.6	0.0024	0.0207	41.4	0.446	0.0023
	CHET2	0.0121	1.360	0.0051	493.1	0.0033	0.0204	37.9	0.445	0.0019
	RMCSET1	-0.0003	0.575	0.0005	422.9	0.0018	0.0193	20.1	0.374	0.0013
	RMCSET2	0.0001	0.340	0.0003	428.7	0.0001	0.0194	25.1	0.351	0.0014
Emissions Limit		0.02	15.5	0.01		0.14				

Source: Cummins Westport Inc.

Table B-8: Pre-Exhaust Aftertreatment Emissions

Emissions Species		BSNOx	BSCO	BSPM	BSCO2	BSNMHC	N2O	BSFC	NO2
Units		(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(lbm/hp-hr)	(g/hp-hr)
Results WithOut DF Factor	CHET	5.21	14.4	N/A	474.1	0.01	0.00	0.4	0.02
	RMCSET	3.23	9.9	N/A	424.5	-0.01	0.01	0.37	0.01

Source: Cummins Westport Inc.

Certification Submission

USEPA Certificates of Conformity and CARB executive orders were received on December 13 and 22, 2017 respectively, certifying the ISX12N to the CARB Optional 0.02 g/bhp-hr NOx level for model year 2018. Copies of the certificates are shown in Figure B-23 and Figure B-24.

OBD deficiencies are common in the heavy-duty market; on initial certification, the ISX12N engine received five. In January 2018, CWI provided documentation showing resolution of four of those deficiencies prior to production start, and in May 2018 provided documentation clearing the final deficiency. The specifics of the deficiencies themselves are considered proprietary.

Figure B-23: Model Year 2018 EPA Certificate of Conformity for ISX12N

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
2018 MODEL YEAR
CERTIFICATE OF CONFORMITY
WITH THE CLEAN AIR ACT

OFFICE OF TRANSPORTATION
AND AIR QUALITY
ANN ARBOR, MICHIGAN 48105

Certificate Issued To: Cummins Inc.
(U.S. Manufacturer or Importer)
Certificate Number: JCEXH0729XBC-014

Effective Date: 12/13/2017
Expiration Date: 12/31/2018

Byron J. Bunker, Division Director
Compliance Division

Issue Date: 12/13/2017
Revision Date: N/A

Model Year: 2018
Manufacturer Type: Original Engine Manufacturer
Engine Family: JCEXH0729XBC
Intended Service Class: Heavy Heavy-Duty Diesel
Fuel Type: Liquefied Natural Gas, Compressed Natural Gas
FELs (g/hp-hr):
NOx: 0.02

Intended Engine Application: Tractor and Vocational
Primary Test Configuration Transient Duty Cycle:
CO2 FCL value (g/hp-hr): 502
CO2 FEL value (g/hp-hr): 517
N2O FEL value (g/hp-hr): 0.10
CH4 FEL value (g/hp-hr): 0.50
Primary Test Configuration Steady-State Duty Cycle:
CO2 FCL value (g/hp-hr): 429
CO2 FEL value (g/hp-hr): 442

Pursuant to Section 206 of the Clean Air Act (42 U.S.C. section 7525), 40 CFR Parts 86 and 1036, and subject to the terms and conditions prescribed in those provisions, this certificate of conformity is hereby issued with respect to the test engines which represent the engine family, and is subject to the terms and conditions prescribed in those provisions.

This certificate of conformity covers only those new motor vehicle engines which conform in all material respects to the design specifications that applied to those engines described in the documentation required by 40 CFR Parts 86 and 1036 and which are produced during the model year stated on this certificate of the said manufacturer, as defined in 40 CFR Parts 86 and 1036.

This certificate of conformity is conditional upon compliance of said manufacturer with the averaging, banking and trading provisions of 40 CFR Parts 86 and 1036. Failure to comply with these provisions may render this certificate void *ab initio*.

It is a term of this certificate that the manufacturer shall consent to all inspections described in 40 CFR Parts 86 and 1068 and authorized in a warrant or court order. Failure to comply with the requirements of such a warrant or court order may lead to revocation or suspension of this certificate for reasons specified in 40 CFR Parts 86 and 1036. It is also a term of this certificate that this certificate may be revoked or suspended or rendered void *ab initio* for other reasons specified in 40 CFR Parts 86 and 1036.

This certificate does not cover engines sold, offered for sale, or introduced, or delivered for introduction into commerce in the U.S. prior to the effective date of the certificate.

Source: Cummins Westport Inc.

Figure B-24: Model Year 2018 CARB Executive Order for ISX12N (3 pages)

CALIFORNIA AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0674 New On-Road Heavy-Duty Engines Page 1 of 2 Pages

Pursuant to the authority vested in the California Air Resources Board by Health and Safety Code Division 26, Part 5, Chapter 2; and pursuant to the authority vested in the undersigned by Health and Safety Code Sections 39515 and 39516 and Executive Order G-14-012;

IT IS ORDERED AND RESOLVED: The engine and emission control systems produced by the manufacturer are certified as described below for use in on-road motor vehicles with a manufacturer's GVWR over 14,000 pounds. Production engines shall be in all material respects the same as those for which certification is granted.

MODEL YEAR	ENGINE FAMILY	ENGINE SIZES (L)	FUEL TYPE [1]	STANDARDS & TEST PROCEDURE	INTENDED SERVICE CLASS [2]	ECS & SPECIAL FEATURES [3]	DIAGNOSTIC [6]
2018	JCEXH0729XBC	11.9	CNG/LNG	Diesel	HHDD-UB	TBI, TC, CAC, ECM, EGR, TWC, HO2S	OBD(S)

PRIMARY ENGINE'S IDLE EMISSIONS CONTROL [5]	ADDITIONAL IDLE EMISSIONS CONTROL [5]
N/A	N/A

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
11.9	See attachment for engine models and ratings

* =not applicable; **GVWR**=gross vehicle weight rating; **13 CCR xyz**=Title 13 California Code of Regulations, Section xyz; **40 CFR 86.abc**=Title 40, Code of Federal Regulations, Section 86.abc; L=liter; hp=horsepower; kw=kilowatt; hr=hour;

[1] **CNG/LNG**=compressed/liquefied natural gas; **LPG**=liquefied petroleum gas; **E85**=85% ethanol fuel; **MF**=multi fuel a.k.a. **BF**=bi fuel; **DF**=dual fuel; **FF**=flexible fuel;

[2] **L/M/H HDD**=light/medium/heavy heavy-duty diesel; **UB**=urban bus; **HDO**=heavy duty Otto;

