Roush Enterprises E-350 LPI System

Task #5 Deliverable Report

& Task #6 Final Report

for:

New Technology Research and Development Program

582-11-11142-3264

Submitted by:

Roush Enterprises

Principal Investigators:
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Table of Contents

Table of Figures

Abstract / Executive Summary

Roush's project goals are to design prototype Liquid Propane Injection (LPI) system hardware and develop calibration of the powertrain control module for the Ford E-350 Cutaway vehicle configuration, build prototype components and E-350 prototype vehicles for hardware design validation, and develop the calibration that runs the powertrain control module and contributes to overall emissions reductions. This program stage will result in the confirmation through emissions testing in an EPA-approved test lab that nitrogen oxide (NO_x) and other emission levels have been improved from the base E-350 gasoline versions. Anticipated emissions reductions over a comparable 2010 gasoline vehicle are 50% for NO_x, 25% for particulate matter (PM), 25% for greenhouse gases (GHG), and 15% for nonmethane hydrocarbons (NMHC). The key benefits of this technology will be reductions of 2.9 tons of NO_x, 0.62 tons of NMHC, 0.07 tons of PM, and over 4,500 tons of GHGs annually by 2012 for fleets operating in Texas' nonattainment areas, as well as support for technology using a Texas-produced alternative fuel.

Introduction / Background

In today's business environment, fleets are challenged with demands for alternative fuel technologies that reduce carbon-based fuel emissions, including NO_x, while also reducing operating costs and dependence on foreign oil. Frito Lay, out of Plano, Texas, as an example, has a need for converting much of their on-road heavy-duty delivery truck fleet to alternative fuel vehicles that reduce emissions.

Propane systems for vehicles, both past and current, have relied on outdated technology (vapor and bi-fuel) which degrade engine performance and compromise quality. Liquid propane injection (LPI) systems, both past and current, have achieved better performance, but technological advancements have been required to effectively manage the flow and pressure of liquid propane, improve upon related emissions attributes and provide a sustainable platform for fleet growth with future LPI vehicles.

Roush has been a leader in improving liquid propane injection (LPI) technology for vehicles, integrating longstanding expertise in OEM level engineering and powertrain calibration with in-house emissions development, testing and certification capabilities. Propane, as an alternative engine fuel, supports the initiative to reduce emissions such as NO_x as well as dependence on foreign oil, while providing a cost benefit over gasoline to fleets. Roush has released for sale a number of Ford-based fleet vehicle LPI applications, including the 2007 ½ - 2008 F-150, 2009 and 2010 F-250, and 2009 – 2011 E-Series Vans.

The advanced technology being developed under this grant project is intended to enable Frito Lay (Plano, Texas) and other large fleets to reduce NO_x and other emissions from their delivery vehicle fleets by enabling the testing and development of a prototype LPI system for the Ford E-350 chassis-cab with 5.4L 2V engine, including hardware and calibration, for in-vehicle testing, development and emissions reduction confirmation. This LPI system would then be certified by EPA for sale to Frito Lay and other large fleets in Texas and around the United States. The E-350 cutaway makes-up a large portion of the delivery vehicle fleets in Texas and the US overall. With the funding provided by the proposed grant, this product will be commercially available as early as the fourth quarter of this year.

This program stage will result in the confirmation through emissions testing in Ford's EPA-approved test labs that NO_x emissions and other criteria pollutant levels have been improved over the baseline E-350 gasoline versions. This stage is especially relevant for the TCEQ's NTRD program because of the significant NO_x reductions predicted from development of this technology at nearly 50% over a comparable gasoline vehicle.

