Roush Enterprises E-350 LPI System

Task #1 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 Dual Rear Wheel (DRW) 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Propane systems for vehicles, both past and current, have relied on outdated technology (vapor and bi-fuel) which degrade engine performance and compromise quality.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 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 first quarter of 0f 2011.

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

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

Task 1: Vehicle and Advanced Prototype procurement and build

2.1. Task Statement: The PERFORMING PARTY will procure the vehicles and advanced prototypes and install the advanced prototypes.

Procurement of Advanced Prototype vehicles

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

2.1.1. The PERFORMING PARTY will procure two Ford 350 gasoline dual rear wheel cutaways from Ford Motor Company.

Roush procured a total of four E-350 vehicles that were used exclusively for this development program. It has been stated prior that this grant project is part of an overall program for Roush that is much larger in scope than contained in the grant scope of work. Although all four E-350's have been utilized, Roush is only seeking reimbursement for two of the E-350's per the approved budget.

In order to complete hot weather testing, a few options were considered that would have significantly increased the timeline and budget. Those options were to wait till the next calendar year to test at Arizona Proving grounds or to rent a heated wind tunnel. In order to avoid these significant timeline and budget increases, it was determined that a couple of small changes to the initial scope needed to be made. The initial plan was to utilize 2008 and 2011 model year E-350 vehicles on the development trip. The reason for two different model years is that in the 2009 model year Ford went to a one touch integrated start (OTIS). The propane system needs to be designed differently on vehicles with and without this feature. The difference is related to hot start testing and how the system needs to flush out propane vapors in the lines before starting.

Since Ford dealers had not received their allotment of 2011 E-350 vehicles in time to support the hot weather development trip defined in this program scope of work, a 2010 model year E-450 was utilized alongside a 2008 model year E-350 on the hot weather trip. The E-450 has very similar Liquid Propane Injection (LPI) system hardware to the E-350, but with a much worse-case scenario for fuel delivery in hot weather due to the fact that the E-450 has a 6.8L V10 engine which requires more fuel than the 5.4L V8 engine in the E-350.

Advanced Prototype (AP) hardware was procured under a few different methods:

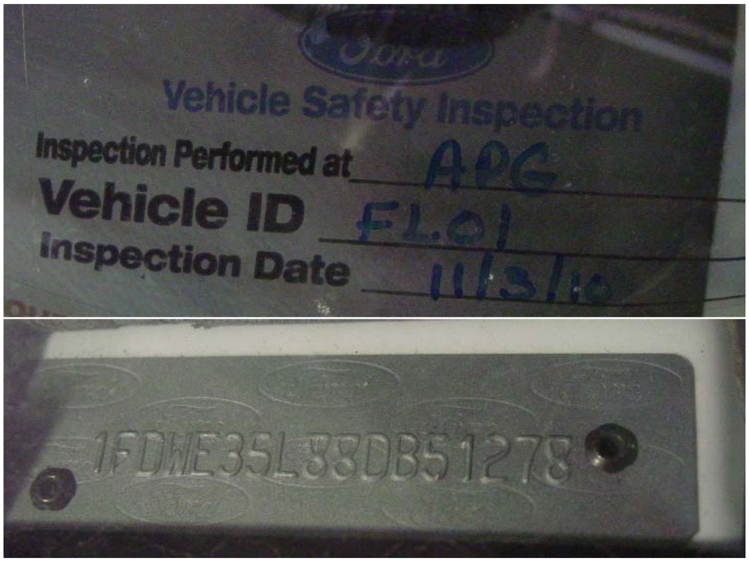
- utilizing pre-production components that had been designed for another Roush development program (the E-450 DRW) and fabricating those components to work in the E-350 vehicle configuration,
- through procurement of true prototype level components that had been designed exclusively for the E-350 DRW program, or
- use of existing production level components from the Roush E-Series LPI systems that are currently in production and commercially available.

The first 2008 vehicle was built at an AP level. This vehicle then was used to conduct hot weather and altitude testing. The first vehicle is shown below in Figure 1.

Figure 1: E-350 box van

The vehicle is labeled “FL01” with a sticker above the VIN on the windshield. The VIN number for this vehicle is 1FDWE35L88DB51278. Figure 2 located below is a picture of the label and VIN tag.

Figure 2: Vehicle ID label and VIN tag for FL01



The second vehicle is a 2008 Ford Frito-Lay box van. This vehicle was built at the AP level and was used for hardware development and calibration purposes. The picture of this vehicle is shown below in Figure 3.