[3] **ECS**=emission control system; **TWC/OC**=three-way/oxidizing catalyst; **NAC**=NOx adsorption catalyst; **SCR-U / SCR-N**=selective catalytic reduction – urea / – ammonia; **WU (prefix)** =warm-up catalyst; **DPF**=diesel particulate filter; **PTOX**=periodic trap oxidizer; **HO2S/O2S**=heated/oxygen sensor; **HAFS/AFS**=heated/air-fuel-ratio sensor (a.k.a., universal or linear oxygen sensor); **TBI**=throttle body fuel injection; **SFI/MFI**=sequential/multi port fuel injection; **DGI**=direct gasoline injection; **GCARB**=gaseous carburetor; **IDI/DDI**=indirect/direct diesel injection; **TC/SC**=turbo/super charger; **CAC**=charge air cooler; **EGR / EGR-C**=exhaust gas recirculation / cooled EGR; **PAIR/AIR**=pulsed/secondary air injection; **SPL**=smoke puff limiter; **ECM/PCM**=engine/powertrain control module; **EM**=engine modification; **2 (prefix)**=parallel; **(2) (suffix)**=in series;

[5] **ESS**=engine shutdown system (per 13 CCR 1956.8(a)(6)(A)(1); **30g**=30 g/hr NOx (per 13 CCR 1956.8(a)(6)(C); **APS** =internal combustion auxiliary power system; **ALT**=alternative method (per 13 CCR 1956.8(a)(6)(D); **Exempt**=exempted per 13 CCR 1956.8(a)(6)(B) or for CNG/LNG fuel systems; **N/A**=not applicable (e.g., Otto engines and vehicles);

[6] **EMD**=engine manufacturer diagnostic system (13 CCR 1971); **OBD**=on-board diagnostic system (13 CCR 1971.1);

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.8; 2) the SET and NTE limits under the applicable California exhaust emission standards and test procedures for heavy-duty diesel engines and vehicles (Test Procedures); and 3) the corresponding certification levels, for this engine family. "Diesel" CO, SET and NTE certification compliance may have been demonstrated by the manufacturer as provided under the applicable Test Procedures in lieu of testing. (For flexible- and dual-fueled engines, the CERT values in brackets [ ] are those when tested on conventional test fuel. For multi-fueled engines, the STD and CERT values for default operation permitted in 13 CCR 1956.8 are in parentheses.). [4]

in g/bhp-hr	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET	FTP	SET
STD	0.14	0.14	0.02	0.02	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.004	0.000	0.01	0.000	*	*	1.5	0.3	0.01	0.000	*	*
NTE	0.21		0.03		*		19.4		0.02		*	

[4] **g/bhp-hr**=grams per brake horsepower-hour; **FTP**=Federal Test Procedure; **SET**= Supplemental emissions testing; **NTE**=Not-to-Exceed; **STD**=standard or emission test cap; **FEL**=family emission limit; **CERT**=certification level; **NMHC/HC**=non-methane/hydrocarbon; **NOx**=oxides of nitrogen; **CO**=carbon monoxide; **PM**=particulate matter; **HCHO**=formaldehyde

BE IT FURTHER RESOLVED: That the listed engine family is certified to the Optional Low NOx Emission Standards as specified in 13 CCR 1956.8(a)(2)(A) and section 11.B.7 of the incorporated "California Exhaust Emission Standards and Test Procedures for 2004 and Subsequent Model Heavy Duty Diesel-Engines and Vehicles" adopted Dec. 12, 2002, as last amended September 1, 2017.

BE IT FURTHER RESOLVED: The listed engine family is certified pursuant to CCR Title 13 Section 2208.1(b)(3), Innovative Technology Regulation for multiple Low NOx engines "enhanced flexibility" option.

BE IT FURTHER RESOLVED: The manufacturer has demonstrated compliance with the Greenhouse Gas Emission Standards as specified in Title 13 CCR 1956.8 and the incorporated "California Exhaust Emission Standards and Test Procedures for 2004 and Subsequent Model Heavy Duty Diesel-Engines and Vehicles" (HDDE Test Procedures) adopted Dec. 12, 2002, as last amended September 1, 2017 using the 2014 model year National Heavy-Duty Engine and Vehicle Greenhouse Gas Program as specified in Section 1036.108 of the HDDE Test Procedures. The manufacturer has submitted the required information and therefore has met the criteria necessary to receive a California Executive Order based on the Environmental Protection Agency's Certificate of Conformity for the above listed engine family.

	EPA CERTIFICATE OF CONFORMITY		PRIMARY INTENDED SERVICE CLASS	
	JCEXH0729XBC-014		TRACTOR / VOCATIONAL	
in g/bhp-hr	CO_2		CH_4	N_2O
	FTP	SET		
STD	555	460	0.10	0.10
FCL	502	429	*	*
FEL	517	442	0.50	0.10
CERT	502	429	0.19	0.02

[4] **g/bhp-hr**=grams per brake horsepower-hour; **FTP**=Federal Test Procedure; **SET**=Supplemental emissions testing; **STD** = standard or emission test cap; **FEL**=family emission limit; **FCL**=family certification level; **CERT**=certification level; CO_2=carbon dioxide; CH_4=methane; N_2O=nitrous oxide; **VOCATIONAL**=vocational engine; **TRACTOR**=tractor engine

CALIFORNIA AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0674 New On-Road Heavy-Duty Engines Page 2 of 2 Pages

BE IT FURTHER RESOLVED: Certification to the FEL(s) / FCL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(s) / FCL(s) is the emission level declared by the manufacturer and serves in lieu of an emission standard for certification purposes in any averaging, banking, or trading (ABT) programs. It will be used for determining compliance of any engine in this family and compliance with such ABT programs.

BE IT FURTHER RESOLVED: For the listed engine models the manufacturer has submitted the materials to demonstrate certification compliance with 13 CCR 1965 (emission control labels), 13 CCR 1971 (engine manufacturer diagnostic) and 13 CCR 2035 et seq. (emission control warranty).

BE IT FURTHER RESOLVED: The listed engine models are conditionally certified in accordance with 13 CCR Section 1971.1(k) (deficiency and fines provisions for certification of malfunction and diagnostic system) because the heavy-duty on-board diagnostic (HD OBD) system of the listed engine models has been determined to have five deficiencies. The listed engine models are approved subject to the manufacturer paying a fine of $75 per engine for the third through fifth deficiencies in the listed engine family that is produced and delivered for sale in California. On a quarterly basis, the manufacturer shall submit to the California Air Resources Board reports of the number of engines produced and delivered for sale in California and pay the full fine owed for that quarter pursuant to this conditional certification. Payment shall be made payable to the State Treasurer for deposit in the Air Pollution Control Fund no later than thirty (30) days after the end of each calendar quarter during the 2018 model-year production period. Failure to pay the quarterly fine, in full, in the time provided, may be cause for the Executive Officer to rescind this conditional certification, effective from the start of the quarter in question, in which case all engines covered under this conditional certification for that quarter and all future quarters would be deemed uncertified and subject to a civil penalty of up to $5000 per engine pursuant to HSC Section 43154.