Project Objectives / Technical Approach

From the grant contract Grant Activities (Scope of Work):

> *"Article 1. Objectives*
>
> *1.1 The objectives for this work are:*
>
> *1.1.1. Design, construct, and test a propane powered Ford E-350 truck.*
>
> *1.1.2. Verify through testing that NO_x emissions have been reduced from gasoline version by up to 50%."*

Tasks

Calibration Sign-Off Cold Weather Testing

From the grant contract Grant Activities (Scope of Work):

> *Task 5: Calibration and emissions testing for confirmation prototype vehicles*
>
> *2.5. Task Statement: The PERFORMING PARTY will complete calibration and emissions tests to evaluate the confirmation prototype vehicles.*
>
> *2.5.1. Calibration Testing*
>
> *2.5.1.1. The PERFORMING PARTY will complete prior calibration work and release the emissions and diagnostic calibration for in-vehicle testing.*
>
> *2.5.1.2. The PERFORMING PARTY will test the two confirmation prototype vehicles in a cold climate such as Minnesota. Testing will include at least: cold starts and drive/loading, hot fuel handling, spark control or octane sensitivity, and knock sensor calibration.*

Cold Weather Testing was performed at the Ford/Smithers Scientific Services Cold Weather Testing Facility in Raco, Michigan (Latitude and Longitude: 46°21′10.03″N 84°49′5.55″W). The major development tasks were designated as cold starts performance, cold drive engagement and drive-away performance, cold-ambient drivability, and LPG fuel system cold-ambient function and performance. A combination of ambient starts and cold chamber starts were performed down to -20°F.

Each vehicle was started twice per day after a minimum 8-hr soak in a temperature-controlled soak room. This resulted in start temperatures ranging from 0°F to -20°F. Starts were also performed outside at ambient conditions ranging from 0°F to 20°F. Issues initially observed included inconsistent start times, stumbles on drive engagements and poor fuel control on drive-away. Changes were made in the transient fuel control, start and run-up fueling, and drive engagement load compensation areas of the calibration to resolve the issues. Cold-ambient idle-entry torque was also adjusted to resolve mild idle-entry surging/rolling idle.

Fully-warm vehicle drivability performance was on-par with 30-40°F ambient drives while fully warm. No fuel-control difficulties were observed with the colder fuel tank temperatures. Full load accelerations at cold and hot engine conditions after various length idles showed good fuel control, no misfires and no indication of fuel vaporization issues. These accelerations were evaluated after various short idles in drive and idle in neutral periods, followed by wide open throttle acceleration to 50 mph on the facility's high-mu (maximum amount of traction available) surface. The vehicles were not loaded due to the size constraints of the cold soak chambers.

As with the warm- and hot-weather Maximum Brake Torque (MBT) spark control, cold MBT control is left as carryover from the base vehicle gasoline calibration. No spark control issues were observed during starts, engagements, part-load driving or full-load driving operation. Cold air change temperature (ACT) and engine coolant temperature (ECT) modifiers functioned as intended.

As was observed in hot-weather conditions, no spark knock was also observed during the cold-weather trip. No knock conditions were discovered during the course of the trip, so the knock sensors were left in the disabled state previously validated in the hot-weather test conditions.

Calibration Sign-Off

From the grant contract Grant Activities (Scope of Work):

> *2.5.2. The PERFORMING PARTY will release the final production calibration based on the calibration testing, reflash the calibration on the confirmation prototype with the final production calibration, and complete the final engineering hardware and calibration sign-off.*

OBD-II testing was performed and fault thresholds verified both on the road and in the emissions lab. The resulting data in addition to emissions data was submitted to the EPA for approval. Approval was granted and a sales certificate was received. See attachments.

At the conclusion of sign-off testing the resulting calibration was released through the Ford SEMA release process. This process ensures that when a Roush LPI vehicle is brought to a Ford service center, the calibration on the PCM will be recognized as valid.

The SEMA released calibration was flashed onto the CP level vehicle and end of line checks were performed. The vehicle passed the end of line inspection and it was determined the truck was ready to ship.

CP Emissions Testing

From the grant contract Grant Activities (Scope of Work):

> *2.5.3. The PERFORMING PARTY will conduct emissions testing on the confirmation prototype vehicles. Testing will include standard ambient urban emissions cycle (FTP75), highway fuel economy test cycle (HWFET), and prep cycles to pre-condition the vehicle for testing (FTP74).*

Baseline gasoline emissions tests were performed at Ford's Allen Park Test Labs located in Allen Park, Michigan. The vehicle was tested per the Federal Test Procedure (FTP) test requirements. The allowable ranges under the FTP for key environmental parameters are as follows:

- temperature: 68 – 86 °F,
- barometer: 28 – 31 inches Hg, and
- absolute humidity: 0 – 150 gr/pound.

