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National Renewable Energy Laboratory

Innovation for Our Energy Future

Natural Gas Engine Development

July 2003 — July 2005

T.C. Lekar and T.J. Martin
Deere & Company
Waterloo, Iowa

Subcontract Report
NREL/SR-540-40816
November 2006

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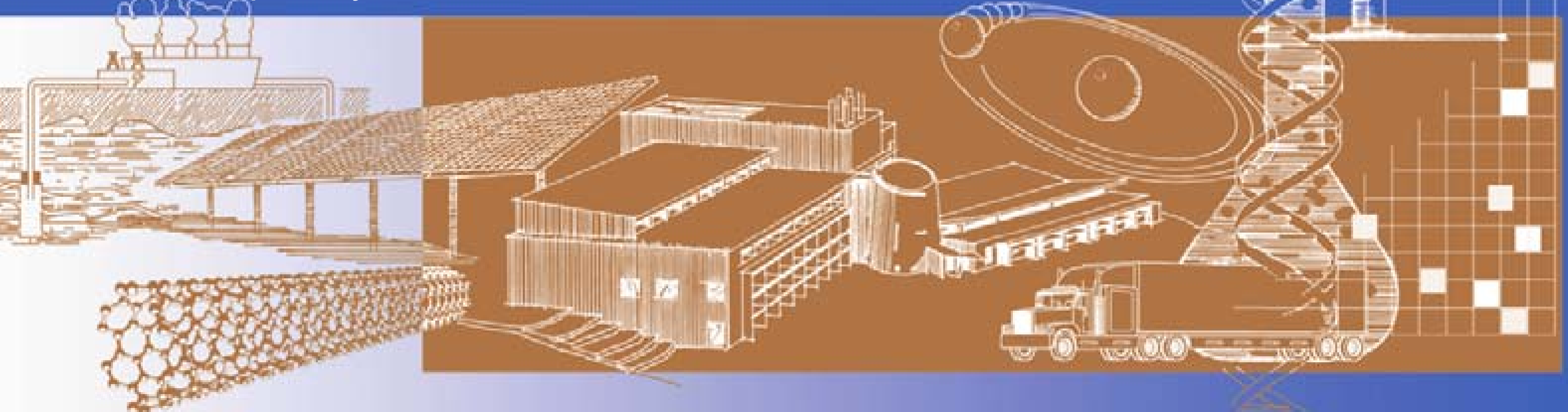

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NREL Technical Monitor: Aaron Williams
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“Natural Gas Engine Development”

Final Technical Report

(July 2003 - July 2005)

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Subcontract No ZCI-3-32027-04

31 October 2005

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CARB	California Air Resources Board
CNG	Compressed Natural Gas
DGE	Diesel Gallon Equivalent
DOE	U.S. Department of Energy
EOL	End of Line
EPA	Environmental Protection Agency
FTP	Federal Test Procedure (for emission compliance)
g/bhp-hr	grams per brake horsepower-hour
JDPS	John Deere Power Systems
L	Liter
mpg	miles per gallon
NMHC	Non-Methane Hydrocarbon
NREL	National Renewable Energy Lab
PM	Particulate Matter
scf	standard cubic feet
SwRI	Southwest Research Institute
THC	Total Hydrocarbons
UEGO	Universal Exhaust Gas Oxygen
UTP	Upstream Throttle Pressure
WMATA	Washington Metro Area Transit Authority

1.0 Executive Summary

The National Renewable Energy Laboratory (NREL) is the field manager for the U.S. Department of Energy's (DOE's) Alternate Fuels Utilization R&D Program (AFUP). NREL submitted a request for proposal number RCI-2-32027 for "Natural Gas Engine Development" in early 2002. The scope of this project was to develop natural gas engines that would be certifiable to emission levels below the 2004 federal standards (2.5 g/bhp-hr NOx + NMHC) and to be commercially viable. After submitting three draft proposals, John Deere personnel traveled to NREL in November 2002 to discuss the project in further detail. The result was NREL awarded a contract to John Deere to further develop the on-highway, heavy-duty 8.1L natural gas engine in July 2003.

The project outlined multiple technical objectives divided into three specific core tasks:
Task 3.1 Completion of Laboratory Engine Development
Task 3.2 On-Road Prototype Engine Development in Vehicles
Task 3.3 Perform FTP Testing / Commercialize Engine

The technical objectives of the program were met or exceeded in the execution of these tasks as follows:

1) The contract called for laboratory development of the engine, specifically ECU development of the proprietary John Deere FOCUS controller. The laboratory and field development and production release of the FOCUS controller was completed by John Deere prior to signing a contract with NREL. However, during the course of completing the NREL contract minor engine recalibration work was conducted. Additionally, Deere conducted work independently and in parallel to the NREL contract, to address field performance issues. The work resulted in the elimination of several recurring nuisance fault codes as well as one significant system control strategy fault that caused engine down time. All of the work conducted during this phase enhanced the commercial viability of the engine and readied it for field and DF testing.

2) The focus of the field test related to task 3.2 was in the nation's capital, Washington, D.C., within the Washington Metro Area Transit Authority fleet. A total of five New Flyer model CF-40 buses were repowered with John Deere 280 hp, 8.1L CNG engines (6081HFN04 model) as part of a marketing demonstration in December 2002 by Bell Power, a John Deere engine distributor. These vehicles went into service in March 2003 for field evaluation at WMATA. All five buses were used in day to day operation within the fleet and had satisfactory performance. One of the buses (bus 2460) was selected in April 2004 for the Task 3.2 field program. The six-month duration test monitored and recorded engine performance, maintenance, fuel consumption, and mileage.

Table 1-1. Summary of Bus 2460 Fuel Economy during Field Test

	Miles	Fuel	Average Fuel Economy (mpg, DGE)
Overall	14546	6200	2.35

(For details, see Table 3-8 and Appendix B)

3) The technical requirements of the proposal called for the achievement of emission levels below the 2004 federal standards of 2.5 g/bhp-hr for NOx + NMHC, and meeting the optional CARB low emission levels of 1.8 g/bhp-hr for NOx+NMHC. Due to independent engine development that Deere pursued prior to signing a contract with NREL, the 1.8 gram target was achieved prior to the start of the program. It was therefore decided to lower the target to 1.2 g/bhp-hr for NOx+NMHC, which was successfully achieved with new DF factors. The 1125 hour DF test was run from April to October 2004, and the test resulted in new, lower DF factors for the 8.1L, which are listed below:

Table 1-2. New DF factors achieved

	MHD DF	UB / HHD DF
NOx	1.00	1.00
PM	1.00	1.01
CO	2.28	4.13
NMHC	1.77	2.87

In addition to the new DF factors, the project also generated new certification results from testing that was completed in February 2005. The new certification results, along with the newly achieved DF factors, allowed all of the John Deere 6081HFN04 model engine ratings to be certified at the 1.2 gram NOx+NMHC target starting in October 2005. For the period of October through December 2005, a customer will be able to purchase engines at 1.2 gram, 1.5 gram, or 1.8 gram certification levels. Beginning in January 2006, Deere will only offer the 1.2 gram certification option, at which point, the Deere 8.1L will offer the lowest certification available in the CNG engine market, for the 250 and 280 hp ratings. Certification results are listed in Table 1-3.

Table 1-3. Summary of Certification Testing Results

Certification Testing Results for 250 hp

		NOx	PM	CO	NMHC
Composite:		0.874	0.003	0.026	0.059
DF factors applied:					
NOx+NMHC = (.874*1)+(.059*1.77)=0.978					0.978
PM = (.003*1.00) = .003					0.003
CO = (.026*2.28) = .059					0.059

Certification Testing Results for 280 hp

		NOx	PM	CO	NMHC
Composite:		1.033	0.004	0.120	0.046
DF factors applied:					
NOx+NMHC = (1.033*1)+(.046*2.87)=1.165					1.165
PM = (.004*1.01) = .004					0.004
CO = (.120*4.13) = .496					0.496

2.0 Introduction

NREL submitted a request for proposal number RCI-2-32027 for “Natural Gas Engine Development” in 2002. The scope of this project was to develop on highway natural gas engines that would certify to emission levels below the 2004 federal standards (2.5 g/bhp-hr NOx + NMHC) and to be commercially viable by meeting the optional CARB specification (1.8 g/bhp-hr NOx + NMHC).

2.1 Project Objective

As a result of the proposal by NREL, John Deere personnel traveled to visit NREL in Golden, Colorado in November 2002 to discuss the project in further detail. The result was NREL awarded a contract to John Deere to further develop the 8.1L on-highway, heavy-duty natural gas engine. At that time, the 8.1L engine was rated at 250 hp and 280 hp and was certified to the 2.5 g/bhp-hr standard.

The project outlined three specific core objectives:
Task 3.1 Completion of Laboratory Engine Development
Task 3.2 On-Road Prototype Engine Development in Vehicles
Task 3.3 Perform FTP Testing / Commercialize Engine

2.2 Project Participants

From the onset, there were several subcontractors identified by John Deere as partners in achieving the project objective. These subcontractors were to be involved in the following portions of the project:

Both Task 3.1 and Task 3.3 were to be completed with the assistance of Electronic Microsystems (EMS) of Boerne, Texas and Southwest Research Institute of San Antonio, Texas. EMS employees were to complete engine development on-site at the SwRI facility. This relationship was a natural one as the staff at EMS had been formerly employed by SWRI and had heavy involvement in past development of the John Deere CNG engine. This subcontractor structure remained intact throughout the entire project.

Task 3.2 was to be completed with the assistance of ECOTRANS of Los Angeles, California, which had specialized for many years in the retrofit and repower of heavy duty vehicles with both Liquefied and Compressed Natural Gas engines. Due to the bankruptcy of ECOTRANS, prior to the beginning of the project, changes were required. Task 3.2 was reconfigured to consist of one bus with a test duration of six months. The support of the test was supplied by Deere employees. This change in task responsibility from an outside contractor to John Deere is noteworthy as it translated into a slight delay of the signing of the contract with NREL in the summer of 2003.

In July 2003, Deere and NREL reached agreement and approved a Statement of Work for RFP No. RCI-2-32027.

2.3 Project Design

The project design was modified from the original agreement, not related to the project objectives, but rather with the order of completion and financial support related to the specific objectives. Initially, the project outlined a progression of Tasks 3.1 through 3.3 from engine design and development in the lab (Task 3.1), followed by field test of the new engine (Task 3.2), and concluding with additional laboratory work for emission work (Task 3.3). As previously mentioned, the delay in achieving contract agreement with NREL forced Deere to move ahead with engine development activities. These activities were required commercially to meet the CARB optional 1.8 gram standard and to provide field support for the engines already produced.

Briefly, in July 2003 production customers began experiencing a significant number of UEGO sensor failures, several repetitive instances of minor nuisance electronic error fault codes being displayed, and two front drive belt failures. Deere determined these issues had to be addressed before work on the NREL proposal could begin. An intense investigation was launched to determine root cause of each problem and to implement corrective action. This culminated in a new production software release in December 2003 that addressed the five separate control problems identified. Of these five problems, three were classified within the nuisance category, but the remaining two problems– new UEGO sensor faults and the Knock Module sensor faults – were considered significant.