Figure 3: Figure 3: 2008 Ford Frito-Lay box van

The VIN number for this vehicle is 1FD2E35L2FDA68699. The vehicle is labeled “FL02” with a sticker on the upper passenger-side windshield shown in Figure 4 below.

Figure 4: Vehicle ID label and VIN tag for FL02

The third vehicle is a 2011 Ford E-350 DRW. This vehicle was used first to establish the baseline for gasoline emissions and then later built to the Confirmation Prototype (CP) level for LPI emissions development. The picture of this vehicle is shown below in Figure 5.

Figure 5: 2011 Ford E-350 cut-away RCT01

The VIN number for this vehicle is 1FDWE3FL7BDA28853. The vehicle is labeled “RCT01”with a sticker on the upper passenger-side windshield shown in Figure 6 below.

Figure 6: Vehicle ID label and VIN tag for RCT01

The fourth vehicle is a 2011 E-350 DRW. This vehicle was built at CP design level for on road calibration development. The picture of this vehicle is shown below in Figure 7.

Figure 7: 2011 Ford E-350 cut-away RCT02

The VIN number for this vehicle is 1FDWE3FL9BDA28854. The vehicle is labeled “RCT02”with a sticker on the upper passenger-side windshield shown in Figure 8 below.

Figure 8: Vehicle ID label and VIN tag for RCT02

Baseline emissions testing of Confirmation Prototype vehicles

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

> *2.1.1.1. The PERFORMING PARTY will measure vehicle emissions on Ford E-350 gasoline dual rear wheel cutaways prior to propane conversion. Testing will include standard ambient urban emissions cycle (FTP75), highway fuel economy test cycle*

(HWFET), coefficient determination to set the vehicle load on the dynamometer (SAE J2264), 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 CV² 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)KMW. 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. The average baseline emissions measured under city conditions were 0.2489 grams/mile of NMHC, 1.9700 grams/mile of CO, and 0.2638 grams/mile of NO_x. The average NO_x emissions under highway conditions was 0.0082 grams/mile.

KMW**Table 1: 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

Fuel economy data was also collected for both city and highway conditions for all three test days, as represented in Table 2. The average city fuel economy was found to be 9.58 miles/gallon, the average highway fuel economy was 12.54 miles/gallon, and the average combined fuel economy was 10.69 miles/gallon.

Table 2: Baseline fuel economy testing for Confirmation Prototype 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	0.16 mpg	0.09 mpg

Building of Advanced Prototypes and installation on vehicles

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

> *2.1.2. The PERFORMING PARTY will procure two advanced prototypes for the liquid propane injections system from PERFORMING PARTY's current supply base for the production E-Series and pre-production E-450 LPI systems, including fabrication of fuel lines, mounting brackets, etc., to be done by PERFORMING PARTY's technicians and/or fabricators.*
>
> *2.1.3. The PERFORMING PARTY will use the advanced prototype components to build two E-350 propane vehicles.*
>
> *2.1.4. Schedule: The PERFORMING PARTY shall complete this task within 2 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.1.5. 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, including pictures, of the completed advanced prototype vehicles.*

Advanced Prototype vehicle #1

Roush converted two E-350 DRW vehicles to Advanced Prototype (AP) level. The first was a purchased 2008 box van. The 2008 E-350 build began on September 22, 2010, and finished on October 14, 2010.

As described above, AP hardware was procured under a few different methods:

- utilizing pre-production components that had been designed for another Roush development program (E-450) and fabricating those components to work in the E-350 vehicle configuration,
- through procurement of true prototype level components that had been designed exclusively for the E-350 DRW program, or
- use of existing production level components from the Roush E-Series LPI systems that are currently in production and commercially available.

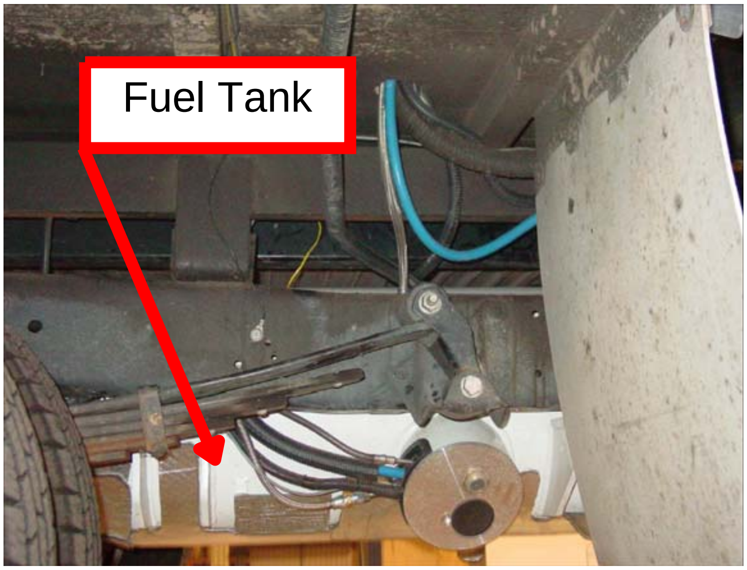
The major AP system level components consisted of the following: fuel rail system, fuel line system, fuel tank system, fuel fill system, pressure relief system, fuel rail pressure control system, electrical system, and an injection pressure and temperature sensor (IPTS) Interface.

