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Development of a Cummins ISL Natural Gas Engine at 1.4 g/bhp-hr NO_x + NMHC Using PLUS Technology

Final Report

M.M. Kamel
Cummins Westport, Inc.
Vancouver, British Columbia, Canada

Subcontract Report
NREL/SR-540-37758
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List of Acronyms and Abbreviations

$BSNO_x$	Brake Specific Nitrogen Oxides
CARB	California Air Resources Board
CFD	Computational Fluid Dynamics
COV	Coefficient of Variation
CWI	Cummins Westport, Inc.
DC	Direct Current
DIA	Denver International Airport
DOE	U.S. Department of Energy
ECM	Engine Control Module
EGR	Exhaust Gas Recirculation
EPA	U.S. Environmental Protection Agency
FTP	Federal Test Procedure
GIMEP	Gross Indicated Mean Effective Pressure
IMEP	Indicated Mean Effective Pressure
LACMTA	Los Angeles County Metropolitan Transportation Authority
NMHC	Nonmethane Hydrocarbons
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
PM	Particulate Matter
SwRI	Southwest Research Institute
THC	Total Hydrocarbons
ULEV	Ultra Low Emission Vehicle

1.0 Executive Summary

The U.S. Department of Energy (DOE) funds research and development that reduces U.S. dependence on imported petroleum and promotes better air quality. Natural gas vehicles help to diversify automotive fuel requirements. In addition, natural gas engines and vehicles have led the way to lower exhaust emission requirements.

The work described in this report was supported through DOE's National Renewable Energy Laboratory (NREL). In April 2003, under a competitive solicitation, NREL awarded Cummins Westport, Inc. (CWI) an advanced development subcontract to develop an 8.9 L natural gas engine capable of meeting increased power ratings and reduced exhaust emissions.

The power target was achieved, and the torque and emissions targets were surpassed. The final ratings were 320 hp and 1,000 ft-lb peak torque, with a California Air Resources Board (CARB) engine emissions certification of 1.4 g/bhp-hr NO_x + NMHC (nitrogen oxides plus nonmethane hydrocarbons). The targets were 320 hp, 950 ft-lb, and a CARB certification of 1.8 g/bhp-hr NO_x + NMHC. Fuel consumption over the Federal Test Procedure was also measured; brake-specific fuel consumption was 201 g/bhp-hr.

Because of the high torque and low NO_x requirements, the engine design required increased levels of turbocharging and lean combustion operation. This created challenges related to the ignition system and mixing of the fuel and air to provide a homogeneous mixture and stable combustion. To meet these challenges, innovative designs for key components of the subsystems were developed and implemented for production. A new spark plug design was also developed to ensure a reliable and reasonable service interval in the field.

Hardware revisions to the engine control module (ECM) were necessary to accommodate the new system requirements for sensors and ignition system interface. The new ECM was developed and verified with bench tests to ensure the reliability of the design and manufacturing process.

The design and development process had three phases:

1) In the concept phase, three engines were built to develop and demonstrate the engine concept; this included rating demonstration, emissions tests, and preliminary vehicle tests.
2) In the Alpha phase, development, field test, and customer prototype engines were built and used to identify issues and achieve a stable design.
3) In the Beta phase, original equipment manufacturer engineering and design verification engines were built.

Emissions development work involved extensive mapping and control techniques to achieve the target levels with a sufficient compliance margin. The work led to a successful certification test and award by the U.S. Environmental Protection Agency and CARB of the necessary documents.

The new parts were released into the Cummins system and all the drafting completed. Suppliers were approved by the quality organization to ship the needed parts to the assembly plant. Plant processes and systems were verified through early Alpha and Beta engine builds and quality measures.

A total of eight engines were built and shipped for field evaluation in customer fleets in transit bus and refuse truck applications. Implementation of five engines in one customer fleet was severely delayed. To increase field experience, the CWI engineering truck was operated on a test route as a simulated field test vehicle and accumulated approximately 10,000 miles before product launch.

2.0 Introduction

The U.S. Department of Energy's (DOE) FreedomCAR and Vehicle Technologies Program is advancing the development of gaseous-fueled internal combustion engines, which have the potential to reduce U.S. dependence on imported petroleum and improve air quality. Natural gas vehicles help diversify U.S. automotive fuel requirements. In addition, natural gas engines and vehicles have led the way to lower exhaust emission requirements. In April 2003, under a competitive solicitation, DOE's National Renewable Energy Laboratory awarded Cummins Westport, Inc. (CWI) an advanced development subcontract to develop an 8.9 L natural gas engine capable of achieving higher power ratings and lower exhaust emissions compared with other CWI natural gas engines.

More than 10,000 CWI natural gas engines are in revenue service in applications such as urban buses, pickup and delivery trucks, and school buses. These engines are certified to U.S. Environmental Protection Agency (EPA) ultra low emission vehicle (ULEV) standards and provide a wide range of power ratings (150–300 hp).

The natural gas engine market has focused primarily on transit buses and medium-duty applications. Expanding into the heavy truck and articulated bus markets requires increased engine power and torque. To meet these requirements, CWI developed a new and larger engine platform based on its PLUS technology.

PLUS technology provides state-of-the-art engine control and operation along with advanced diagnostic capabilities. CWI's C Gas Plus (8.3 L) and B Gas Plus (5.9 L) natural gas engines have demonstrated market acceptance among natural gas fleet operators. The Cummins ISL (8.9 L) diesel engine is also a market-accepted product. By combining PLUS natural gas technology with the larger ISL engine, CWI aims to meet the market opportunity in heavy truck and articulated bus applications.