In fact, both problems required additional control system development through spring of 2004. The knock sensor control strategy required additional development work to develop the ability to discriminate between actual combustion knock and structurally-transmitted vibration. The work resulted in additional software code changes designed to enable the sensor to ignore the spurious mechanical vibration signals and prevent transmission of false codes. These changes were validation tested on a 12-bus fleet in California with 100% success.

The UEGO Sensor control strategy required two additional changes in March 2004 to prevent false sensor failure codes. The two changes were validated on a three week test on the same 12-bus fleet in California with a 100% success rate during the test period. During this time period, the original software with the December 2004 control system changes ran on the WMATA buses without any UEGO-related fault codes.

The final FOCUS controller operating code release was delayed until the Controls Group completed new base code to correct UTP fault codes and subsequent engine power derates. The results from both laboratory and field test were combined into the final production version of the software that was released in April 2004.

In the completion of the engine problem resolution and software development just described, Deere absorbed the full cost of the work. The optional low NOx standard of 1.8 gram was maintained for the 280 hp ratings of the John Deere engine, with the 250 hp ratings maintaining an emission output of 1.5 gram.

Due to this problem resolution and software development, the overall project was delayed further as neither fleet evaluation (Task 3.2) nor laboratory Deterioration Factor (DF) testing (Task 3.3) could be started until the new control system software was available in April 2004. At that point, with new production software available, one of the five WMATA buses previously repowered with the Deere 6081HFN04 model was selected as the test bed for Task 3.2, field test. A. Hageman from JDPS traveled to Washington, D.C., April 13-16, 2004 to install the updated software. New oxidation catalysts with higher precious metal loading required to meet the 1.8 gram NOx+NMHC standard were also installed. (Note: The five engines when installed in December 2002 were originally certified to the 2.0 gram NOx+NMHC level).

Additionally, Deere participated in the NREL sponsored mobile chassis dynamometer emission testing of in-use engines conducted by the University of West Virginia. Engines tested included three 280hp Deere 8.1L Natural Gas engines configured to meet 1.8g/bhp-hr NOx + NMHC and three competitive diesel and natural gas engines. Bus 2460, which was one of the three buses used in chassis dynamometer tests, was identified for use in field test (Task 3.2). It began accumulating hours on April 19, 2004, marking the start of a six-month tracking period through November 18, 2004. During this period, maintenance and other information was collected and recorded on a monthly basis for this bus/engine combination (See section 3.2.2).

Work on Task 3.3 also began in April 2004. Approval had been previously secured from the EPA for the final version of the 1125-hour Deterioration Factor test sequence plan. The test engine RG6081HFN228450, was built September 18, 2003 at the John Deere Engine Works in Waterloo, IA. It was rated at 280 hp @ 2200 rpm and 900 lb-ft peak torque at 1500 rpm. The engine was shipped to the test facility at SwRI, prepared for testing, and installed in an engine dynamometer cell. The official hour accumulation began at the end of April when the new production release software became available. The engine DF test required approximately six months to accumulate the planned 1125 hours. Emission data was collected at 125 hours (baseline), 375 hours, 750 hours, and at 1125 hours. The data collected allowed curve fit lines to be plotted through the data points, to project emission output at the useful life limits. Deterioration factors were then calculated from the actual and projected emission data.

Application of the new DF factors showed the 280 hp rating certification could be reduced from its current 1.8 gram level to the 1.5 gram level. However, it was not possible with the existing engine calibration to achieve a 1.2 gram certification for either the 250 hp or 280 hp ratings. Given the incipient 2007 on-road regulation requiring the 1.2 gram certification, Deere petitioned NREL to use the remaining funding from Task 3.1, Laboratory Engine Development, to create a new engine calibration. (The work originally planned for Task 3.1 had been skipped because Deere had already achieved the original 1.8 gram program goal). The goal of the new calibration work was to enable the 8.1L engine, with the new DF factors, to meet the 1.2 gram certification level in all three (MHDD, HHDD, and Urban Bus) use categories. In addition to recalibration, Deere further proposed that a shortened and modified Task 3.2 field test be conducted.

The Task 3.1 laboratory engine work was completed in February 2005, with small calibration changes made to fueling and spark timing to obtain the needed emission reduction. In order to validate the software changes, Deere outlined a three-phase test and evaluation program at Deere-owned and external test sites. The Deere test site work included SAE test cycles on a test track; simulated school bus/ transit bus operating cycle of multiple start/ stop sequences with idle time; and an extended, over-the-road, high speed operation. All of these operations were successful with no fault codes generated. In addition, two external test sites (a school bus fleet and a transit bus fleet) were identified. Both sites were provided with experimental software for three existing John Deere 1.8 gram engines, which were then evaluated for several weeks. Again, no fault codes were generated with the new software version. The external testing of the 1.2 gram software continued through the end of July 2005, at which time the work associated with the project ceased.

The software changes used to achieve the reduction to 1.2 gram NOx + NMHC was released to the Deere production system in August 2005, concurrent with applications for the lower certification levels with both EPA and CARB. Production is scheduled for October 2005, after the emission certification approvals have been received.

3.0 Task Specifications

As noted earlier, JDPS contracted with several organizations through the project, primarily Electronic Microsystems (EMS) and Southwest Research Institute (SwRI). All of the engine development was completed at SwRI institute, under the direction of EMS. Deere personnel communicated on a daily basis with both subcontractors during testing and also worked with the subcontractors on-site and in the field, as required during lab and field test. There were several engines used during testing; engine serial number RG6081H228450 was evaluated on the 1125 hour DF test, and engine serial numbers RG6081H224392 and RG6081H256433 were used during development in the dynamometer test cell (software changes to achieve the 1.2 gram emission target). The five engines that were installed for field evaluation in WMATA transit buses are still in service at that site.

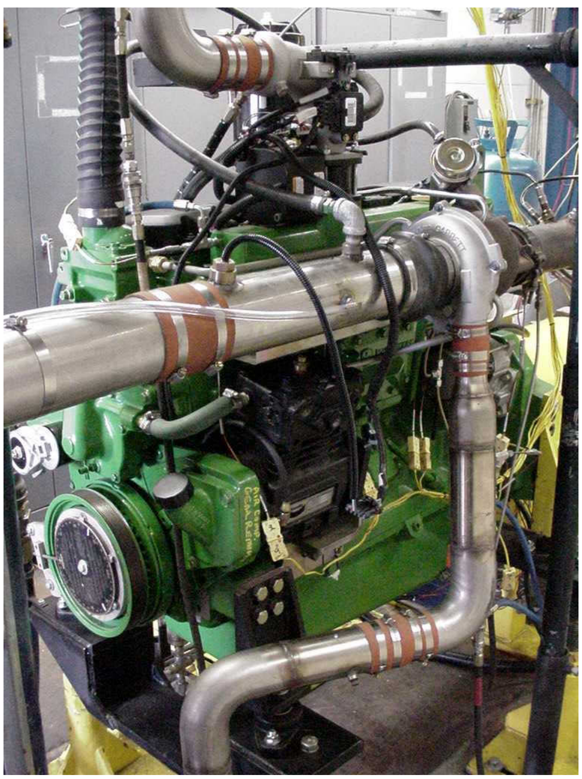
3.1 Engine Design, Performance and Emissions (Task 3.1)

The goal of the project was to attain HFN04 engine certification levels below the 2004 EPA standards of 2.5 g/bhp-hr (NOx+NMHC), and also at or below the optional CARB low-NOx emission standard of 1.8 g/bhp-hr (NOx+NMHC). Due to commercial imperatives, Deere obtained (and funded) certification to the 1.5 gram and 1.8 gram levels in Summer 2003. Consequently, very little Task 3.1 activity took place at the start of the project and the original funding was still available in late 2004, when Task 3.2 and Task 3.3 were completed. This led to the proposal by John Deere to complete additional laboratory engine development with the remaining funds to potentially allow certification at 1.2 g/bhp-hr (NOx+NMHC).

The Deere 8.1L CNG engine was installed in a transient-capable development test cell in the Emissions Research Department at SwRI in February 2005. A gaseous fuel blend that conforms to EPA and CARB specifications (composition shown in Table 3-1) was used for testing.

Table 3-1. Gas Composition for 280 hp Certification Testing

Component	***Formula***	***Mole Fraction (%)***
Methane	CH_4	90.42
Ethane	C_2H_6	4.04
Ethylene	C_2H_4	0.14
Propane	C_3H_8	2.05
Nitrogen	N_2	3.32



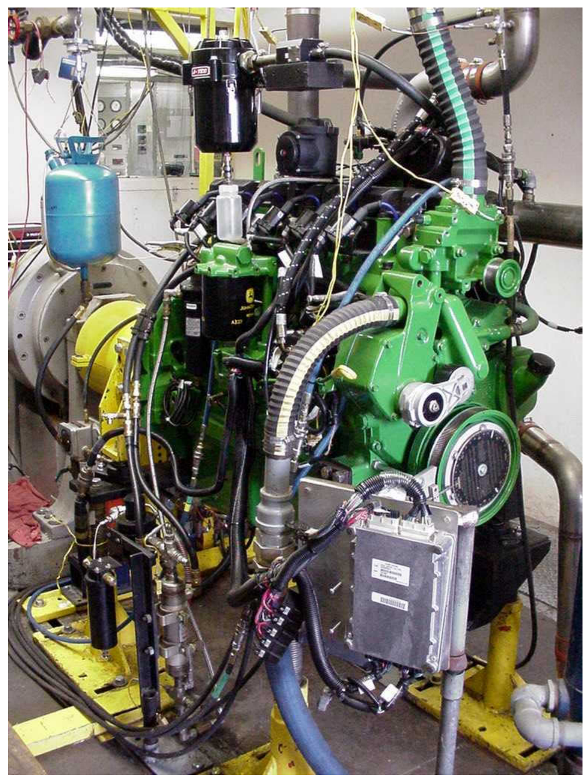


Photo 3-1 and 3-2: John Deere 8.1L deterioration factor engine installed in laboratory dynamometer at SwRI

The certification data was obtained in compliance with the rules for dynamometer testing of heavy duty compression-ignition engines, as outlined in 40 CFR part 86, subpart N. The compression-ignition engine test cycle was used since the base engine is a diesel engine.

3.1.1 Engine Specifications

(For detailed engine technical and design specifications, refer to Appendix A). Prior to testing, target emission levels for certification were determined. In particular, certification data was required for two power ratings; the 280 hp, 900 lb-ft rating and the 250 hp, 800 lb-ft ratings, which would be used to create emission families. For each rating, a target NOx value was calculated and used as a guide during the calibration process. This target NOx value was provided by John Deere and was based on a statistical analysis of emission results from prior tests on similar engines. The statistical analysis took into account the variability in emissions on an engine-to-engine basis. The emission targets also used newly-developed deterioration factors for the various combustion by-products. Since this engine is equipped with a catalyst, multiplicative deterioration factors are used. Table 1 summarizes the DF values used.