The fuel rail system consists of the fuel injector rail system (left and right hand), transmission dipstick support bracket and fuel rail mounting - M6 x 1.0 x 20 bolt.

The fuel line system consists of two major areas: fuel lines and fuel retention. The fuel line area consists of the fuel rail supply assembly, fuel rail return assembly, forward supply line (brake/flex line), forward return line, rear supply line (brake/flex line), and the rear return line. The fuel line retention area consists of the rear fuel line support bracket, ethylene propylene diene monomer (EPDMKMW) sleeve (1/4 to 1/2 - 38.1mm length), EPDM sleeve (1/4 to 3/8 - 38.1mm length), bolt (M8 x 1.25 x 20, fuel line bracket to frame), and a double snail retainer clip.

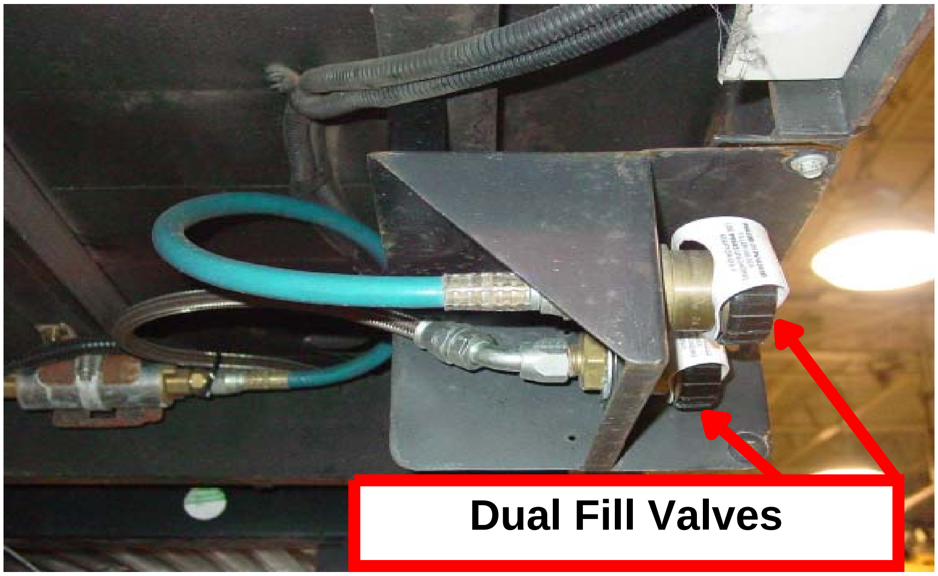
The fuel tank system is comprised of two major areas: aft axle fuel tank & heat shields and fuel tank mounting & miscellaneous hardware. The first group called aft axle fuel tank & heat shields is made up of the following components: aft axel fuel tank assembly, aft axle tank frame mounting bracket right and left, aft axle tank body fuel tank heat shield right and left, and the fuel tank heat shield-tank header cap (16 inch). The second group of the fuel tank mounting & miscellaneous hardware area consists of the following: vibration isolator, isolator crush limiter, washer–mounting brackets to tank, nut (12x1.75) for the tank to frame brackets, bolt (M12 x 1.75 x 55) for the tank to frame brackets, bolt (M12 x 1.75 x 35) for aft tank mounting bracket to frame, and a tank collar–grommet. The fuel tank system is shown in Figure 9 below.

Figure 9: Fuel tank system



The fuel fill system is made up of the following items: 3/8 remote fill line-nozzle to filter, 3/8 remote fill line-filter to tank, fuel filter assembly, fuel filter bracket, fill valve, custom fill valve bracket, bolt and washer (M5 x 16), bolt for the filter bracket mounting (M8 x 1.25 x 20), and a wormgear clamp. Figure 10 below shows dual fill valves installed in FL01. The second fill valve was installed to fill the auxiliary tank used for development purposes.