3.0 Project Objectives

The overall objective was to develop a commercially viable natural gas engine platform with higher engine ratings and lower exhaust emissions compared with other CWI natural gas engines. The project duration was 18 months. The following were the specific engine targets:

- Engine ratings of 320 hp and 950 ft-lb
- Federal emission certification to 2004 EPA standards
- California Air Resources Board (CARB) low-NO_x certification of 1.8 g/bhp-hr NO_x + NMHC (nitrogen oxides plus nonmethane hydrocarbons).

4.0 Development Schedule

Table 1 outlines the three major tasks and corresponding sub-tasks for the L Gas Plus development, showing planned (P) and actual (A) completion dates for each milestone. The 10 deliverables were completed in 20 months.

Months

Task #	Deliverable #	MILESTONE NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3.1		**Completion of Laboratory Development**																				
3.1	1	Concept Demo				A																
3.1	2	Design Freeze						A														
3.1	3	Performance & Emissions Capability Demonstrated							P	A												
3.1		Production Software available											P			A						
3.1	4	Final Performance & Software Completed												P							A	
3.1	5	Mechanical Development Completed														P						A
3.2		**On-Road Prototype Engine Development in Vehicles**																				
3.2		Field Test Software available							P	A												
3.2		Engineering Vehicle Tests Start								P	A											
3.2	6	Field Test Engines Available										P			A							
3.2	7	Fied Test Evaluation Completed																		P		A
3.3		**Perform FTP Testing/Commercialize Engine**																				
3.3	8	Certification Test Completed														A	P					
3.3	9	Production Readiness Completed																			P	A
3.3	10	Limited Production																				A

P = Plan, F= Forecast, A= Actual

Table 1: L Gas Plus Schedule

The engine has been put into production at the Cummins facility in Rocky Mount, North Carolina. All design elements and the required design validation work have been completed. The remaining implementation issues are being addressed as part of the normal product launch process.

5.0 Development Summary

5.1 Completion of Laboratory Development (Task 3.1)

This was the project's major development task. The engine design concept was completed. A prototype engine was built to test the capability of the design to operate on natural gas and demonstrate the overall capability of the concept. During the concept phase, the ignition system failed to reliably ignite the lean mixture, requiring a redesign to correct. Once the concept engine met overall capability requirements, major development efforts related to performance, emissions, electronics, and mechanics were performed. Design details, supplier identification, and hardware procurement were completed in parallel.

Extensive laboratory development established that the prototype engines with developed hardware and software were ready for installation and testing in an engineering vehicle. One purpose of the engineering vehicle was to determine initial operation and drivability.

Based on the laboratory concept tests, the engineering vehicle feedback, and the design review process, the design team froze the engine design. The design freeze allowed the release process to commence for all engine components, i.e., a bill-of-material for the L Gas Plus natural gas engine could be released into the system. The engine was now ready to proceed with field testing and verification.

Extensive performance and emissions development concluded with the demonstration of the design's capability to achieve the power, torque, and emissions targets. Emissions were demonstrated over the Federal Test Procedure (FTP) transient test cycle. Based on field performance and test cell data, software and calibrations were developed further. The final software and calibrations to achieve the targets and provide acceptable vehicle performance were released into the production system in preparation for product launch.

Extensive bench, test cell, and field evaluations of all new hardware were completed in this task. This ensured the integrity of the design and robustness of the hardware for the applications and the intended duty cycle in the field.

5.1.1 Concept Demonstration

Three concept engines were built and used to develop and demonstrate the design capabilities relative to the performance targets. The target for peak torque was increased from 950 to 1,000 ft-lb to satisfy customer requirements for refuse truck applications, a growth market for CWI. One engine was used for performance development, another for emissions testing, and the third for installation in an engineering vehicle to evaluate drivability. The initial focus was on demonstrating the engine rating. Subsequently, the details of the combustion recipe and emissions capability were explored. Figure 1 is a computer-generated layout of the concept design.

An issue was encountered with the ignition system's capability to reliably ignite the lean mixture required to achieve the emissions targets. The issue was discovered by monitoring and identifying unstable combustion events and by observing high total hydrocarbons (THC) emissions. A current production ignition system was verified to perform adequately and produce acceptable combustion stability and THC levels for the concept phase; therefore, it was used in the initial development stage, including field testing.

Design revisions were later made to the new ignition, which resulted in significant performance improvement at steady state and transient engine operating conditions. This improved design produced equivalent performance compared with the interim field test hardware. As a result, the revised design was selected for production implementation. The evolution of the design from concept to production is discussed later in this report.