Table 3-2. Deterioration Factors

Rating	*DF Type*	*NO_x DF*	*NMHC DF*	*PM DF*	*CO DF*
280 hp	UB / HHD DF	1.00	2.87	1.01	4.13
250 hp	MHD DF	1.00	1.77	1.00	2.28

At the start of testing, the performance of the engine was verified by running a power validation test. During this test, the engine was operated at rated power with the inlet restriction, aftercooler pressure drop, and aftercooler outlet temperature set to target application values. The exhaust restriction was not set independently since it is controlled by the restriction of the catalyst. The target values for these settings are shown in Table 4.

Table 3-3. Target values for Power Validation test conditions

Parameter	*Value*
Intake restriction	2 kPa
Exhaust restriction	10 kPa
Aftercooler outlet temperature	52 °C
Aftercooler pressure drop	7 kPa

The engine power at 2200 rpm rated speed was found to be 280 hp (209 kW) so the engine was deemed to be operating correctly. A wide-open-throttle torque curve sweep was then conducted, and the measured data was subsequently used by the test cell control computer to generate speed and torque set points for the transient cycle. A trial emission cycle was run to verify the ability of the engine to properly track the test cycle. The engine ran well through the trial cycle with good performance verified by the high regression coefficients produced by the cycle matching statistics. In particular, the torque correlation coefficient was 0.956, which is similar to that obtained with typical diesel engines.

Since calibration modifications primarily affect NOx, the NOx output of the engine was used to control the overall NOx + NMHC level, and the catalyst was relied upon to eliminate as much NMHC as possible. The NOx measured during the trial test was higher than desired, so modifications were made to the engine calibration in an attempt to reduce NOx. These changes concentrated on the equivalence ratio and spark timing setpoint tables. In general, a slightly leaner equivalence ratio was adopted over a large part of the engine map, and spark timing retard was also used in various regions. Some slight changes were made to the volumetric efficiency table used to estimate open loop fueling, and the maximum fuel table was modified accordingly to maintain the proper torque curve after the other calibration changes were made.

The changes made were incremental based on test results and analysis of the test cell data acquisition logs and data logs of relevant parameters from the engine controller. This process resulted in an engine calibration that produced a repeatable NOx and THC level that was expected to meet the targets set by John Deere. The final calibration had changes that were considered to be relatively minor from a driveability standpoint, and this view was confirmed by the good cycle-tracking performance seen during the trial cycles. A copy of this modified calibration information was compiled in a format compatible with the FOCUS controller and supplied electronically to John Deere. The results shown in the next section are with this modified calibration.

The discussion in this section is all related to CNG fuel. Previous gas development experience has shown LNG calibrations can be directly derived from the engine CNG calibration. The only changes necessary are to customize the engine control software to provide the correct fuel delivery levels with the LNG fuel system hardware. Therefore, all development work in this project was conducted on CNG fuel, but is also applicable for the LNG models.

3.1.2 Torque and power curves

The certification data presented in this section are composite cold start-hot start results unless otherwise noted. Certification data was obtained after all calibration and engine changes had been made and trial cycles were run to verify the engine's performance and emissions. Upon satisfactory completion of these cycles, the engine was shut down in preparation for a cold start-hot start sequence.   The cold start was conducted on the following morning to insure the engine was fully cooled to ambient conditions, followed by two hot starts. The second hot start was used to confirm repeatability of the first hot start. A 20-minute soak period with the engine shut down occurred between tests. The composite emission numbers were calculated from the cold start cycle data and the first hot start cycle data, using a weighted sum of the results for the two cycles (1/7 for the cold data, and 6/7 for the first hot start data). In all cases, the data from the second hot start was found to repeat well with the first hot start data, thereby verifying the repeatability of the engine. The following sections contain certification data for the 280 hp – 900 lb-ft rating and the 250 hp – 800 lb-ft rating, respectively.

280 hp – 900 lb-ft CNG Rating

A power validation test and a torque map were conducted with certification fuel using the 280 hp – 900 lb-ft rating. The power validation test confirmed this power rating. The engine full load torque curve was then mapped, and the resulting torque curve is shown in Figure 3-1.

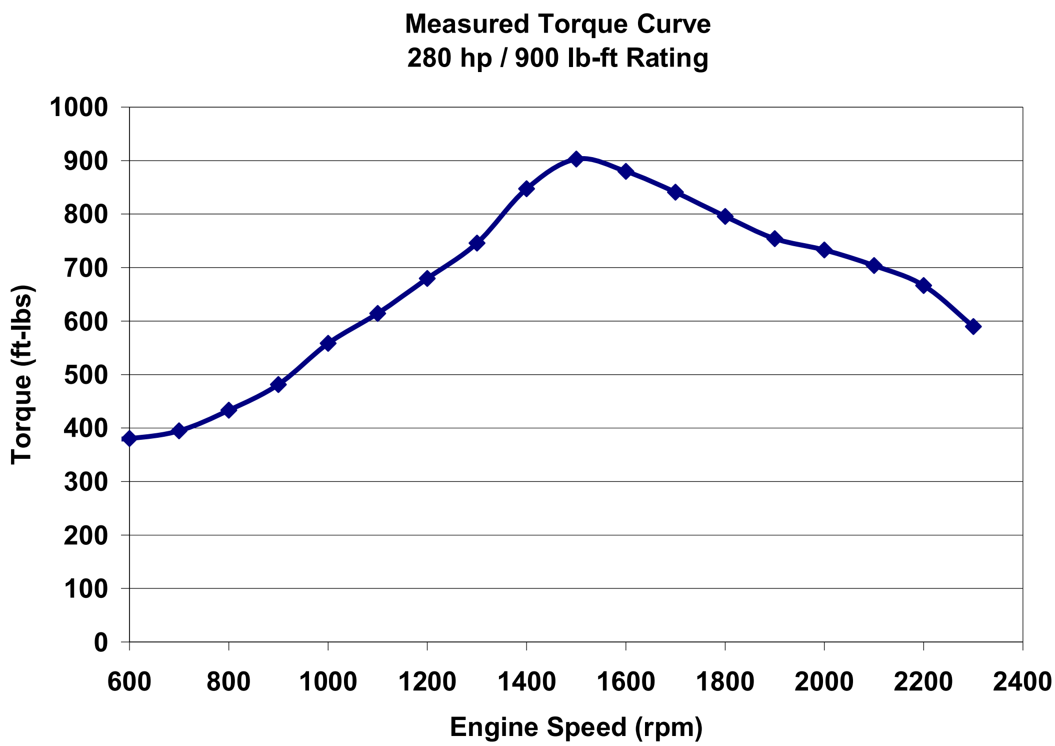


Figure 3-1. Torque curve for 280 hp-900 lb-ft rating

Following the torque map generation testing, a preparation cycle was run to verify that the engine NOx emissions were in the correct range. The engine ran well through the preparation cycle, and it was shut down in preparation for a cold start and two hot starts the next day. The subsequent cold start test was invalidated by a fuel delivery problem with the gas trailer. The two hot starts were run, however, to help provide additional engine performance repeatability data.

The subsequent cold start and two hot start tests were completed the next day. Emission results for these tests which constitute the certification data for the 280 hp - 900 lb-ft rating are shown in Figure 3-2. Note that all of the composite emission numbers are well below the standards. Figure 3-3 shows a comparison between the certification test results and the standard (1.2 gram NOx+NMHC, and .01 gram PM). Note that the PM values in Figure 3-3 are multiplied by 100 to maintain a consistent y-axis and clarity in this plot. Also note that the CO emissions were not been included in Figure 3-3. CO emissions, even with the DF applied, are less than 4 percent of the standard and are of no concern for meeting the certification. The baseline NO_x +

NMHC level of 1.079 is significantly lower than the CARB standard of 1.2 g/bhp-hr, but increases to 1.165 when the DF factor is applied. This value is still well below both the CARB standard. In the case of PM with a DF of 1.01, the deteriorated value is essentially the same as the baseline result of 0.004 gram, well below the 0.01 gram standard.

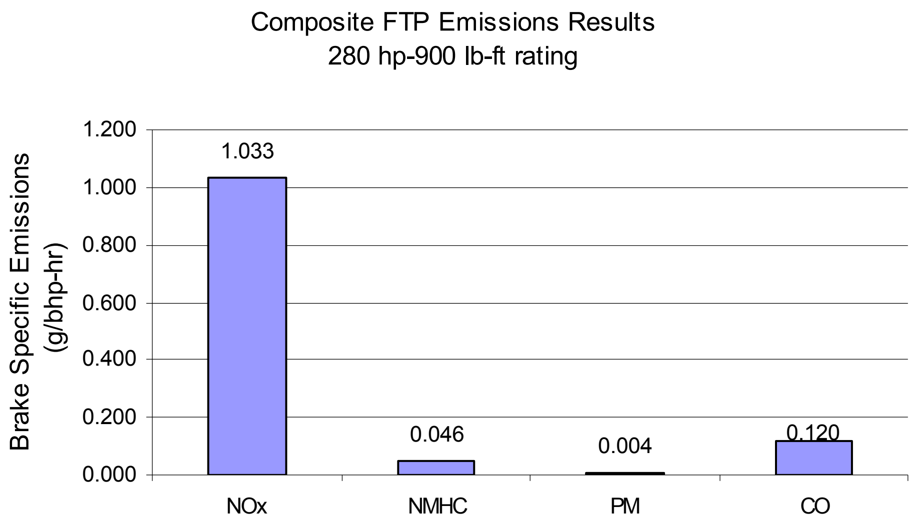
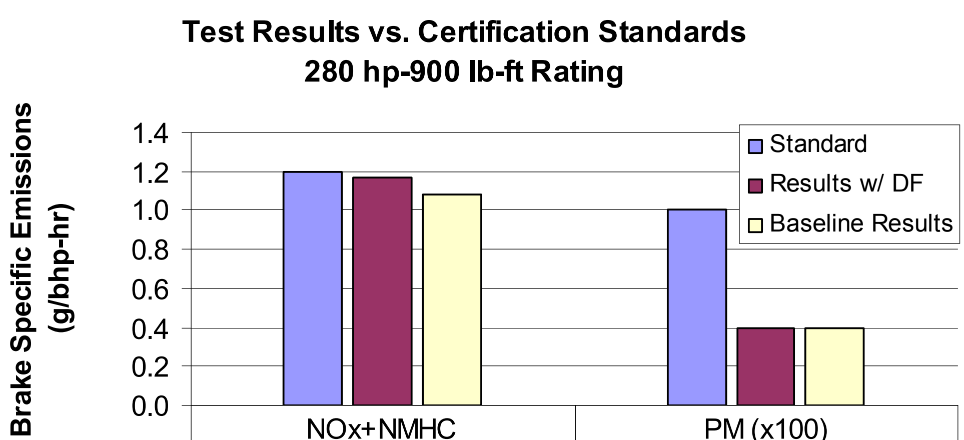


Figure 3-2. Summary of emission results for 280 hp rating



	NOx+NMHC	PM (x100)
Standard	1.200	1.000
Results w/ DF	1.165	0.400
Baseline Results	1.079	0.400

Figure 3-3. Comparison of emission results versus targets for 280 hp rating

250 hp – 800 lb-ft CNG Rating

Prior to certification testing of the 250 hp rating, additional fuel was required so a new fuel batch was blended. The composition of this fuel is shown in Table 3-4. This fuel was used for running the 250 hp power validation and torque map as well as all of the certification test runs.