Engines certified under this Executive Order must conform to all applicable California emission regulations.

The Bureau of Automotive Repair will be notified by copy of this Executive Order.

Executed at El Monte, California on this 22nd day of December 2017.

[signature] FOR

Annette Hebert, Chief
Emissions Compliance, Automotive Regulations and Science Division

Engine Model Summary Template

Attachment: Page 1 of 1 EO#: A-021-0674

Engine Family	1.Engine Code	2.Engine Model	3.BHP@RPM (SAE Gross)	4.Fuel Rate: mm/stroke @ peak HP (for diesel only)	5.Fuel Rate: (lbs/hr) @ peak HP (for diesels only)	6.Torque @ RPM (SEA Gross)	7.Fuel Rate: mm/stroke@peak torque	8.Fuel Rate: (lbs/hr)@peak torque	9.Emission Control Device Per SAE J1930
JCEXH0729XBC	4875;FR20866	ISX12N 400	400@1800	N/A	N/A	1450@1200	N/A	N/A	~~H02S, PCM, TWC,~~
JCEXH0729XBC	4875;FR20867	ISX12N 385	385@1700	N/A	N/A	1350@1200	N/A	N/A	~~H02S, PCM, TWC,~~
JCEXH0729XBC	4875;FR20868	ISX12N 350	350@1700	N/A	N/A	1350@1200	N/A	N/A	~~H02S, PCM, TWC,~~
JCEXH0729XBC	4875;FR20869	ISX12N 350	350@1700	N/A	N/A	1450@1200	N/A	N/A	~~H02S, PCM, TWC,~~
JCEXH0729XBC	4875;FR20870	ISX12N 330	330@1700	N/A	N/A	1250@1200	N/A	N/A	~~H02S, PCM, TWC,~~
JCEXH0729XBC	4875;FR20871	ISX12N 320	320@1700	N/A	N/A	1150@1200	N/A	N/A	~~H02S, PCM, TWC,~~
	Urban bus	Ratings	Below						
JCEXH0729XBC	4875;FR20872	ISX12N 400CC	400@1800	N/A	N/A	1450@1200	N/A	N/A	~~H02S, PCM, TWC,~~

TBI, TC, CAC, ECM, EGR, TWC, H02S

Source: Cummins Westport Inc.

APPENDIX C:
Original Equipment Manufacturer Engine-Vehicle Integration

Original Equipment Manufacturer Customer Impact Identification

Cummins Westport Inc. (CWI) worked closely with existing ISX12 G engine vehicle original equipment manufacturer (OEM) customers during the development of the ISX12N to identify the impact of the new engine on the OEM. CWI assessed the design differences between the existing ISX12 G engine and the new ISX12N engine to determine which design changes impacted the vehicle OEMs. Table C-1 through Table C-3 list the changes impacting the OEMs and how they were addressed.

Table C-1: Engine Design Changes Impacting Vehicle OEMs
Mechanical Hardware Interfaces

Engine design change	Vehicle OEM solution
Changed engine fuel connection location	Changed chassis fuel connection point to match
Changed fuel inlet pressure range	Adjustment of the off-engine fuel high pressure regulator
Altered space claim around air compressor	Redesigned compressor discharge line
New plumbing on the front of the engine impacting space claim around the fan shroud	Redesigned the fan shroud support bracketry
New fuel system changed space claim near cab of truck	Added cut out to chassis or trimmed insulation when clearance below minimum allowed
New fuel system impacted space claim resulting in unacceptable clearance, CWI blocked chassis options (such as step-forward axle) from being selected by vehicle OEM	Selected other engine option with acceptable clearance (not expected to impact sales).
Three way catalyst length increase of approximately 80 mm.	Exhaust routing and or bracket changed if necessary

Source: Cummins Westport Inc.

Table C-2: Engine Design Changes Impacting Vehicle OEMs Electronic Hardware Interfaces

Engine design change	Vehicle OEM solution
New pin assignments on engine harness	Redesigned chassis wiring harness to match
Added datalink low pressure fuel pressure lamp on gauge cluster as part of OBD requirements	Alter cab wiring harness and dash display programming
Added ambient air temperature sensor	Altered chassis wire harness
Malfunction indicator lamp addition/improvement on instrument cluster as part of OBD requirements	Altered wire harness and dash display programming

Source: Cummins Westport Inc.

Table C-3: Engine Design Changes Impacting Vehicle OEMs Software Interfaces

Engine design change	Vehicle OEM solution
Datalink changes to support 500k baud rate	Altered chassis wire harness and some components and software to be compatible
Scan Tool Interface changes	Altered chassis software to be compatible

Source: Cummins Westport Inc.

Original Equipment Manufacturer Integration Work

At the time of this report, numerous OEMs have completed or are part way through the completion of the items outlined in Table C-1. As part of the Cummins Installation Quality Audit (IQA) process, the vehicle OEMs are required to prove the vehicle design meets all required installation requirements, through paper analysis and/or actual testing and measurements. As of December 31, 2017 the status of the vehicle OEMs progress is shown below by OEM and vehicle model. Vehicle OEM integration work will continue on additional models.

- Autocar ACX
    - Installed prototype engine in test truck, conducted all required IQA testing.
    - IQA complete
- DTNA Next Gen Cascadia
    - Installed prototype engines in test trucks, completed cooling testing, other testing in progress.
- DTNA 114SD
    - Installed prototype engines in test trucks, completed cooling testing, other testing in progress.

- Mack Pinnacle
  - Installed prototype engines in test trucks, completed cooling testing, other testing in progress.
- MCI Coach
  - Installed prototype engine in test truck, identified fit issues which will be addressed by selecting other available engine options.
- Peterbilt 520
  - Installed prototype engine in test truck, completed majority of IQA testing.
- Volvo VNL
  - Installed prototype engines in test trucks, completed cooling testing, other testing in progress.

APPENDIX D: Field Testing

Rapid Truck Testing

Rapid truck testing used prototype ISX12N engines in vehicles operated with the main goal of accumulating on-road mileage quickly. These vehicles were not driven for commercial operation.

