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Energy Research and Development Division

FINAL PROJECT REPORT

Development, Integration, and Demonstration of 6.7-Liter Natural Gas Engine in Medium-Size Heavy-Duty Vehicles

Gavin Newsom, 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

Development, Integration, and Demonstration of 6.7 Liter Natural Gas Engine in Medium-Size Heavy-Duty Vehicles is the final report for this project (Contract Number PIR-15-008 and Subcontract S689) conducted by the Gas Technology Institute and Cummins Westport Inc. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the 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 among the top sources of oxides of nitrogen (NO_x) emissions in the South Coast Air Basin. The Cummins Westport Inc. ISB6.7 G is a low-emission 6.7-liter natural gas engine that can support school bus, shuttle bus, transit bus, medium-duty truck, and yard tractor applications as an alternative to diesel engines. The ISB6.7 G is certified to emit 50 percent lower NO_x emissions than the current standard for diesel engines.

For 2018 model year natural gas engines, heavy-duty on-board diagnostics are required to monitor engine system or component parameters to identify malfunctions or deterioration that can cause increases in emissions. This project further developed the ISB6.7 G with the addition of heavy-duty on-board diagnostics, conducted vehicle integration and demonstration, and laid the foundation for future work to reduce NO_x emissions by an additional 80 percent. Heavy-duty on-board diagnostics protect the environment from excess emissions resulting from engine issues that may arise during the useful lives, which will assist regions like the South Coast Air Basin in attaining and maintaining ambient air quality standards.

The project culminated with an engine (B6.7N), receiving certification to the United States Environmental Protection Agency's current criteria pollutant and greenhouse gas emission standards, the California Air Resources Board's Optional Low NO_x Standard of 0.10 grams per brake horsepower-hour, and heavy-duty on-board diagnostics compliance. The project team demonstrated 11 vehicles—including delivery trucks, shuttle buses, and yard tractors—for more than six months, and they accumulated more than 357,000 miles. The University of California, Riverside, conducted chassis dynamometer testing to evaluate real-world emissions. The B6.7N began commercial production in January 2018 and was offered in the market segments of school buses and yard tractors.

Keywords: Heavy-duty onboard diagnostics, ISB6.7 G, B6.7N, low emissions, NO_x

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

The United States Environmental Protection Agency (U.S. EPA) sets the health-and welfare-based National Ambient Air Quality Standards . These standards define the maximum levels of various pollutants that can be present in outdoor air including oxides of nitrogen, referred to as NO_x. 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. NO_x can also affect the environment by forming acid rain. As a result, California's ambient air quality standards and climate change policies have promoted the development and use of strategies and technologies to reduce NO_x emissions.

According to the California Air Resources Board (CARB), nearly 80 percent of NO_x 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 onroad diesel vehicles are among the top sources of NO_x. This source category is projected to continue to be one of the largest contributors to NO_x emissions, even though vehicles meeting newer and more stringent emission standards are gradually replacing the legacy fleet of older and higher-polluting vehicles.

One way to help address this problem is to develop low-NO_x natural gas engines that can displace diesel engines and reduce emissions from this onroad source category. Heavy-duty on-board diagnostics enable customers to better monitor and maintain the performance of vehicles using low-NO_x engines. Heavy-duty onboard diagnostics protect the environment from excess emissions due to engine issues that may arise during the useful life. This protection will assist regions like the South Coast Air Basin in attaining and maintaining federal ambient air quality standards

Low-emission natural gas engines are used in the transit, refuse, regional haul truck, shuttle bus, and school bus markets. Cummins Westport Inc. designs, engineers, and markets natural gas engines for commercial applications, including trucks and buses. Cummins Westport natural gas engines are built on the proven line of Cummins diesel engines and share many of the same components. More than 80,000 Cummins Westport natural gas engines are in service worldwide.

Project Purpose

This project developed a prototype 6.7-liter natural gas engine with heavy-duty on-board diagnostics that can meet the CARB 0.10 gram per brake horsepower-hour (g/bhp-hr) Optional Low NO_x standard with the intention of entering commercial production. The availability of such an engine in the market will help improve California's air quality and support efforts to achieve and maintain ambient air quality standards.

The addition of a 6.7-liter engine to Cummins Westport Inc.'s North American product offering gives customers the option of a smaller, more optimized engine for lighter loads than the larger available 8.9-liter and 11.9-liter engines, especially for fleets operating vehicles requiring a gross vehicle weight rating of fewer than 33,000 pounds. The 6.7 liter has market share mainly in the school bus and shuttle bus markets.

The specific objectives of this project were to:

- Design, develop, and demonstrate a production-ready 6.7 liter medium-duty natural gas engine that can be certified compliant with the U.S. EPA 2018 heavy-duty on-board diagnostics requirements and certified at or below CARB optional low NO_x emission standard of 0.10 gram per brake horsepower hour for on-road heavy-duty engines.
- Demonstrate greenhouse gas emissions levels that will enable certification at or below the U.S. EPA 2017 greenhouse gas emissions standards.
- Demonstrate a peak rating of 240 horsepower and 560 pound-feet peak torque.

Project Approach

The heavy-duty on-board diagnostics system development consists of three portions: the infrastructure and algorithm development, diagnostic algorithm and software creation, and calibration. The infrastructure and algorithm development create the software used to acquire and communicate data from the engine and aftertreatment (emissions reduction device). The diagnostic algorithm/software creation develops the monitors used to detect and diagnose issues that lead to emissions exceeding predetermined levels. Following these two development steps, the project team confirmed that the calibrated monitors were detecting accurately and repeatedly at the desired levels.

The required changes to the engine and aftertreatment because of implementing heavy-duty on-board diagnostics were identified and communicated to the vehicle original equipment manufacturers through customer engineering bulletins, computer-aided design models, and other supplemental information sources. These changes allow the vehicle manufacturers to work in parallel to develop the new engine and ensure commercial vehicle availability once production starts.

The project team installed prototype engines in eight vehicles with four commercial fleets and three engineering vehicles. The commercial fleets included Blue Water Area Transit, Kwik Trip, Walmart, and United Parcel Service. The vehicles operated in commercial service for more than six months. Testing the engines and aftertreatment systems during actual vehicle operation confirmed overall performance in real-world environments and accumulated sufficient mileage to prove reliability and durability.

To evaluate real-world NO_x emissions, one of the field test vehicles was delivered to University of California, Riverside, for chassis dynamometer testing. Testing was conducted at the University of California, Riverside, College of Engineering Center for Environmental Research and Technology emission test center. Data were collected during four drive cycles chosen to represent vehicle operation in the South Coast Air Basin.

Project Results

The project achieved all technical objectives:

- Cummins Westport Inc. successfully developed a low-emission engine equipped with heavy-duty on-board diagnostics offered commercially as the B6.7N. This engine received U.S. EPA certificate of conformity number for Model Year 2018 and CARB Executive Order A-021-0678 indicating it met Optional Low NO_x standard of 0.10 gram per brake horsepower hour.
- University of California, Riverside, concluded from its chassis dynamometer testing, "In general, the B6.7N 240 was well below the Executive Order NO_x emissions standard of 0.1 gram per brake horsepower hour and maintained those emissions over the range of realistic duty cycles found for yard spotter and bus applications in the South Coast Air Basin."
- The greenhouse gas emissions of the B6.7N engine and aftertreatment system were below U.S. EPA greenhouse gas standards, allowing it to receive U.S. EPA certificate of conformity for Model Year 2018.
- The B6.7N entered commercial production in January 2018 with the peak rating of 240 horsepower and 560 pound-feet.

Cummins Westport Inc. began production of the 6.7-Liter engine in January 2018. Vehicle manufacturers who offered the prior Cummins Westport Inc. engine (ISB6.7 G) have integrated the B6.7N and are offering commercial availability of the vehicle chassis with the B6.7N. Sales projections show a steady growth in volume depending on rules and incentive funding.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Cummins Westport Inc. has transferred the knowledge gained because of this project to the public and has promoted the technical and economic benefits of the resulting product in the following ways:

- Cummins Westport Inc. initiated commercial production of the B6.7N, and various vehicle original equipment manufacturers commenced commercial production of their vehicles with the B6.7N engine.
- Cummins Westport Inc. publicized engine and aftertreatment emissions certification results. The University of California, Riverside, will publish real-world emission test results.

- Cummins Westport Inc. presented information about low- and near-zero emissions technology and the B6.7N product at technology forums, trade shows, and industry events.
- Cummins Westport Inc. gave new technology and product presentations to original equipment manufacturers to use internally within their companies, as well as with their customers.
- Cummins Westport Inc. provided engine training through the Cummins dealer network that includes information on the B6.7N engine.
- Cummins Westport Inc. included current information on the B6.7N on its public website.

Recommendations

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

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

Benefits to California

Various industry stakeholders, including consultants, government agencies, and original equipment manufacturers, are projecting continued natural gas vehicle penetration in the North American heavy-duty commercial vehicle market. The beneficial technical achievements resulting from this project will help support that market penetration. California fleets have used vehicles powered by the B6.7N, including the Los Angeles Unified School District and the United Parcel Service.

This project resulted in a heavy-duty on-board diagnostics compliant, certified low-emissions natural gas engine for use in heavy-duty onroad vehicles. Using this engine to power vehicles that would otherwise use diesel will reduce NO_x emissions, which are associated with health problems such as asthma, bronchitis, lung cancer, and heart disease. It is difficult, however, to estimate precisely the direct emissions benefits of the ISB6.7 G (and now the B6.7N engines) in California because Cummins Westport Inc.

does not publish sales by engine platform, and engines are sold to various vehicle manufacturers and may be resold through distributors.

The team used Argonne National Laboratory's Heavy-Duty Vehicle Emissions Calculator (https://afleet-web.es.anl.gov/hdv-emissions-calculator/) to estimate environmental benefits in a fleet replacement scenario where 400 diesel school buses are replaced with natural gas buses using the B6.7N and renewable natural gas. The results show a reduction of about 250,000 pounds of NO_x and 1,000 tons of carbon dioxide equivalent emissions.

Using these engines with renewable natural gas can provide significant greenhouse gas reductions. Renewable organic material such as food and animal waste come together to compose renewable natural gas. 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 transportation fuel to displace fossil fuels and thereby reduce greenhouse gases. Reducing greenhouse gas emissions is important for addressing climate change and the 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 cost-effective, lower-emission technologies by bringing to market heavy-duty natural gas engines. Incentive funding and public fleet mandates will help accelerate use of the B6.7N engine to realize emission reductions in the heavy-duty onroad vehicle sector.

CHAPTER 1: Introduction

Background

The market demand for natural gas-powered commercial vehicles has increased significantly in recent years. However, the unavailability of certain engine sizes and performance ratings have constrained the expansion of natural gas vehicle penetration. This led to an Energy Commission funded project awarded to Gas Technology Institute (GTI) and Cummins Westport Inc. (CWI) to develop a 6.7-liter stoichiometric spark ignited natural gas engine referred to as the ISB6.7 G (based on the Cummins ISB6.7 diesel engine). This engine began full production in April of 2016 and is suited for Class 5 through 7 commercial vehicle markets including pickup and delivery trucks, utility trucks, school buses, shuttle buses, yard tractors, and specialized municipal work vehicles such as street sweepers. The production launch of the ISB6.7 G began with OEM partner, Thomas Built Bus, in their C2 school bus platform. Further integration work is required to expand the vehicle OEM offerings of this engine in the medium heavy-duty market.

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 6.7-liter spark ignited natural gas engine and exhaust aftertreatment system with Heavy-Duty On-Board Diagnostics (HD OBD) that could also achieve California Air Resources Board Optional Low NOx standard of 0.10 grams per brake horsepower-hour (g/bhp-hr).

CWI assembled a comprehensive team comprised of internal CWI engineers and supporting expertise within Cummins and Cummins Distributors. In addition, several commercial fleets were recruited to assist with the testing of prototype engine systems, including Kwik Trip, United Parcel Service (UPS), Blue Water Area Transit, and Walmart.

This project builds on prior work funded by the California Energy Commission for development of the ISB6.7 G natural gas engine and reported under PIR-12-017. In that project, CWI developed a 6.7-liter natural gas engine utilizing stoichiometric combustion with cooled exhaust gas recirculation and a maintenance- free three-way catalyst aftertreatment. This engine entered commercial production in 2016 filling a gap with available natural gas engines in the heavy-duty on-road space. The engine was certified to CARB's Optional Low Oxides of Nitrogen (NOx) standard of 0.10 g/bhp-hr. The addition of the 6.7-liter ISB6.7 G engine to CWI's North American product offering gave customers the option of a small, more optimized engine for lighter loads than the available 8.9-liter ISL G and 11.9-liter ISX12 G, especially for fleets operating vehicles needing a gross vehicle weight rating (GVWR) of less than 33,000 lbs. The ISB6.7 G gained market share mainly in the Type C school bus and shuttle bus markets.

The United States Environmental Protection Agency (U.S. EPA) and CARB required that HD OBD be implemented in heavy-duty alternative fueled vehicles beginning in the 2018 model year. Heavy-duty diesel vehicles were required to implement HD OBD for model year 2013 vehicles, while implementation in alternative fueled vehicles was delayed until 2018. This was necessary due to the immense development effort associated with this new level of diagnostics and the comparatively smaller volume of heavy-duty alternative fueled vehicles. To ensure that the ISB6.7 G was commercially available past the end of 2017, development of HD OBD was essential.

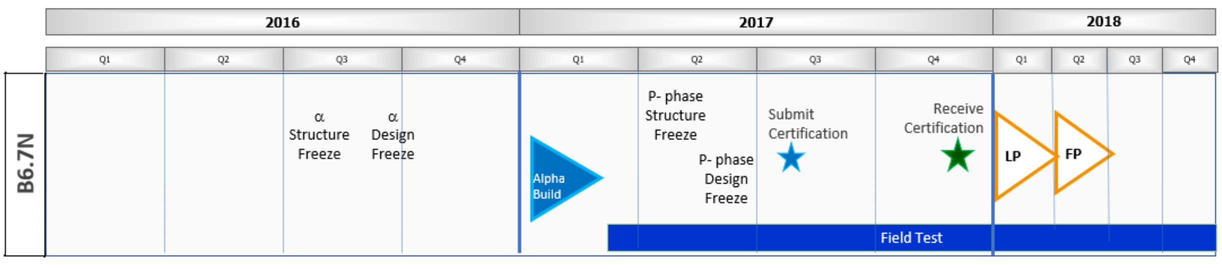
An OBD system monitors the emissions impacting components on the vehicle to ensure the vehicle remains within pre-determined emissions thresholds throughout the life of the vehicle. The OBD system also aides with the diagnosis of emissions related faults to properly identify what equipment requires repair or replacement. This prevents excess emissions due to engine issues and mitigates costly progressive engine damage. If an issue is detected by the OBD system, the operator is notified through a "Check Engine" warning signal on the vehicle dash. The operator is expected to bring the vehicle in for repair as soon as possible. The OBD system also stores information about the fault and relays this information to a technician when a diagnostic readout tool is connected to the engine control unit. This enables more efficient troubleshooting and quicker, more accurate repairs.