Table 3-4. Gas Composition for 250 hp Certification Testing

Component	***Formula***	***Mole Fraction (%)***
Methane	CH_4	90.33
Ethane	C_2H_6	4.13
Ethylene	C_2H_4	0.13
Propane	C_3H_8	2.03
Nitrogen	N_2	3.37

To obtain data for the 250 hp certification, the ECU calibration tables were updated with the setting values for the 250 hp – 800 lb-ft rating. The engine's performance was verified by conducting a new power validation and torque map. The power validation data test confirmed the proper power and peak torque levels, and a torque map was generated. A plot of the torque curve generated at the 250 hp – 800 lb-ft rating is shown in Figure 3-4.

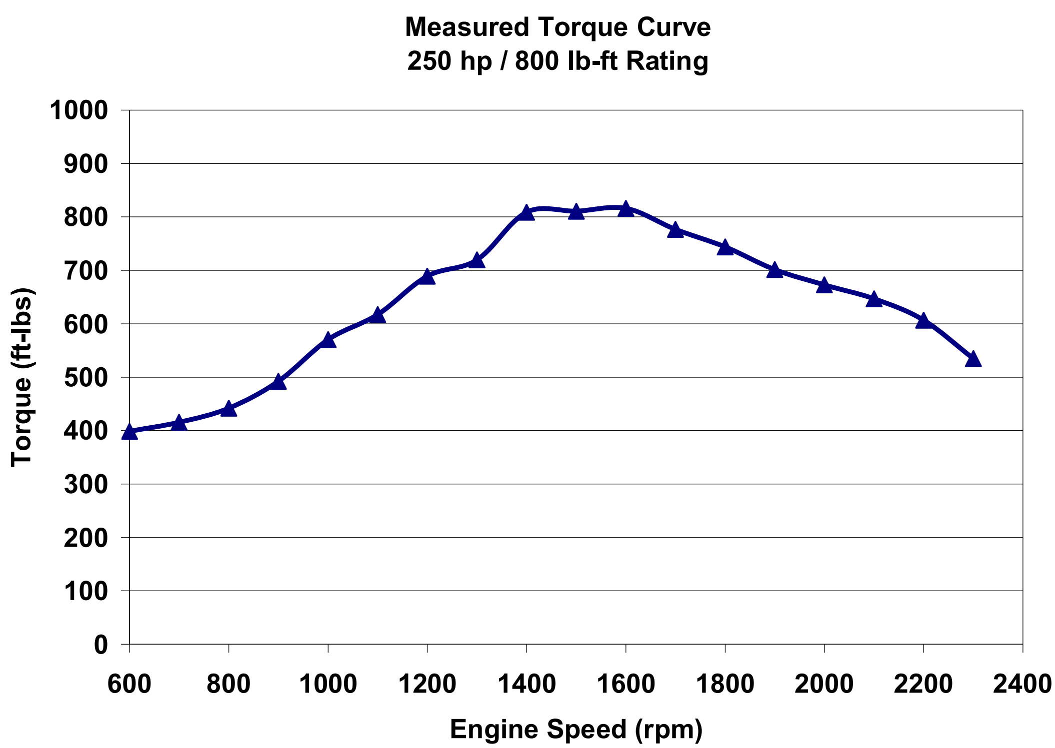


Figure 3-4. Torque curve for 250 hp – 800 lb-ft rating

The feed forward throttle map and test cell controller gains used with the 280 hp testing were reused for these tests due to the similarity of the ratings. The emission results for the 250 hp-800 lb-ft rating are shown in Figure 3-5. The results for these tests were quite good, with NOx emission significantly lower than those obtained with the 280 hp, 900 lb-ft rating. The other emissions were slightly lower but similar to the 280 hp rating. Figure 3-6 below illustrates that the baseline emissions of NOx+NMHC and also PM for the 250 hp rating were significantly below the CARB standards. (Again, please note that the PM values are shown multiplied by 100 to maintain consistent graph scaling).

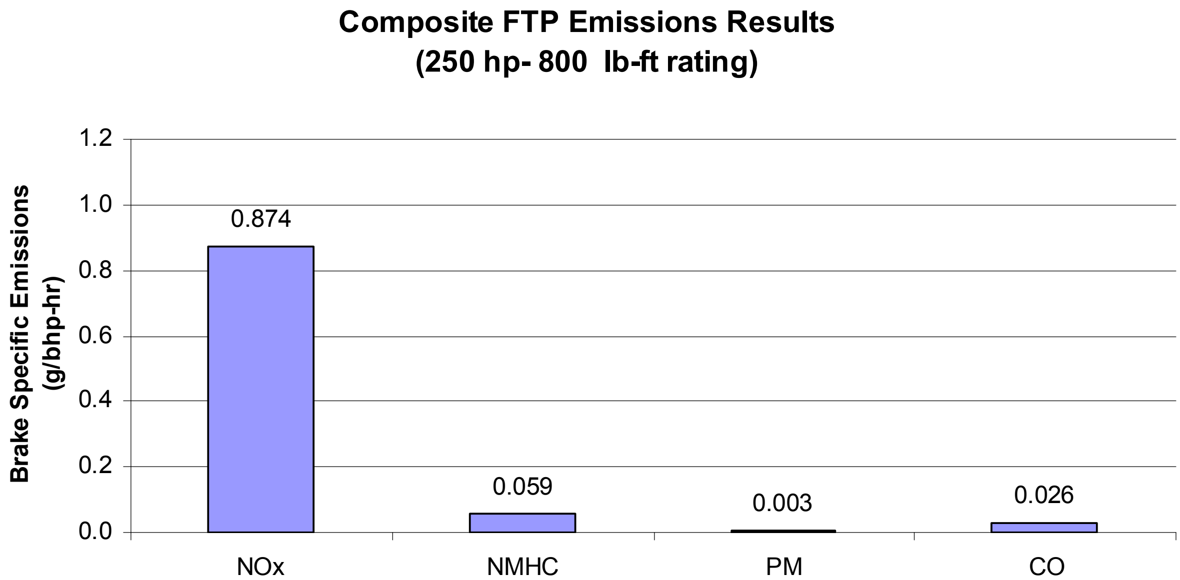
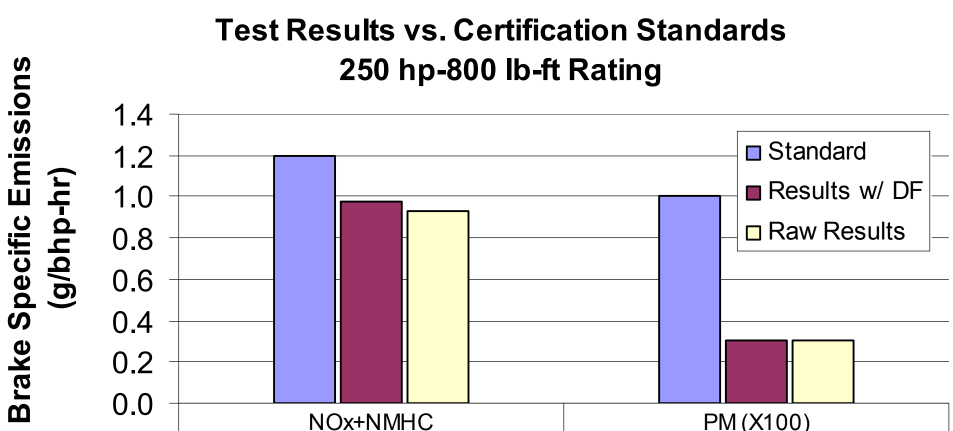


Figure 3-5. Summary of emission results for 250 hp rating



	NOx+NMHC	PM (X100)
Standard	1.200	1.000
Results w/ DF	0.978	0.300
Raw Results	0.933	0.300

Figure 3-6. Comparison of emission results versus targets for 250 hp rating

The maximum torque curve for each family (280 hp-900 lb-ft and 250 hp-800 lb-ft) were formulated during the emission certification process. It was now necessary to develop the alternative ratings in each family, namely the 275 hp-800 lb-ft and the 250 hp-735 lb-ft ratings. The calibration work that is listed next was related to the development of two additional ratings. The calibration process consisted of verifying the performance of the engine with the two existing calibrations and then modifying the appropriate fuel control table to produce a modified torque curve.

The additional calibration work was conducted on John Deere 8.1L natural gas engine, serial number RG6081H256433. The engine was mounted to an absorbing dynamometer in a steady-state test cell at SwRI. The test cell was equipped to measure speed, torque, and fuel flow, and the engine had a limited amount of pressure and temperature instrumentation installed on it. The engine was operated on a typical pipeline natural gas fuel and a conditioned air supply was used to maintain a nominal inlet air temperature of 25 °C with a nominal dewpoint temperature of 15 °C.

Prior to testing, the engine controller was reprogrammed with the newly-developed low NOx calibration for the 280 hp – 900 lb-ft rating. This particular calibration had been developed in the transient test cell during the certification process and represented the latest calibration for the maximum engine rating available. Test preparations consisted of warming the engine to operating temperature, and setting exhaust back pressure at rated power. The performance of the engine at the 280 hp – 900 lb-ft rating was verified by collecting full load data at 100 rpm intervals from 2200 rpm to 800 rpm. After successful completion of these test runs, the low NOx calibration for the 250 hp – 800 lb-ft rating was loaded, and the torque curve for this rating was also measured. The data obtained from these torque curves was found to be comparable to the torque curve data produced in the transient emissions test cell on the certification test engine, thereby verifying the performance of this engine.

To produce the new torque curves, the 280 hp – 900 lb-ft was used as the base calibration and changes were made to the fuel limiting table that governs the maximum fuel flow for a given speed. Iterative changes to the fueling amount were made in order to achieve torque levels similar to those of current engine ratings (torque curve data was supplied by John Deere to EMS for reference). When the match between the test data and the reference torque data was satisfactory, a full torque curve data set was collected. This procedure was conducted for the 275 hp – 800 lb-ft rating and repeated for the 250 hp – 735 lb-ft rating. The resulting torque curve data for all four engine ratings is plotted in Figure 3-7.