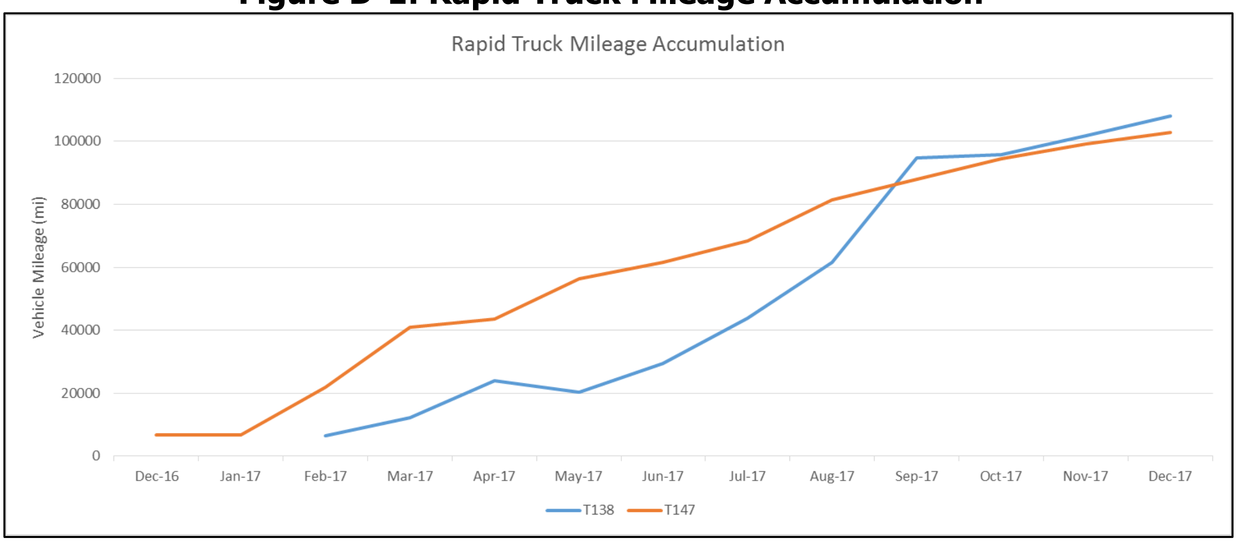
Two Rapid truck test vehicles were put into operation in December of 2016 and February 2017. Details on these two units are shown in Table D-1. The units accumulated approximately 100,000 miles each as shown in Figure D-1. Any issues observed during operation were entered into the Failure Incident Reporting Group process which tracks issues from first reporting through to issue resolution.

Table D-1: Rapid Truck Details

Prototype Level	ESN	Chassis	Application	Rating	Unit	VIN	Trans	Location
Alpha	75053840	2005 KW T800	Truck	400 hp 1450 lb-ft	T138	1XKDD49X15J090696	Allison 6spd Auto	Columbus, IN
Alpha	75053841	2007 KW T800	Truck	400 hp 1450 lb-ft	T147	1XKDD49X67J164245	Eaton 10spd Manual	Columbus, IN

Source: Cummins Westport Inc.

Figure D-1: Rapid Truck Mileage Accumulation



Source: Cummins Westport Inc.

Field Test

The goal of the Field Test was to integrate and implement at least five field test units with alpha and beta engine versions, and operate these vehicles for at least six months with one of these vehicles located within the South Coast Air Basin. From an engineering standpoint, the goal of these vehicles was to perform daily commercial service as they did prior to this project, and to accumulate mileage so that issues could be uncovered prior to the commercial launch of the product.

Field test units supplemented the rigorous performance testing conducted on individual parts and also on complete engine and aftertreatment systems in the test cells. The fleets did not perform specific tests; rather, they operated the vehicles in commercial service and looked for system issues through the engine fault lamp. Operator feedback helped confirm adequate performance and identify issues. In the event of product issues that affect or prevent normal vehicle operation, Cummins Westport Inc.'s (CWI) 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 electronic calibrations on the field test engines as product improvements were developed throughout the program. These field test units did not have emissions measuring equipment onboard, but the newly developed HD-OBD system was in operation and any faults detected were conveyed to the driver through the fault lamp and investigated.

In addition to the system monitoring, the fleets recorded mileage. Fuel economy assessment of the fleets was not performed because of accuracy concerns: measuring fuel economy in a test cell is preferred due to the ability to consistently control input factors such as engine load and engine speed and to minimize potential error-inducing environmental factors.

The maintenance schedule of the new ISX12N engine was taken from the existing ISX12 G engine schedule, and therefore, fleets continued to use the existing ISX12 G maintenance schedule. Fleets also documented planned maintenance according to existing schedules, such as oil changes, and unplanned maintenance due to component failures. No specific oil consumption tests were conducted with the field test units. Instead, fleets adhered to scheduled maintenance, including oil changes, and would only note abnormal consumption from the need to add oil in between the maintenance intervals.

The ISX12 G engine, on which this project is based, was first introduced in mid-2013 and met then-current United States Environmental Protection Agency (USEPA) and California Air Resources Board (CARB) emission standards. The addition of the 11.9-liter ISX12 G engine to CWI's North American product offering gave customers the option of a larger, more powerful engine to the available 8.9-liter ISL G, especially for fleets operating vehicles for more than 60,000 annual miles and needing a gross vehicle weight rating (GVWR) of greater than 66,000 lbs. (up to a maximum 80,000 lbs.). The ISX12 G became a popular alternative fuel choice in regional haul trucking fleets, refuse fleets hauling heavier loads, and motor coach applications. CWI has worked closely with all major vehicle OEMs to integrate the ISX12 G and offer this engine in a wide variety of models within these applications. Figure 42 shows the OEM vehicle manufacturers and models which offer the model year 2017 ISX12 G.

Figure D-2: Vehicle OEM Availability for Cummins Westport Inc. ISX12 G

OEM	Freightliner 	Peterbilt 	Kenworth 	Volvo 	Autocar 
Model	Cascadia Day Cab, Sleeper 114SD	320 384 365 579 567	W900S T660 T800 SH T680 T880	VNL	Xpeditor
Engine	ISX12 G	ISX12 G	ISX12 G	ISX12 G	ISX12 G
Application	Tractor	Refuse Tractor Vocational	Tractor Vocational	Tractor	Refuse

COACH	
OEM	MCI 
Model	Commuter Coach
Engine	ISX12 G 400

Source: Cummins Westport Inc.

UPS, FedEx Freight, and Dillon Transport, currently use the ISX12 G engine in tractor applications, and Waste Management currently uses the engine in refuse applications. CWI approached these fleets to be the demonstrating customers for this project because they have experience with natural gas engines, specifically with the ISX12 G, and are environmental leaders in their industries. Many of these fleets have previously participated with CWI to demonstrate new technologies and products, and therefore understand that including real-world testing early in the development process with actual fleets is one of the key steps to a successful commercial product. CWI confirmed the fleets' participation by entering into an agreement with each fleet that outlined the scope of the demonstration and the obligations by both the fleet and CWI. Table D-2 lists the nine fleets (13 vehicles, not including the two Rapid Test vehicles) that agreed to participate in the field test program.

