California Energy Commission

Clean Transportation Program

**FINAL PROJECT REPORT**

# Gas Technology Institute: Medium and Heavy-Duty Vehicle Technologies

## 13 Liter Dual-Fuel Natural Gas Engine Demonstration

**Prepared for: California Energy Commission**

**Prepared by: Gas Technology Institute**

**Gavin Newsom, Governor**

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# California Energy Commission

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# PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

The Energy Commission issued PON-10-603 for selected CTP projects under "Advanced Medium- and Heavy-Duty Vehicle Technologies Pre-Commercial Demonstrations." To be eligible for funding under this solicitation, the projects also needed to be consistent with the Energy Commission's CTP Investment Plan, which is updated annually. In response to PON-10-603, the recipient, Institute of Gas Technology, doing business as Gas Technology Institute, submitted Proposal 4, which was approved for funding in the Energy Commission's notice of proposed awards on June 13, 2012. The agreement was executed as ARV-11-029 on September 18, 2012 in the amount of $4,562,532.

# ABSTRACT

This collaboration between the Gas Technology Institute and Clean Air Power, Inc. sought to demonstrate the commercial potential of a 13-liter, dual-fuel diesel engine fired with compression ignition of a mixture of natural gas and diesel. The two diesel engines models were retrofit with Clean Air Power's dual-fuel system. The demonstration used 12 trucks in California's South Coast and Mojave Desert air basins. Data and experiences captured during the in-use demonstration were compiled in this report. During the 20-month demonstration period from December 2013 to July 2015, the 12 heavy-duty vehicles fitted with Clean Air Power's dual-fuel technology accumulated more than 1.6 million miles in real-world conditions. Clean Air Power asserted that the trucks demonstrated overall viability, reliability, drivability, efficiency and robustness, making it worthy of commercialization.

These demonstrations have resulted in a patented and California Air Resources Board-certified dual-fuel system for 2012 Volvo/Mack D13/MP8 heavy-duty diesel engines. Clean Air Power's dual-fuel conversion system is an add-on technology that adapts the base diesel engine to operate using a combination of natural gas (CNG or LNG) and diesel.

**Keywords**: California Energy Commission, dual-fuel, natural gas, diesel, engine, demonstration, 13-liter natural gas engine, Gas Technology Institute, Clean Air Power

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# EXECUTIVE SUMMARY

The California Energy Commission awarded a Clean Transportation Program grant to Gas Technology Institute to demonstrate an engine for medium- and heavy-duty vehicles that can run on diesel and natural gas. This report summarizes and evaluates the demonstration, which was performed largely under subcontracting partnership with Clean Air Power Inc., based in Poway (San Diego County).

Clean Air Power focused on converting, demonstrating, and optimizing its dual-fuel natural gas system. It developed a diesel engine retrofit package that allows dual-fuel combustion of diesel and natural gas when applied certain diesel engine models.

Clean Air Power's dual-fuel conversion system is an add-on technology that has been adapted to the base diesel engine (for example, the model year 2012 Volvo D13 and Mack MP8 diesel engines). With the retrofit package, these engines can operate on a combination of natural gas (as either compressed or liquefied) and diesel as the fuel source. The diesel fuel component is used as a pilot fuel to ignite the air/fuel mixture. The diesel pilot fuel is ignited at high temperatures induced by adiabatic compression occurring in engine cylinders during the compression stroke. (*Adiabatic compression* is compression in which no heat is added or subtracted from the air, and the internal energy of the air is increased by an amount equivalent to the external work done on the air.) The diesel pilot fuel is always present in the fuel mix and adds to the total energy content of the fuel mixture. But fuel composition entering engine cylinders can vary from pure diesel to a diesel substitution rate by natural gas greater than 50 percent.