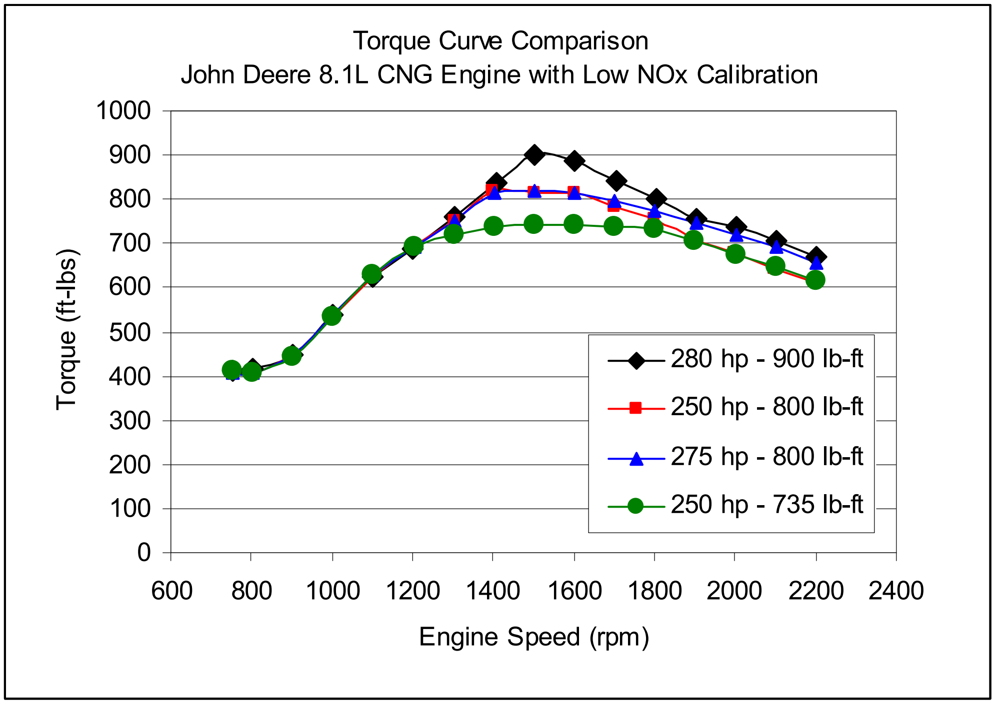


Figure 3-7. Torque Curve Comparison

The fuel table calibration changes were exported and used to prepare new parameter pages to communicate these changes to John Deere. The PRM files were then used by John Deere to build new production software.

In summary, transient emission testing confirmed the HFN04 engine platform can achieve the 1.2 g/bhp-hr combined NOx + NMHC standard at the 280 hp-900 lb-ft and 250 hp-800 lb-ft family ratings. Calibration changes and the use of the 69X60449 oxidation catalyst were required for the engine to achieve these ratings. In the 250 and 280 hp configurations, the engine NOx + NMHC emissions were below the CARB standards. PM emissions were significantly below the standard. Fuel economy for the 1.2 gram calibration, as measured during the FTP test cycle, showed a small (approximately 2%) loss compared to the previous 1.8 gram calibration.

Table 3-5. Certification Results

Certification Testing Results for 250 hp rating:

		NOx	PM	CO	NMHC
Cold Start:		0.824	0.005	0.070	0.061
Hot Start:		0.883	0.003	0.018	0.059
Hot Start:		0.909	0.004	0.007	0.045
Composite:		0.874	0.003	0.026	0.059
DF factors applied:					
NOx+NMHC = (.874*1)+(.059*1.77)=0.978					0.978
PM = (.003*1.00) = .003					0.003
CO = (.026*2.28) = .059					0.059

The required Cold/Hot/Hot FTP cycle sequences were run, which confirmed the calibration changes were successful in reducing the emission output. The results table indicates the baseline emission results from this testing, and also depicts the useful life output by applying the appropriate multiplicative DF factors to each of the baseline constituent results.

Certification Testing Results for 280 hp rating:

		NOx	PM	CO	NMHC
Cold Start:		0.946	0.004	0.158	0.060
Hot Start:		1.048	0.004	0.114	0.044
Hot Start:		1.031	0.004	0.099	0.044
Composite:		1.033	0.004	0.120	0.046
DF factors applied:					
NOx+NMHC = (1.033*1)+(.046*2.87)=1.165					1.165
PM = (.004*1.01) = .004					0.004
CO = (.120*4.13) = .496					0.496

As evident in the results table, the calibration changes for both power ratings were successful in meeting the targeted level of 1.2 g/bhp-hr for NOx+NMHC. The 250 hp rating output at useful life is .978 g/bhp-hr for NOx+NMHC and the 280 hp rating output at useful life is 1.165 g/bhp-hr for NOx+NMHC. The PM and CO results at both power ratings were well below the limits of .01 g/bhp-hr and 15.5 g/bhp-hr.

With confirmation that no further calibration changes were necessary, the engine was removed from the test lab. Both the certification engine and DF engine were returned to John Deere, for storage.

Table 3-6. Certification Test Hardware

Component Description	Part Number	Serial Number
Engine	n/a	RG6081H224392
ECU	RE520420	100201
UEGO Sensor	RE519691	1817
Humidity Sensor	RE508476	FR-A146
Catalyst Muffler	69X60449	SwRI 11-29-04

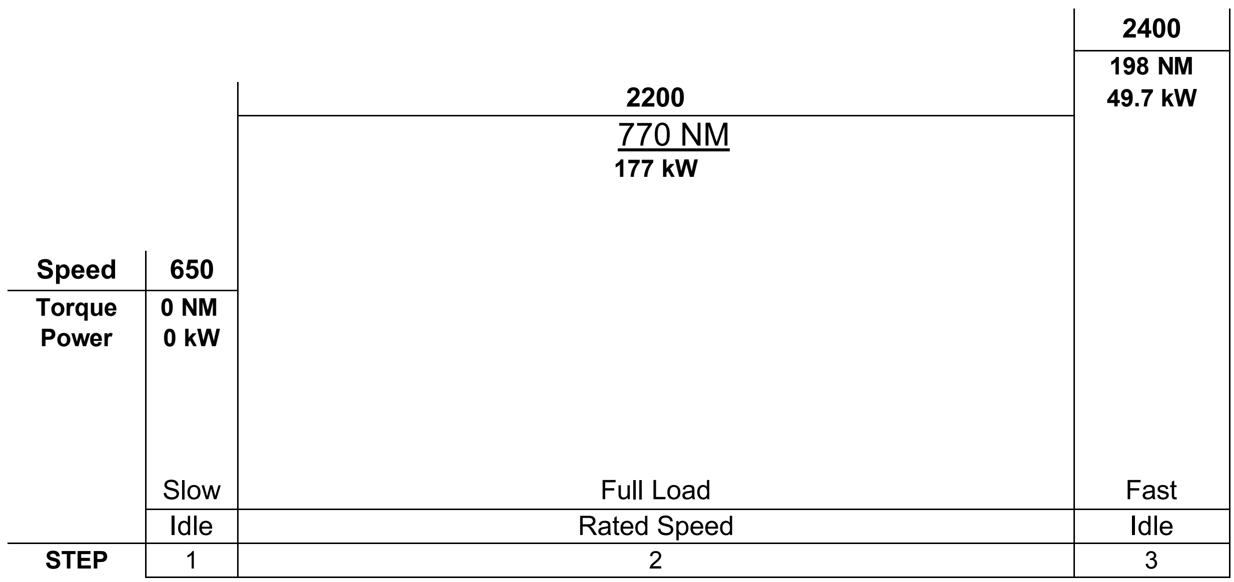
3.1.3 Vehicle/Fleet Description

See Appendix A for Fleet Vehicle Specification Form.

3.1.4 Duty Cycle Description

Actual vehicle testing has shown an average speed of 33 mph (100,000 miles in 3000 hours of driving) and an average load factor (actual fuel usage divided by fuel usage at rated power) of 28%. The cycle set up for the DF test has a load factor of 84% - a factor of 3.0 times the typical customer load factor of 28%.

Table 3-7. John Deere 6081 NG Engine Deterioration Factor Test Cycle



Step	Duration (minutes)	Condition
1	0.5	NO LOAD SLOW IDLE – 650 RPM
2	29	85% LOAD RATED SPEED - 2200 RPM
3	0.5	50% LOAD OVERSPEED - 2400 RPM

*** Note: Small adjustments in the cycle may be necessary to achieve the target load factor of 84%**

3.2 On-Road Engine Development (Task 3.2)

As previously mentioned, the field test was completed at the nation's capital, Washington, D.C. within a large transit fleet, Washington Metro Area Transit Authority (WMATA). A total of five New Flyer buses were repowered with John Deere 280 hp, 8.1L CNG engines (6081HFN04 model) in December 2002 by Bell Power, a John Deere engine distributor. These vehicles went into service in March 2003 for field evaluation at WMATA. All five buses were used in day to day operation within the fleet, and had satisfactory performance.

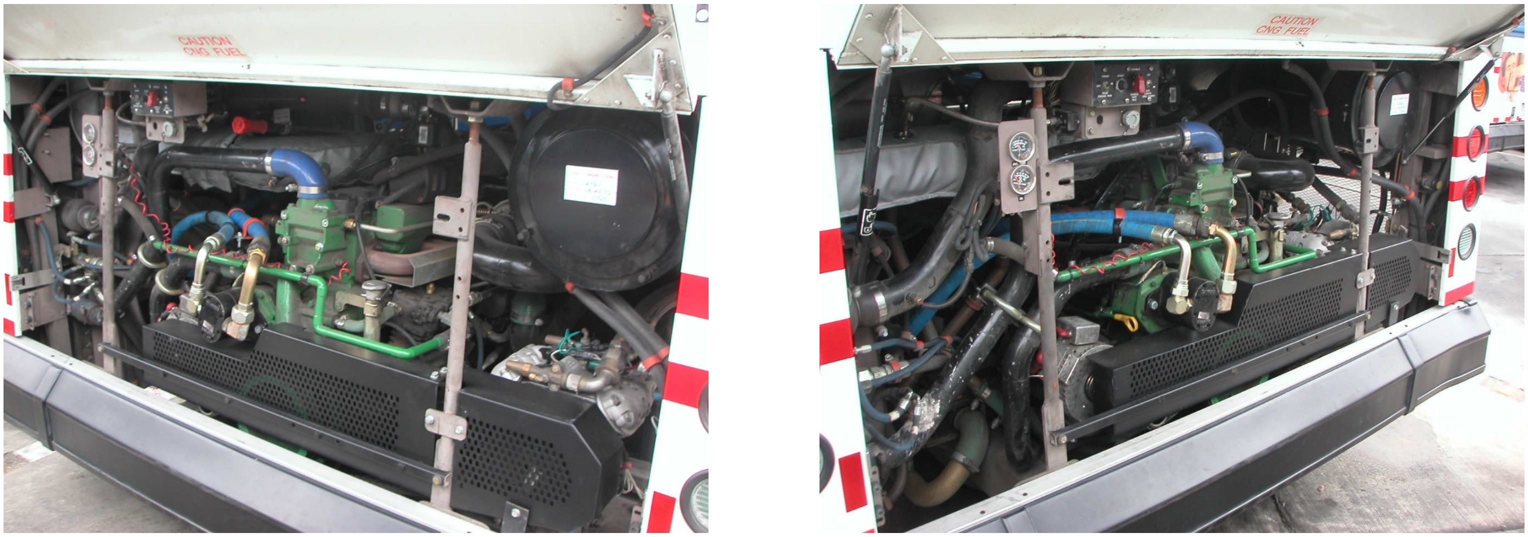


Photo 3-3 and 3-4: Views of John Deere 8.1 L engine installed in New Flyer Bus

Photo 3-5: View of WMATA buses

3.2.1 Description of Development Work

The only development work associated with task 3.2 was loading the 1.8 gram software, changing the catalyst, and then a relatively short test drive before putting the bus back into service.