CHAPTER 2: Project Approach

Work Plan Development

At the start of the project, Cummins Westport Inc. (CWI) developed a detailed work-plan for the development of the natural gas engine and aftertreatment system focusing on the heavy-duty onboard diagnostic system being developed for the first time on natural gas engines. A high-level development schedule over about two years is shown in Figure 1 and culminates with limited production in January of 2018 ramping up to full (unlimited) production shortly thereafter.

Figure 1: B6.7N Development Schedule



Source: Cummins Westport Inc. (LP: limited production, FP: full production)

CWI followed an established CWI and Cummins product development process referred to as Value Package Introduction (VPI) that is intended to validate engine performance, emissions, reliability, durability, and manufacturability. A project team was assembled consisting of representatives from all areas involved with developing and launching a product to commercial production, including technical, marketing, customer care, customer engineering, reliability, manufacturing, and purchasing.

The main upgrade to the existing ISB6.7 G was the integration of Heavy-Duty On-Board Diagnostics maintaining the performance and emissions attributes of the existing ISB6.7 G. The peak rating was kept at 240 hp and 560 lb-ft while emissions were maintained at CARB's Optional Low NOx level of 0.10 g/bhp-hr. Most of the major components including the base engine, power cylinder, fuel system and exhaust gas recirculation systems essentially remained the same. CWI worked with existing ISB6.7 G vehicle OEMs to have them integrate the advanced B6.7N to their chassis. CWI then installed prototype B6.7N engines and aftertreatment systems into three engineering and eight customer vehicles to conduct customer field trials.

While CWI originally intended to evaluate the possibility of releasing a 260 hp, 660 lb-ft product, the development required much more effort than the allocated resources. To launch the product on schedule, CWI reverted back to the released power rating and focused on lowering NOx emissions by 50 percent and implementing a full OBD solution.

Heavy-Duty On-Board Diagnostic Compliance

The U.S. EPA and CARB require that On-Board Diagnostics (OBD) be implemented in heavy-duty alternative fueled vehicles for the 2018 model year. Heavy-duty diesel vehicles were required to implement OBD for model year 2013 vehicles while implementation in alternative fueled heavy-duty vehicles was delayed until 2018 due to the immense development burden of this new level of diagnostics and the comparatively small volume of heavy-duty alternative fueled vehicles being manufactured.

The OBD system monitors all emissions impacting components on the vehicle to ensure the vehicle remains below pre-determined emissions thresholds throughout the life of the vehicle equipment. This in turn protects the environment from excess emissions due to engine issues and prevents costly progressive engine damage. If an issue is detected by the OBD system, the operator is notified through a Malfunction Indicator Lamp (MIL) on the vehicle dash and the operator is expected to bring the vehicle in for repair. The OBD system stores information about the fault and relays this information to a technician when connected to the engine control module. This allows for more efficient troubleshooting and quicker and more accurate repairs. Development of HD OBD to meet 2018 U.S. EPA & CARB regulations for alternative fueled heavy-duty vehicles is required for continued sales and market expansion from January 1, 2018 and beyond.

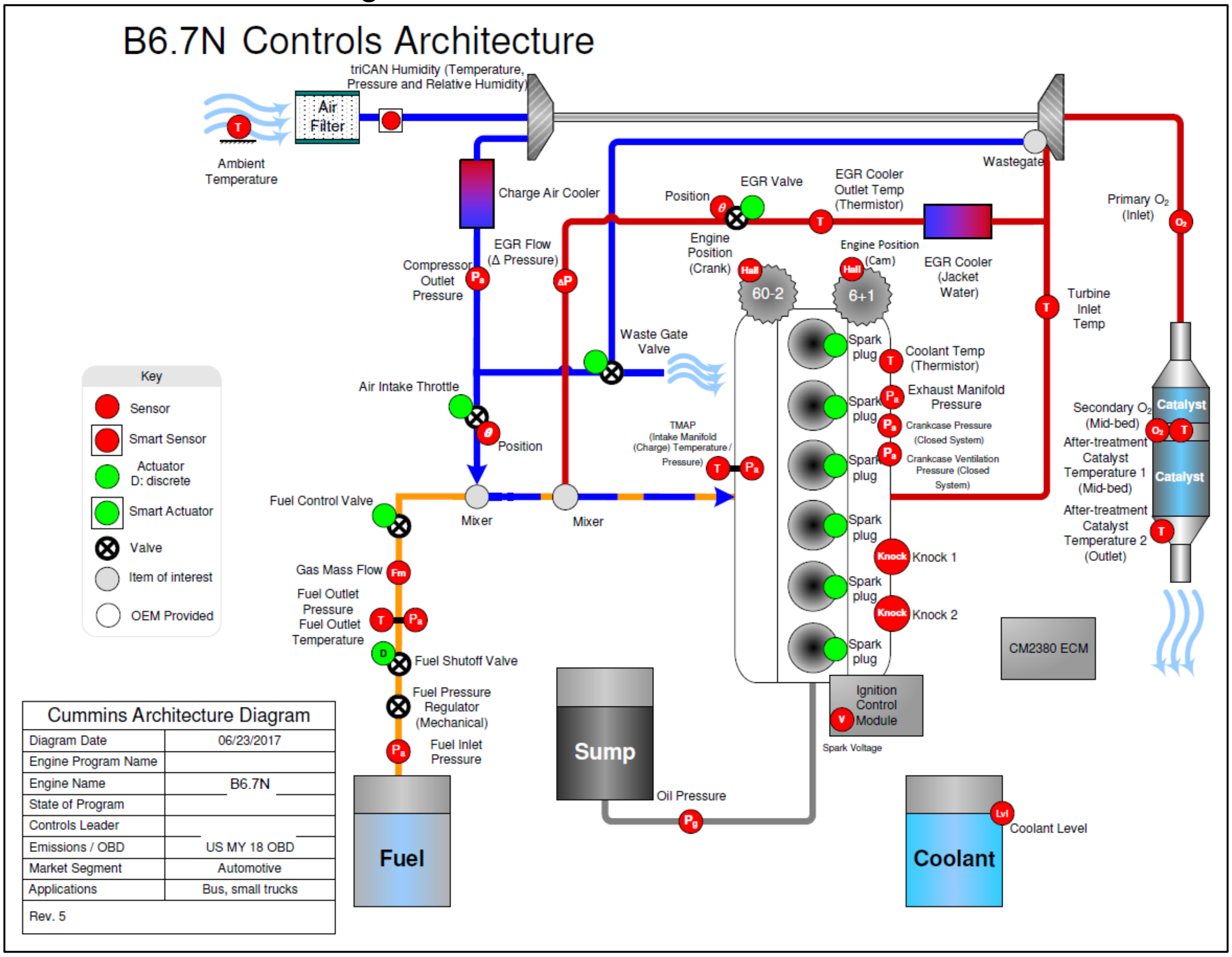
Heavy-Duty On-Board Diagnostic Development Process

The development of Heavy-Duty On-Board Diagnostics can be broken into three portions; infrastructure development, diagnostics algorithm / software creation, and calibration. The infrastructure and algorithm development establish 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 logging when an engine or aftertreatment fault occurs. The diagnostics algorithm / software creation is the creation of the specific algorithms referred to as monitors. These monitors are used to detect and diagnose issues that lead to emissions exceeding predetermined levels. The calibration portion involves tuning the previously developed algorithms, so that the monitor can detect accurately and repeatedly at the desired level.

Key Emissions Control System Components

The B6.7N shares the same engine architecture as CWI’s other engines, the L9N and ISX12N. The engine utilizes stoichiometric spark ignited combustion with cooled exhaust gas recirculation. The B6.7N also makes use of a closed crankcase ventilation (CCV) system to eliminate crankcase emissions by recirculating crankcase gases through the air intake system to the combustion chamber where they can be burned. A schematic of the B6.7N controls architecture is shown in Figure 2.

Figure 2: B6.7N Controls Architecture



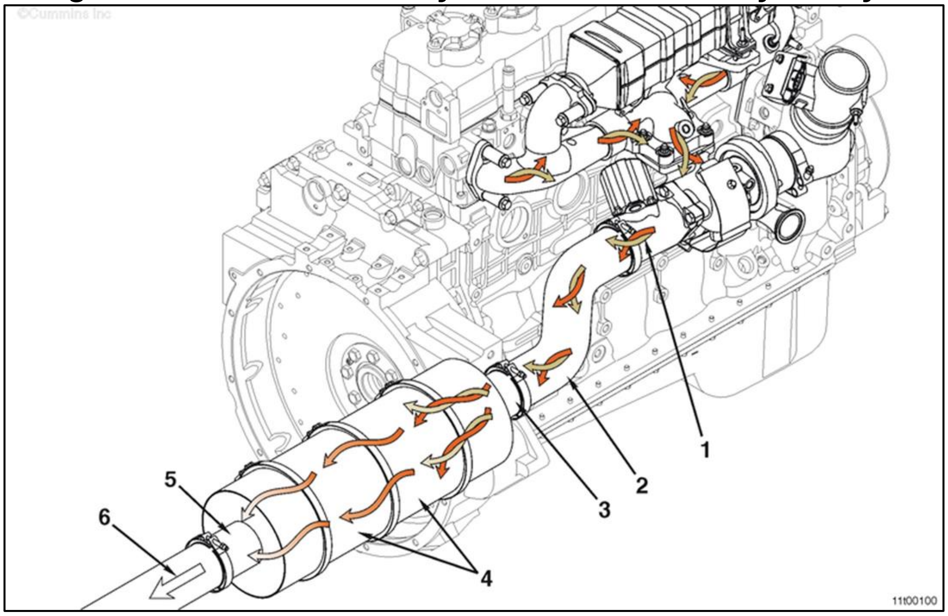
Source: Cummins Westport Inc.

The following key control system components on the engine and aftertreatment can impact tailpipe emissions.

Three-Way Catalyst Aftertreatment

The three-way catalyst aftertreatment (TWC) is a passive device mounted in the vehicle exhaust system, like the catalyst on passenger cars but larger (see item 4 in Figure 3). The inside of the catalyst has a support structure, called the substrate, typically in a honeycomb geometry to maximize surface area. The substrate is coated with a wash coat which holds the precious metal catalytic material. Exhaust flows through the TWC and chemically reacts with the catalytic material to convert oxides of nitrogen (NOx), carbon monoxide (CO) and hydrocarbons (HC) to nitrogen (N_2), carbon dioxide (CO_2) and water (H_2O). Referring to Figure 2, the TWC is equipped with three sensors: an oxygen and temperature sensor at the midway location, and a temperature sensor at the outlet. The engine control software utilizes these sensors to manage the air / fuel mixture in combustion. The HD OBD system also monitors and analyzes signals from these sensors.

Figure 3: B6.7N Exhaust System With Three-way Catalyst

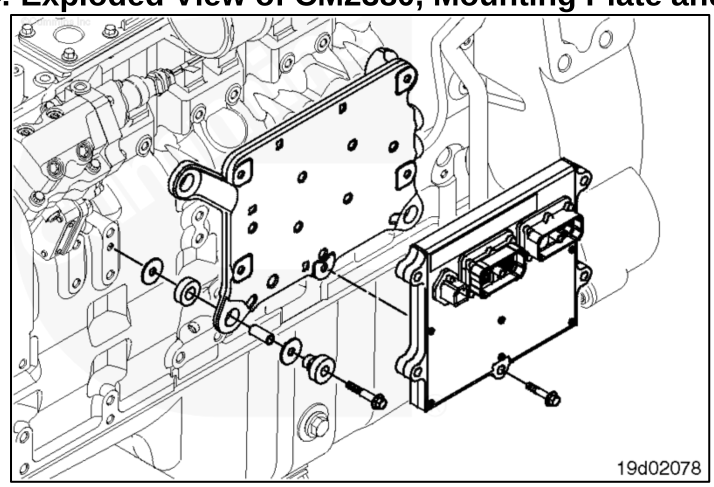


Source: Cummins Westport Inc.

Engine Control Module

The engine control module (ECM) is the engine computer which stores and operates the control software. It reads data from all engine sensors to determine which actuators and valves to operate to achieve the performance expected by the vehicle operator. The B6.7N utilizes a new ECM model, the CM2380 shown in Figure 4. Additional inputs and outputs plus increased memory and computing power were incorporated (compared to its predecessor) to accommodate HD OBD requirements.

Figure 4: Exploded View of CM2380, Mounting Plate and Engine

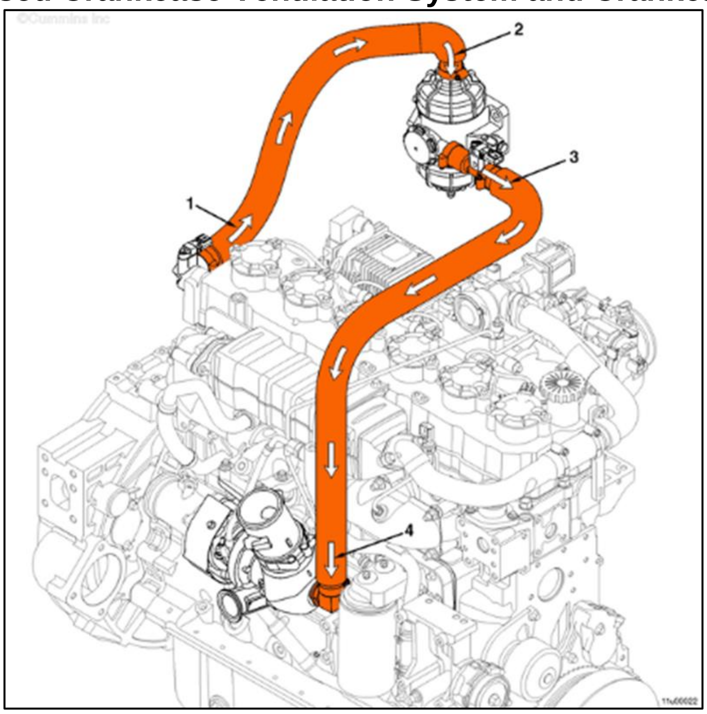


Source: Cummins Westport Inc.

Closed Crankcase Ventilation System

The closed crankcase ventilation (CCV) system consists of various hoses and a coalescing filter. The crankcase emissions are pulled from under the valve cover and routed to a chassis mounted filter where the oil is separated before sending gases to the turbocharger compressor inlet (see Figure 5) where they combine with the air intake to be sent to the combustion chamber. The oil separated from the crankcase gases is returned to the engine sump. Removing this oil prevents fouling of the turbocharger compressor wheel. The filter contains a pressure sensor to measure crankcase pressure and detect an open hose which would allow crankcase emissions escape to atmosphere.

Figure 5: Closed Crankcase Ventilation System and Crankcase Gas Flow



Source: Cummins Westport Inc.