In addition to the 2012 Volvo D13 and Mack MP8 diesel engines mentioned above, the retrofit package has been used on diesel engines manufactured by Caterpillar, International, and Navistar diesel engines. In this project, the retrofit package was installed only on the 2012 Volvo D13 and Mac MP8 diesel engines. The engines were installed in 12 heavy-duty vehicles and operated over 1.6 million miles in California's South Coast and Mojave Desert air basins. The demonstration period started in December 2013 and ended in July 2015. Natural gas tractors were deployed into 10 test fleets to (1) identify and solve technical issues, (2) monitor and characterize performance of the demonstration vehicles, (3) gather vehicle performance data and feedback from fleet operators, and (4) optimize calibration settings prior to commercial introduction of the technology.

Clean Air Power and Gas Technology Institute collaborated on the grant proposal submitted under the California Energy Commission's PON-10-603 for Advanced Medium and Heavy-Duty Vehicle Technologies Pre-Commercial Demonstrations. The efforts associated with the demonstration included securing the required permits, selecting demonstration fleets, evaluating baseline vehicles, and converting 12 fleet vehicles with Clean Air Power's dual-fuel conversion system.

United Parcel Service demonstrated 10 Mack CXU613 vehicles in a variety of duty-cycles over a 19-month period, from December 2013 to June 2015. During this time, the test group accumulated more than 1.5 million miles of service and achieved a 52 percent average natural gas substitution rate for diesel. The UPS test group substitution rate ranged from a low of 43 percent to a high of 56 percent, with fuel economy ranging from 7.04 to 8.17 miles per natural gas diesel gallon equivalent and diesel combined on an energy (British thermal unit) basis. This is in the range of what would be expected given the wide range of duty-cycles experienced by the test group and comparable to the baseline vehicle fuel economy data.

TEC Leasing demonstrated two Volvo vehicles converted with Clean Air Power's dual-fuel conversion system. The demonstration vehicles operated in short-term (one- to two- week) demonstrations with a variety of fleets over a four-month period, from March 2015 to June 2015. During this time, the test group accumulated 5,651 miles of service and achieved an average substitution rate of 48 percent. Similar to UPS's results, the TEC Leasing test group achieved an average fuel economy of 7.49 miles per natural gas diesel gallon equivalent and diesel combined on a Btu basis.

Before the demonstrations of these two tractors, Clean Air Power's engineering team used the vehicles for drivability and performance development. During that period, one tractor was operated for 24,333 miles and the other for 34,482 miles, a total of 58,815 miles.

These demonstrations have resulted in a California Air Resources Board-certified dual-fuel system for 2012 Volvo D13 and Mack MP8 heavy-duty diesel engines. The dual-fuel system modifies the base diesel engine to enable it to operate on a mixture of diesel and natural gas fuel. Securing the ARB certification confirmed that the modifications do not result in exhaust emissions greater than that to which the engine was originally certified. During this demonstration, improvements were made to maximize diesel substitution rates, maximize efficiency, and improve drivability. The product is shown to be commercially viable and is available for sale, with several expressions of interest.

Although the retrofit package performed well enough to be considered commercially available for two models of diesel engine, it still has barriers to widespread use. The need for electronic data logging of engine performance characteristics to adapt to engines and their emission controls to different duty cycles reflecting expected conditions of operation, will restrict the use of this technology to retrofit applications. If the retrofit applications could be broadened to more diesel engines makes and models, the potential retrofit market would probably broaden considerably. If a way could be found to overcome the need for data logging and duty-cycle adaption, the technology could be sold as original equipment on new trucks for general duty-cycle use. Then the market would open up for use on new and used trucks with diesel engines for general use.

There are several benefits of moving away from diesel toward natural gas. For example, both carbon black emissions and diesel exhaust are reduced. Carbon black is a short-lived climate pollutant composed of colloidal black substances, including soot. Diesel exhaust is a listed toxic air contaminant composed of up to 40 components arising from diesel combustion. With a need to reduce carbon black and diesel exhaust, regulatory measures or market incentives could be used to accelerate emission reductions.

# CHAPTER 1: Introduction and Background

## Introduction

This project grant, entitled "Advanced Medium- and Heavy-Duty Vehicle Pre-Commercial Demonstrations," contained two technical tasks, Tasks 2 and 3.