Table D-2: Field Test Fleet and Vehicle Details

Prototype Level	Customer	ESN	Chassis	Application	Fuel	Rating	Unit	VIN	Transmission	Location
Alpha	FedEx Freight	75053845	Peterbilt 579	Truck	CNG	400 hp 1450 lb-ft	R18836	1NPBAH8X7HD421474	Eaton UltraShift PLUS	Oklahoma City, OK
Alpha	UPS	75053844	KW T680	Truck	CNG	400 hp 1450 lb-ft	277073	1NKYA38X3GJ477575	Eaton UltraShift	Dallas, TX
Alpha	Dillon	75054059	2014 Peterbilt	Day cab	CNG	400 hp 1450 lb-ft	6006	1NPVDH9X1ED225464	Allison 4500RDS	Mulberry, FL
Alpha	Dillon	75054058	2015 Pete 579	Day cab	CNG	400 hp 1450 lb-ft	6154	1NPBDH9X6FD279928	Eaton UltraShift PLUS	Dallas, TX
Alpha	Frito Lay	75054062	2017 Volvo VNL 42T300	Line haul	CNG	400 hp 1450 lb-ft	C14812	4V5N39UG2HN975428	Eaton UltraShift	Dallas, TX
Alpha	Thatcher Chemical	*75054061 75053838	2014 KW T800	Day cab	CNG	400 hp 1450 lb-ft	316	1NKDD39X3EJ409536	Allison 4000 RDS 6spd Auto	Salt Lake City, UT

Prototype Level	Customer	ESN	Chassis	Application	Fuel	Rating	Unit	VIN	Transmission	Location
Alpha	UPS	75054057	KW T680	Truck	CNG	400 hp 1450 lb-ft	279063	1NKYD39X6HJ152250	Eaton UltraShift	Denver, CO
Alpha	UPS	75054060	Mack	Truck	LNG	400 hp 1450 lb-ft	274895	1M1AW28Y0EM010021	Manual	Knoxville, TN
Alpha	T138	75053840	2005 KW T800	Truck	CNG	400 hp 1450 lb-ft	T138	1XKDD49X15J090696	Allison 6spd Auto	Columbus, IN
Alpha	T147	75053841	2007 KW T800	Truck	CNG	400 hp 1450 lb-ft	T147	1XKDD49X67J164245	Eaton 10spd Manual	Columbus, IN
Alpha	TTSI 1	75053847	Freightliner Cascadia	Truck	LNG	400 hp 1450 lb-ft	555421	1FUJGBD97FLFY9734	Allison Auto	Los Angeles, CA
Beta	TTSI 2	75061442	2015 Freightliner Cascadia	Line haul	LNG	400 hp 1450 lb-ft	555419	1FUJGBD93FLFY9732	Allison Auto	Los Angeles, CA
Beta	Sheehy 1	75061436	Freightliner Cascadia	Line haul	CNG	400 hp	350	1FUJGBD92GLGT2491	Eaton 10spd Manual	Des Moines, IA

Prototype Level	Customer	ESN	Chassis	Application	Fuel	Rating	Unit	VIN	Transmission	Location
						1450 lb-ft				
Beta	Sheehy 2	75061695	Freightliner Cascadia	Line haul	CNG	400 hp 1450 lb-ft	323	1FUJGBD96GLGN0975	Eaton 10spd Manual	Des Moines, IA
Beta	WM Bristol	75061696	2014 Peterbilt 320	Refuse	CNG	400 hp 1450 lb-ft	211565	3BPZXHEX1EF232509	Allison	Toms River, NJ

Source: Cummins Westport Inc.

There were three options for how the ultra-low NOx technology could be installed in these customer vehicles for demonstration:

1. First Fit: A new vehicle can be built with an ultra-low NOx engine and aftertreatment installed as a first fit. This option is likely the most expensive and most time-consuming because a build slot at the vehicle plant would need to be secured and special provisions made to install a prototype engine and aftertreatment. The First Fit option is CWI's main path to market for this technology once it is in production.
2. Repower: An existing ISX12 G powered vehicle can be taken out of service and the ISX12 G engine removed and replaced with an ultra-low NOx engine. The existing aftertreatment would also be replaced with a new ultra-low NOx aftertreatment unit. This repower option is a better solution if the existing engine is not suitable for replacement or retrofit of the specific engine parts. Engine repowers will be offered when this technology is brought to commercialization. Repowering an existing diesel-powered vehicle is not ideal, due to the complexity of replacing an existing diesel fuel storage system with a new natural gas fuel storage system, but would be considered if an existing ISX12 G powered vehicle is not available.
3. Retrofit: Using an existing ISX12 G powered vehicle and replacing only the "new" parts for the ultra-low NOx version is not feasible due to the changes made to the fuel system and associated engine options. This option is not CWI's intended path for commercial product.

Discussions with the fleets assessed which of the above three options were best suited for the fleets operation, individual vehicles, and timeframe of this project. Due to the complexity of the changes to the engine, and the tight project schedule, a repower option was the most cost effective. The fleets identified one or more existing vehicles and locations within their operation that were best suited for this field test. The intention for this project was to use the vehicle in real world operation for at least six months in a variety of conditions, terrains, and duty cycles that represent how a commercial product would be used by most customers of the ultra-low NOx engine (for example, hills, steady state and transient operation).

New prototype ISX12N engines were built at the Cummins engine assembly plant in Jamestown, New York. Because the emissions impacting equipment and the engine emissions have been altered, emissions exemption engine data tags were obtained for each of these engines from CARB and USEPA.

All field test vehicles were originally equipped with ISX12 G natural gas engines. The existing engines were replaced with new prototype ISX12N engines with the work conducted by local Cummins distributors. Besides the removal and installation of the engine, the project required fabrication of mounting components for the new aftertreatment and significant re-plumbing and rewiring to connect the prototype ISX12N engine components and aftertreatment system to the vehicle.

Telemetry equipment was installed in these field test vehicles to monitor, collect and send data back to the field test team. The telemetry system consisted of a data logger connected to the under dash service port that transmitted data via cellular network or downloaded directly. Typically, the vehicle data was not investigated unless there was an issue observed. Issues may be detected by either the operator raising a concern through his maintenance department, or the engine control system may detect an issue in which case it will flag a fault code. In both cases, issue information was passed onto CWI engineering through a Failure Incident Reporting Group process. The engineering group followed a multistep process that determined how to protect the customer, identified the root cause and solution, validated the solution, implemented the solution, and then monitored the solution. Issues were addressed in priority order determined by a combination of the issue severity and the number of issue occurrences.

