Roush Enterprises E-350 LPI System

Task #2 Deliverable Report

for:

New Technology Research and Development Program

582-11-11142-3264

Submitted by:

Roush Enterprises

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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 oxides (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Propane systems for vehicles, both past and current, have relied on outdated technology (vapor and bi-fuel) which degrade engine performance and compromise quality.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 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):

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

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

Task 2 Calibration testing for advanced prototype vehicles

2.2. Task Statement: The PERFORMING PARTY will complete calibration tests to evaluate the advanced prototype vehicles.

Calibration testing

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

2.2.1. Calibration testing

2.2.1.1. The PERFORMING PARTY will complete calibration development work and release the emissions and diagnostic calibration for in-vehicle testing.

Software background

The initial strategy build used in the AP level vehicle is a modified version of the 2008 Ford VN127 5.4L engine 5R110W transmission strategy. Unique versions of the propane features were developed to work with the older strategy level.

A desktop calibration was developed by drawing together elements of the Roush 2010 Liquid Propane Gas (LPG) E-Series, data generated during the 5.4L-2V engine mapping and emissions certification process, and crank and warm up fuel from the 2008 F150 calibration. Further desktop calibration was performed to develop a theoretically equivalent calibration to the 2010 E-Series. This was required as the following software features were incompatible with current Roush production vehicles: purge compensation, idle speed control, dashpot, crank fuel, and open loop fuel.

Hot weather testing

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

2.2.1.2. The PERFORMING PARTY will test the two advanced prototype vehicles in a hot weather climate such as Death Valley, Arizona. Testing will include at least: cold *starts and drive/loading, hot fuel handling, spark control or octane sensitivity, and knock sensor calibration.*

Hot weather testing was completed at the Volvo Arizona Proving Grounds (APG) in Phoenix, Arizona.

Vehicles

Three vehicles were tested. The 2010 E250 Van Wagon (PE251) had a test weight of 7,500 lbs. It had production multivalve fuel lines and series fuel rails. The 2008 E350 Duel Rear Wheel (DRW) Cube Van (FL01) had a test weight of 12,500 lbs (GVW). The multivalve had a 4mm passage with the excess flow valve (XFV) removed, the fuel lines had 3/8 inch supply and 1/4 inch return, the fuel rails were parallel and had an injection pressure and temperature sensor (IPTS) in the left bank. The 2010 E450 Service Bed (PE451) had a test weight of 14,500 lbs (GVW). The multivalve had 4mm passage with XFV removed, the fuel lines had a 3/8 inch supply with a 1/4 inch return, the fuel rails were parallel and had IPTS in the left bank

Hot fuel handling

As part of the E350 propane engine conversion and development program, hot fuel handling testing was performed at the APG Oval Track. The ambient temperature was 94 degrees Fahrenheit while the track temperature was 104 degrees Fahrenheit. The test vehicle used was the 2008 E350 DRW Cutaway Van with Roush Propane System.

Testing was performed per the Roush Volvo Arizona Proving Grounds (VAPG) Hot Fuels Handling Procedure. The Roush VAPG Hot Fuels Handling Procedure is a control test that is used to qualify vehicles or components throughout the world. The procedure outlines the requirements for the instrumentation, equipment and facilities, vehicle preparation, operating conditions for road and environmental dynamometer, general operating procedures, and how to present the data.

At a very high level the basics of the Procedure are as follows:
1) Drain and fill the fuel tank to 35% of capacity.
2) Run laps at 75 mph.
3) Accelerate at wide open throttle to 75 mph for baseline acceleration.
4) Attach dynamometer trailer and set the grade.
5) Accelerate to 30 mph under load.
6) Park vehicle in soak shed for 25 minutes.
7) Restart vehicle.
8) Perform a simulated city traffic drive cycle.
9) Accelerate at wide open throttle to 75 mph and compare to baseline.
10) Idle vehicle in drive and neutral in soak shed for 50 minutes.
11) Accelerate at wide open throttle to 75 mph and compare to baseline

The vehicle restarted after both soak periods, and no additional crank cycles were required. During the 50 minute soak period the engine coolant degas bottle overflowed. No stumbles or drivability issues were noted during any acceleration periods, or the simulated traffic drive cycle. The current combination of hardware and calibration passed the requirements of the hot fuel handling procedure and showed that the prototype is ready to proceed to the Confirmation Prototype phase.