The goal of Task 2 was to produce, demonstrate, refine, and eventually commercialize a 13-liter, dual-fuel engine produced by CAP through addition of its retrofit package to a diesel engine. Engines using this retrofit package were fired on diesel as a pilot fuel in a compression-ignition diesel engine. The engines were already certified to run exclusively on diesel. Modifications by CAP do not affect the ability of the engine to operate on diesel fuel alone. Part of the goal was to demonstrate the engine could operate on a fuel mix averaging of 75 to 90 percent natural gas. Diesel would be used as both a pilot fuel in the compression ignition and as a "co-fuel" in the diesel-natural gas mixture, thus contributing to the energy content of the dual-fuel mixture. The natural gas fuel can be either compressed or liquefied natural gas.

Funding for this grant included $4,562,532.00 from the Energy Commission and $1,895,535.00 in match funding from GTI. Total project amount was $6,458,067.00.

## Background

### Clean Air Power, Inc. Dual-Fuel Retrofit System

Clean Air Power, Inc. (CAP) developed and manufactured the retrofit for the dual-fuel (bifuel) natural gas system. To optimize the system for maximized substitution rates and minimized exhaust emission, CAP partnered with the Gas Technology Institute (GTI) on a grant proposal submitted to the California Energy Commission. Subsequently, GTI executed a subcontract with CAP for conversion, demonstration, and optimization of CAP's dual-fuel natural gas system. Ultimately, CAP plans to demonstrate commercial viability for the retrofit package.

### Objective of Dual-Fuel Conversion In-Use Demonstration Test Plan

As described, CAP developed an in-use demonstration test plan to monitor, characterize, and optimize the in-use performance of 12 demonstration vehicles fitted with CAP's dual-fuel conversion system. As part of the test plan, CAP identified a comparable diesel vehicle (baseline vehicle) that was used to measure, record, and evaluate fuel consumption and performance data. This activity characterized a baseline vehicle to define a point of reference against which the dual-fuel demonstration vehicles will be evaluated.

Once baseline fuel-consumption and performance metrics were established, the demonstration vehicles were deployed over 20 months in similar operational and duty-cycle environments to the baseline vehicles. During this time, CAP measured and recorded specific operational data and operator feedback to analyze the in-use performance of the demonstration vehicles. The data and operator feedback collected were used to optimize the system in several ways. The in-use performance metrics provided CAP with the data necessary to identify potential technology or control system improvements intended to maximize the substitution rate. The primary objective of the in-use testing was to maximize the substitution rate while maintaining a level of drivability adequate for commercial acceptance. Drivability and operator satisfaction were measured using daily operator reports. Vehicle operators were asked to comment on the operating qualities of the demonstration vehicle, such as idle smoothness, cold and hot starting, throttle response, power delivery, and tolerance for altitude changes. As a secondary objective, the in-use demonstration tests provided critical customer feedback and "real-world" operator assessments that were used to improve the product prior to commercialization. Achieving these objectives has resulted in a heavy-duty dual-fuel engine conversion system that provides superior environmental and economic performance at a price that can be supported by the market.

## Overview of In-Use Demonstration Test Procedure

The in-use demonstration test consisted of several activities specifically designed to refine a 13-liter compression ignition engine to maximize the ratio of natural gas to diesel fuel consumed during operation. The activities included in the in-use demonstration test are defined below:

- Identify and obtain required permits
- Identify and select demonstration fleets
- Measure, record, and analyze baseline diesel vehicle performance data
- Convert and configure demonstration vehicles based on baseline results and intended duty cycles
- Deploy demonstration vehicles within fleets for a six-month period
- Measure, record, and analyze dual-fuel vehicle performance data
- Develop design improvements and implement design modifications to optimize dual-fuel vehicle performance

Each activity provided the critical feedback necessary to optimize the system prior to becoming commercially available. Further, the data collected and experience gained during the testing were used to support ARB certification efforts by validating dual-fuel performance and system durability/integrity.