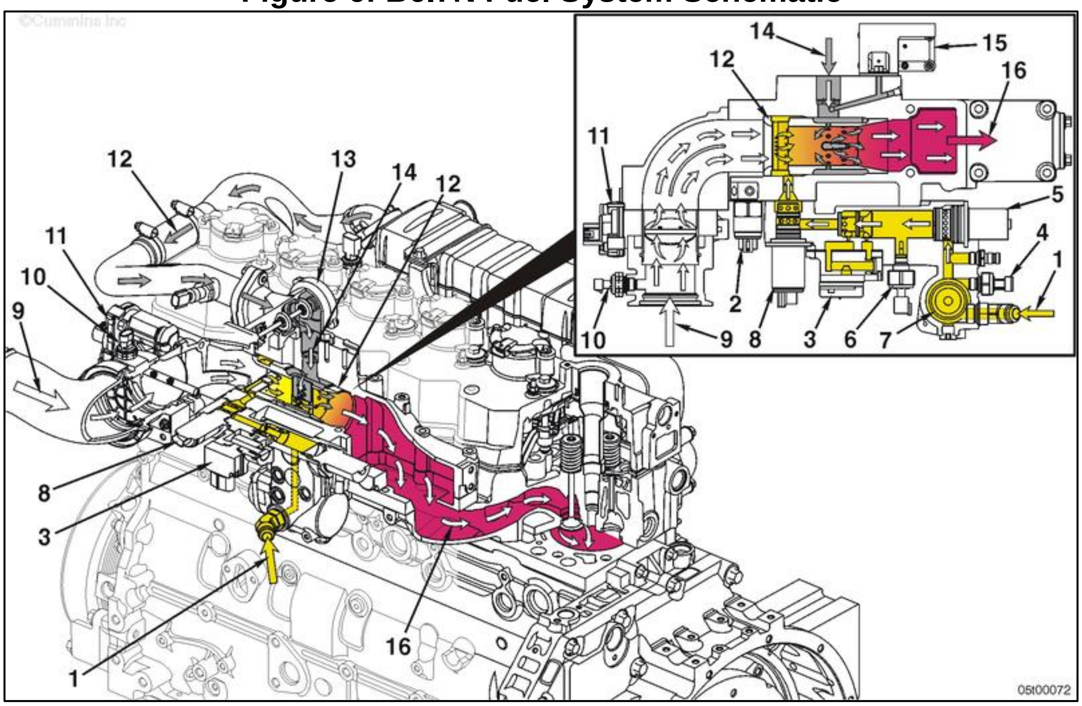
Fuel System

A flow diagram for the fuel system is shown in Figure 6. The fuel system controls and mixes the air, fuel, and EGR prior to delivering it to the cylinder head. Air enters the fuel system and is controlled by the electronic throttle (11). Fuel enters the fuel system (1) where the pressure is regulated (7) and the regulated pressure and temperature of the fuel is measured (6) and the mass is also determined (3). The fuel flow is controlled (8) prior to being introduced into the air stream (12). After passing through the EGR valve (14), EGR enters the fuel system downstream of the fuel introduction. The air, fuel and EGR enter the cylinder head and the combustion chamber.

The following is a list of emissions control-related components within the fuel system.

- Inlet air pressure sensor (10)
- Electronic throttle (11)
- Fuel inlet pressure sensor (4)
- Fuel pressure regulator (7)
- Fuel shutoff valve (5)
- Fuel outlet pressure / temperature sensor (6)
- Mass flow sensor (3)
- Fuel control valve (8)
- EGR valve (not shown)
- EGR delta pressure sensor (15)

Figure 6: B6.7N Fuel System Schematic

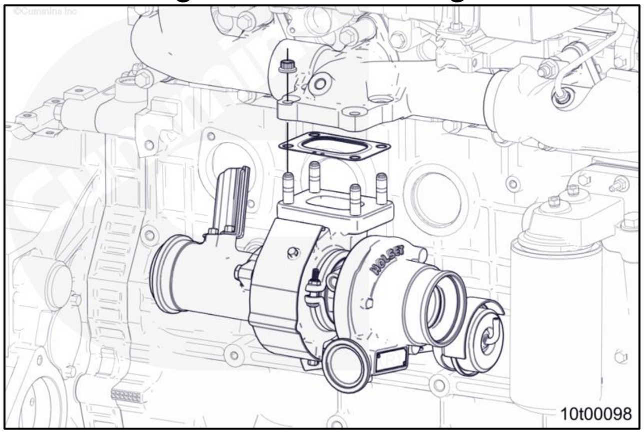


Source: Cummins Westport Inc.

Turbocharger and Exhaust Pressure Sensor

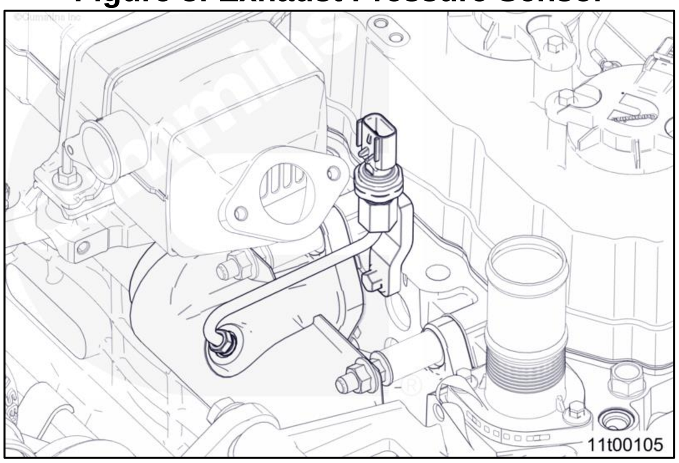
The B6.7N uses a wastegate type of turbocharger (Figure 7) to control and deliver pressurized air to the engine, allowing for increased power and efficiency compared to a naturally aspirated engine. Exhaust pressure is measured indirectly from the exhaust manifold (Figure 8).

Figure 7: Turbocharger



Source: Cummins Westport Inc.

Figure 8: Exhaust Pressure Sensor

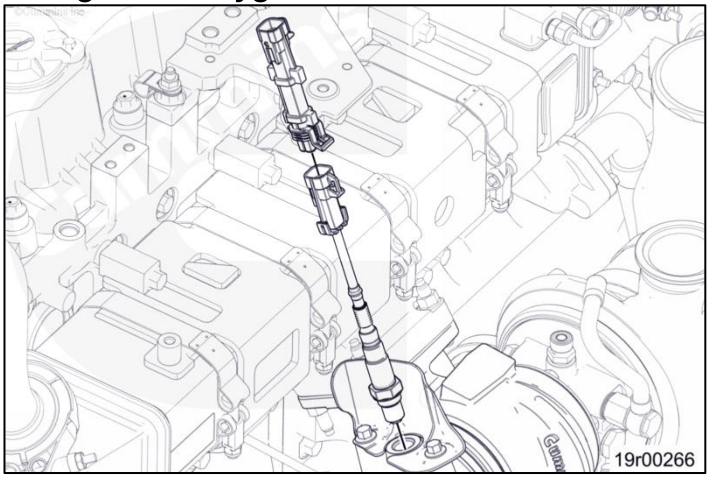


Source: Cummins Westport Inc.

Oxygen Sensors

There are two heated exhaust gas oxygen (HEGO) sensors used on the B6.7N. One sensor is located at the turbo outlet (Figure 9) and a second sensor in the aftertreatment at the mid-bed location. These sensors measure the proportion of oxygen in the exhaust stream at those locations and are utilized by the engine controls to determine appropriate fuel metering.

Figure 9: Oxygen Sensor in Turbo Outlet



Source: Cummins Westport Inc.

Infrastructure and Algorithm Development

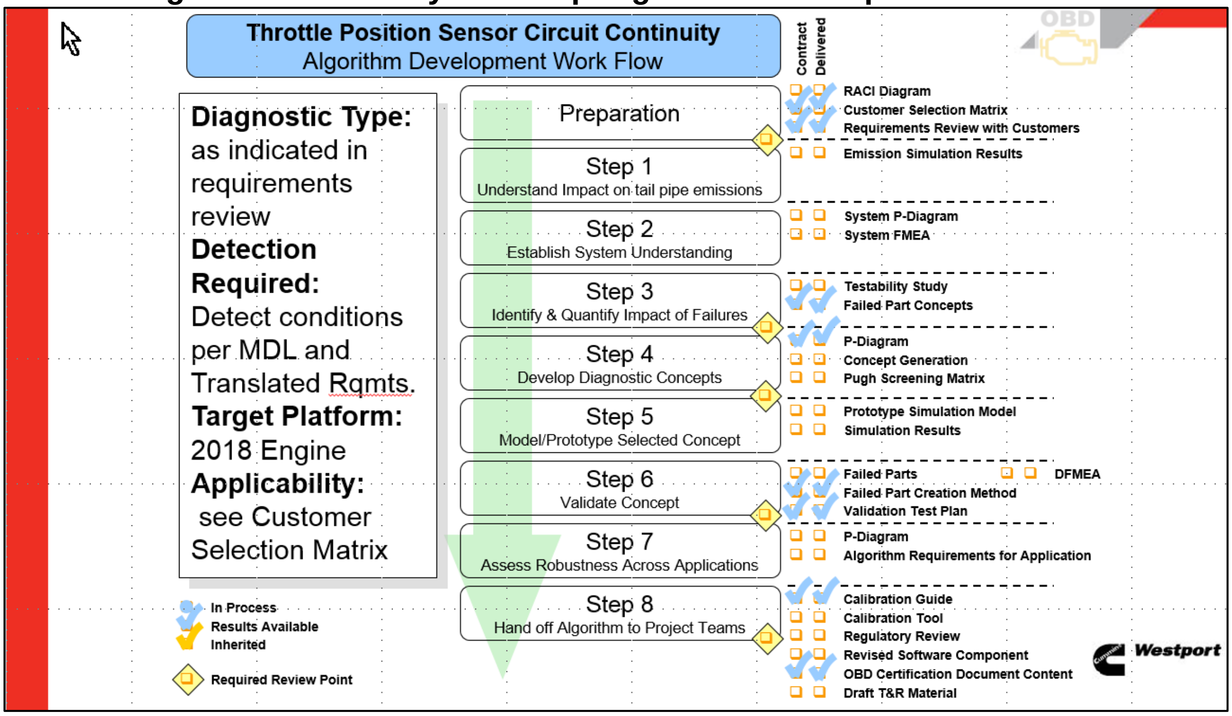
During infrastructure and algorithm development, the team established the software used to acquire and communicate data from the engine and aftertreatment. This included developing the datalink communication to interface with generic scan tools and data logging when an engine or aftertreatment fault occurs. Testing of the standardized data logging, reporting and communication protocol capability was completed to conform to the SAE J1939/84 standard.

Diagnostics Algorithm and Software Creation (Monitors)

During diagnostics algorithm and software creation, the specific algorithms referred to as monitors were developed. These monitors are used to detect and diagnose issues that will lead to engine emissions exceeding predetermined levels. California Code of Regulations (CCR) 1971.1, the HD OBD regulation, sets out the requirements for the monitors along with the thresholds for emission detection by those monitors.

Cummins has in place a proprietary process for OBD algorithm and calibration development. This process is defined in internal standards and requires that reviews and documentation be completed prior to release of each algorithm. As an example, a summary of the 8-step algorithm development process is shown in Figure 10.

Figure 10: Summary of 8-Step Algorithm Development Process



Source: Cummins Westport Inc.

Reviews were imbedded within the process and each yellow diamond in Figure 10 represents a potential review point. The tasks listed along the right side were selected based on the requirements and complexity of the diagnostic. This example shows the chart for the intake air throttle position sensor's out-of-range diagnostics.

An initial step was to review and analyze the requirements, both those from the OBD regulation and internal sources. Table 1 and Table 2 show the requirements that were reviewed and determined to be applicable to this diagnostic.

Table 1: MCID Conditions and Diagnostic Requirements

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 2: Requirements for Intake Air Throttle Diagnostics

Condition	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 MIL illumination and fault code storage protocols to those specified in these requirements.

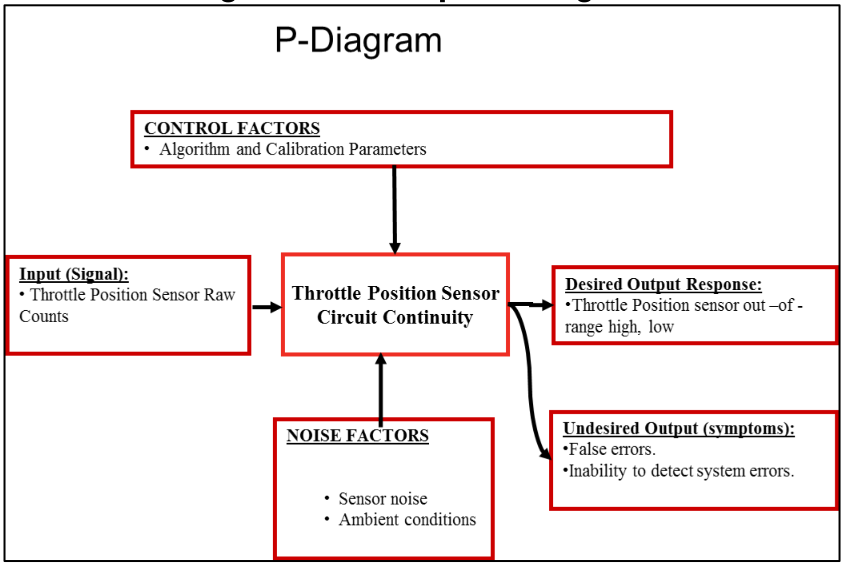
Condition	MCID 82	MCID 83	Description
MON055			Manufacturers may request Regulatory Agency approval to disable an OBD system monitor at ambient engine start temperatures below -6.7 deg C (20 deg F)
MON056			Manufacturers may request Regulatory Agency approval to disable monitoring systems that can be affected by low fuel level.
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 percent 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)

Condition	MCID 82	MCID 83	Description
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 Parameter or 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 11.

Figure 11: 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 3).