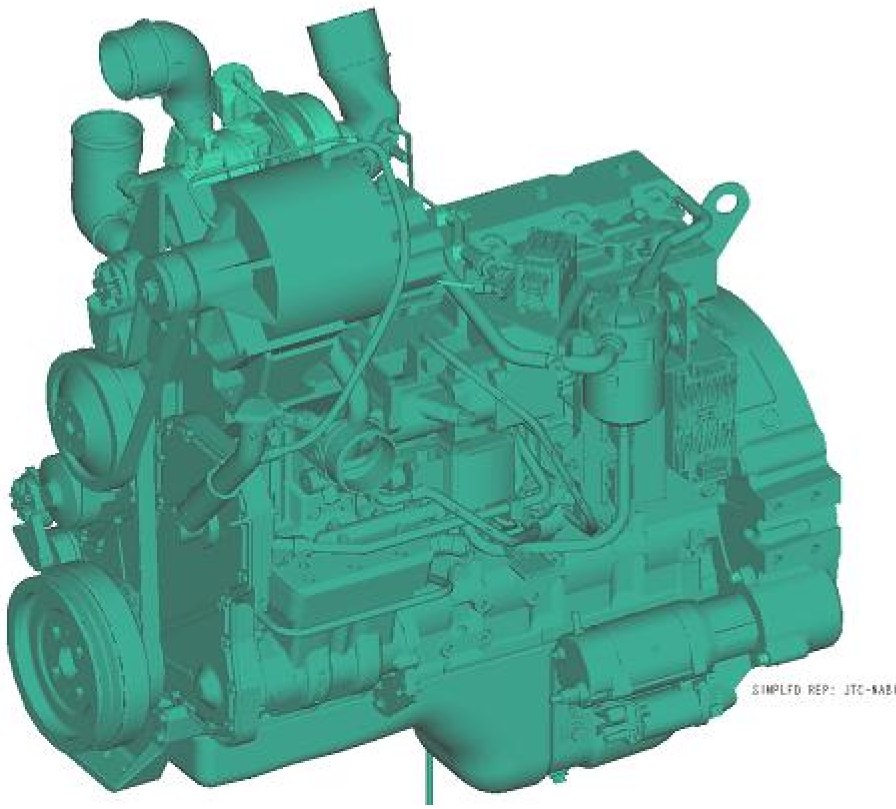

Figure 1: Concept Engine Layout

5.1.2 Design Freeze

Table 2 shows the major elements of the design and the progress made over the development period in freezing these elements as the systems or components were verified. The yellow bars indicate periods in which issues were encountered in the development or when component optimization was underway.

The engine control module (ECM) manufacturing process was modified by the supplier, which resulted in the oxygen sensor circuitry gain being slightly more sensitive. This did not affect the project, but backward compatibility concerns with older products had to be addressed. Hardware options were evaluated but were not robust enough solutions. An algorithm was developed to address the backward compatibility concerns.

During the endurance portion of the design validation, evidence was discovered of the second piston ring sticking because of carbon build up. Analysis of the ring dynamics revealed no issues with the ring lifting in the groove. Thermal modeling revealed no temperature issues compared with the production engines. Further examination of the test uncovered an issue with the way the test was conducted: the oil was not changed at the correct interval. The test specifications were reviewed and corrected. When the tests were repeated with the correct process no issues were found with the second ring.

Subsystem Design Status

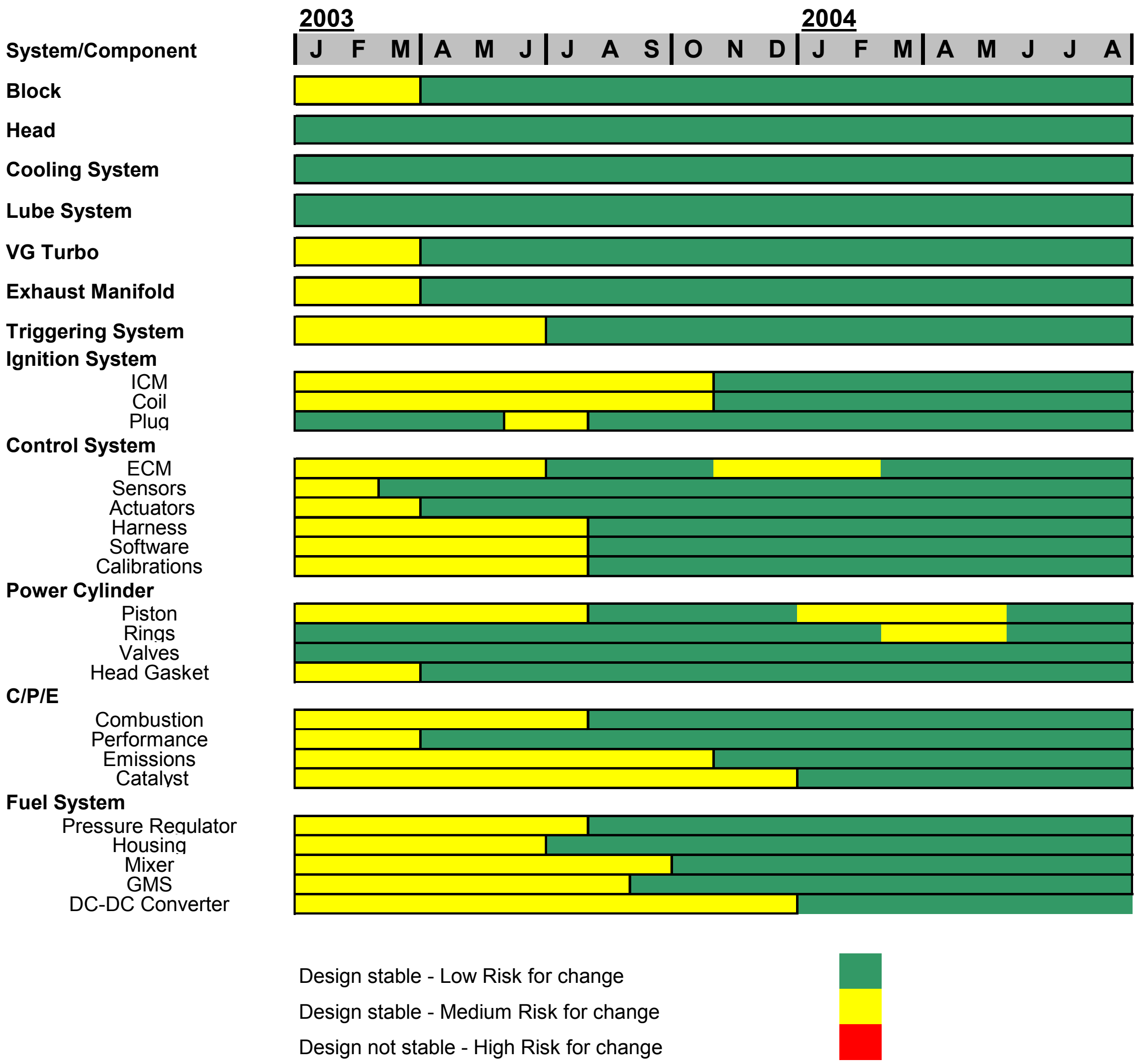

Table 2: Subsystem Design Status

Because of the sensitivity of the fuel control system to supply voltage, a DC/DC converter was developed and implemented to supply the desired voltage to the engine irrespective of the vehicle supply voltage, provided it was above a certain minimum. The fuel system is sensitive because the gas flow sensor requires a minimum supply voltage to maintain accuracy. A supplier was identified, and the converter was added to the list in Table 2. The converter was fully developed and validated to achieve the desired capability to compensate for supplier voltage dropping to 9 V without sensor and system impact. The converter was verified for production as part of the engine control system and released to production.