# CHAPTER 2: Technical Description of 13-Liter Dual Fuel Natural Gas Engine

## Dual-Fuel Conversion System

CAP's dual-fuel conversion system is an add-on technology that adapts the base diesel engine (model year [MY] 2012 Volvo D13 and Mack MP8 engines) to operate on a combination of natural gas (CNG or LNG) and diesel as the fuel source. As a true add-on system, CAP's dual-fuel technology does not require any significant modifications to the base diesel engine. The MY 2012 Volvo D13 and Mack MP8 diesel engines are physically identical and are differentiated only by the engine model name and corresponding calibration settings for engine brake-horsepower (bhp) and torque. In fact, the MY 2012 Volvo D13 and Mack MP8 are ARB-certified under the same engine family name (CVPTH12.8S01). The following table provides pertinent ARB certification information for the base diesel engine:

**Table 1: CARB Certification Information**

<table>
<tr><td colspan="7">CARB Certification Details – Diesel Engine</td></tr>
<tr><td colspan="2">Model Year (MY)</td><td colspan="2">2012</td><td colspan="3">Emission Control System and Features</td></tr>
<tr><td colspan="2">Engine Family Name</td><td colspan="2">CVPTH12.8S01</td><td colspan="3" rowspan="2">DDI, TC, CAC, ECM, EGR, OC, PTOX, SCR-U, AMOX</td></tr>
<tr><td colspan="2">Executive Order</td><td colspan="2">A-242-0068</td></tr>
<tr><td colspan="7">FTP Emission Certification Details</td></tr>
<tr><td>g/bhp-hr</td><td>NMHC</td><td>NOx</td><td>NMHC+NOx</td><td>CO</td><td>PM</td><td>HCCO</td></tr>
<tr><td>Std.</td><td>0.14</td><td>0.20</td><td>*</td><td>15.5</td><td>0.01</td><td>*</td></tr>
<tr><td>Cert.</td><td>0.01</td><td>0.12</td><td>*</td><td>0.1</td><td>0.003</td><td>*</td></tr>
<tr><td>NTE</td><td>0.21</td><td>0.30</td><td>*</td><td>19.4</td><td>0.00</td><td>*</td></tr>
</table>

Source: GTI Based on ARB Emissions Data

CAP's patented dual-fuel natural gas conversion system enables the engine to operate on a combination of natural gas and diesel fuels simultaneously while maintaining the ability to operate as a standard production diesel engine running on 100 percent diesel fuel. The ability to operate entirely on diesel fuel is maintained because the dual-fuel system retains all of the diesel engine hardware that was part of the originally certified engine. When operating in the dual-fuel mode, a converted engine will operate with the highest percentage of natural gas possible for a given operating condition and use diesel fuel solely as a pilot for initiating combustion of the fuel mixture. Under ideal conditions, a converted engine will operate using the highest percentage of natural gas possible. Ideal conditions represent specific periods of a driving cycle in which factors such as load, elevation, temperature, and driver input align to maximize the energy efficiency of converting the fuel mixture to mechanical power.