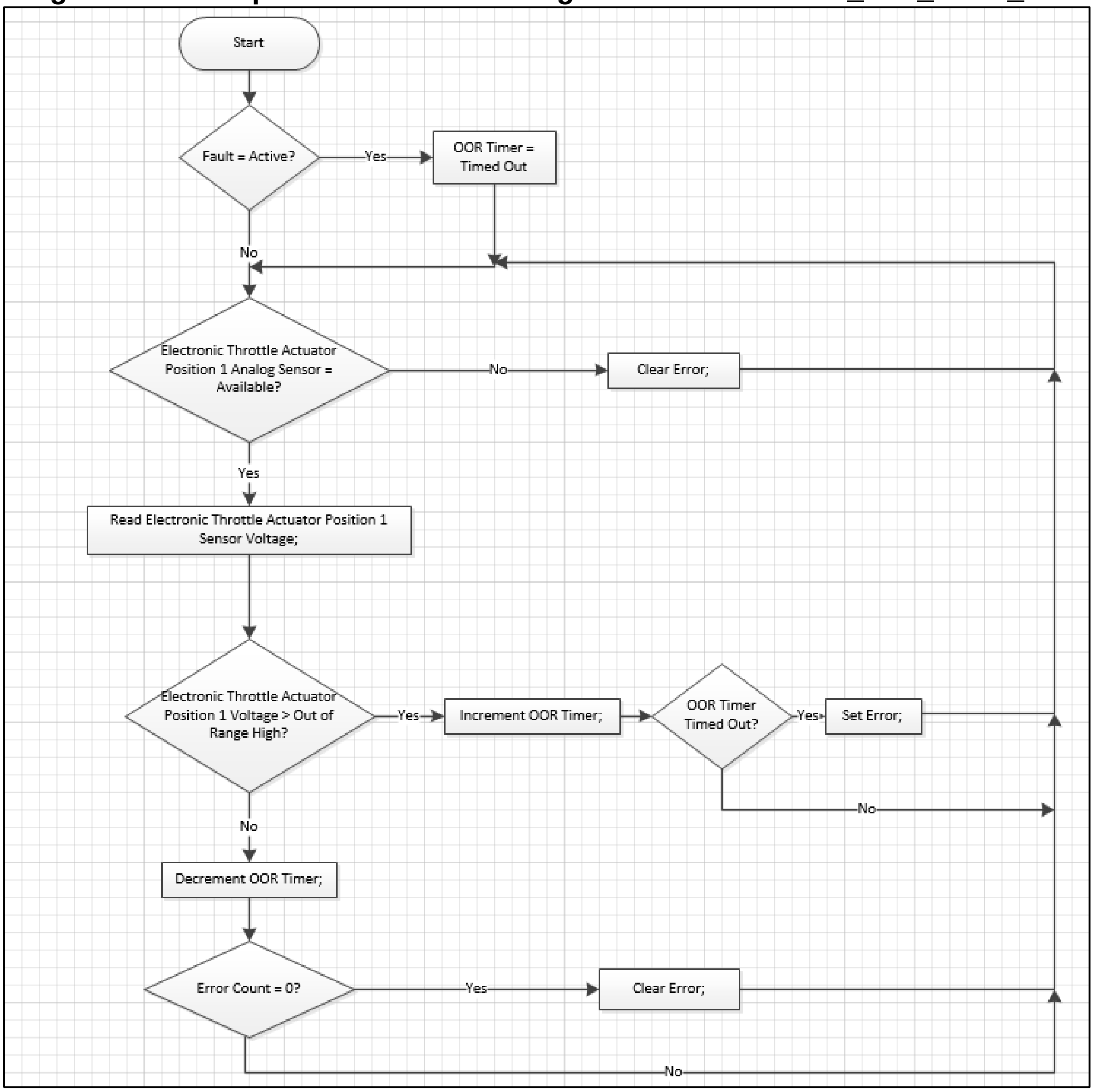
Table 3: Diagnostic Design Checklist

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-Steo_3-Step_Material\8-/Step\2037.1_2038.1_2039.1_2040.1 – Throttle Position Sensor Circuit Continuity-CWI_Application Tuning and Validation Guide.doc
Cert Doc content	Complete	Devide 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 each algorithm and was included in the OBD certification documentation submission to the regulatory agencies. An example of one of the flow charts from this diagnostic is shown in Figure 12.

Figure 12: Example Flow Chart for Diagnostic 2037.1 – TP1_00R_HIGH_ERROR



Source: Cummins Westport Inc.

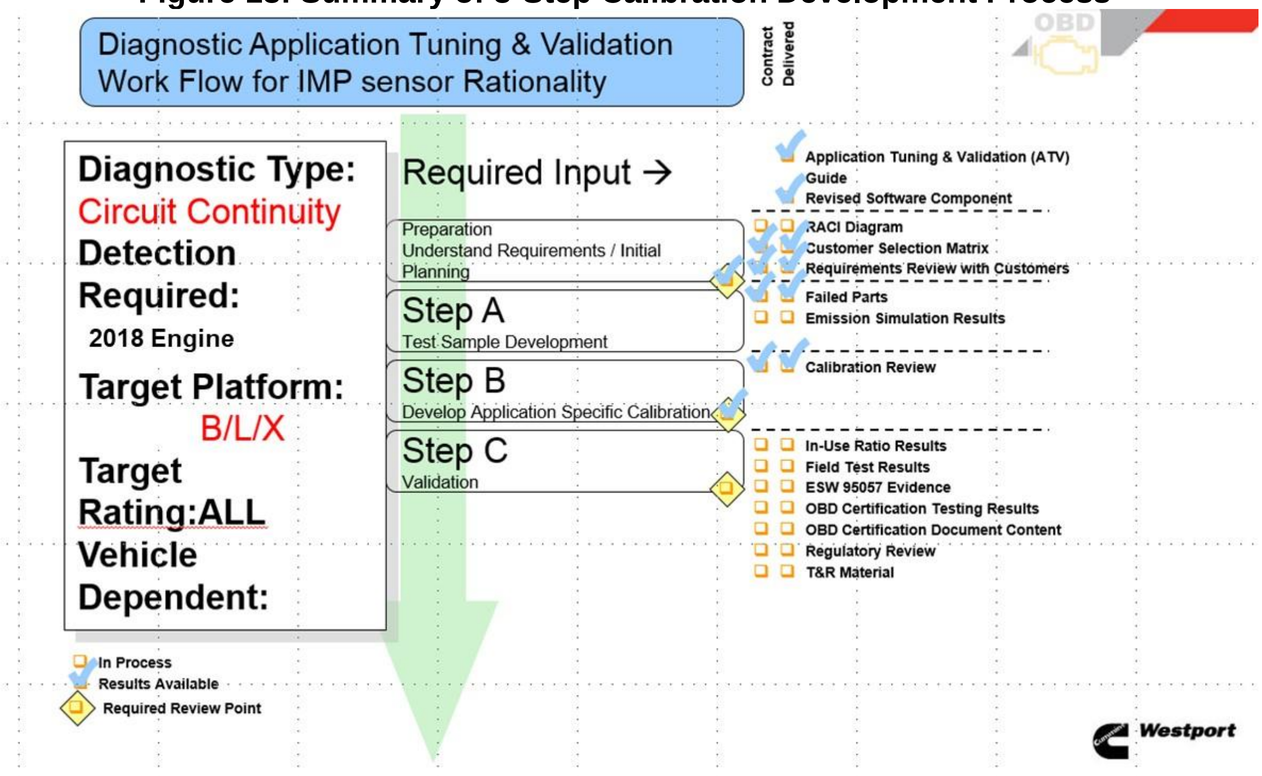
Calibration

Following the completion of the algorithm development process, the calibration development process commenced. The calibration portion consisted of tuning the previously developed algorithms, so that the monitors can detect accurately and repeatedly at the desired level. The calibrations may be unique to each of the power ratings even within the same engine. A summary of the 3-step calibration development process is show in Figure 13. A summary of the diagnostic strategy for the intake manifold pressure sensor readings is shown in Table 4.

Data was collected to understand the system performance and build a statistical model of the component's behavior so that abnormal behavior could be identified (see Figure

14). Following collection and analysis of the data, calibrations were created (see Table 5) and tested.

Figure 13: Summary of 3-Step Calibration Development Process



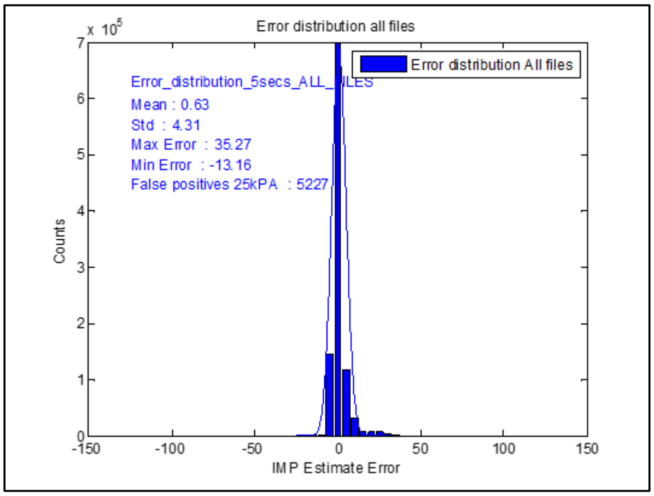
Source: Cummins Westport Inc.

Table 4: Diagnostic Strategy for Intake Manifold Pressure (IMP) Sensor

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

Source: Cummins Westport Inc.

Figure 14: Data Collected to Build Statistical Model



Source: Cummins Westport Inc.

Table 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.

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

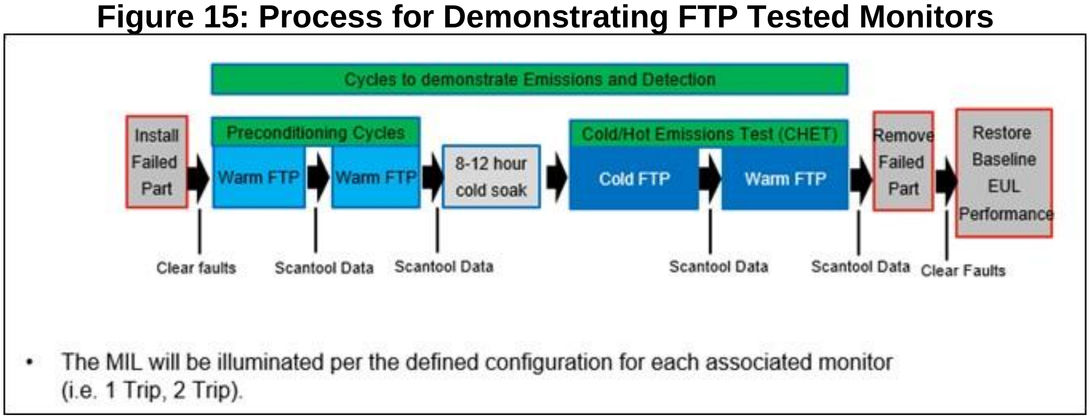
To track all the diagnostics required for full OBD compliance a Master Diagnostic List (MDL) was created for the B6.7N and progress was tracked against completion of algorithms and calibrations separately. There were 363 individual diagnostics required and tracked on the MDL.

Diagnostic Demonstration

Based on California Code of Regulations (CCR) 1971.1, the HD OBD regulation, a list of engine and aftertreatment components was identified for diagnostic demonstration testing and the demonstration plan was reviewed and approved by 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 this discovery would be communicated to the operator through the activation of fault code(s) and the Malfunction Indicator Lamp (MIL). Additionally, the required data would be logged by the ECM and reported properly over the required OBD datalink for communication to the service technician when using an appropriate scan tool. The effect of the failed part on tailpipe emissions was also measured.

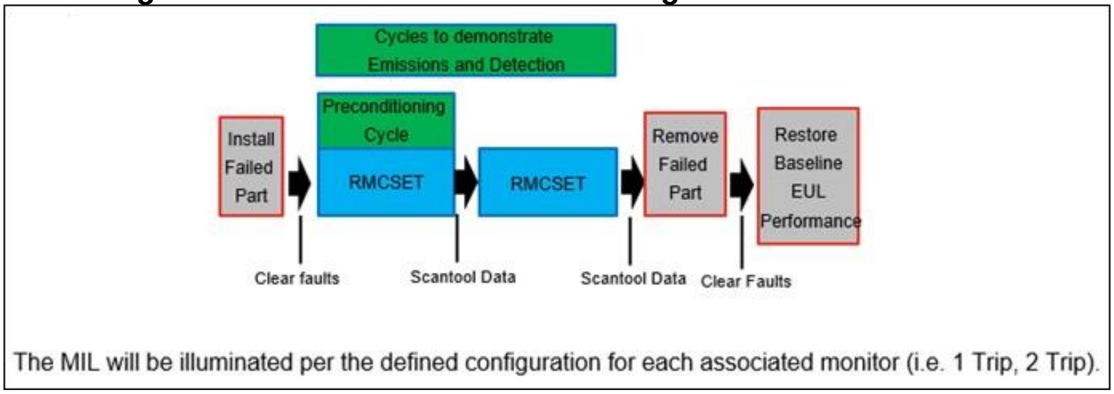
The process used to demonstrate the emissions and detection is shown in Figure 15 for monitors requiring the Federal Test Procedure (FTP) test and in Figure 16 for monitors requiring the Ramped Mode Supplemental Test (RMCSET). For the FTP tested monitors, the known failed part was installed on the engine. Any existing fault codes were erased to ensure the test was started with no fault codes present. The engine was preconditioned by operating a warm FTP test followed by an assessment and recording of scan tool data to document the fault status. A second warm FTP test and subsequent scan tool data collection was repeated. The engine was allowed to soak at room temperature for 8 to 12 hours and then a Cold/Hot emissions test (CHET) was conducted consisting of a cold FTP test, scan tool data collection, warm FTP test and another scan tool data collection. The expectation from these monitor tests was that the failed part would cause the emissions to be just below the predetermined threshold limit and the diagnostic monitor would detect this and record a fault code along with activating the engine MIL to notify the operator.

Figure 15: Process for Demonstrating FTP Tested Monitors



Source: Cummins Westport Inc.

Figure 16: Process for Demonstrating SET Tested Monitors



Source: Cummins Westport Inc.

Table 6 shows a summary of the key emissions monitors along with the emissions thresholds for each pollutant emission including NOx, CO, Non-methane hydrocarbons (NMHC), and Particulate Matter (PM). Greenhouse gas emissions are not included in the HD OBD program. The demonstration test required to prove the detection for each monitor under FTP or RMCSET cycles is also shown in Table 6 along with the pass / fail results of these tests.

Table 6: B6.7N 240HP MY2018 OBD Demonstration Testing Summary

Sequence Number	CCR 1971.1 Monitor Requirement	Demonstration Required	Detection Test Cycle	Detection Demonstrated	Worst-Case Emissions Test Cycle	Emissions Thresholds Demonstrated	NOX OBDEL (g/hp-hr)	NMHC OBDEL (g/hp-hr)	CO OBDEL (g/hp-hr)	PM OBDEL (g/hp-hr)
1	(f)(1.2.1): Fuel System Monitoring- Adaptive Learn Limits Reached (Lean) DTC 4237.0-SE13858	Y	FTP		FTP		0.4	0.21	23.25	0.015
2	(f)(1.2.1): Fuel System Monitoring- Adaptive Learn Limits Reached (Rich) DTC 4237.1-SE13859	Y	FTP		FTP		0.4	0.21	23.25	0.015
3	(f)(1.2.1): Fuel System Monitoring- Air-fuel-ratio Imbalance (Lean) DTC 6575.2-SE14417	Y	FTP		FTP		0.4	0.21	23.25	0.015
4	(f)(2.2.2): Misfire Monitoring- 1000rev monitor DTC 1322.11-SE12019, 1323.11-SE12011, 1324.11-SE12012, 1325.11-SE12013, 1326.11-SE12014, 1327.11-SE12015, 1328.11-SE12016	Y	FTP		FTP	F	0.4	0.21	23.25	0.015
8	(f)(6.2.1): Catalyst Monitoring DTC 6652.18-SE14237	Y	RMCSET		FTP		0.4	0.245	N/A	N/A
9	(f)(8.2.1)(A): Exhaust Gas Sensor Monitoring- Primary O2 Sensor- Rich Bias DTC 3217.18-SE13884	Y	FTP		FTP		0.4	0.21	23.25	0.015
10	(f)(8.2.1)(A): Exhaust Gas Sensor Monitoring- Primary O2 Sensor- Lean Bias DTC 3217.16-SE13885	Y	FTP		FTP		0.4	0.21	23.25	0.015
11	(f)(8.2.1)(A): Exhaust Gas Sensor Monitoring- Primary O2 Sensor- Rich to Lean Delayed Response DTC 3217.2-SE13883	Y	FTP		RMCSET		0.4	0.21	23.25	0.015
13	(f)(6.2.1): Empty Catalyst Monitoring DTC 6652.18-SE14237	Y	RMCSET		NA	NA	N/A	N/A	N/A	N/A

Legend	
	Pass
	Pass with Issues
F	Fail

Source: Cummins Westport Inc.