5.1.3 Performance and Emissions Capability

To meet the low NO_x and high torque targets, the engine had to be operated at very lean (high air/fuel ratio) conditions. For the highest load (torque or power) conditions, lean operation resulted in significantly increased supply pressure (boost). Increasing the boost pressure resulted in higher cylinder pressure at the required spark ignition timing. This resulted in combustion instability issues, especially at high-speed conditions. The coefficient of variation (COV) of indicated mean effective pressure (IMEP), which indicates the gross torque of the engine, is used as a measure of combustion stability.

Cylinder pressure data were collected from the test engine (Figure 2). A COV of 5 or lower is the acceptable threshold. The data show that the performance of the new SEM ignition system was inferior to that of the current Bravo production system. This deficiency was evaluated extensively. In the interim, the decision was made to fit the current Bravo hardware for the development engines and procure it for field evaluation. Development of the new ignition system was conducted in parallel.

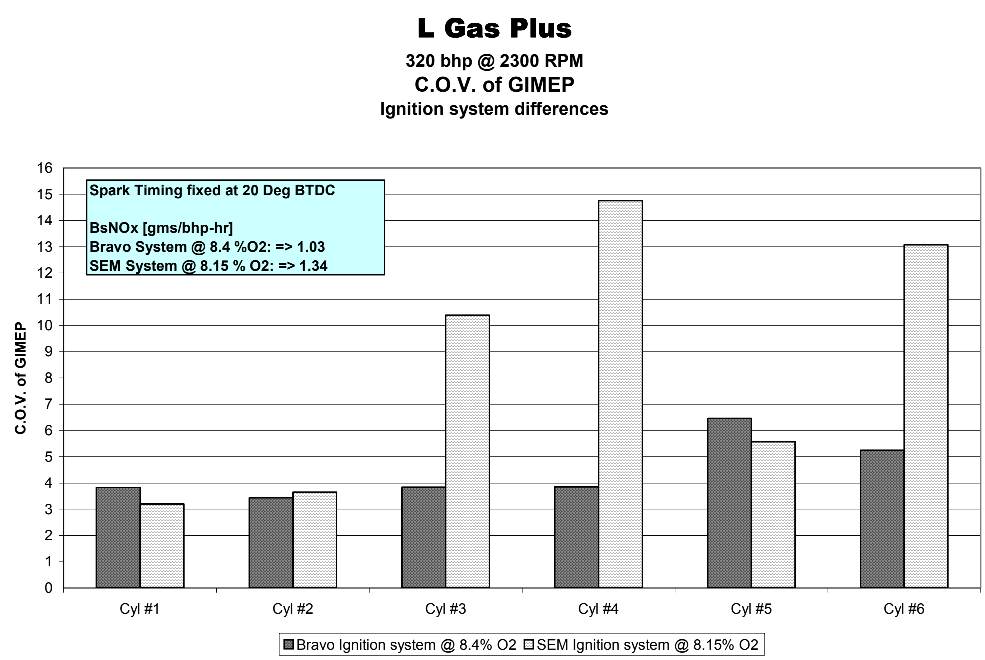

Figure 2: Bravo and SEM Ignition System Comparison

The ignition system development resulted in redesign of the coil and coil driver. Analysis of the system performance indicated that a longer duration spark is needed to achieve the required ignitability performance. This necessitated changes to the coil configuration and the coil driver, which resulted in the required performance being attained. Hardware was procured, and all engines, including field test units, were up-fitted with the production-intent design. Figure 3 shows the final SEM production hardware, including the coil driver and a three-coil assembly.