The vehicle went through a required precondition soak within the same temperatures for a minimum 12 hours and no longer than 36 hours/level prior to the emission test.

Manufacturers use procedures to convert coast down time, track road load coefficients, and the 50 mph road load horsepower for a vehicle to determine dynamometer road load horsepower settings (PAU). As part of the procedure, the coefficients (F0, F1, F2) are derived and represent the mechanical drag coefficients for a vehicle. The values listed were derived by Ford for this vehicle and since our modifications don't change the weight class Roush can use the same ones derived by the OEM. Ford's values were:

- F_0: 96.87
- F_1: 1.3226
- F_2: 0.06673

The drag coefficients are then used to derive the electric 48 inch roll diameter dynamometer road load coefficients (A, B, C) for certification testing.

- A: 63.09 pounds
- B: 0.5919 pounds/miles/hour
- C: 0.07087 pounds/miles/hour^2

D_{MECH} is part of the equation to calculate the effective mass of the vehicle. D_{MECH} is the mechanical drag force acting on the vehicle which is the sum of the tire rolling resistance and the losses due to friction inboard of the hubs at the front and rear axles.

$$D_{MECH} = F_0 + F_1 V + F_2 V^2$$

V = vehicle speed.

Gasoline emissions tests are performed on a dynamometer. Since the test vehicle is not driving down a road, the dynamometer must simulate forces that are present when the vehicle is driven down a road. Those variables that the dynamometer simulates are forces associated with inertia and road load forces. Those forces can be frictional, inertial, and windage. Road load forces are represented by the formula:

RL=A BV CV[2] DW.

A = vehicle constant load coefficient (e.g., effects of breakaway force)

B and C = vehicle load coefficient dependent on velocity and velocity squared (e.g., windage)

D = grade coefficient (e.g., slope of the grade). (Load coefficient based on velocity cubed may be added if desired).

V = vehicle velocity

W = vehicle weight (10,000 pounds)

The ABC's above were used to setup the dynamometer to perform the test on the 2011 E350 Dual Rear Wheel Cutaway (RCT01) test vehicle. Only one gasoline vehicle was baseline tested to provide sufficient data to compare to the vehicle on LPG at the end of the program. It was Roush's intention to test only one gasoline vehicle, and the original SOW was incorrectly written with vehicle(s) in plural. The original budget reflects funds for one gasoline baseline test.

The tests were run as three combos (CVS75 + HWFET). The CVS75 is also known as FTP75 and is a city emissions test and a city fuel economy test. HWFET is a test of highway fuel economy as well as highway emissions. The tests were conducted over 3 days. The results of all three tests, as well as average results and the standard deviations for each factor, are presented in Tables 1 and 2, below. Table 1 presents the baseline emissions testing results. In city conditions testing was done for NMHC, CO, and NO_x, while under highway conditions only data on NO_x emissions was collected.

Table 1: Gasoline Baseline Emissions Testing for Confirmation Prototype Vehicle RCT01

Test	Date	City NMHC	City CO	City NO_x	Highway NO_x
8527117	12/1/10	0.2516 g/mi	1.9740 g/mi	0.2390 g/mi	0.0143 g/mi
8527124	12/2/10	0.2673 g/mi	2.0036 g/mi	0.2714 g/mi	0.0052 g/mi
8527134	12/3/10	0.2278 g/mi	1.9325 g/mi	0.2811 g/mi	0.0051 g/mi
Average	NA	0.2489 g/mi	1.9700 g/mi	0.2638 g/mi	0.0082 g/mi
Standard Deviation	NA	0.0198 g/mi	0.0356 g/mi	0.0087 g/mi	0.0018 g/mi

The LPG tests were also run as three combos (CVS75 + HWFET). The tests were conducted over 3 days. The results of all three tests, as well as average results and the standard deviations for each factor, are presented in Table 2 below. Table 2 presents the LPG emissions testing results. Similar to the baseline testing, in city conditions testing was done for NMHC, CO, and NO_x, while under highway conditions only data on NO_x emissions was collected. The average LPG emissions measured under city conditions were 0.0713 grams/mile of NMHC, 2.0575 grams/mile of CO, and 0.1587 grams/mile of NO_x. The average NO_x emissions under highway conditions was 0.0047 grams/mile.