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 the diagnostic system properly identified the fault(s).

All but one monitor successfully passed during the demonstration testing. The monitor which did not pass was the "Misfire Monitoring". The NOx emission level was slightly above the 0.4 g/bhp-hr threshold limit with the production-intent calibration. CWI looked at lowering the allowable percentage of misfire but found that solution was not practical as it posed a high risk for false faults. Therefore, CWI requested, and ARB approved, an OBD deficiency for this misfire rate.

Engine Certification

The results of the HD OBD demonstration tests were documented and included along with the emissions testing results and other required certification data before submitting to CARB and U.S. EPA for engine certification. CARB and U.S. EPA treat the certification submissions from each engine and vehicle OEM as confidential information, although key pieces of information are contained on the publicly issued Executive Order and Certificate of Conformity issued by CARB and the U.S. EPA respectively. Copies of the CARB issued Executive Order and the U.S. EPA issued Certificate of Conformity for the model year 2018 B6.7N engine are shown in Appendix A. In the CARB Executive Order A-021-0678, the "OBD($)" value in the "Diagnostic" box in the upper right of the first page indicates the engine meets HD OBD requirements.

Original Equipment Manufacturer Engine-Vehicle Integration

The development of the B6.7N is based on the current production ISB6.7 G, which has been in production since 2016. During the initial development of the ISB6.7 G, the vehicle OEMs were part of the development process and successfully integrated the ISB6.7 G into their chassis. Physical interface differences were minimized with most of the changes between the ISB6.7 G and the B6.7N focused on the addition of HD OBD. 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.

Engine Design Goals

The overall goal of the B6.7N engine development was to meet 2018 U.S. EPA HD OBD, and continue meeting CARB's Optional Low NOx 0.1g/bhp-hr emissions level. The intended application of this engine was maintained similar to the ISB6.7 G with a focus on school bus, shuttle bus, yard spotter and delivery Truck. As a result, the peak power and peak torque goals were the same as the ISB6.7 G at 240 hp and 560 lb-ft, respectively. From a vehicle OEM integration standpoint there was an underlying goal to minimize the design change impact on the vehicle OEMs because they had previously invested in the integration of the ISB6.7 G.

With the design goals for the B6.7N set, an evaluation of the ISB6.7 G determined the changes needed included the following:

- New engine control module (ECM),
- Engine harness changes,
- HD OBD specific control software addition,
- Change scan-tool communication rate from 250 kbaud to 500 kbaud with associated wire harness changes,
- Additional crankcase pressure sensor and associated OEM chassis wire harness connection changes,
- Utilize a one-piece aftertreatment "can" for HD OBD tamperproof requirements,
- Relocation of the aftertreatment O2 sensor from outlet location to mid-bed location,
- Relocation of existing aftertreatment temperature sensor from outlet pipe to end of catalyst housing,
- Addition of second aftertreatment temperature sensor located at mid-bed location and associated OEM wire harness changes.

The engine and chassis interface requirements are conveyed mainly through Customer Engineering Bulletins (CEB), formerly called Application Engineering Bulletins (AEB), as well as through engine computer-aided design (CAD) models and general engine data sheets. This information is stored on a secured Cummins website, called Global Customer Engineering (GCE), with access given to each of vehicle OEM.

Vehicle OEM Interface Changes

Based on the planned engine and aftertreatment changes to meet the goals of the B6.7N, the components required to integrate/interface the new B6.7N engine and aftertreatment with the vehicle chassis were identified, interfaces set and the information to be communicated to the vehicle OEMs were determined as follows:

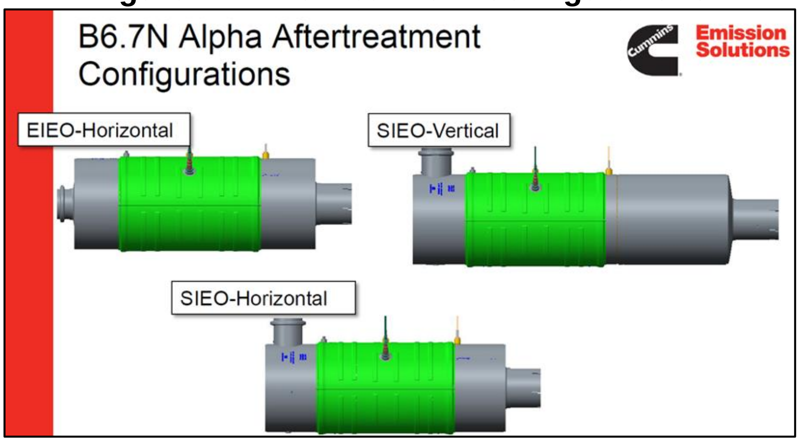
- Changes to chassis electrical harness interface, communicated in wire harness drawing.
- Aftertreatment mounting zone and body diameter decreased approximately 16 mm from the ISB6.7 G.
- Exhaust connection interfaces remained the same with a 4" standard or spherical Marmon adaptor available on the inlet and a 5" Torca slotted tube connection available on the outlet.
- Aftertreatment configuration options were identified and are outlined in Table 7 and shown in Figure 17 for visual purposes.

Table 7: Aftertreatment Configuration Options for the B6.7N

Orientation	Inlet Config	Outlet Config	Acronym	Application
Horizontal	End In	End Out	EIEO	School Bus
Horizontal	Side In	End Out	SIEO	Shuttle Bus
Horizontal	Side In	Side Out	SISO	Baseline
Vertical	Side In	End Out	SIEO	Yard Spotter, Shuttle Bus
Vertical	End In	End Out	EIEO	Baseline

Source: Cummins Westport Inc.

Figure 17: Aftertreatment Configurations

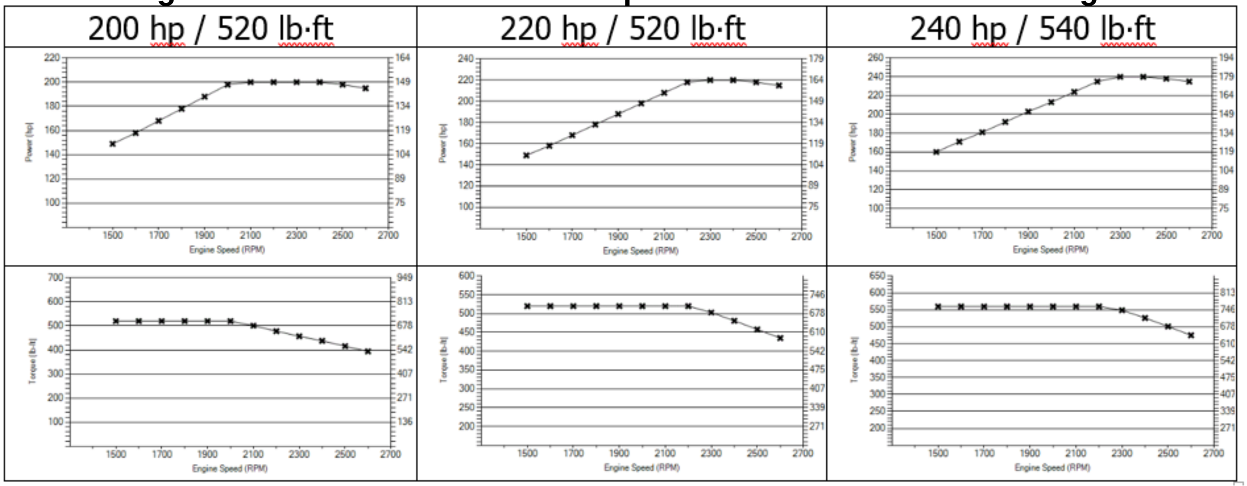


Source: Cummins Westport Inc.

Basing the B6.7N on the existing ISB6.7 G ensured that significant vehicle interfaces remained the same and therefore, did not require changes by the vehicle OEMs. For example, the following changes remained the same from the previous integration work the vehicle OEMs completed for the ISB6.7 G:

- Heat rejection requirements of vehicle cooling package remained the same due to maintaining the same three ISB6.7 G ratings (200 hp and 520 lb-ft, 220 hp and 520 lb-ft, and 240 hp and 540 lb-ft) and combustion architecture (stoichiometric, cooled exhaust gas recirculation),
- Vehicle transmission and drivetrain performance interface requirements were maintained due to utilizing the same torque and power curves for each rating. The power and torque curves for each of the three ratings are shown in Figure 18.
- Engine mounting and connection interfaces (i.e. coolant, air intake, exhaust, transmission, etc.) with chassis remained the same as the ISB6.7 G.

Figure 18: B6.7N Power and Torque Curves for the Three Ratings



Source: Cummins Westport Inc.

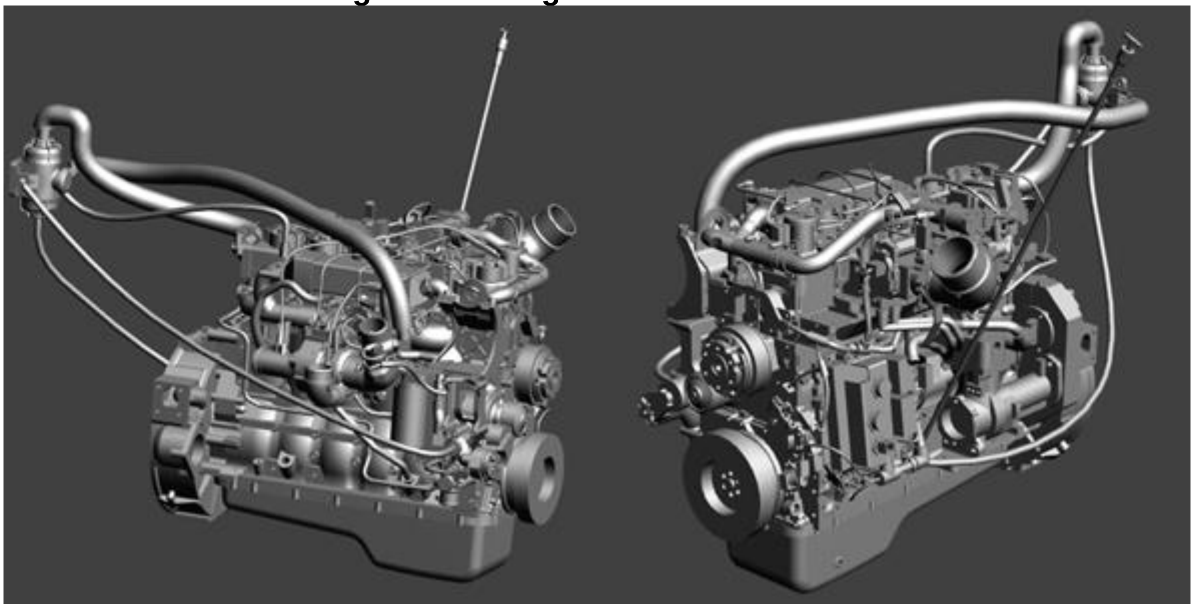
Customer Engineering Bulletin Revisions

A review of existing CEBs was conducted to determine which CEBs needed to be revised to update the changes in engine requirements from the production ISB6.7 G as discussed above. The CEB's requiring changes are listed in Appendix B with some of the key changes outlined below each CEB.

Early in the B6.7N development process, CWI notified the vehicle OEMs of the engine development program, the goals of the program, and the intended technical solution. Details of the engine changes and the potential impact to the vehicle OEMs were communicated initially at a high level and subsequently with drafts and final copies of the CEBs.

Prior to actual engines being available, CAD models of the engine and the various engine options were shared, allowing the OEMs to virtually build a desired engine and install it in their vehicle chassis to check for interference or space claim issues. Sample images of the B6.7N engine CAD model, in a school bus configuration, are shown in Figure 19.

Figure 19: Images of B6.7N CAD Models



Source: Cummins Westport Inc.

The development of the B6.7N engine and aftertreatment system included a prototype build. The purpose of this build was to build several prototype engines and: place them in test cells for validation and performance testing; install them in field test vehicles to accumulate reliability mileage as well as confirm real world driving performance; and, to provide prototypes to vehicle OEMs and allow them to confirm the fit of the engine in the vehicle chassis as well as conduct integration activities that could not be performed using CAD models. Actual hose and wire harness routing can often benefit from actual working prototypes to determine optimal routing as CAD models may not reflect true flexibility properties.

Cummins requires vehicle OEMs to pass an Installation Quality Audit (IQA) for each chassis the engine is integrated into. Various checks are performed to ensure all the engine installation requirements are met. Some of these checks may be paper studies, while others may require a specific test be conducted and measurements taken to ensure performance values meet the requirements.

For the B6.7N, a smaller subset of the full IQA is only required for those vehicle OEMs that already had the ISB6.7 G integrated into their chassis. The subset consists of the differences in design between the ISB6.7 G and B6.7N as outlined above.

Vehicle Demonstration

Further information on the vehicle demonstration portion, including vehicle specifications and mileage accumulation are included in Appendix C.

Vehicle Demonstration Goals

The project goals of the vehicle demonstration were to place between three and eighteen vehicles powered by the B6.7N prototype engine and aftertreatment system into commercial operation with suitable fleets, with at least two of these vehicles located in California, preferably in the South Coast Air Basin. The fleets operated these natural gas-powered vehicles for a period of at least six months to show their suitability in real world operation. 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.

The fleets did not perform specific tests; rather, they operated the vehicles in commercial service and monitored the vehicles for system issues through the engine fault lamp. Operator feedback helped confirm adequate performance and identify issues. In the event of product issues that affected or prevented 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.

Fleet Selection

CWI approached a number of fleets with experience in operating natural gas-powered vehicles and specifically with CWI engines for this field test project. The prior experience increased the chances of a successful project as fleets understood the differences with fueling, operation and maintenance of natural gas vehicles, in addition to eliminating other challenges such as infrastructure and facility compatibility. It was also beneficial that these fleets understood 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.

The fleets that agreed to participate in this project were Blue Water Area Transit (BWAT), Kwik Trip, Walmart and UPS with a total of eight vehicles and included shuttle bus, transit bus, truck, and yard spotter applications. In addition to those commercial fleets, there were three vehicles operated by CWI in non-commercial service and included truck and school bus applications. CWI encountered a challenge locating a California operating fleet after an initially identified fleet withdrew due to circumstances outside of this project. The issue was resolved but after incurring many months delay. Two new TICO Pro Spotters were fitted with production Intent B6.7N engines and placed into service at a UPS facility in Ontario, California in August of 2018.

Table C-1: Field Test Fleet and Vehicle Details, included in Appendix C, lists the owners, locations and owners for commercial vehicles that participated in the vehicle demonstration program. Table C-10 of the Appendix provides individual mileage totals for the field test vehicles. Representative photos of a four of the field test vehicles are provided in the Appendix C in Figures C-23 through C-27.