Spark control

The combustion characteristics of the Ford 5.4L – 2V engine combined with the octane of LPG permits setting spark advance to Maximum Brake Torque (MBT). Using a trailer dynamometer to maintain high rpm and load conditions, spark was advanced past MBT by as much as 6 degrees to determine if detonation could be induced at different speeds and loads. Advancing spark further than 6 degrees is generally considered an unsafe practice with respect to engine durability, hence no testing was conducted past this point. No detonation could be induced.

While trying to induce detonation, the knock sensor activity was monitored. No knock sensor activity was observed. This would indicate that the knock sensor calibration is robust against false detection. The knock sensors have no advance authority so this was not evaluated. Due to the fact that the knock sensor performance could not be evaluated as detonation could not be induced in vehicle, the knock sensors have been disabled to ensure that there is no erroneous knock sensor activity.

These findings correlated to the mapping performed on the engine dynamometer which indicated that detonation could only be induced at 150°F air charge temperature, 250°F engine coolant temperature, wide open throttle, 4000 rpm and above. The calibration was modified to ensure the engine would not detonate when operating under those conditions.

Other testing performed

Purge monitor verification

Purge monitor data was collected to determine the capability of the system to detect a 0.020 inch leak. The data collected indicates that the monitor is capable of detecting a 0.020 inch leak.

Purge system performance

The 2008 purge control software is an older version of the feature than is in the current production E-Series, hence the current purge calibration could not be carried over. A new purge calibration was developed to deliver target purge flow with minimal resets and air/fuel disturbances. An evaluation of the purge system performance was conducted after the calibration was developed. The results are as follows:

- idle resets – none,
- air/fuel disturbances – none,
- nominal purge flow measured – 0.07 lb/min, and
- target nominal purge flow – 0.07 lb/min.

Extended idle performance

Extended idles were performed to determine the vehicles' ability to idle for extended periods of time without adversely affecting fuel control and engine stability. The calibration was able to maintain adequate fuel control and engine stability under extended idle conditions.

Stabilized drive evaluation

Stabilized drives were performed. Conditions included hot and cold ambient temperatures (65°F to 94°F), level and grade roads, highway speeds, and city drive cycles. Evaluations included tip-in/tip-out clunk/shuffle, transmission shift quality, idle dips/oscillations/stalls, run-on feel, idle drive performance, etc.

The drivability rating system assigns a number to the intensity of driveability concerns. The rating scale is as follows:

- 1 = Moving Stall
- 2 = Stationary Stall
- 3 = Severe
- 4 = Heavy
- 5 = Moderate
- 6 = Light
- 7 = Trace
- 8+ = None

Sea level stabilized driveability scored an overall 7.5. Sea level stabilized driveability is comprised of the following areas: starting, idle, pullaway in drive, smooth traffic crawl/creep (first/second gear, no acceleration), acceptable engine braking (fifth gear, deceleration from 55 to 45 mph, closed throttle), low speed driveability, and high speed driveability.

Starting scored an overall 8.0 and includes the following areas and scores: flush time 7.0, cranking time 8.0, run up overshoot 8.0, and stalling / stumbling which scored an 8.0.

Idle scored 7.5 and includes the following areas and scores: idle stability w/o accessories in neutral (surging, stumbling) 7.5, idle stability without accessories in drive (surging, stumbling) 7.5, return to idle without consumers 7.5, idle undershoot in neutral (response to accessories & steering inputs) 7.0 and idle undershoot in drive (response to accessories & steering inputs) 7.0.

Pullaway in drive scored 8.0 and includes the following areas and scores: light (e.g. in stop and go traffic situations) 8.0 and normal (e.g. when merging with moving traffic but not 'racing') 8.0.

Smooth traffic crawl/creep (first/second gear, no acceleration) scored 8.0 and includes the following areas and scores: steady state - all accessories off 8.0, light tipin / backout 7.5, and steady state - switching accessories on/off 8 out of 8.