Table 2: LPG Baseline Emissions Testing for Confirmation Prototype Vehicle RCT01

Test	Date	City NMHC	City CO	City NO_x	Highway NO_x
8741687	2/22/11	0.0821 g/mi	3.1267 g/mi	0.1408 g/mi	0.0034 g/mi
8741709	2/24/11	0.0643 g/mi	1.4584 g/mi	0.1590 g/mi	0.0040 g/mi
8741719	2/25/11	0.0676 g/mi	1.5872 g/mi	0.1764 g/mi	0.0067 g/mi
Average	NA	0.0713 g/mi	2.0575 g/mi	0.1587 g/mi	0.0047 g/mi
Standard Deviation	NA	0.0095 g/mi	0.9283 g/mi	0.0178 g/mi	0.0018 g/mi

Table 3 shows the percent change in emissions when comparing gasoline baseline data to LPG testing data. The following fuel economy differences were found between gasoline and LPG: City NMHC decreased 71%, City CO increased 4%, City NO_x was reduced by 40%, and Highway NO_x was also reduced 43%.

Table 3: Percent Reduction / (Increase) in Emissions

Test Type	NMHC	CO	NO_x
City	71%	(4%)	40%
Highway	NA	NA	43%

City, highway, and combined fuel economy results were also obtained on both the gasoline baseline and LPG test runs. These results are displayed in Tables 4 and 5.

Table 4: Gasoline Baseline Fuel Economy Testing in Gasoline Gallon Equivalents for CP Vehicle RCT01

Test	Date	City Fuel Economy	Highway Fuel Economy	Combined Fuel Economy
8527117	12/1/10	9.58 mpg	12.57 mpg	10.73 mpg
8527124	12/2/10	9.63 mpg	12.54 mpg	10.75 mpg
8527134	12/3/10	9.53 mpg	12.23 mpg	10.58 mpg
Average	NA	9.58 mpg	12.45 mpg	10.69 mpg
Standard Deviation	NA	0.05 mpg	0.19 mpg	0.09 mpg

Table 5: LPG Baseline Fuel Economy Testing in Gasoline Gallon Equivalents for CP Vehicle RCT01

Test	Date	City Fuel Economy	Highway Fuel Economy	Combined Fuel Economy
8741687	2/22/11	9.12 mpg	11.85 mpg	10.17 mpg
8741709	2/24/11	9.12 mpg	11.82 mpg	10.16 mpg
8741719	2/25/11	9.08 mpg	11.83 mpg	10.14 mpg
Average	NA	9.10 mpg	11.83 mpg	10.16 mpg
Standard Deviation	NA	0.02 mpg	0.01 mpg	0.02 mpg

There was a decrease in city fuel economy by 5% in the LPG system over gasoline. The highway and combined fuel economy also saw a reduction by 5%. These results are shown in Table 6.

Table 6: Percent Decrease in Fuel Economy:

Test	Fuel Economy Decrease
City	5%
Highway	5%
Combined	5%

Reporting Deadlines

From the grant contract Grant Activities (Scope of Work):

2.5.4. Schedule: The PERFORMING PARTY shall complete this task within 6 months of the signed Notice to Proceed Date as issued by TCEQ.

2.5.5. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to documentation of all test results for vehicle performance and emissions.

Also from the grant contract Grant Activities (Scope of Work):

Task 6: Reporting

2.6. Task statement: The PERFORMING PARTY will prepare and submit monthly detailed project reports and a comprehensive final report while ensuring compliance with all TCEQ program requirements

2.6.1. The PERFORMING PARTY will coordinate all project resources to ensure compliance with NTRD program requirements while providing deliverables on-schedule and on-budget.