All but two of the vehicles were equipped with compressed natural gas storage systems. The two TTSI vehicles had liquefied natural gas fuel storage systems. After repowering the vehicles with new engines and aftertreatment systems, the vehicles were checked for proper operation and then returned to the fleets to put back into commercial service. Figure D-3 through D-12 show some of the field test vehicles in this project.

Figure D-3: Dillon Transport, Florida

Source: Cummins Westport Inc.

Figure D-4: Dillon Transport, Texas

Source: Cummins Westport Inc.

Figure D-5: FedEx Freight, Oklahoma

Source: Cummins Westport Inc.

Figure D-6: Sheehy 1, Iowa

Source: Cummins Westport Inc.

Figure D-7: Thatcher Transportation, Utah

Source: Cummins Westport Inc.

Figure D-8: TTSI 1, California

Source: Cummins Westport Inc.

Figure D-9: TTSI 2, California

Source: Cummins Westport Inc.

Figure D-10: UPS, Tennessee

Source: Cummins Westport Inc.

Figure D-11: UPS, Texas

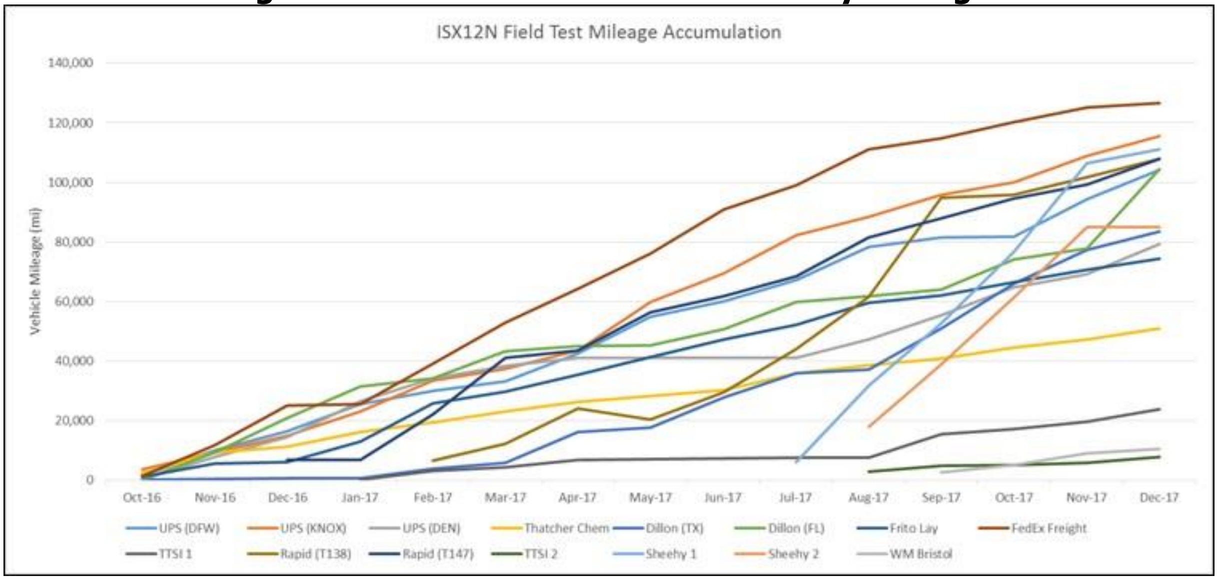
Source: Cummins Westport Inc.

Figure D-12: Waste Management, New Jersey

Source: Cummins Westport Inc.

Each fleet reported the vehicle mileage to CWI for tracking. The field test fleet, including the two Rapid vehicles, accumulated a combined 1.25 million miles during this project. Figure D-13 shows the monthly mileage accumulated by each of these vehicles throughout the duration of this project. Table D-3 lists the total miles accumulated by each vehicle. The Thatcher Chemical vehicle experienced an engine failure due to a dropped valve seat, which required the replacement of the prototype ISX12N. The cause of this failure is currently being investigated.

Figure D-13: Field Test Vehicle Monthly Mileage



Source: Cummins Westport Inc.

Table D-3: Field Test Vehicle Mileage Totals

Fleet	Application	Prototype Level	ESN	Vehicle Make/Model	Vehicle Unit #	Location	Test Miles
FedEx Freight	Class 8 Tractor	Alpha	75053845	Peterbilt 579	R18836	Oklahoma City, OK	126,758
UPS	Class 8 Tractor	Alpha	75053844	Kenworth T680	277073	Dallas, TX	115,614
Dillon	Class 8 Tractor	Alpha	75054059	Kenworth T800	6006	Mulberry, FL	104,446
Dillon	Class 8 Tractor	Alpha	75054058	Peterbilt 579	6154	Dallas, TX	83,381
Frito Lay	Class 8 Tractor	Alpha	75054062	Volvo VNL	C14812	Dallas, TX	74,358
Thatcher Chem	Class 8 Tractor	Alpha	75054061 75053838	Kenworth T800	316	Salt Lake City, UT	50,805
UPS	Class 8 Tractor	Alpha	75054057	Kenworth T680	277189	Denver, CO	79,271
UPS	Class 8 Tractor	Alpha	75054060	Mack	274895	Knoxville, TN	115,614
TTSI 1	Class 8 Tractor	Alpha	75053847	Freightliner Cascadia	555421	Los Angeles, CA	23,798
Rapid	Class 8 Tractor	Alpha	75053840	Kenworth T800	T138	Columbus, IND	107,982
Rapid	Class 8 Tractor	Alpha	75053841	Kenworth T800	T147	Columbus, IND	107,903
TTSI 2	Class 8 Tractor	Beta	75061442	Freightliner Cascadia	555419	Los Angeles, CA	7,778
Sheehy 1	Class 8 Tractor	Beta	75061436	Freightliner Cascadia	350	Des Moines, IA	111,184
Sheehy 2	Class 8 Tractor	Beta	75061695	Freightliner Cascadia	323	Des Moines, IA	84,890
WM Britsol	Refuse	Beta	75061696	Peterbilt 320	211565	Toms River, NJ	10,334
						Total:	**1,249,530**