Vehicle Preparation

There are three options for installing the low NOx technology in these customer vehicles for demonstration:

1. First Fit: A new vehicle can be built with a 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 commercial path to market.
2. Repower: An existing B6.7 G or ISL G powered vehicle can be taken out of service and the engine removed and replaced with a new prototype B6.7N engine. The existing aftertreatment would also be replaced with a new 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 ISB6.7 G powered vehicle is not available.
3. Retrofit: An existing ISB6.7 G powered vehicle is used and only the "new" parts for the prototype B6.7N are installed. This option is not feasible due to the changes made to the engine, such as the wire harness, and the uncertainty of the engine history. This option is not CWI's intended path for commercial product.

Discussions with the fleets assessed the suitability of the three installation options for the fleet's operation, individual vehicles, and timeframe of this project. 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 low NOx technology and after-treatment unit was to repower existing vehicles. This involved removing the original engine and aftertreatment and replacing them with new prototype B6.7N engine and aftertreatment systems. The exception to this were the two TICO Pro Spotters where new engines were assembled in new vehicles as first fits. The timing of a customer's vehicle order and the desire for a natural gas engine resulted in a preference for this engine installation option.

New prototype B6.7N engines were built at the Cummins engine assembly plant in Rocky Mount, North Carolina. 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 U.S. EPA. The existing engines were replaced with new prototype B6.7N 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 re-plumbing and rewiring to connect the prototype B6.7N engine components and aftertreatment system to the vehicle.

Telemetry equipment was installed in these field test vehicles (except the two UPS TICO Pro Spotters due to the delayed timing of these two units and the availability of the data loggers) 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 their 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 vehicles were equipped with compressed natural gas 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.

Demonstration Achievements

The field test fleet, including the two three engineering vehicles, accumulated a combined 357,625 miles during this project.

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 subsequently investigated. CWI also installed upgraded hardware and electronic calibrations as deemed necessary on the engines as products improved throughout the program.

Fuel economy assessment of the fleets was not performed because of accuracy concerns. Measuring fuel economy in a test cell is the preferred method 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 B6.7N engine was taken from the existing ISB6.7 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.

Chassis Dynamometer Testing

To evaluate real world B6.7N emissions, one of the field test vehicles was delivered to University of California Riverside for chassis dynamometer testing. Testing was conducted at the University of California, Riverside (UCR) College of Engineering Center for Environmental Research and Technology emission test facility. Data was collected over four drive cycles chosen to represent vehicle operation in the South Coast Air Basin. These cycles included two Yard Tractor cycles, the Central Business District (CBD) cycle and the ARB Steady State 8-Mode off-road cycle. The test vehicle was a TICO Pro Spotter yard spotter being operated by UPS at its facility in Ontario California which had been configured with a top speed of 40 mph. This top speed configuration played into the selection and/or modification of the test cycles to accommodate. UCR conducted the testing in October of 2018. Details of the testing and results are included in Appendix C and in UCR's published report[1].

[1] Johnson, Kent, George K., Zhu, Hanwei and Li, Chunggu Low NOx Natural Gas Near-Zero B6.7N Yard Truck Evaluation. January 2019. For availability refer to https://www.cert.ucr.edu/research/efr/

CHAPTER 3: Project Results

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

- Design, develop and demonstrate a production intent 6.7 liter natural gas engine that can be certified to be compliant with the U.S. EPA 2018 HD OBD requirements while continuing to be certified at the CARB Optional Low NOx standard corresponding to the following emission levels: 0.10 g/bhp-hr NOx, 0.14 g/bhp-hr NMHC, 0.01 g/bhp-hr PM, 15.5 g/bhp-hr CO.
    - CWI successfully developed a low emission engine equipped with HD OBD that is offered commercially as the B6.7N. This engine received U.S. EPA certificate of conformity number JCEXH0408BBB-006 for model year 2018 and CARB Executive Order A-021-0678 indicating it met Optional Low NOx standard of 0.10 g/bhp-hr.
    - UCR concluded from their chassis dynamometer testing that "In general, the B6.7N 240 was well below the Executive Order NOx emissions standard of 0.1 g/bhp-hr and maintained those emissions over the range of realistic duty cycles found in while performing yard spotter and bus type of work in the South Coast Air Basin."
- Demonstrate GHG emissions (CO_2, CH_4 and N_2O) that will enable emissions certification at or below the U.S. EPA 2017 GHG emissions standards.
    - The B6.7N engine and aftertreatment system's GHG emissions were below U.S. EPA GHG standards allowing it to receive U.S. EPA certificate of conformity number JCEXH0408BBB-006 for model year 2018.
- Demonstrate a peak rating of 240 horsepower and 560 lb-ft of torque.
    - The B6.7N entered commercial production in January 2018 with the peak rating of 240 hp and 560 lb-ft.

In addition to achieving the project objectives, the eight demonstration vehicles accumulated 357,625 miles with the majority obtained in commercial operation. Fleets responded very positively to the demonstration vehicles as this third CWI engine platform is a very mature technology and leverages the lessons learned from past releases.

The B6.7N entered commercial production in January 2018 and is being produced at the Cummins engine plant in Rocky Mount, North Carolina. The B6.7N is available in the school bus, shuttle bus, and yard spotter markets through Thomas Built Bus, ARBOC

Bus, Vicinity Bus, TICO and CAPACITY Trucks. Efforts are being carried out to expand the availability into delivery trucks.

CHAPTER 4:
Technology Transfer Activities

CWI has made the knowledge gained in this project available to the public and promoted the technical and economic benefits of this project through many technology transfer activities:

- Commercial Product: The commercial B6.7N, certified to CARB Optional Low NOx 0.1 level, went into production in January of 2018. CWI has worked with existing vehicle OEMs that offered the model year 2017 ISB6.7 G to offer these vehicles with the B6.7N. CWI is looking at expanding market penetration in three major segments in North America: medium-duty trucks (including applications up to 33,000 GVWR) and yard tractors; refuse (small packers and support vehicles); and buses (including shuttle, transit, and school). All OEMs providing vehicles to these segments are being pursued.
- Emissions Results: The B6.7N 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, UCR will publicly release the results of their chassis dynamometer testing which includes real world emission test results.
- CWI Presentations: CWI regularly attends and presents at technology forums, tradeshows and industry events related to the heavy-duty on-road transportation industry. For the B6.7N engine and aftertreatment system, the target market is school bus, shuttle bus, yard spotter, and medium-duty truck applications as summarized in Table 8. CWI has included HD OBD and near zero technology information as well as B6.7N specific information at these events. A list of CWI attended events is shown in Table 9.

Table 8: B6.7N Target Market and Availability

Appli-cation:	School Bus	Shuttle Bus	Shuttle Bus	Yard Spotter	Yard Spotter	Truck	Yard Spotter
OEM / DOEM:	Thomas Built Bus	ARBOC	Vicinity	TICO	Capacity	Kenworth	Freightliner
Model:	Saf-T-Liner C2	Spirit of Equess	27.5' / 30'	Pro Spotter	TJ	T370	M2

Source: Cummins Westport Inc.

Table 9: CWI 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
Energy Vision & NW RNG Workshop, Portland, OR	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
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
Natural Gas Vehicle Technology Forum (NGVTF), Downy, CA	February 21, 2018
ACT Expo (Alternative Clean Transportation Expo), Long Beach, CA	April 2018
BC Transit Annual Conference, Parksville, BC	June 4-7, 2018
STN Expo & Summit, Reno, NV	July 13-18, 2018
California Transit Association (CTA) Fall Conference & Expo, Long Beach, CA	October 24-26, 2018

Source: Cummins Westport Inc.

- OEM Product Information Sessions: Product presentations were created for the Cummins OEM Account teams and the Cummins Distributors who handle the smaller Distributor OEMs (DOEM). These teams interface directly with each of the vehicle OEMs and DOEMs (i.e. Thomas Built Bus, ARBOC, TICO, etc.). The product presentations tend to be marketing and sales focused. Variations of these presentations were also created for the OEMs to use both internally within their company and externally with their customers, the end user of the vehicle and engine system. Vehicle OEMs have access to engine and aftertreatment integration information through Cummins Global Customer Engineering (GCE) website. Typically, this information includes, but is not limited to, engine and aftertreatment installation requirements, engine option information, and performance information.

- Maintenance Training: CWI engine maintenance training is offered to service providers through the Cummins dealer network and through the Cummins Quick Serve On-Line (QSOL) website. Updates to the training material and to the service information contained on QSOL addresses the changes between the existing ISB6.7 G and the new B6.7N engine. There are extensive updates to the troubleshooting / fault codes associated with the HD OBD added to the model year 2018 B6.7N.Cummins Westport's website has dedicated pages to each of the commercially available engines it produces (http://www.cumminswestport.com/models). These engine pages provide an overview of each engine, its features and performance specifications along with maintenance information. The website also has a "Natural Gas Academy" page where more technical information is shared.

The results of this project, as presented in the final report and disseminated through technology transfer activities, could be used by many stakeholders for various intended purposes as outlined below:

- Government emission regulators will be able to use the final report of this project to confirm low NOx natural gas internal combustion engines in heavy-duty vehicle applications are capable of achieving heavy-duty on-board diagnostics. This will provide valuable insight into the capability of current technology as well as the potential capability of future technology and related costs. That data will enable regulators to make better informed decisions for the content and timing of both State and Federal emission regulations.
- Air quality policy makers will also be able to use the information in the final report to confirm natural gas engine technology is a viable option to reach current optional low NOx standards. Confirmation of this technology's capability allows policy makers to substantiate air quality improvement roadmaps with higher confidence both from a technical capability standpoint but also from 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 and integration information, the information in the final report will provide additional information on the process CWI used to achieve these results. For those OEMs not familiar with CWI products, they will be informed of the engine and aftertreatment technology architecture used to achieve ultra-low NOx emissions with HD OBD and the durability testing conducted on real world vehicles.
- For heavy-duty fleets that are evaluating new engine technology, the information in the final report will provide them with a technical assessment of the complexity and emission performance of CWI's low NOx technology. These fleets are faced with significant vehicle and infrastructure investment costs both for capital assets as well as personnel training for future low emissions technology. This report will aid with their evaluation of low emissions technology and provide a better understanding of the expected heavy-duty vehicle availability utilizing this technology. Sustainability managers within these companies will be able to use this information as they establish their plans to meet sustainability goals through fleet vehicle acquisition.

CHAPTER 5: Conclusions and Recommendations

Conclusions

Based on the results of this project and the data presented in this report, the project team's primary conclusion is that HD OBD can be implemented on the CWI 6.7 liter natural gas engine utilizing stoichiometric, cooled exhaust recirculation, and spark ignition technology to meet U.S. EPA GHG emissions standards and CARB Optional Low NOx standards. The resulting commercial product, the B6.7N engine, incorporates the OBD developed under this project and offers a cost effective, low emissions alternative for the school bus, shuttle bus, yard spotter, and delivery truck market segments.

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 low and 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 B6.7N engine offers an immediate cost-effective low NOx emission solution for these clean air plans, especially in yard spotter use.
- Continue to aid with near zero and low NOx technology development and commercialization by expanding low NOx engine offerings.
- Continue to advance natural gas engine and vehicle development in the areas of emissions reductions (e.g. 0.02 NOx), including fuel efficiency improvements.

CHAPTER 6: Benefits to Ratepayers

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 can cost effectively achieve and maintain low emissions with HD OBD.

Heavy-duty on-road vehicles contribute heavily to NOx emissions in California, particularly in the South Coast Air Basin which faces many air quality challenges.[2] 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 U.S. EPA and the CARB. According to the U.S. EPA, 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.

California has air districts in nonattainment relative to the National Ambient Air Quality Standards that 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[3] 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 B6.7N with HD OBD continues the offering of a smaller engine displacement option for heavy-duty on-road commercial engines. Incentive funding and public fleet mandates will help accelerate deployment of the B6.7N engine to quickly realize emission reductions.

The South Coast Air Basin requires a 45 percent reduction in total NOx emissions by 2023 to meet U.S. EPA ambient ozone standards. The B6.7N reduces NOx emissions by more than 50 percent from the current federal standard for heavy-duty on-road engines. The B6.7N serves medium-duty vehicles requiring a smaller displacement engine and can play an important role in ensuring a cost effective, low emissions engine

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

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

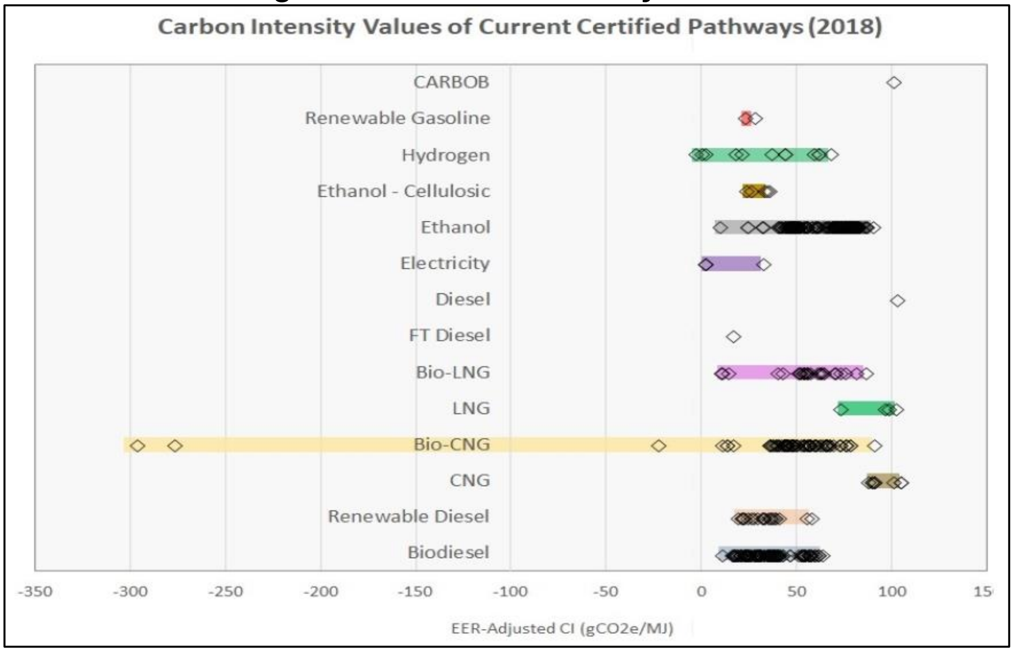
is available to help achieve the region's aggressive NOx reduction targets ahead of the development of a mandatory low NOx engine standard.

Widespread adoption of the B6.7N 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 B6.7N 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 20 compares the carbon intensity of 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. The feedstocks with the greatest CI reduction are both from animal wastes: CN056, with a CI value of -272.97 grams of CO_2 equivalent per megajoule (gCO_2e/MJ), and CNGDD201, with a CI value of -254.94 gCO_2e/MJ. In both 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.

Figure 20: 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 number of engines operating in California was analyzed to evaluate local benefits of the CWI 6.7-liter engine. Annual deployment of a specific heavy-duty engine at either the state or national levels is difficult to track because engines are sold to a wide variety of vehicle OEMs across the country and then may be resold through distributors, sometimes more than once, before they are domiciled at a specific fleet location. Furthermore, it is difficult to precisely estimate the direct emissions benefits of the ISB6.7 G (and now the B6.7N engines) in California because CWI does not publish sales by engine platform. Nevertheless, an approximation for the current benefits from deployment was established below by analyzing the school bus market in California. The school bus market was chosen because it is the dominant application for current sales of the 6.7-liter engine.