Acceptable engine braking (fifth gear, deceleration from 55 to 45 mph, closed throttle) scored 7.5.

Low speed driveability scored 7.0, and includes the following areas and scores: hesitations 7.0, surging 7.0, sagging 7.5 and deceleration feel 7.0.

High speed driveability scored 7.7 and includes the following areas and scores: hesitations 7.5, surging 8.0, and sagging 8.0.

Exhaust temp evaluation

Exhaust temps were monitored during extended high load operation to evaluate the effectiveness of the exhaust temperature model. A combination of trailer dynamometer testing during the hot fuels handling and extended grades (I-17 from Phoenix, Arizona, to Flagstaff, Arizona) was used to allow high load operation for prolong periods of time. It was determined that the calibration was effective at controlling exhaust temperatures under these situations.

Fuel Rail Pressure Control Module (FRPCM) performance evaluation

The FRPCM was monitored to determine its effectiveness in the following areas: Fuel Rail Pressure Control – Acceptable and Fuel Rail Sealing – Acceptable

Software verification/development

Due to the age of the target vehicle for this program, unique versions of the current unique LPG software features were created in order to properly interface with the older software (Crank Fuel, Open Loop Fuel, Purge Control, Dashpot, Idle Speed Entry, etc.). These features, as well as their interface with the rest of the strategy, were evaluated to ensure they were capable of delivering comparable performance to the current production software. Additionally, calibrations were developed to deliver comparable performance to the current Roush LPI models.

Hardware verification/development

The new fuel system design was evaluated against the current production E-Series. Evaluations were made with respect to flush times and hot fuels handling. The new hardware was equivalent to or better performing than the current production hardware.

Extended grade evaluation

Extended grades were driven to determine the prolonged wide open throttle capability of the vehicle. Fuel control was maintained and all critical engine temperatures remained within acceptable operating limits.

Cold start/Warm-up performance evaluation

Cold starts and the subsequent warm-up period were evaluated. The evaluation included air/fuel control, tip-in/tip-out clunk/shuffle, transmission shift quality, idle speed control, etc. These evaluations confirmed the 2008 E350 DRW performs comparably to the current Roush LPI models.

Hot restart performance evaluation

Variable soaks were performed to condition the engine and fuel rail to different temperatures. Starts were then performed and the subsequent drive was evaluated. The evaluation included air/fuel control, tip-in/tip-out clunk/shuffle, transmission shift quality, idle speed control, etc. These evaluations confirmed the 2008 product performs comparably other Roush LPI models.

Other issues/ deficiencies

Regarding the E350 DRW, software issues surrounding the purge feature and the purge monitor were identified. The controls group evaluated and corrected this issue. Issues were not temperature or altitude related.   Cruise control was not evaluated as the vehicle was not equipped with it.

High altitude testing

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

> *2.2.1.3. The PERFORMING PARTY will test the two advanced prototype vehicles in a high altitude setting such as the Rocky Mountains of Colorado. Testing will include at least: cold starts and drive/loading, hot fuel handling, spark control or octane sensitivity, and knock sensor calibration.*

Hot weather testing was completed in Flagstaff, Arizona, and surrounding areas.

Vehicles

The 2008 E350 DRW Cube Van (FL01) had a test weight of 12,500 lbs (GVW). The multivalve had a 4mm passage with XFV removed, the fuel Lines had 3/8 inch supply and 1/4 inch return, the fuel rails were parallel and had IPTS in the left bank.

Altitude hot fuels handling

As part of the E350 propane engine conversion and development program, hot fuel handling testing was performed at altitude.

The test vehicle used was a 2008 E350 DRW Cutaway Van with Roush Propane System. Testing was done at Snowbowl Ski Area in Flagstaff, Arizona, at an altitude of 9300 feet. During testing the ambient temperature was 35 degrees Fahrenheit.

The vehicle was driven for 9 miles up an average 5.5% grade at wide open throttle. The vehicle was then soaked for 30 minutes at the top of the grade, restarted, and driven. The vehicle started and drove with no noticeable stumbles or hesitations. No detonation was observed during altitude testing.