3.2.2 Fuel Economy and mileage accumulation

One of the five buses (bus 2460) was selected for evaluation over a six month period, spanning from April 19 to October 18, 2004, during which engine performance was monitored and fuel consumption and mileage were recorded. The bus operated successfully in normal daily service at WMATA over the six month period, accumulating 14,546 miles without any engine related problems. A summary of the monthly test reports is shown below. Details of the daily test log are listed in Appendix B.

Table 3-8. Field Test Data

Summary of data

	Miles	Fuel	Average Monthly Fuel Economy(mpg, DGE)
April	1212	422	2.87
May	3758	1554	2.42
June	2328	1007	2.31
July	2137	955	2.24
August	2136	865	2.47
September	1302	712	1.83
October	1673	685	2.44
Overall	14546	6200	2.35

3.2.3 Future Plans for the engine model

Given that the project timeline more than doubled for the various reasons already discussed, most of the originally conceived “future plans” have already been accomplished. The plans for commercialization of the 6081HFN04 engine at reduced emissions level have already occurred with the release of the 1.5 gram /1.8 gram software which was completed in September 2003. Engines have been successfully installed into multiple applications since that time including school buses, industrial trucks, and transit buses with multiple OEM customers. The initial introduction of the John Deere engine into the New Flyer chassis (repower) during the field demonstration led to a production build of New Flyer buses powered by John Deere CNG engines in Spring 2005. Additional builds with New Flyer are scheduled for Fall 2005, and a large build is scheduled with Orion for 100 WMATA buses during late 2005 into 2006. Depending on contract details and engine order dates, the 1.2 gram software could be programmed in engines for either of the two customers just mentioned. Beginning in 2006, all John Deere CNG engines will be built with the 1.2 gram software, available in either CNG or LNG versions.

3.3 FTP Results (Task 3.3)

The John Deere 6081HFN04 engine model is offered with 3 power levels; 250 Hp, 275 Hp, and 280 Hp. The engine is certified at 250 Hp for the medium-heavy-duty class with a useful life of 185,000 miles, at 275 and 280 Hp for the heavy-heavy-duty class with a useful life of 435,000 miles, and at 250, 275, and 280 Hp for the urban bus duty class with a useful life of 435,000 miles. The DF test was completed at the 280 horsepower rating, and it was intended to achieve lower DF factors for all three engine classifications.

A DF test, consisting of overall hour accumulation of 1125 hours was completed, with emission testing at 125 hours, 375 hours, 750 hours, and 1125 hours. The 1125 hours of dynamometer testing on the DF test cycle corresponds to 3375 hours of actual operation which equates to 111,375 miles in a vehicle application. The data from the DF test is then extrapolated, as necessary, to obtain additive and multiplicative DF's at 185,000 and 435,000 miles. The DF test was run from April to October 2004.

DF factors were calculated by plotting hot test data for each of the exhaust constituents of NOx, PM, CO, and NMHC. Initially (at 125 and 250 hours) six sets of data for each of the constituents were plotted. However, due to variability (instrumentation repeatability) in measuring the very low levels of PM, starting at 750 hours, the test plan was modified with CARB approval to take 18 data points at 750 and 1125 hours. The 18 data points were then reduced to six by averaging the six sets of three data points.

Once data points have been plotted for the emission results from 125, 375, 750, and 1125 hours, a curve fit line was established through the data points. A data outlier test was conducted to ensure that none of the data points were excessively deviant of the overall plot pattern. Using the curve fit line's equation, the engine emission results were projected out to the appropriate useful lives for the respective engine classifications (again 185,000 miles for MHD classification, and 435,000 miles for HHD and UB classifications). The results of the DF test were new lower, DF factors for each of the exhaust constituents; the newly obtained DF factors are listed below:

Table 3-9. DF factors

	Slope	Offset	MHD DF	UB / HHD DF
NOx	-0.0003	1.8351	1.00	1.00
PM	0.0000	0.0090	1.00	1.01
CO	0.0000	0.0097	2.28	4.13
NMHC	0.0000	0.0409	1.77	2.87

3.3.1 Commercial Engine Ratings

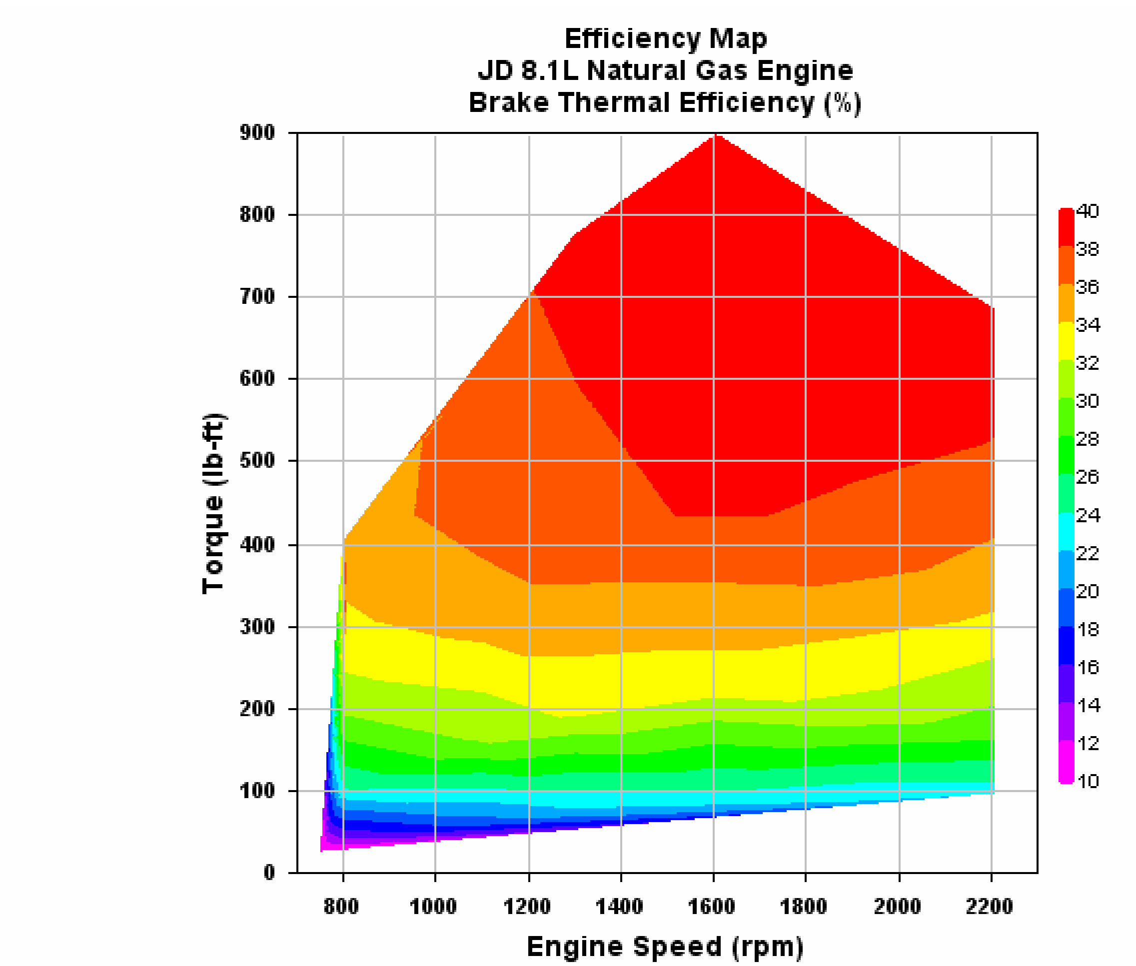
The 6081HFN04 model engine has three power ratings of 250 hp, 275 hp, and 280 hp; there are also three different peak torque levels of 735 lb-ft, 800 lb-ft, and 900 lb-ft. The specific ratings and their appropriate engine classifications are listed in Table 3-10:

Table 3-10. 6081HFN04 Engine Ratings

Rated Power / Peak Torque	***Specifics***
250 hp - 735 lb-ft	250 hp 735 lb-ft, MHD rating and UB rating
250 hp – 800 lb-ft	250 hp 800 lb-ft, MHD rating
275 hp – 800 lb-ft	275 hp 800 lb-ft, HHD rating
280 hp – 900 lb-ft	280 hp 900 lb-ft, HHD rating and UB

3.3.2 Commercial Engine Efficiency Map

Figure 3-8. John Deere 8.1 L Engine Efficiency Map



3.3.3 Narrative Description of Test Results

April 2004

The DF test officially started April 29, when the engine setup was complete and hour accumulation began. The engine, serial number 6081HFN228450, was programmed at the 280 hp / 900 ft-lb rating. During the month of April, the engine accumulated 20 hours.

May 2004

The DF test accumulated hours during May in preparation for the baseline emission test sequence at 125 hours. During the beak-in test, the steady-state engine emissions were checked every 10 hours to document the emissions break-in characteristics of the engine and the oxidation catalyst. On May 10 at 70 engine hours, the engine suffered a spark plug failure in cylinder No. 6. Permission was received from EPA/CARB to replace the spark plug and the test continued. On May 24, the engine again developed a mis-fire in No. 6 cylinder. Again, the plug was replaced. However, as part of the continuing investigation, it was found that damage to the No. 6 spark plug wire was actually root cause of the failure, allowing arcing that caused the apparent mis-firing of the spark plug. (Detailed investigation showed that when the spark plugs were installed at SwRI prior to the start of test, the di-electric grease specified for boot assembly was omitted, leading to the spark plug wire boot being damaged.) The engine reached the 125 hour break-in point on May 25 and was removed from the development cell in preparation for baseline emission tests.

June 2004

Due to SwRI's schedule at the time being very busy, the actual baseline test wasn't run until June 11. The DF test engine ran the 125 hour break-in point baseline test from June 11 – 15 and was then put back on the life test portion of the test. By June 30, the engine accumulated a total of 283 hours with no problems.

July 2004

The DF test engine continued to accumulate hours at SwRI during July without problems. The engine began the month at 283 hours and ended the month at 557 hours, for a monthly accumulation of 274 hours. The engine was ready for the 350 hour emission test on July 13, but again due to workloads at SwRI, the test wasn't started until July 19. The engine was put back on the DF test starting July 23. At the 350 hour point, the engine emissions (NOx, NMHC, PM, and CO) had remained the same as at the 125 hour baseline test or actually slightly declined.