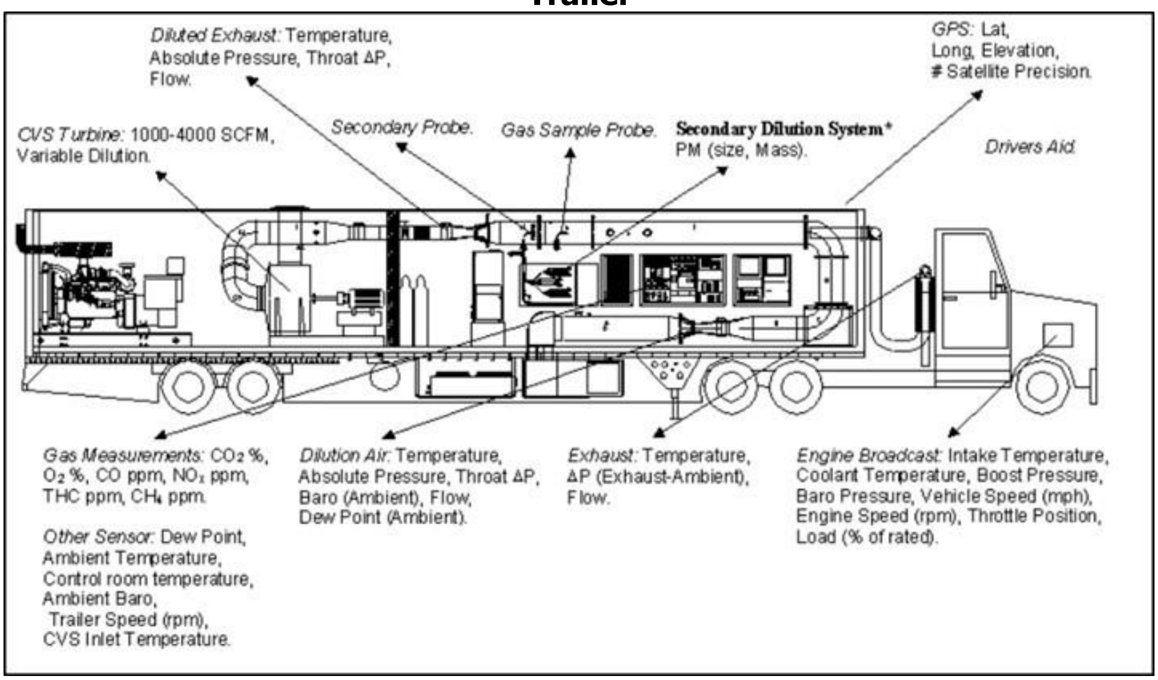
Source: Cummins Westport Inc.

Chassis Dynamometer Testing

To test real world ISX12N emissions, chassis dynamometer testing of one field test vehicle was conducted to evaluate non-methane hydrocarbons, oxides of nitrogen (NOx), carbon monoxide, particulate matter, ultrafines, ammonia (NH_3), greenhouse gas emissions, and brake-specific fuel consumption.

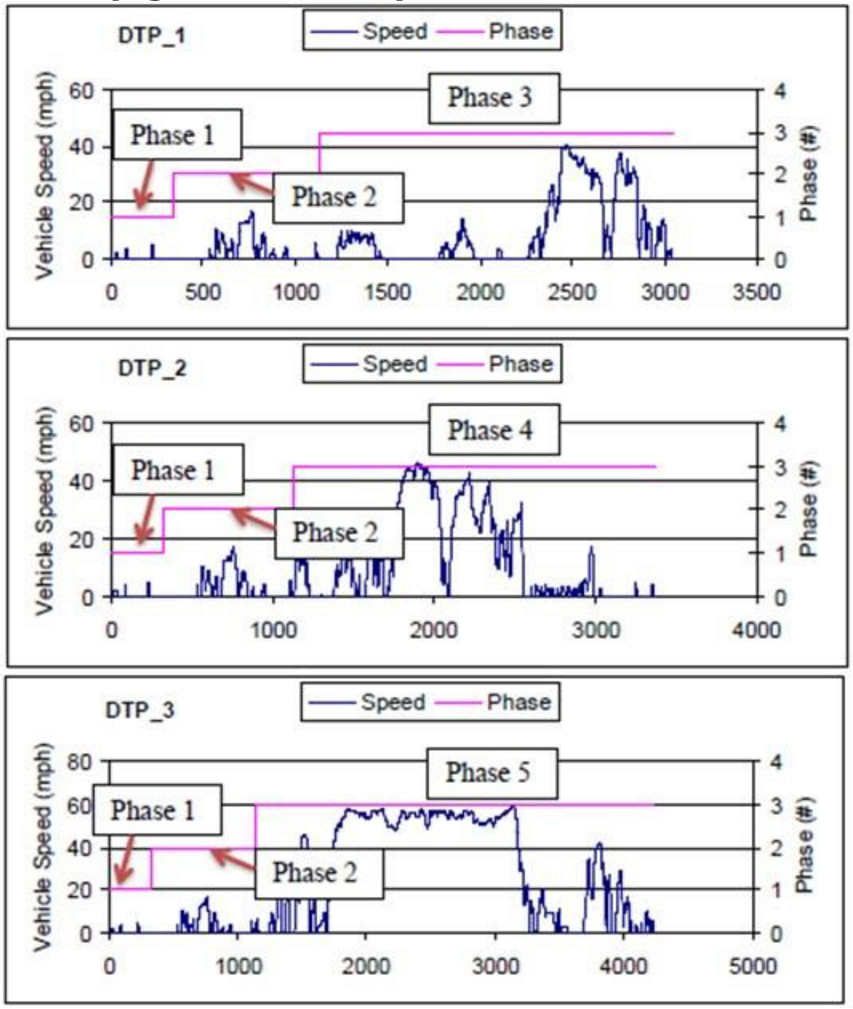
Testing was conducted at the University of California, Riverside College of Engineering, Center for Environmental Research and Technology emission test facility. The facility is a recognized heavy-duty emission testing laboratory and was approved by the South Coast Air Quality Management District (SCAQMD) for this project. The emissions measurement equipment was contained in a mobile van, shown in Figure D-14. Data was collected over three drive cycles chosen by SCAQMD to represent operation in the South Coast Air Basin: the Drayage Truck Port cycles (near dock, local and regional), the Urban Dynamometer Driving Schedule (UDDS), and the CARB Heavy Heavy-Duty Diesel Truck cycle (Figure D-15 to Figure D-17). The testing used natural gas that was laboratory tested at the beginning and end of emission testing to confirm its adherence to specifications in California Code of Regulations Title 13 Section 2292.5.