The team developed a reasonable estimate of the current emissions benefits from deployment of the 6.7-liter engine by comparing the reported number of miles traveled by school buses in California to the total school bus miles reported for North America, and then using the resultant figure to estimate how many Type C school buses are sold into California. This results in an estimate that California school bus sales account for 7.4 percent of sales in North America. The calculations carry an assumption that there is an even split of Type C school buses sold by each of three major school bus OEMs: Thomas Built Buses (TBB), Blue Bird, and IC Bus. Furthermore, CWI only sells into TBB and it is assumed that 20 percent of TBB sales include the CWI 6.7-liter natural gas engine platform. Following the calculations summarized below leads to an estimate of 155 units deployed per year or approximately 400 units in California over the less than three years of commercial sales for the B6.7N. On average, school buses travel approximately 7,200 miles per year and use about 1,000 gasoline gallon equivalents (GGEs) per year[4]. That leads to total petroleum displacement of 400,000 gallons of diesel per year for the vehicles currently on the road in California.

The team used Argonne National Laboratory's Heavy-Duty Vehicle Emissions Calculator[5] to calculate the benefits of a vehicle replacement scenario in which 400 diesel school buses are replaced with low NOx natural gas school buses. The calculation assumed an annual fuel consumption of 1,000 GGEs per vehicle of RNG sourced from anaerobic digestion. The calculated benefits over the lifetime of the vehicles included a reduction of 255,605 lbs of NOx and 93,645 short tons of CO_2 equivalent emissions.

Projections for future sales show a steady growth in volume depending on rules and incentive funding. Since the 6.7 liter's initial launch in the school bus market, it has also been added to the shuttle bus market with Arboc (Spirit of Equess chassis[6]), and volumes should increase due to this newer offering. Yard spotter availability with TICO is another new offering which should increase deployment of the B6.7N. There is still a push to have medium-duty truck OEMs integrate the B6.7N into their chassis which would open a larger market opportunity with potential to see B6.7N volume increase to 2,000 to 3,000 units per year in the next five years.

Table 10: Estimated Deployment of ISB6.7 N in California School Buses

Market	North America Annual Sales[7]	CA Annual Sales (7.4%)	TBB Annual Sales (33%)	CWI 6.7 L Deployment Estimate per year
School Bus (Type C)	31,505 units	2,331 units	777 units	155 units

Source: Gas Technology Institute

[4] https://files.schoolbusfleet.com/stats/SBFFB19-transportation.pdf

[5] https://afleet-web.es.anl.gov/hdv-emissions-calculator/

[6] https://www.arbocsv.com/media/brochures/SpiritEQUESS_2019.pdf

[7] https://files.schoolbusfleet.com/stats/SBFFB19-sales.pdf

LIST OF ACRONYMS

Term	Definition
AEB	Application Engineering Bulletin
CARB	California Air Resources Board
CCR	California Code of Regulations
CCV	Closed Crankcase Ventilation
CEB	Customer Engineering Bulletin
CHET	Cold/Hot Emission Test
CI	Carbon Intensity
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CWI	Cummins Westport Inc.
EGR	Exhaust Gas Recirculation
FTP	Federal Test Procedure
gCO_2e/MJ	Grams of Carbon Dioxide Equivalent per Megajoule
g/bhp-hr	Grams per Brake Horsepower-hour
GGE	Gasoline Gallon Equivalent
IQA	Installation Quality Audit
HD OBD	Heavy-Duty Onboard Diagnostics
HHDDT	CARB Heavy Heavy-Duty Diesel Truck cycle
lb-ft	Pound-Feet
LCFS	Low Carbon Fuel Standard
MIL	Malfunction Indicator Lamp
NH_3	Ammonia
NMHC	Non Methane Hydrocarbons
NOx	Oxides of Nitrogen
NO_2	Nitrogen Dioxide

Term	Definition
N_2O	Nitrous Oxide
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
U.S. EPA	United States Environmental Protection Agency

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APPENDIX A:
CARB and U.S. EPA Emissions Certificates

Following are the emissions certification documents provided by the United States Environmental Protection Agency (Figure A-1) and California Air Resources Board (Figure A-2) for model year 2018 B6.7N engine and aftertreatment system.

Figure A-1: Model Year 2018 U.S. EPA Certificate of Conformity for B6.7N

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: JCEXH0408BBB-006

Effective Date: 11/29/2017

Expiration Date: 12/31/2018

Byron J. Bunker, Division Director
Compliance Division

Issue Date: 11/29/2017

Revision Date: N/A

Model Year: 2018
Manufacturer Type: Original Engine Manufacturer
Engine Family: JCEXH0408BBB
Intended Service Class: Medium Heavy-Duty Diesel
Fuel Type: Liquefied Natural Gas, Compressed Natural Gas
FELs (g/hp-hr):
NOx: 0.10

Intended Engine Application: Vocational
Primary Test Configuration Transient Duty Cycle:
CO2 FCL value (g/hp-hr): 555
CO2 FEL value (g/hp-hr): 572
N2O FEL value (g/hp-hr): 0.10
CH4 FEL value (g/hp-hr): 0.90
Primary Test Configuration Steady-State Duty Cycle:
CO2 FEL value (g/hp-hr): null

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: United States Environmental Protection Agency

Figure A-2: Model Year 2018 CARB Executive Order for B6.7N

CALIFORNIA AIR RESOURCES BOARD	CUMMINS INC.	EXECUTIVE ORDER A-021-0678 New On-Road Heavy-Duty Engines Page 1 of 2 Pages

Pursuant to the authority vested in the 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	JCEXH0408BBB	6.7	CNG/LNG	Diesel	MHDD	TBI, TC, CAC, ECM, EGR, TWC, HO2S	OBD(\$)

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)
6.7	B6.7N 260 / 4965;FR96385 (260), B6.7N 240 / 4965;FR95841 (240), B6.7N 220 / 4965;FR96279 (220), B6.7N 200 / 4965;FR96280 (200)

* =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(F) / (P) / (\$)=full / partial / partial with a fine / on-board diagnostic;

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	0.10	0.10	*	*	15.5	15.5	0.01	0.01	*	*
CERT	0.01	0.004	0.08	0.001	*	*	3.0	1.9	0.000	0.000	*	*
NTE	0.21		0.20		*		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 Oct. 21, 2014.

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 Oct. 21, 2014 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	
	JCEXH0408BBB-006		VOCATIONAL	
in g/bhp-hr	CO_2 FTP	CO_2 SET	CH_4	N_2O
STD	576	*	0.10	0.10
FCL	555	*	*	*
FEL	572	*	0.90	*
CERT	485	*	0.25	0.03

[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-021-0678 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 1971.1 (on-board diagnostic, full or partial compliance) 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 nine deficiencies. The listed engine models are approved subject to the manufacturer paying a fine of $175 per engine for the third through ninth 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 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 7 day of December 2017.

Annette Hebert

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

Source: California Air Resources Board

APPENDIX B: Customer Engineering Bulletin Changes

The following Customer Engineering Bulletins were identified as requiring a revision to reflect the changes between the ISB6.7 G and the B6.7N.

- ISB6.7 G (Natural Gas) U.S. EPA 2015 Mechanical Product Information
  - Added summary of ISB6.7 G / B6.7N changes as shown below:
  - Added reference to aftertreatment changes including the sensor and sensor location
  - Added reference to crankcase pressure sensor
  - Changed reference to new ECM
  - Added reference to scan tool interface and pin changes at main wire harness connection.
- ISB6.7 G Automotive and Bus Installation Requirements
  - Added reference to pin assignment changes at engine power and controls connections.
  - Added reference to aftertreatment wire harness changes.
  - Revised locations for Engine Compartment Heat temperature test procedure.
- CM2380 Electronic Subsystem Technical Package – OEM Components
  - Initial release of CEB to assist OEMs in designing and interfacing with Engine Electronics and Electrical components.
- CM2380 Electronic Subsystem Technical Package – OEM Interfaces
  - Initial release of CEB assisting OEMs in designing and interfacing with Engine Electronics and Electrical components.
- CM2380 Electronic Subsystem Technical Package – OEM Programming Guide
  - Initial release of CEB providing information for the CM2380A electronic subsystem and contains OEM features and OEM programming information
- CM2380 2018 Electronic Subsystem Technical Package – Serial Communication
  - Initial release of CEB provides application information for the CM2380 electronic subsystem.
- Simultaneous Lamp Verification Test Procedure
  - Initial release of Appendix Test Procedure to ensure the lamp messages are communicating properly and that simultaneous fault codes will illuminate the appropriate lamps.
- Automotive/Bus Installation Requirements - CNG Fuel Systems
  - Revised low fuel pressure lamp requirements
  - Added low fuel pressure lamp test procedure.
- Cooling System Heat Transfer - Auto & Bus Installation Requirements

    - Engine name reference change
- Body Builder Guide – Automotive Natural Gas
    - Engine name reference change
- Installation Requirement Body Builder IQA Worksheet
    - Engine name reference change
    - Added check items to note if system is same as ISB6.7 G
- Remote Mount Crankcase Ventilation Filter (breather) - Installation Requirements
- Emissions Compliance: On Board Diagnostics (OBD) Master Document - HD OBD
    - Existing CEB for Cummins diesel products, added to the B6.7N with HD OBD requirements. Identifies the list of CEB that include HD OBD Requirements for the various Cummins engine families. The components and system that are supplied by the vehicle OEM must satisfy all the requirements specified in the AEB/CEBs.
- Emission Compliance: OEM reporting process on OBD product for CAL IDs and CVNs
    - Existing CEB for Cummins diesel products, added to the B6.7N with HD OBD requirements. Defines a process for the OEM to report calibration identifications and calibration verification numbers to Cummins on a quarterly basis so that Cummins can meet agency reporting requirements.
- Automotive and Bus Installation Requirements – Natural Gas and LPG/Propane Catalyzed Exhaust Aftertreatment Systems
    - Added mounting requirements for unibody three-way catalyst.
    - Reference to revised dimensions of three-way catalyst
- Emission Compliance: Production Vehicle Evaluation (PVE) Scan Tool Interface (STI) Test-Vehicle Configuration
    - Existing CEB for Cummins diesel products, added to the B6.7N with HD OBD requirements. Satisfies HD OBD Product Vehicle Evaluation (PVE) Scan Tool Interface (STI) requirements for the SAE J1393-84 datalink.

APPENDIX C:
Vehicle Demonstration

Vehicle Demonstration Vehicles

Table C-1: Field Test Fleet and Vehicle Details, lists the four fleets with eight vehicles, and the three Engineering vehicles that participated in the vehicle demonstration program.

Table C-1: Field Test Fleet and Vehicle Details

Fleet	Location	Chassis	Application	Unit	ESN
Blue Water Area Transit 1	Port Huron, MI	32' El Dorado	Shuttle / Transit	28595	74099951
Blue Water Area Transit 2	Port Huron, MI	32' El Dorado	Shuttle / Transit	28591	74099955
Blue Water Area Transit 3	Port Huron, MI	32' El Dorado	Shuttle / Transit	28592	74099959
Kwik Trip 1	La Crosse, WI	2013 KW T370	Truck	4302	74098817
Kwik Trip 2	La Crosse, WI	2015 KW T370	Truck	5308	74098821
Walmart	Menomonie, WI	Kalmar (Ottawa)	Terminal Tractor	M-1515	74099962
UPS 1	Ontario, CA	TICO	Terminal Tractor	51600	74101038
UPS 2	Ontario, CA	TICO	Terminal Tractor	51601	74101042
CWI (T3180)	Columbus, IN	2009 Freightliner M2	Truck	T3180	74098809
CWI (T2093)	Columbus, IN	Thomas Built Bus	School Bus	T2093	74101050
CWI (T135)	Columbus, IN	Ford F750	Truck (School Bus cycle)	T135	74098813

Source: Cummins Westport Inc.

Representative pictures of some of the field test vehicles in this project are shown in the following figures.

Figure C-1: Blue Water Area Transit, Michigan

Source: Cummins Westport Inc.

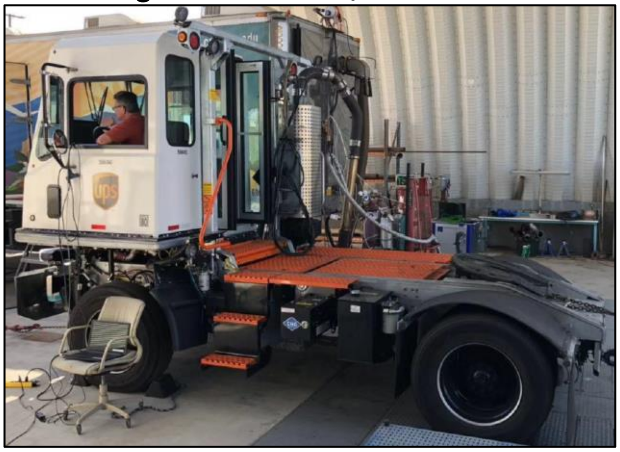
Figure C-2: Kwik Trip, Wisconsin

Source: Cummins Westport Inc.

Figure C-3: Walmart, Wisconsin

Source: Cummins Westport Inc.

Figure C-4: UPS, California

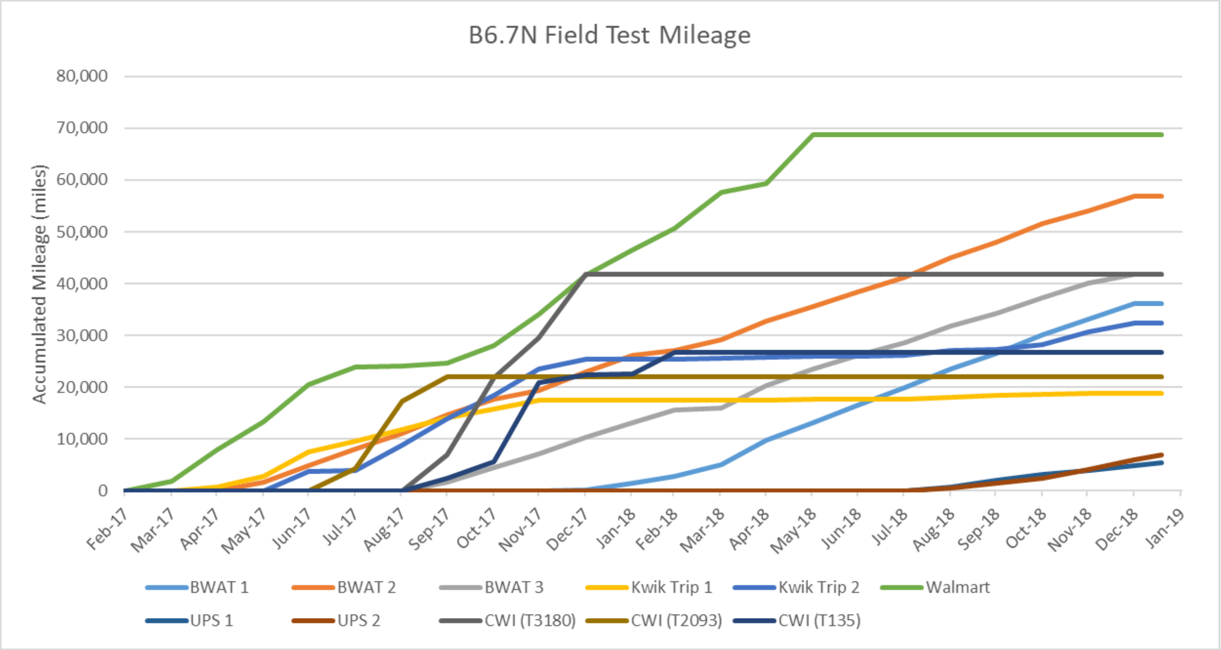


Source: University of California Riverside

Each fleet reported the vehicle mileage to CWI for tracking. The field test fleet, including the three engineering vehicles, accumulated a combined 357,625 miles during this project.