2.6.2. The PERFORMING PARTY will generate monthly progress reports and a final report summarizing all aspects of the project based on data from the task completion reports.

2.6.3. Schedule: The PERFORMING PARTY shall submit monthly reports to the TCEQ by no later than 10 days after the end of each month. The PERFORMING PARTY shall submit the final report to complete this task within X months of the signed Notice to Proceed Date as issued by TCEQ.

2.6.4. Deliverables: The PERFORMING PARTY shall submit monthly progress reports with associated billing statements and a final project summary report to the TCEQ upon completion of this task.

Monthly status reports with the associated billing statements were submitted to TCEQ during this project. This final project summary report fulfills the last reporting deliverable per our agreement. After receiving the last notice to proceed, the work was completed well before the required deadline. Roush also was able to complete the work without requesting an overall contract extension.

Discussion / Observations

Objectives vs. Results

The project objectives for these tasks and deliverables have been met. The AP level vehicles have been shown to be functionally equivalent to CP level, and have provided the engineering team with the necessary feedback to continue on with the CP level hardware design and calibration.

Critical issues

There are no critical issues documented at this time.

Technical and commercial viability of the proposed approach

The Liquid Propane Injection System, at the AP level, has shown through this stage that the E-350 vehicle is a good platform for this technology and that the assumed scope of work for this program should meet the objectives.

Scope for future work

The scope of work for the E-350 program under the grant contract has been successfully completed. At this time there is not an outstanding work related to this contract.

Intellectual Properties / Publications / Presentations

The Roush LPI system uses a unique integrated system for controlling injector leakage during engine-off soak periods. Roush considers this technology to be proprietary, and has submitted notice of intent to patent. This system allows the propane in the fuel rail to be isolated from the rest of the system and vented to the evaporative emissions canister, where it is stored until the vehicle is started again. This system eliminates any propane leakage past the injectors, which historically has been a concern with liquid injection systems due to the relatively high system pressures.

Summary / Conclusions

The program tasks and deliverables as described above have been completed successfully and it has been determined by Roush that the scope of work defined in the grant has been completed and there are not any remaining deliverables.

Acknowledgements

Roush has an excellent working relationship with Ford Motor Company. Roush has long been a strategic partner with Ford Motor Company in the area of powertrain design, development and engine calibration, providing a strong foundation and experience level for the propane program. Leveraging that foundation, the LPI systems developed by Roush incorporate the creation of advanced calibrations and improved hardware systems, greatly impacting the vehicles performance characteristics and its emission performance.

Appendices

Appendix A: EPA Certificates of Conformity

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

CERTIFICATE OF CONFORMITY
2011 MODEL YEAR

Manufacturer:	**ROUSH**		
Engine Family:	**BRIIE05.4AS8**		
Certificate Number:	**RII-ONHWY-11-07**		
Intended Service Class:	**HDG 1 (<=14K LBS)**		
Fuel Type:	**PROPANE**		
FELs: g/bHp-hr	NMHC + NOx: **0.85**	NOx: **0.64**	PM:
Effective Date:	**2/4/2011**		
Date Issued:	**2/4/2011**		

Karl J. Simon, Director
Compliance and Innovative Strategies 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 subject to the terms and conditions prescribed in those provisions, this certificate of conformity is hereby issued with respect to the test engines which represent the following motor vehicle engines, by engine family, and is subject to the terms and conditions prescribed in those provisions.

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

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

It is a term of this certificate that the manufacturer shall consent to all inspections described in 40 CFR 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. 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.

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

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

CERTIFICATE OF CONFORMITY
2011 MODEL YEAR

Manufacturer:	**ROUSH**		
Engine Family:	**BRIIE05.4AS7**		
Certificate Number:	**RII-ONHWY-11-08**		
Intended Service Class:	**HDG 1 (<=14K LBS)**		
Fuel Type:	**PROPANE**		
FELs: g/bHp-hr	NMHC + NOx: **0.85**	NOx: **0.64**	PM:
Effective Date:	**2/4/2011**		
Date Issued:	**2/4/2011**		

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