Figure D-14: University of California Riverside Emissions Measurement Trailer



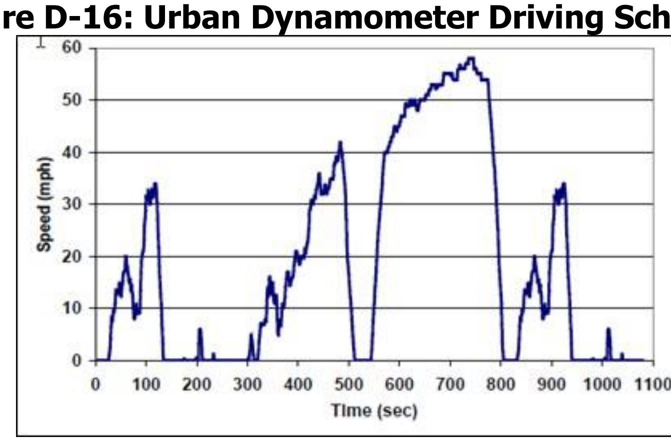
Source: Cummins Westport Inc.

Figure D-15: Drayage Port Truck Cycles – Near Dock, Local, and Regional



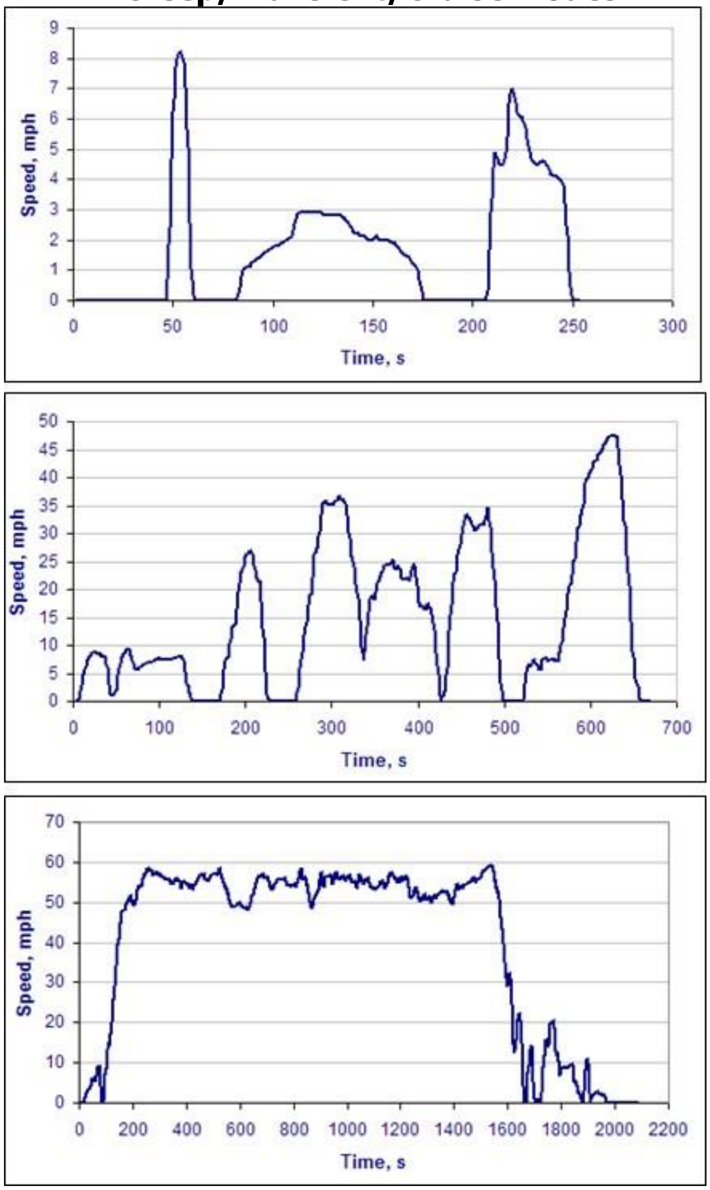
Source: Cummins Westport Inc.

Figure D-16: Urban Dynamometer Driving Schedule



Source: Cummins Westport Inc.

Figure D-17: California Air Resources Board Heavy Heavy-Duty Diesel Truck – Creep/Transient/Cruise Modes



Source: Cummins Westport Inc.

Testing was conducted from January 30 to February 6, 2018 using the TTSI 1 vehicle. According to the University of California, Riverside (UCR) report[12], the testing found "The ISX12N 400 NG engine met and exceeded the target NOx emissions of 0.02 g/bhp-hr and maintained those emissions during in-use duty cycles found in the South Coast Air Basin. The other gaseous and particulate matter were below the standards and/or similar to previous levels. Particle number, ammonia emissions, and

[12] Johnson, Kent and George K. Ultra-Low NOx Near-Zero Natural Gas Vehicle Evaluation ISX12N 400. April 2018. https://ucrtoday.ucr.edu/wp-content/uploads/2018/08/CWI-LowNOx-12L-NG_v03.pdf

methane emissions were higher than current 2010 certified diesel engines on similar drive cycles." The main conclusions described in the UCR report are listed below.

- The ISX12N engine showed NOx emissions that ranged from 0.012 to 0.006 grams per brake horsepower-hour (g/bhp-hr) (port cycles) and from 0.001 to 0.02 g/bhp-hr for CARB's transient truck cycles.
- The cold start emissions averaged 0.130 g/bhp-hr for the UDDS test cycle. The UDDS hot/cold weighted (1/7 cold start weighted) emissions was 0.028 g/bhp-hr which is above the certified 0.02 g/bhp-hr emission factor. It is expected the impact of the cold start emissions real in-use emissions could be lower and depend on the real fraction of time a NG truck operates in cold mode vs hot operation.
- The NOx emissions did not increase with lower power duty cycles and showed the opposite trend where the lower power duty cycles showed lower NO_x emissions unlike the diesel counterparts.
- The real time NOx emissions show consistent NOx spikes resulting during transient de-accelerations. The cause for variability was the result of the magnitude of the spikes. More than 90 percent of the hot running emissions resulted from these NOx spikes. This suggests possible driver behavior may impact the overall NOx in-use performance of the vehicle and more gradual de-accelerations are desired for minimum emissions.
- Total particulate number (PN) averaged from 2e14 #/mi for the ARB Creep cycle and lowest on the Regional and Cruise cycles (~8e12 #/mi).
- The solid PN averaged about 50 percent for all the test cycles.
- PN is higher (20 times) for natural gas vehicles (8e12 #/mi) compared to diesels equipped with a diesel particulate filter (1e11 #/mi). It is unclear what impact this will have locally and regionally.
- NH_3 emissions appeared to be lower for the ISX12N engine compared to the previous testing of the ISL G NZ 8.9L engine.

Particulate matter mass was low for the ISX12N truck, but seemed slightly higher than the previous ISL G NZ 8.9L engine tested.