Figure C-5 shows the monthly mileage accumulated by each of these vehicles throughout the duration of this project. Table C-2 lists the total miles accumulated by each vehicle.

Figure C-5: Field Test Vehicle Monthly Mileage



Source: Cummins Westport Inc.

Table C-2: Field Test Vehicle Mileage Totals

Customer	ESN	Chassis	Application	Unit	Location	Jan-19
BWAT 1	74099951	32' El Dorado	Shuttle / Transit	28595	Port Huron, MI	*36,139*
BWAT 2	74099955	32' El Dorado	Shuttle / Transit	28591	Port Huron, MI	*56,888*
BWAT 3	74099959	32' El Dorado	Shuttle / Transit	28592	Port Huron, MI	*41,758*
Kwik Trip 1	74098817	2013 KW T370	Truck	4302	La Crosse, WI	*18,866*
Kwik Trip 2	74098821	2015 KW T370	Truck	5308	La Crosse, WI	*32,340*
Walmart	74099962	Kalmar Ottawa)	Terminal Tractor	M-1515	Menomonie, WI	68,750
UPS 1	74101038	TICO	Terminal Tractor	51600	Ontario, CA	5366
UPS 2	74101042	TICO	Terminal Tractor	51601	Ontario, CA	6997
CWI (T3180)	74098809	2009 Freightliner M2	Truck	T3180	Columbus, IN	41,829
CWI (T2093)	74101050	Thomas Built Bus	School Bus	T2093	Columbus, IN	22,042
CWI (T135)	74098813	Ford F750	Truck (School Bus cycle)	T135	Columbus, IN	26,650
					Total:	357,625

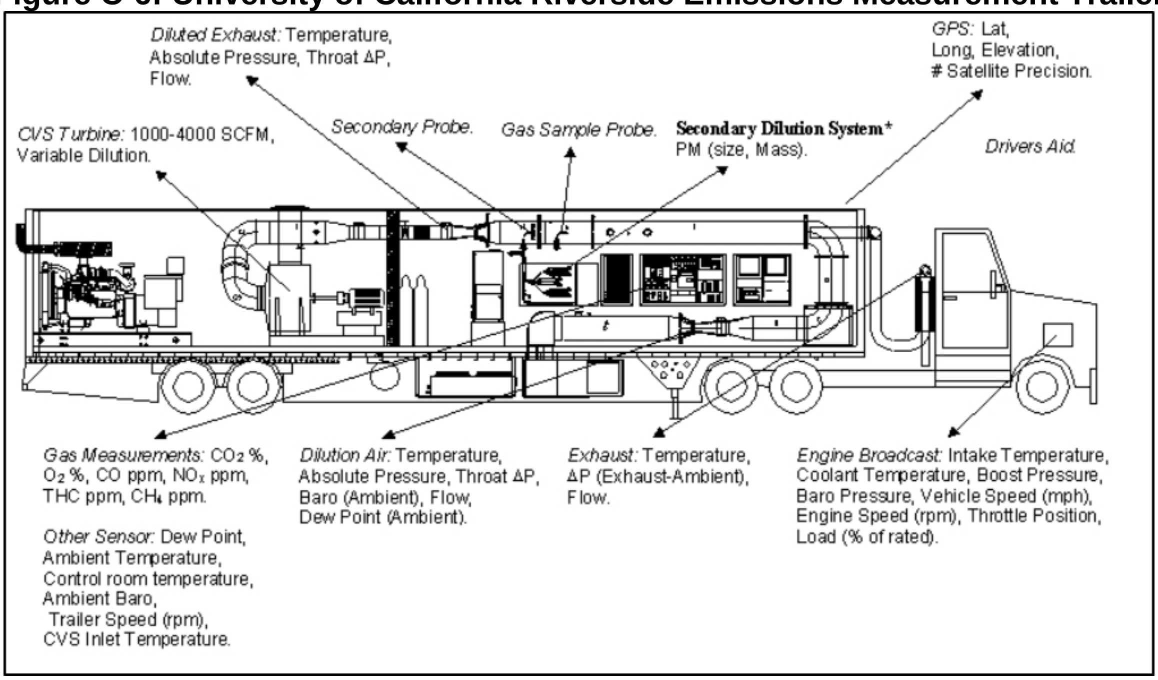
Source: Cummins Westport Inc.

Chassis Dynamometer Testing

To test real world B6.7N emissions, chassis dynamometer testing of one field test vehicle was conducted to evaluate non-methane hydrocarbons, oxides of nitrogen (NOx), carbon monoxide, particulate matter, ultra fines, ammonia (NH_3), greenhouse gas emissions, and brake-specific fuel consumption.

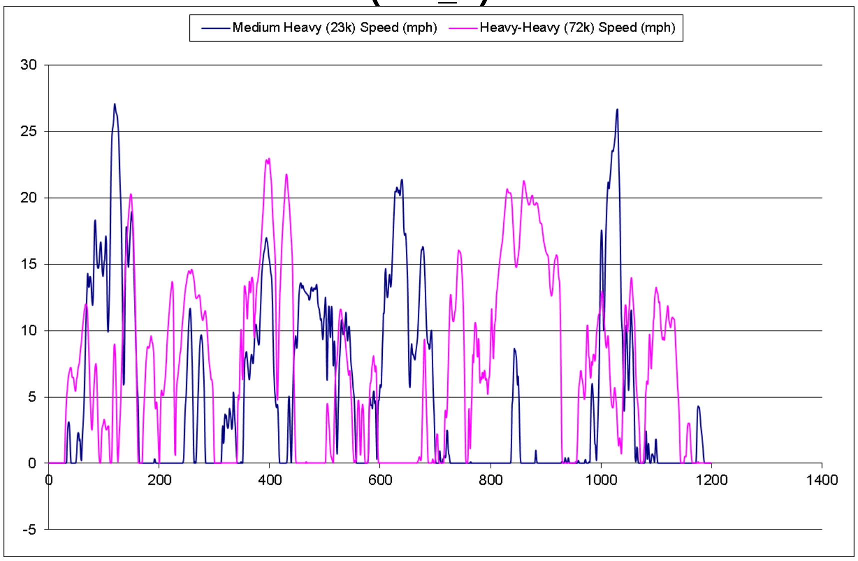
Testing was conducted at the University of California, Riverside College of Engineering, Center for Environmental Research and Technology emission test facility. The facility is a recognized heavy-duty emission testing laboratory and was approved by the South Coast Air Quality Management District (SCAQMD) for this project. The emissions measurement equipment was contained in a mobile trailer, shown in Figure C-6. Data was collected over four drive cycles chosen to represent operation in the South Coast Air Basin: two yard tractor cycles, the Central Business District (CBD) cycle, and the ARB Steady State 8-Mode off-road cycle (Figure C-7 to Figure C-9). 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 C-6: University of California Riverside Emissions Measurement Trailer



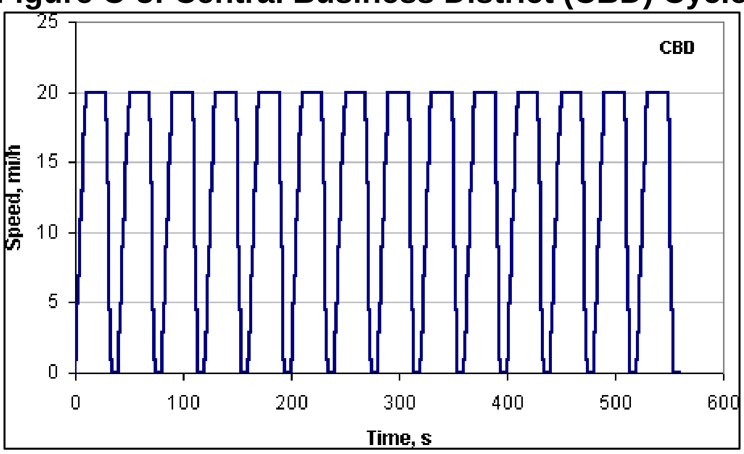
Source: University of California, Riverside

Figure C-7: Transient test yard tractor (YT) cycles, medium (YT2_L) and heavy (YT1_H)



Source: University of California, Riverside

Figure C-8: Central Business District (CBD) Cycle



Source: University of California, Riverside

Figure C-9: ARB Steady State 8-Mode Off Road Cycle

Mode number (cycle B)	1	2	3	4	5	6	7	8	9	10	11
Mode number (cycle C1)	**1**	**2**	**3**		**4**	**5**	**6**	**7**			**8**
Speed 1)	Rated speed					Intermediate speed					Low-idle speed
Torque 1), %	100	75	50		10	100	75	50			0
Weighting factor	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15

Source: University of California, Riverside

Testing was conducted October 9th through the 12th of 2018 using the UPS 1 vehicle (1T9TSNA83KR825001). According to the University of California, Riverside (UCR) report[1], the testing found "the B6.7N 240 was well below the EO NOx emissions standard of 0.1 g/bhp-hr and maintained those emissions over the range of realistic duty cycles found in while performing yard tractor and bus type of work in the South Coast Basin. It is expected the NG vehicles could play a role in the reduction of the south coast high NOx inventory given the near zero emission factors demonstrated". The main conclusions described in the UCR report are listed below.

- The B6.7N 240 6.7 liter NG engine showed hot start NO_x emissions that ranged from 0.017 g/bhp-hr (CBD_M) to 0.003 g/bhp-hr (YT2_L).
- The cold start emissions averaged 0.115 g/bhp-hr for the transient yard tractor cycle at full GVW (YT1_H). The hot/cold weighted (1/7 cold start weighted) emissions was 0.02 g/bhp-hr which is 80 percent below the 0.1 g/bhp-hr emission standard. It is expected the impact of the cold start emissions real in-use emissions should be lower than reported here and depends on the real fraction of time a NG truck operates in cold mode vs hot operation. One example would be 164 seconds out of a 4 hr shift would be a real impact of cold start emissions for yard tractors. More research on cold starts and restarts per day are needed to quantify the real impact.
- The NOx emissions did not increase with lower power duty cycles like the diesel counterpart (pre and post 2010 certified engines). The non-sensitivity to engine load was demonstrated on the other near-zero (NZ) engines tested by UCR (ISX12N and L9N).
- The real time NOx emissions show very low emissions with short NOx spikes amounting to 60 percent to 80 percent of the total emissions. These spikes occur, mostly, from rapid transitions from idle. The NOx spikes occurred for all the NZ engines where the L9N showed spikes on acceleration transitions and the ISX12N showed NOx spikes occurring during de-accelerations. This suggests possible driver behavior may impact the overall NOx in-use performance of all NZ engines and more gradual accelerations are desired such as with automatic transmissions and hybrid applications.
- N2O and NO2 emissions also showed cold start and hot start transient spikes which represent 99 percent and 60-80 percent of their emissions, respectively.
- If the transient emission spikes could be eliminated, NO, NO2, and N2O could be minimized to a running emissions of around 0.001 g/bhp-hr (each), but NH3 emissions would still be high. NH3 emissions may be controllable with a changes to the engine calibration. More work is needed here to evaluate an optimized engine for controlled transient responses, such as for a hybrid application.
- It is unclear what the impact of start-stop hybrid technology would have on the warm restart emissions of a NG NZ engine. Some observation in this study suggest the critical temperature for a low emitting warm start NOx emissions is around 400 C where 1/3 the starting NOx emissions occurred compared to 350C

warm start. Further investigation is needed to understand impacts from start-stop technology.

- The lower cut point CPCs (2.5 nm) showed higher solid PN emissions compared to the 23 nm cut point CPC and averaged (2.8E13 #/mi). There were no significant differences between solid and total particles as measured for the transient tests between the CVS and PMP measurement systems. However, the steady state test (SS_Modes), showed much higher PN (4E14 #/mi) emissions (around 8.8 times higher) than the transient tests for the CVS measurement, but not for the PMP sampling system. This suggest the steady state PN was volatile and was removed by the PMP sampling system. This also suggests PN measurements for NG vehicles needs to be well planned out to prevent over reporting PN emissions from NG vehicles.
- The AVL APCplus solid PN measurement system was added to this year's testing to investigate the regulatory impact of PN emissions from NG vehicles. The sold PN emissions at 23nm cut point averaged from 1.7e13 #/mi for the stead state test (SS_Modes) to 1.3e14 #/mi for the hot start transient test (YT1_H). The 23nm PN were higher than the Euro 6 standard (9.7e11 #/mi) by a factor of 9 on average and would be a factor of 23 higher on average if the lower cut point (2.5 nm) CPC were used as is being considered for future regulations in Europe.
- The B6.7N PN is approximately 279 times higher compared to diesels equipped with a DPF (1e11 #/mi), as measured with a 2.5 nm CPC from a dilution tunnel. It is unclear what impact this will have locally and regionally.
- NH3 emissions appeared to be higher for the B6.7N compared to the ISX12N, but about the same as the L9N and lower than that of the ISL G 8.9L 2010 certified engine.
- PM mass was low for the B6.7N yard tractor and was below the standard by 50 percent or more. Due to the low emission levels the filter weights were close to UCR's tunnel blank and thus represented measurements near the detection limit. Thus, actual PM emissions may be lower since contamination biases PM higher not lower generally.
- The gaseous PEMS system measured drift correct NOx at values less than 0.1 g/bhp-hr and these values agreed well with the laboratory where a paired t-test showed the means were not statistically different (p-value = 0.25). The drift corrected results at 0.02 g/bhp-hr represented 90 percent of the emissions measured where the means differences between the PEMS drift-corrected and non-drift-corrected results were statistically significant (p-value < 0.006)
- The PM PEMS emissions were also well below the 10 mg/bhp-hr standard and averaged 1.8 mg/bhp-hr for all the cycles which is a factor of 2 lower than the gravimetric method (the mean differences were statistically significant with a p-value of 0.002. The PM PEMS variability was also lower by a factor of 4. The PEMS tunnel blank, higher filter weight, and improved real time soot measurement accuracy would suggest PM PEMS measurements may be more

representative of the PM emissions from NG engines and thus, may be more accurate than the laboratory measurement method.

- Engine load reported by the ECU varied by 24 percent between the cold start tests and the hot start tests. 24 percent is higher than what is expected from in-use testing and was investigated. It was found that the actual torque was 8 percent higher, but the frictional torque was 20 percent lower for a combined 24 percent higher load on the cold start test when compared to the same cycle and test weight of the hot start test. Using the lower load test does change the cold start emissions from 0.115 to 0.143 g/bhp-hr and the cold start weighted emissions would increase from 0.02 to 0.024 g/bhp-hr (both of which are above the 0.10 g/bhp-hr certification value).