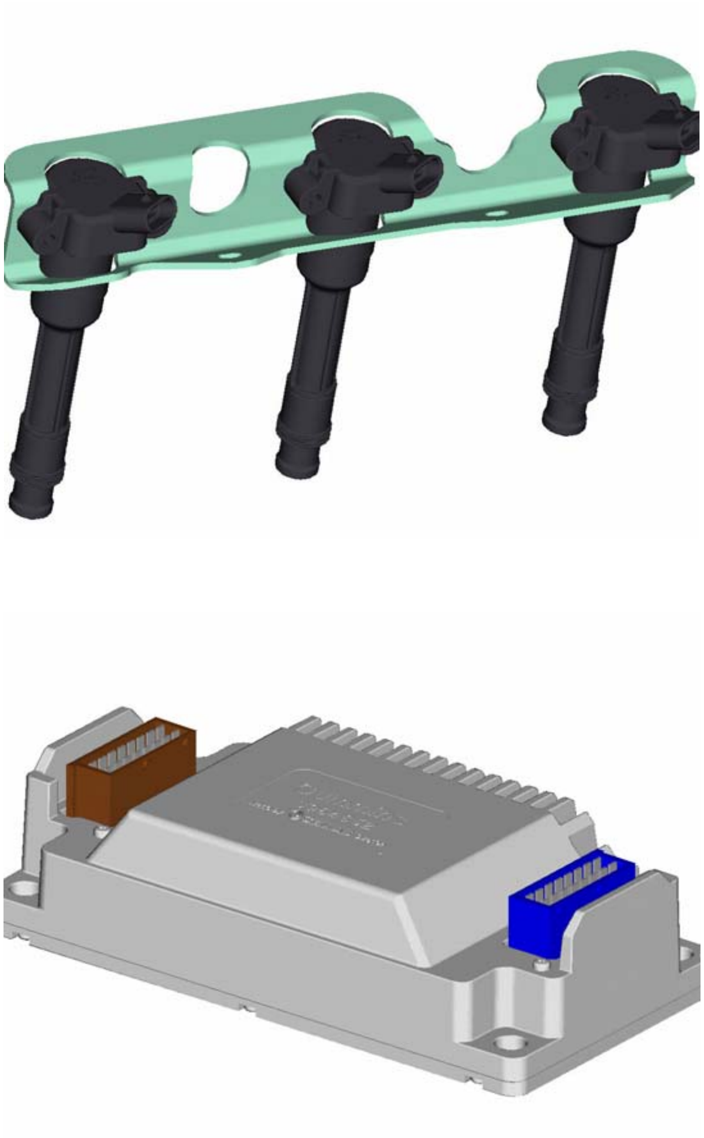

Figure 3: Ignition Coils (top) and Driver (bottom)

Figure 4 shows the production-intent ignition system performance as tested on the Alpha engine. (Alpha engines are engines built and tested during early development when not all design elements are completed or frozen.) The “current” data refer to the SEM system initially used on the engine, which resulted in misfire as the air/fuel ratio became leaner (increased percent oxygen). The other data refer to two development iterations of the system resulting in the production-intent design, which is represented by the green squares. This shows good performance at very lean conditions, indicated by COV values below the target 5%.

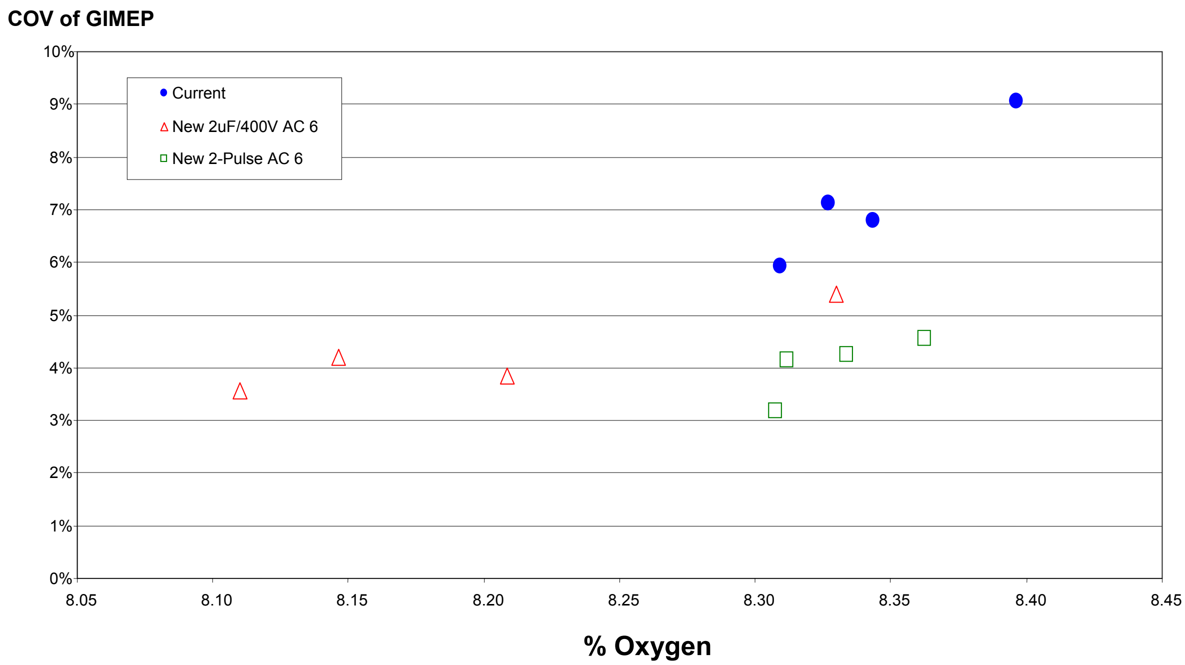

Figure 4: Alpha Ignition System Comparison

Transient FTP emissions tests were conducted, and calibrations were developed to facilitate vehicle evaluation with the Alpha engines equipped with the "interim" ignition system hardware. The calibration produced NO_x emissions of 1.4 g/bhp-hr. Once the production ignition system was proven, the emissions recipe required further development to suit the operation of the system, including development of the ignition timing tables and transient air/fuel ratio logic. Figure 5 illustrates the engine torque curve over the NO_x emissions for all engine speeds and loads. This calibration was initially used in the field test engines. The calibration produced acceptable transient performance per the prescribed requirements and the following emissions on the FTP test cycle (without a catalyst):

- NO_x 1.4 g/bhp-hr
- THC 4.0 g/bhp-hr
- Particulate matter (PM) 0.03 g/bhp-hr

The following Steady State Emissions Test (SET) numbers were estimated from special tests conducted:

- NO_x 1.2 g/bhp-hr
- THC 2.9 g/bhp-hr

The emissions work also included development of the oxidation catalyst, which was used to control CO and PM emissions.