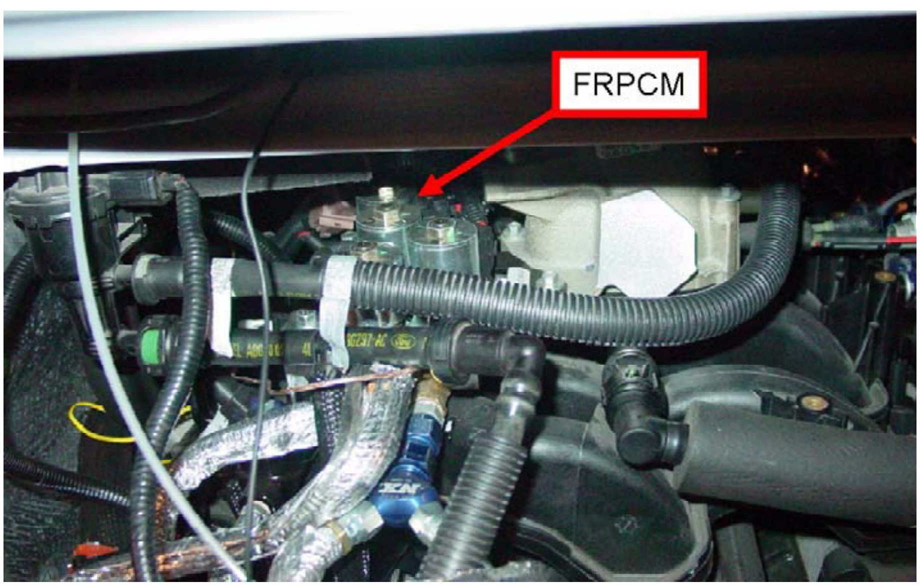
Figure 10: Dual fill valves



The pressure relief system is comprised of a pressure relief cap.

The fuel rail pressure control system consists of the following components: modified FRPCM (enlarged supply-side circuit), FRPCM to intake bracket, FRPCM purge hose assembly, prototype FTP sensor/hose assembly, bolt (M6 x 1.0 x 16) for the FRPCM to intake bracket, and bolt (M6 x 62) for the FRPCM to intake manifold. The FRPCM is shown installed in Figure 11 below.

Figure 11: FRPCM for FL01



The electrical system and IPTS interface consists of: the IPTS interface module (Woodward controller), main vehicle wiring harness, fuel injector jumpers, IPTS jumper harness, (#12-14 x 0.75 inch) self tapping & drilling screw-fuse box mounting, and the self tapping & drilling (#12-14 x

1.50 inch) screw-IPTS module mounting.

The following additional equipment was also installed: laptop stand, vacuum gauge, mini-view gauge, fuel gauge (auxiliary tanks), auxiliary battery, remote display module gauge (auxiliary battery), electric power box (auxiliary battery), ATI data logging equipment, one transducer in the fuel tank pump-out press, and one additional transducer after the MV supply side.

Advanced Prototype vehicle #2

The second vehicle was a 2008 Frito-Lay box van. The 2008 Frito-Lay E-350 build began on October 9 and finished on November 16, 2010. VIN number for this vehicle is 1FD2E35L2FDA68699. The vehicle is labeled "FL02" with a sticker on the upper passenger-side windshield.

The second vehicle had the same major AP system level components which consisted of the following: the fuel rail system, fuel line system, fuel tank system, fuel fill system, pressure relief system, fuel rail pressure control system, electrical system, and the IPTS Interface. The variances from the first vehicle are outlined below. All the parts from vehicle #1 should be considered a part of the second vehicle unless noted.

The fuel line system only deviated from the first vehicle in one of the two major areas, the fuel lines. The fuel line area added the rear intermediate line which is required for the 176 inch wheelbase vehicle.

The fuel tank system was the same as the first vehicle above except it utilized modified aft axle tank frame mounting bracket right and left.

The second vehicle had the following changes made to the additional equipment that was noted prior. It did not have the two additional transducers one of which is in the fuel tank pump-out press and the other after the MV supply side, but it did get a toggle switch to override the idle shutdown.

Discussion / Observations

Objectives vs. Results

The project objectives for these tasks and deliverables have been met. E-350 vehicles and advanced prototype hardware was procured, gasoline baseline emissions testing was run and data collected, and the AP level vehicles were built in support of the critical hot weather testing.

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 the remainder of the 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 previously defined 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:

(512) 239-4950

Or

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