August 2004

The DF test engine continued to accumulate hours at SwRI during the initial portion of August without problems. The engine began the month at 557 hours and reached the next emissions checkpoint of 750 hours on August 9. Again, due to workloads at SwRI, the emission test wasn't conducted until August 17. At the 750-hour point, the engine emissions (NOx, NMHC, and CO) had remained roughly the same as at the 375 hour point or actually slightly declined. A very slight trend of increased Particulate matter

(PM) caused concern, as it would calculate a DF factor >1. Due to this concern an engine analysis and inspection program of the DF engine was executed. It included:

- Visual inspection of valve guide seals for damage
- Visual inspection (borescope) of the power cylinders, including the valve face and tulip areas for deposits
- Visual inspection of spark plugs for deposits
- 12 additional hot FTP tests, 6 per day, were run. The tests were conducted on a Friday and Tuesday purposely to provide a 72 hour separation between the test events to allow check for test stability, or "drift".
- Elemental analysis of the PM matter collected during the 12 additional FTP tests.

The apparent cause of the increase in the PM measurements between 375 hours and 750 hours is in test stability or drift. This is proven by the results of the three sets of FTP's conducted at 750 hours.

	PM Average
Test 1	.011 gram
Test 2	.0083 gram
Test 3	.0085 gram

This shows the average =.0093 gram under the same test conditions on different days, so the PM test stability is not zero. In fact, there is "drift" in the results and all of the tests are equally valid. Considerable effort was expended to identify the cause of the PM increase, including engine mechanical inspection, emission measurement equipment calibration and validation by SwRI, and engine performance validation. There were no conditions or changes found that could have caused the increase observed.

Based on previous experience by both Deere and SwRI, the leading suspect became stability (or drift) of the PM measurements during the hot FTP tests. This means that minor changes in test conditions, <u>while remaining within specification</u>, can cause changes in the amount of PM measured. Because the CARB 0.01gram PM spec the engine is attempting to meet is so low, even very minor measurement variation can cause a significant upturn in the slope of the regression line of the measurements. This in turn can, when extrapolated out to the 435,000 mile HHDD/Urban Bus useful life point, cause the engine to not meet the 0.01gram spec.

This information was submitted to and discussed with CARB with a request to continue the DF test and use the grand average of all the FTP PM results for use in calculating the DF factor; the request was approved.

September 2004

The PM measurement problem investigation started in August and continued through September.

October 2004

CARB, after a considerable length of time, agreed on October 8 with the Deere request to run two additional FTP tests at 750 and 1125 hours and average the results for PM. The DF engine was put back into the dyno to resume hour accumulation on October 11. Upon re-start, the engine wasn't able to run the durability cycle without a noticeable misfire; it was necessary to change out spark plugs and wires due to damage incurred on the ignition components at the last transient emission test point. The engine also had ignition components serviced on October 20 (#6 spark plug and wire) and October 27 (#2 spark plug and wire). In both cases, misfire was noticed by lack of engine power. Subsequent diagnostic work identified a specific cylinder miss in both cases, and service work was completed. The engine reached 1125 hours on October 31 and was shutdown and required maintenance was completed. The ignition component service was approved by CARB.

November 2004

The engine underwent the 1125 hour emission testing from November 15-17. As was discussed previously, the extra data collected included 18 data points from hot FTP cycles, and then the 18 points were averaged in sets of three down to 6 data points.

Following completion of the last emission data collection on the DF, the 1125 hour data was plotted along with data collected at 125, 375, and 750 hours and a curve fit line was established through the data points. The final curve fit lines were then evaluated to obtain the slope of each line. In turn the calculations were carried out to project emission levels at the useful life for both Medium-Heavy Duty (185,000 miles) and Heavy-Heavy Duty (435,000) ratings.

The DF factors calculated were an improvement to the previous DF factors, with the improved software control strategy utilized on the HFN04 model engine and improved engine oil control being the main contributors.

December 2004

Initial calculations were made with the new DF factors, and the certification results from Summer 2003 (1.5 / 1.8 software) to determine if the new DF factors would allow certification down to 1.2 g/ bhp-hr for NOx +NMHC. These calculations showed that although emission levels with the new DF factors were very close to the 1.2 gram target, they were not under the target. It was therefore planned to go back into the engine development dynamometer to make base engine calibration adjustments.

January 2005

No engine lab development was completed due to lack of test cell availability at SwRI during this month. Emission targets to achieve the 1.2 gram target, with satisfactory margin were set and provided to EMS in preparation for upcoming engine calibration work.

February 2005

The development engine, RG6081H224392, was installed in the test cell, and engine testing was completed. New calibrations (slight changes in spark timing and fueling) were established.

March 2005

The calibration changes were evaluated in the lab for each of the four power ratings for the 6081HFN04 model engine. This lab work confirmed that power output was unaffected by changes, and yielded power output at the specified levels.

The calibration changes were then compiled into experimental software. This software was then loaded into a test vehicle on-site at the John Deere PEC and the test vehicle was evaluated on multiple cycles. These cycles included short internal test track and external routes around the PEC site, extended stop-start sequences, and a long distance route. The experimental software performance was satisfactory, so the experimental software was made available for external evaluation.

April 2005

Experimental software was provided to the first test site, Poway Unified School district in Poway, California. This test site is a school district with multiple CNG-powered buses. Six engines were identified to be programmed with the experimental 1.2 gram software. These engines were programmed on April 25-26. The engines performed well with the software, and no fault codes were generated due to the software.

May 2005

A trip was taken from May 23-26 to the second test site, Placer County Transit in Auburn, California. This test site is a transit bus operation with multiple CNG-powered buses. Three engines were programmed on May 24 and then monitored as the buses were placed into route operation. The engines performed well with the software, and no fault codes were generated due to the software.

June 2005

As mentioned in previously, the first field evaluation ran from April to June 2005 in a school bus fleet at Poway Unified School district fleet (Poway, CA). The second field evaluation ran from May to June 2005 at Placer County Transit in Auburn, CA. Both field tests yielded good performance with the 1.2 gram software in place; there were no engine problems associated with the new 1.2 gram software.

July 2005

John Deere Engine Engineering prepared the internal documentation to release the 1.2 gram software for production; the new release will offer a 1.2 gram performance option along with the current 1.5/1.8 gram options through the end of 2005. At the end of the year, the 1.5/1.8 gram performance options will be cancelled, with only the 1.2 gram performance option available starting in January 2006. Given the release internal option code processing time, it is projected to have the 1.2 gram option available on production engines by October 2005. Concurrently emission certification applications to 1.2 gram were submitted to both EPA and CARB (July 14). Past experience had shown that 6-8 weeks are required to receive certificates back, which will meet the October start of production target.

4.0 Conclusion

- The Deere 8.1L - HFN04 model - successfully completed a 1125 hour deterioration factor test as part of Task 3.3, achieving critical reductions, especially in the NOx level.
- The engine performance development work in Task 3.1 was successful in providing new calibrations for both the 250 hp and 280 hp power levels.
- The new, lower DF factors combined with the new calibrations allow the 8.1L - HFN04 model to be certified to the CARB optional 1.2 gram NOx + NMHC standard for the MHDD, HHDD, and Urban Bus classes.
- The 8.1L - HFN04 model successfully completed a six month field test in a New Flyer transit bus in Washington, D.C. (WMATA) as part of the project. The bus performed without fault during the six month test, covering 14,500 miles at an average fuel economy of 2.35 mpg (diesel equivalent). Additionally, the HFN04 model when compared to three other competitor diesel and natural gas engines using the West Virginia University mobile chassis dynamometer, obtained higher fuel economy ratings. (Testing was conducted under NREL contract in March 2004; pending NREL document "Heavy Duty Vehicle Emission Testing").
- A separate, abbreviated three-phase drivability field test was conducted to evaluate the final 1.2 gram calibration before production release. Phase 1, using captive Deere vehicles, was conducted in Waterloo, IA. Phases 2 and 3 both took place in California, using public school bus and transit bus fleets. No drivability faults were found in any of the Phases, demonstrating the commercial viability of the new calibrations.
- Due to earlier Deere development work, little work was required to the ECU and/or the control system strategy overall. The only real changes required to achieve the 1.2 gram calibrations were to the EOL files regarding spark timing, fuel quantities, etc.
- The 1.2 gram calibration will be available for commercial application as soon as the certification documents are received from EPA and CARB. This is anticipated to be in Oct 2005.

5.0 Appendix

Appendix A

FLEET VEHICLE SPECIFICATIONS FORM

Revised 1/12/96

FLEET VEHICLE SPECIFICATIONS

HDV_VEH Table

Vehicle ID Number (VIN)	Vehicle identification number	5FYC2LP172U023665
Fleet_Veh_ID	Vehicle identification number used by fleet	2460
Vehicle_Make	Name of vehicle manufacturer	New Flyer
Vehicle_Model	Truck model number	C40LF
Vehicle_Year	Year vehicle was manufactured	2002
Service_Date	Date vehicle was put into service by fleet	10/25/02 (repower complete date)
Start_Mileage	Mileage on vehicle at the start of the fleet demonstration	1630 miles (when repower with John Deere engine was complete)
Activity_Code	Type of activity vehicle is used for (Code 1 from VMRSH)	NA; doesn't refer to transit buses
Equipment_Category_Code	Type of optional equipment installed on vehicle	Commercial Bus Body
Body_Mfgr_Code	Name of body manufacturer	New Flyer
Body_Descr_Code	Type of body attached to cab (Code 48 from VMRSH)	Code 161 (Bus, Transit)
Engine_Serial	Serial number of the engine	RG6081H209814

HDV_ENGINE Table

OEM_Retrofit	Is the engine OEM or a retrofit?	Retrofit
Eng_Mfgr_Code	Name of engine manufacturer	John Deere
Eng_Model	Engine model number	RG6081HFN04

Eng_Config_Code	Engine Configuration Code (Code 35 from VMRSH)	Code 12 (inline 6 cylinder)
Eng_Cu_In	Engine size in cubic inches	496
Num_Cylinders	Number of cylinders	6
Eng_Year	Year engine was manufactured	2002
Cycle	Is the engine 2 cycle or 4 cycle ?	4
Compr_Ratio	Compression ratio	11:1
Ignition_Aid_Type	Type of ignition aids used	None
EPA Certified (Y/N)	Is the engine configuration EPA certified	Yes
Maximum bHp	Rated maximum brake horsepower of engine	280 hp
Rpm of Max bHp	Rpm at rated maximum brake horsepower	2200 rpm
Maximum Torque (ft-lbs)	Rated maximum torque of engine	900 lb-ft
Rpm of Max Torque	Rpm at rated maximum torque	1500 rpm
Oil Capacity (qts)	Oil capacity in quarts	24 (engine and filter)
Blower? (Y/N)	Does the engine have a blower?	No
Turbocharger? (Y/N)	Does the engine have a turbocharger?	Yes