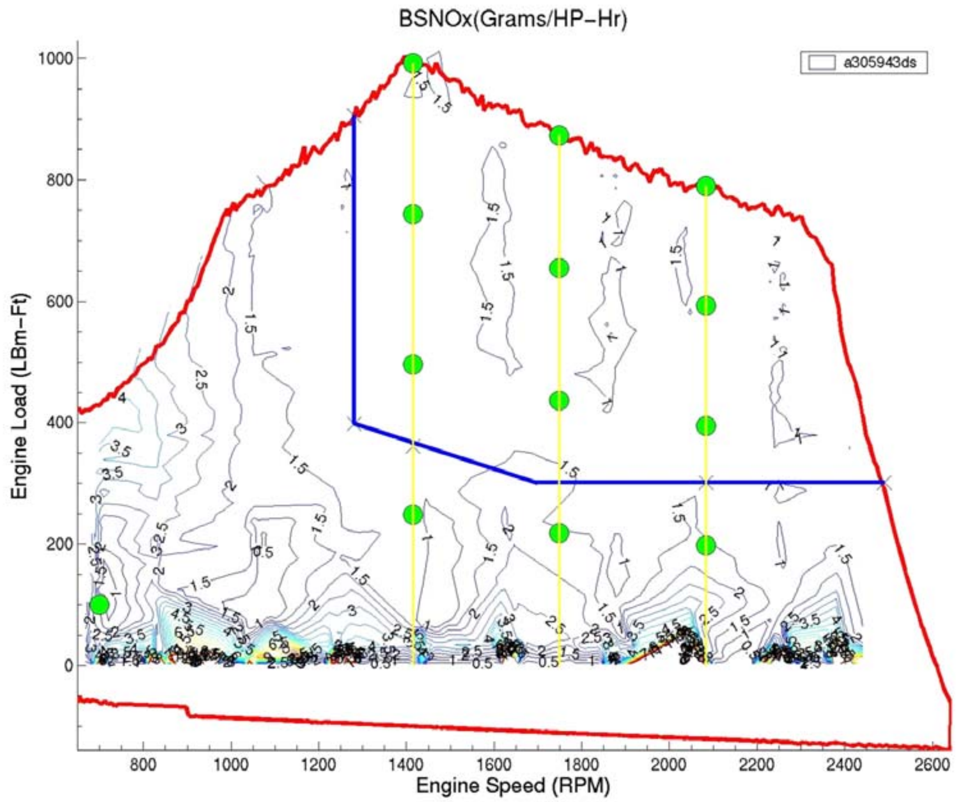

Figure 5: Engine NO_x Map

To improve the margin for lean operation, the design team used computational fluid dynamics (CFD). CFD modeling indicated that better mixing of the natural gas and intake air was possible. The mixer design was modified, and significant mixing improvements were achieved with the laboratory engine. Figure 6 and Figure 7 illustrate the original and improved mixer designs and cross sections. Very good results were achieved with the final design, as indicated by the uniformity of the green shades. In the original design, blue color indicates air and red indicates fuel. The model results were confirmed by engine and emissions tests. Prototype parts were procured and used to up-fit the field and laboratory engines. This design was implemented in production.

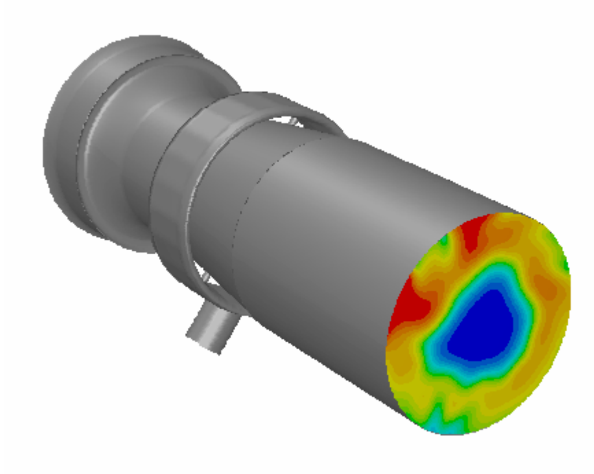

Figure 6: Original Mixer and Cross Section

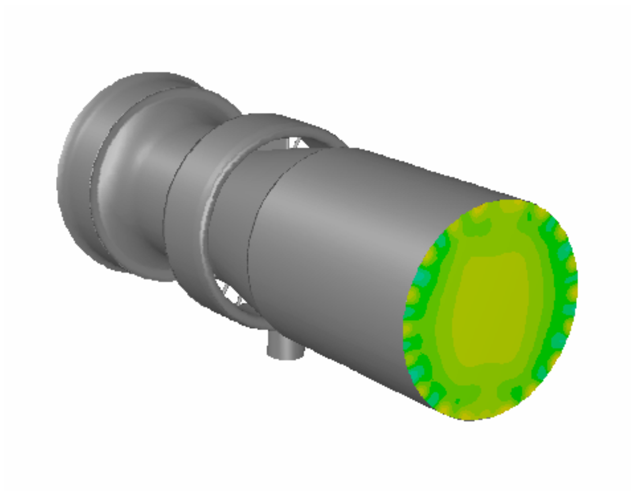

Figure 7: Improved Mixer (Final Design) and Cross Section

5.1.4 Mechanical Development

Four engines were built and used for the mechanical development of the engine subsystems. These engines were rebuilt and reused for several tests during the verification phase of the design.

Vibration data for the new components were obtained from running engines. These data were used to conduct accelerated equivalent life tests for the components on shaker rigs. To verify designs, parts were examined after completion of the tests. If problems were found, the design was modified and the test rerun. Brackets and control modules are examples of parts verified by shaker rigs.

Engine endurance tests were used to verify the design of the pistons, rings, cylinder head, valve train, gaskets, manifolds, and turbocharger. These tests included the following:

- Hot box: The engine is run on an endurance test at high coolant and intake manifold temperatures.
- Thermal cycle: The engine is operated on a cycle, and the engine coolant is cycled between high and low values.
- Overload: The engine is operated at loads higher than the rated output.
- Over speed: The engine is operated at speeds higher than the rated speed.
- Hot shutdown: The engine is operated on a cycle and periodically shut down and restarted.

Evidence was found of carbon packing of the second ring piston groove, resulting in ring sticking during endurance testing of the early development (Alpha) engines. Thermal analysis of the piston, as well as ring dynamics modeling, did not indicate ring or groove design issues. Predictions of design iterations to lower the mid-land area temperature did not reveal significant improvement. Further evaluation of the test data indicated issues with the way the test was conducted. Two Beta engines (engines built with production-intent hardware, representing the final design) were built and run on the same test, and results showed no issues with ring sticking. Actual piston temperature measurements were obtained and fell within current production values. This further confirmed that the issue was confined to early Alpha-level design and operating conditions of the test.