Other testing performed

Inferred barometric pressure model verification

The inferred BP model was evaluated to ensure the inferred BP model was within ± 1inHG of the actual barometer. This objective was met.

Purge monitor verification

Purge monitor data was collected to determine the capability of the system to detect a 0.020 inch leak at altitude. The data collected indicates that the monitor is capable of detecting a 0.020 inch leak at altitude.

Purge system performance

The purge flow performance was monitored at altitude to ensure performance was comparable to sea level. Sea level performance was maintained.

Idle performance

Idles were performed to determine effectiveness of the altitude idle air compensation. The altitude idle air compensation performed satisfactorily.

Stabilized drive evaluation

Stabilized drives were performed at altitude. Conditions included ambient temperatures ranging from 28°F to 45°F, level and grade roads, highway speeds, and city drive cycles. Evaluations included tip-in/tip-out clunk/shuffle, transmission shift quality, idle dips/oscillations/stalls, run-on feel, idle drive performance, etc.

The drivability rating system assigns a number to the intensity of driveability concerns. The rating scale is as follows:

- 1 = Moving Stall
- 2 = Stationary Stall
- 3 = Severe
- 4 = Heavy
- 5 = Moderate
- 6 = Light
- 7 = Trace
- 8+ = None

Altitude stabilized driveability scored an overall 7.5. Altitude stabilized driveability is comprised of the following areas: starting, idle, pullaway in drive, smooth traffic crawl/creep (first/second gear, no acceleration), acceptable engine braking (fifth gear, deceleration from 55 to 45 mph, closed throttle), low speed driveability, and high speed driveability.

Starting scored an overall 8.0 and includes the following areas and scores: flush time 7.0, cranking time 8.0, run up overshoot 7.0, and stalling / stumbling which scored an 8.0.

Idle scored 7.5 and includes the following areas and scores: idle stability w/o accessories in neutral (surging, stumbling) 7.5, idle stability without accessories in drive (surging, stumbling) 7.5, return to idle without consumers 7.5, idle undershoot in neutral (response to accessories & steering inputs) 7.0, and idle undershoot in drive (response to accessories & steering inputs) 7.0.

Pullaway in drive scored 8.0 and includes the following areas and scores: light (e.g. in stop and go traffic situations) 8.0 and normal (e.g. when merging with moving traffic but not 'racing') 8.0.

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High speed driveability scored 7.7 and includes the following areas and scores: hesitations 7.5, surging 8.0, and sagging 8.0.

Exhaust temperature evaluation

Exhaust temperatures continued to be monitored at altitude. No issues were identified.

FRPCM performance evaluation

The FRPCM continued to be monitored at altitude. No issues were identified.

Software verification/development

No software issues unique to altitude were identified.

Hardware verification/development

No hardware issues unique to altitude were identified.

Extended grade evaluation

Extended grades were driven to determine the prolonged wide open throttle capability of the vehicle. Fuel control was maintained and all critical engine temperatures remained within acceptable operating limits.

Cold start/warm-up performance evaluation

Cold starts and the subsequent warm-up period continued to be evaluated at altitude. It was determined that altitude performance was comparable to the sea level performance.

Hot restart performance evaluation

Variable soaks were performed to condition the engine and fuel rail to different temperatures while at altitude. Starts were then performed and the subsequent drive was evaluated. It was determined that altitude performance was comparable to the sea level performance.

Other issues/ deficiencies

No unique issues or deficiencies were identified at altitude.

Submission of deliverable report

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

> *2.2.2. Schedule: The PERFORMING PARTY shall complete this task within 4 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.2.3. 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.*

Discussion / Observations

Objectives vs. Results

The project objectives for these tasks and deliverables have been met. Calibration testing was performed in the evaluation of the advanced prototype vehicles in hot weather and at altitude.

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 remainder of the E-350 program under the grant contract should continue as defined and under the previous assumptions.

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 and it has been determined by Roush to be appropriate to proceed with the scope of work defined in the next scheduled tasks and 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: Supporting Documentation

The information in this appendix was claimed by the grantee as Proprietary and/or Confidential. To view this information please contact the New Technology Research and Development program at:

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Or

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