HDV_FUEL_SYSTEMS Table

Fuel_ Type_Code	What type of fuel is engine designed for?	Natural Gas
Diesel Additives	Type of additives used in diesel fuel	NA
Alt Fuel Additives	Type of additives used in alternative fuel	NA
Mech_Elec	For liquid fuel engines, are the injectors mechanically or electronically controlled?	Electronically
Injector Mfr	Name of liquid fuel injector manufacturer	Bosch
Inj Model	Liquid fuel injector model number	280 K40 485
Num of Injectors	Number of liquid fuel injectors	Eight
Liq-Fuel Filter Mfr	Name of liquid fuel filter manufacturer	Racor
Liq-Fuel Filter Model	Liquid fuel filter model number	FFC-110L-06
Fuel_Induction	For gaseous fuel engines, is it injection or fumigation?	Injection
Air Intake Throttle (Y/N)	Does the engine use an air intake throttle	Yes
Gas Equip (OEM/Retrofit)	Is the gas fuel system OEM or retrofit?	OEM

Number of Alt Fuel Tanks	Number of alternative fuel tanks	Seven
Number of Diesel Tanks	Number of diesel tanks	NA
AF Max Work Press (psi)	Alternative fuel maximum working pressure in psi	3600 psi
Amount of Useable AF	Total useful alternative fuel in tank(s)	3023
Alt Fuel Units	Units used for alternative fuel tank(s) useful volume	Standard cubic feet (scf)
Amount of Useable Diesel	Total useful diesel fuel in tank(s)	NA
Diesel Fuel Units	Units used for diesel fuel tank(s) useful volume	NA
AF Tank Manufacturer	Name of alternative fuel tank(s) manufacturer	General Dynamics (Lincoln Composites)
Diesel Tank Manufacturer	Name of diesel fuel tank(s) manufacturer	NA
Alt Fuel Tank Model	Alternative fuel tank(s) model number	Tuffshell
Diesel Tank Model	Diesel fuel tank(s) model number	NA
Alt Fuel Empty Tank Wt	Alternative fuel tank(s) empty weight	235
Alt Fuel Tank Wt Units	Units used for alternative fuel tank(s) empty weight	pounds
Diesel Empty Tank Wt	Diesel fuel tank(s) empty weight	NA
Diesel Tank Wt Units	Units used for diesel fuel tank(s) empty weight	NA

HDV_TRANS Table

Transmission Mfr	Name of transmission manufacturer	Allison
Trans Model Number	Transmission model number	B400R
Trans Year of Mfr	Transmission year of manufacture	2002
Trans_Type_Code	Type of Transmission (Code 7 from VMRSH)	Code 2 (automatic transmission)
Forward Speeds	Number of forward speeds	5
Reverse_Speeds	Number of reverse speeds	1

HDV_AXLE Table

Axle_Type_Code	Type of axle configuration (Code 3 from VMRSH)	Code D
Axle_Front_Weight	Axle front weight	12,000 lb rating
Front_Tire_Size	Size of front tire	B275/70R22.5
Rear_Tire_Size	Size of rear tires	B275/70R22.5

Axle_Mfgr_Code	Name of drive axle manufacturer (from VMRSH)	Meritor
Axle Model	Drive axle model number	RC2663NFRF121
Rear_Axle_Config_Code	Rear axle configuration (Code 37 from VMRSH)	Code 1 (Single Speed, Single Reduction)
Rear_Axle_Setup_Code	Setup of rear axle configuration (Code 38 from VMRSH)	Code 1 (Single Axle)
Axle_Ratio_Low	Low axle ratio	1:5.25
Axle_Ratio_High	High axle ratio	NA
Total GVW Wt (lb)	Total gross vehicle weight in pounds	40,600 lbs
Total Curb Wt (lb)	Total weight with the truck in curb weight configuration	29,700 lbs
Torque Converter Ratio	Torque converter ratio	4:3
Wheelbase	Length of wheelbase	293 inches

HDV_EMISSION Table

Cat_Conv	Does the vehicle have a catalytic converter? Y or N	Yes
Cat_Conv_Mfg	Name of catalytic converter manufacturer.	Johnson Matthey Brick/ Nelson muffler
Cat_Conv_Model	Model number of the catalytic converter.	Johnson Matthey 36095/ Nelson 201107A
Dsl_Prt_Trap	Does the vehicle have a diesel particulate trap? Y or N	No
Trap_Mfg	Name of the particulate trap manufacturer.	NA
Trap_Model	Model number of the particulate trap.	NA
Trap_Regen_Type	Type of trap regeneration process	NA
Trap_Conf	Particulate trap configuration	NA
Num_Trap_Ele	Number of particulate trap elements	NA
Trap_Sys_Wt	Weight of the particulate trap system	NA

Appendix B

Summary of data collected for task 3.2, WMATA bus 2460

	Miles	Fuel		Average Monthly Fuel Economy(mpg, DGE)
April	1212	422		2.87
May	3758	1554		2.42
June	2328	1007		2.31
July	2137	955		2.24
August	2136	865		2.47
September	1302	712		1.83
October	1673	685		2.44
Overall	14546	6200		2.35

Month	**Date**	**Mileage**	**Fuel Usage***	**Maintenance or Problem Log**
			(*Fuel usage is in gallon equivalent)	
Apr	19	30744	42.0	
	20	30744	0.0	Changed engine oil & filter on PMI (preventative maintenance interval)
	21	30778	25.0	
	22	30824	22.0	
	23	30824	0.0	
	24	31160	67.0	
	25	31319	69.0	
	26	31465	50.0	
	27	31559	43.0	
	28	31626	36.0	
	29	31810	53.0	
	30	31956	57.0	Average for April: 2.87 mpg
May	1	32105	59.0	
	2	32302	78.0	
	3	32451	62.0	
	4	32666	70.0	
	5	32862	84.0	
	6	32920	40.0	
	7	33026	40.0	
	8	33149	60.0	
	9	33267	57.0	
	10	33333	34.0	
	11	33490	56.0	
	12	33593	56.0	
	13	33649	25.0	
	14	33737	62.0	
	15	33737	0.0	
	16	33737	0.0	
	17	33753	37.0	
	18	33816	28.0	
	19	33973	47.0	
	20	34177	72.0	
	21	34391	88.0	
	22	34531	60.0	
	23	34701	73.0	
	24	34878	9.0	
	25	34952	34.0	
	26	35048	49.0	
	27	35219	67.0	

	28	35302	49.0	
	29	35526	79.0	
	30	35616	44.0	
	31	35714	35.0	Average for May: 2.42 mpg
Jun	1	35714	35.0	
	2	35821	48.0	
	3	35938	63.0	
	4	36190	92.0	
	5	36190	0.0	
	6	36190	0.0	
	7	36294	38.0	
	8	36407	24.0	
	9	36544	48.0	
	10	36662	47.0	
	11	36672	45.0	
	12	36763	16.0	
	13	36763	0.0	
	14	36763	0.0	Changed engine oil, oil filter, pressure washed engine, replaced belt guard on PMI (preventative maintenance interval
	15	36909	51.0	
	16	36948	19.0	
	17	37074	41.0	
	18	37268	94.0	
	19	37452	74.0	
	20	37452	0.0	
	21	37515	38.0	
	22	37668	52.0	
	23	37881	71.0	
	24	37881	0.0	
	25	37881	0.0	
	26	37881	0.0	
	27	37881	0.0	
	28	37889	38.0	
	29	37949	42.0	
	30	38042	31.0	Average for June: 2.31 mpg
Jul	1	38110	41.0	
	2	38247	57.0	
	3	38247	0.0	
	4	38261	24.0	
	5	38261	0.0	
	6	38326	27.0	
	7	38543	64.0	
	8	38711	70.0	
	9	38849	52.0	
	10	38849	0.0	
	11	38849	0.0	
	12	38849	0.0	No power, check engine light on
	13	38849	0.0	
	14	38902	42.0	
	15	39006	46.0	
	16	39223	79.0	
	17	39223	0.0	
	18	39223	0.0	
	19	39361	43.0	

	20	39483	59.0	
	21	39567	43.0	
	22	39685	59.0	rd tested, sluggish while driving, check engine light on - checked codes "fuel derate codes" no other problem
	23	39773	48.0	
	24	39773	0.0	
	25	39773	0.0	
	26	39876	52.0	
	27	39928	31.0	
	28	39988	31.0	
	29	40124	53.0	
	30	40179	34.0	
	31	40179	0.0	Average for July: 2.24 mpg
Aug	1	40179	0.0	
	2	40324	41.0	
	3	40461	54.0	
	4	40660	59.0	
	5	40660	0.0	
	6	40660	0.0	
	7	40660	0.0	
	8	40752	33.0	
	9	40828	42.0	
	10	40899	26.0	
	11	40910	16.0	
	12	40936	12.0	
	13	40969	22.0	
	14	41156	27.0	
	15	41308	62.0	
	16	41308	0.0	
	17	41430	54.0	
	18	41540	37.0	
	19	41682	65.0	
	20	41733	25.0	
	21	41733	0.0	
	22	41733	0.0	
	23	41766	23.0	
	24	41769	10.0	
	25	41857	42.0	
	26	41923	33.0	
	27	42012	45.0	
	28	42024	16.0	
	29	42093	36.0	
	30	42270	58.0	
	31	42315	27.0	Average for August: 2.47 mpg
Sep	1	42420	60.0	
	2	42464	29.0	
	3	42576	54.0	
	4	42576	0.0	
	5	42576	0.0	
	6	42576	0.0	
	7	42615	47.0	
	8	42752	60.0	
	9	42889	47.0	
	10	42902	22.0	Changed engine oil & filter

	11	42902	0.0	Checked for oil leaks/Tightened oil clamps
	12	42998	32.0	
	13	43054	44.0	
	14	43077	23.0	
	15	43146	29.0	
	16	43235	21.0	
	17	43235	0.0	
	18	43235	0.0	
	19	43235	0.0	
	20	43257	19.0	
	21	43257	0.0	
	22	43262	6.0	
	23	43343	62.0	
	24	43435	35.0	
	25	43435	0.0	
	26	43435	0.0	
	27	43504	65.0	
	28	43561	19.0	Check for idle low, cleared codes, rd tested
	29	43561	0.0	
	30	43617	38.0	Average for September: 1.83 mpg
Oct	1	43686	23.0	
	2	43686	0.0	
	3	43686	0.0	
	4	43872	62.0	
	5	43989	39.0	
	6	43992	79.0	
	7	44118	42.0	
	8	44292	58.0	
	9	44433	47.0	
	10	44433	0.0	
	11	44433	0.0	
	12	44553	40.0	
	13	44655	34.0	
	14	44805	50.0	
	15	44928	41.0	
	16	45048	40.0	
	17	45285	79.0	
	18	45290	51.0	Average for October: 2.44 mpg

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