5.2 On-Road Prototype Engine Development in Vehicles (Task 3.2)

Prototype hardware was procured, and eight engines were built, tested, and shipped to prototype fleet customers in various geographic areas. The first two engines were only partially built at the production facility and were completed at the engineering facilities. The remaining engines were built as complete engines at the production facility. All verification testing was conducted at the engineering facilities.

CWI identified specific customers to test performance, design integrity, and robustness in real-world operation. Field test agreements were completed, with the vehicle users agreeing to supply the required vehicle operation information. Typical data collected from these sites included general satisfaction with performance, report and return of operational issues or failures, oil consumption, and spark plug life. These data were used to initiate corrective actions as needed. General customer satisfaction was reported with vehicle performance, and targets were met regarding spark plug life and oil consumption. No fuel consumption or vehicle performance complaints were reported for any of the applications.

5.2.1 Field Test Software Available

During the early development stages, an issue was uncovered with the new ECM. Variations were recorded in engine output and emissions when using the new ECM compared with using the production ECM. This was traced to the analog-to-digital converter output, which was resulting in variation in closed-loop performance between the two modules. The issue was further traced to stray capacitance (electrical noise) from the new board manufacturing process. Hardware designs could not eliminate the problem completely. A logic fix was developed to correct for this effect in software and validated.

Field test software was developed as indicated in the *Performance and Emissions Capability* section above. The calibrations delivered 1.4 g/bhp-hr NO_x, and good performance was verified on the engineering vehicle. This software was used on all the field test engines initially. Subsequent software and calibrations were downloaded in the field test units as improvements were made. The final software and calibrations were developed to achieve the required performance, emissions, and transient response. These were loaded into the field test engines and were tested for several months before production release.

5.2.2 Engineering Vehicle Tests

A prototype engine was built and tested to verify performance. The engine was installed in an engineering truck and used for initial shakedown of performance and calibration issues (Figure 8). The engine was initially built with Alpha-level hardware duplicating the field test hardware and calibrations. The engine was later upgraded to production-intent (Beta) level hardware and software and used as a simulated field test vehicle by operating it on specific routes in Southern Indiana. The vehicle (Figure 9) was very useful for evaluating and optimizing calibration and provided a way of rapidly checking the impact of changes on vehicle performance.

Figure 8: Alpha Engine Installation

Figure 9: Engineering Truck

5.2.3 Field Test Engines

Parts were procured and received for building field test engines, and agreements were secured with selected field test customers. The field test applications covered the intended market segments of transit bus and refuse truck operators, applications that traditionally use or are expected to use natural gas engines. Five engines were planned for one customer (Norcal Waste Systems, Inc.), and two were CWI-funded units. An additional CWI-funded unit was added because of delays at Norcal. The three CWI-funded units were for retrofit of existing vehicles; as a result, they were completed quickly.

Table 3 outlines the field test plans and delivery dates for the engines. The table shows that the first two engines were built (Build Spec) as short blocks in the manufacturing plant, which means they were later up-fitted to complete engines. All remaining engines were built at the plant to the specification of the Norcal or Los Angeles County Metropolitan Transportation Authority (LACMTA) shop orders.

LG+ Development Engines Build/Test Plan

#	Task	Build Spec	Customer	Application	Ship Date/Forecast
1	Field Test Engine	S Block	Norcal2	Truck	10/1/2003
2	Field Test Engine	S Block	LACMTA	Bus	10/10/2004
3	Field Test Engine	Norcal	DIA	Bus	12/1/2003
4	Field Test Engine	Norcal	Wastemgt	Truck	11/4/2003
5	Field Test Engine	Norcal	Norcal1	Truck	12/12/2004
6	Field Test Engine	LACMTA	Norcal3	Truck	1/9/2004
7	Field Test Engine	Norcal	Norcal5	Truck	12/17/2004
8	Field Test Engine	Norcal	Norcal4	Truck	1/26/2004

Table 3: Field Test Engines

5.2.4 Field Test Evaluation

The objective of the field test task was to facilitate operation of several engines by end users in the major target market applications (Figure 10). Because of continued delays in readying the five Norcal trucks for service, these trucks were not expected to generate significant mileage and experience for the program. The focus was directed at getting the three CWI-funded field test vehicles operational by year-end 2003. In addition, the engineering truck (Figure 9) was up-fitted with production-intent hardware and software and operated in field test mode to accumulate experience from June to August 2004. The truck was not operated by a customer but was managed by Cummins and run on specific routes around Columbus, Indiana.

Figure 10: Field Test Vehicles

5.3 Perform Federal Test Procedure/Commercialize Engine (Task 3.3)

This task comprised several activities required to ready the L Gas Plus engine for production. For the engine to be assembled in the plant, the required parts had to be released into the parts management system. Coordination efforts were conducted with suppliers to complete practice builds in the manufacturing plant.

5.3.1 Certification Test

Upon reaching the design freeze stage, hardware was procured and delivered to the production facility for the build of the certification engine. The engine was built and production tested in February. Engine break-in was also completed at the production facility, and the engine was shipped to Southwest Research Institute (SwRI) for certification testing.

Emissions certification tests were successfully completed at SwRI. All necessary documents were submitted to EPA and CARB, and certification documents were awarded for 1.4 g/bhp-hr NO_x + NMHC and 0.01 g/bhp-hr PM (Appendix A). Fuel consumption over the FTP was also measured; brake-specific fuel consumption was 201 g/bhp-hr.

5.3.2 Production Readiness

The product introduction team ensured that all the new parts were approved for use by the plant and that suppliers were ready to meet the orders. Supplier quality assurance activities were completed to ensure good quality and process control from the suppliers. In total, seven pre-production engines were built, tested, and shipped by the production facility to identify and correct issues in these processes, train the assembly personnel, and practice the complete process from order entry though product shipment. Issues were identified and resolved, and readiness for production was assured as part of the review process before product release.

5.3.3 Limited Production

Management approval to proceed to limited production was obtained on August 30, 2004 following a review of development status. The “limited “specification for the release is to control the sale of the product only to original equipment manufacturers who have completed their installation review process. The product launch remains under the control of the introduction team to ensure smooth processes while identifying and addressing any remaining issues. Once issues are resolved and production is proceeding in normal mode, the introduction team reviews the status with the management group and the restrictions are removed.

Appendix A: EPA/CARB Certifications

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

2005 Model Year Certificate of Conformity

Manufacturer:	**Cummins Inc.**
Certificate Number:	**CEX-MHDD-05-02**
Effective Date:	**6/29/04**
Date Issued:	**6/29/04**

Merrylin Zaw-Mon, Director
Certification and Compliance Division
Office of Transportation and Air Quality

Pursuant to Section 206 of the Clean Air Act (42 U.S.C. section 7525), 40 CFR Part 86, and the Consent Decree (Civil Action No. 98-02546) entered and approved by the U.S. District Court for the District of Columbia on July 1, 1999, this certificate of conformity is hereby issued with respect to the test engines which represent the following motor vehicle engines, by engine family, and is subject to the terms and conditions prescribed in those provisions and the Consent Decree.

Heavy Duty (MHDD) Natural Gas Engine Family: 5CEXH0540LBA

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 Part 86 and the Consent Decree.

This certificate of conformity covers those new motor vehicle engines produced by Cummins Engine Company during that production period of the model year stated on this certificate (model year as defined in 40 CFR Part 86).

This certificate of conformity is conditional upon compliance of said manufacturer with the provisions of 40 CFR 86.090-15, 86.091-15, 86.094-15 and other banking, averaging and trading provisions of 40 CFR Part 86 and the Consent Decree, including those applicable after model year production. Failure to comply with applicable sections of 40 CFR Part 86 (including 40 CFR 86.090-15, 86.091-15 and 86.094-15) or the Consent Decree may render this certificate void ab initio.

Family NMHC+NOx emission limit: 1.4 g/BHP-hr
Family PM emission limit: 0.01 g/BHP-hr

It is a term of this certificate that the manufacturer shall consent to all inspections described in 40 CFR 86.096-7, 86.606, and 86.1006 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 Part 86 including 40 CFR 86.095-30, or render the certificate void ab initio as specified in 86.096-7. 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 Part 86, including 40 CFR 86.095-30, 86.612, 86.096-7, and 86.1012.

California Environmental Protection Agency AIR RESOURCES BOARD	CUMMINS, INC.	EXECUTIVE ORDER A-021-0372 New On-Road Heavy-Duty Engines

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-02-003;

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]
2005	5CEXH0540LBA	8.9	CNG/LNG	Diesel	MHDD	OC, HO2S, PCM, TBI, TC, CAC

ENGINE (L)	ENGINE MODELS / CODES (rated power, in hp)
8.9	LG-320 / 8828;FR91036 (320)
*	*
*	*
*	*

* =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;
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; [illegible] 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; [illegible] IDI/DDI=indirect/direct diesel injection; TC/SC=turbo/super charger; CAC=charge air cooler; EGR=exhaust gas recirculation; 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;

Following are: 1) the FTP exhaust emission standards, or family emission limit(s) as applicable, under 13 CCR 1956.1 (urban bus) or 13 CCR 1956.8 (other than urban bus); 2) the EURO 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, in g/bhp-hr, for this engine family. "Diesel" CO, EURO 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 1956.1 or 13 CCR 1956.8 are in parentheses.)

	NMHC		NOx		NMHC+NOx		CO		PM		HCHO	
	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO	FTP	EURO
STD	0.5	0.5	*	*	*	*	15.5	15.5	*	*	*	*
FEL	*	*	*	*	1.4	1.4	*	*	0.01	0.01	*	*
CERT	0.00	0.00	*	*	1.2	1.0	0.4	0.3	0.01	0.002	*	*
NTE	0.625		*		1.75		19.375		0.0125		*	

* =not applicable; g/bhp-hr=grams per brake horsepower-hour; FTP=Federal Test Procedure; EURO=Euro III European Steady-State Cycle; 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: Certification to the FEL(s) listed above, as applicable, is subject to the following terms, limitations and conditions. The FEL(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) and 13 CCR 2035 et seq. (emission control warranty).

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 4th day of August 2004.

Allen Lyons, Chief
Mobile Source Operations Division

REPORT DOCUMENTATION PAGE

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Development of a Cummins ISL Natural Gas Engine at 1.4 g/bhp-hr NOx + NMHC Using PLUS Technology: Final Report

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
In April 2003, under a competitive solicitation, the U.S. Department of Energy's National Renewable Energy Laboratory awarded Cummins Westport, Inc. an advanced development subcontract to develop an 8.9 L natural gas engine capable of meeting increased power ratings and reduced exhaust emissions. The power target was achieved, and the torque and emissions targets were surpassed. The final ratings were 320 hp and 1,000 ft-lb peak torque, with a California Air Resources Board (CARB) engine emissions certification of 1.4 g/bhp-hr NOx + NMHC (nitrogen oxides plus nonmethane hydrocarbons). The targets were 320 hp, 950 ft-lb, and a CARB certification of 1.8 g/bhp-hr NOx + NMHC. Fuel consumption over the Federal Test Procedure was also measured; brake-specific fuel consumption was 201 g/bhp-hr.

15. SUBJECT TERMS
cummins westport; natural gas vehicle; isl; natural gas engine; national renewable energy laboratory; l gas plus

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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