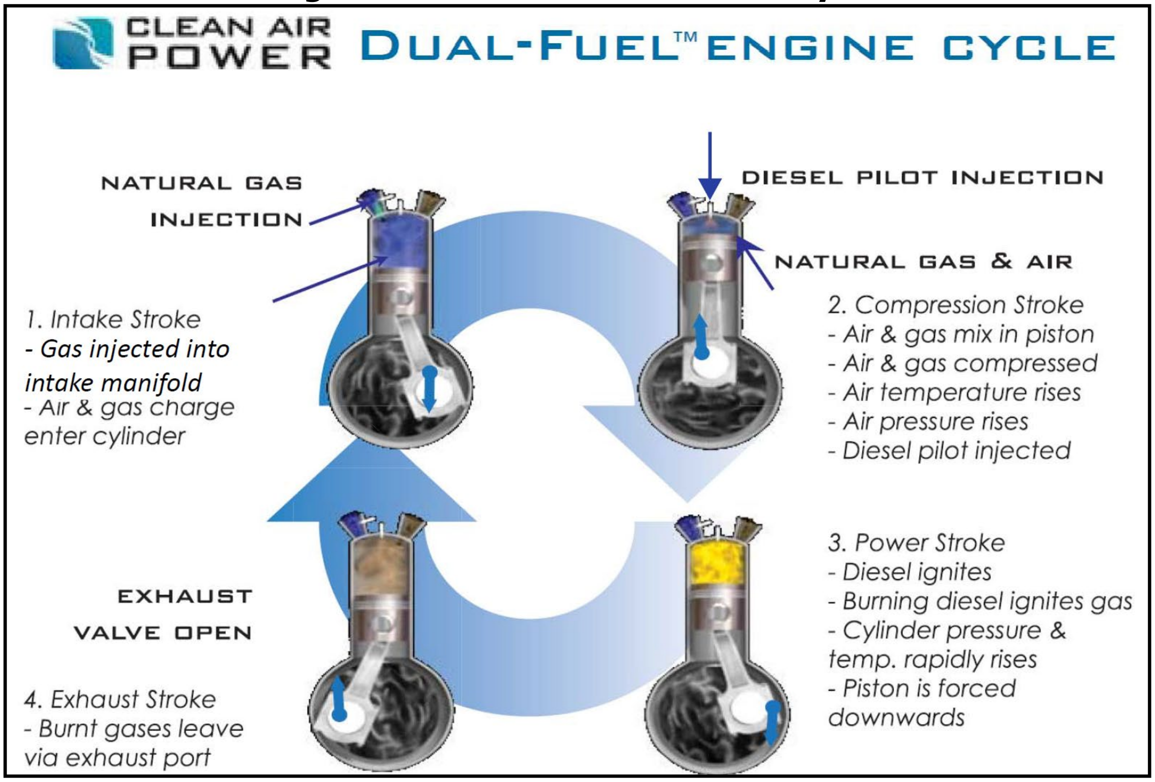
**Dual-Fuel Conversion Kit System Design and Principles of Operation**

The base MY 2012 Volvo D13 and Mack MP8 diesel engines operate under the principle of compression ignition (diesel cycle). Air is first drawn into a cylinder where it is highly compressed – far more so than in a gasoline (Otto cycle) engine. This high compression ratio is one of the factors that make a diesel engine more efficient than a comparable gasoline engine. Diesel fuel is injected into the cylinder when in-cylinder pressures are near maximum. The combination of diesel fuel and heated compressed air within the cylinder results in ignition. The rapid combustion of the fuel and air mixture results in increased pressure and temperature within the cylinder. The increased pressure and temperature generate the force that drives the piston back down the cylinder. It is through this process that the chemical potential energy of the diesel fuel is converted into mechanical energy.

Applying CAP's dual-fuel conversion system does not change the basic diesel engine architecture or principle of diesel combustion. The base diesel engine remains unaltered aside from the addition of a gas injection system and an externally fitted electronic control unit (ECU) that manages communication between the base engine and vehicle ECUs. Under the same principles described above, the combustion of a mixture of natural gas and diesel fuel results in pressures and in-cylinder temperatures consistent with those generated when operating on 100 percent diesel. As a result, the converted engine operates within the design limits and parameters of the originally certified engine.

The key distinction in the operating principles of CAP's dual-fuel engine is that the diesel fuel injector plays the role of a liquid spark plug that initiates combustion whenever the engine is operating in dual-fuel mode. Because natural gas is injected into the intake system and subsequently drawn into the cylinder during the intake stroke, the resulting pressurized homogenous charge inside the cylinder is a combination of natural gas and air. Diesel fuel is then injected into the cylinder to ignite the compressed mixture of natural gas and air. Because the resulting combustion environment is comparable to that when operating with 100 percent diesel, CAP's dual-fuel technology does not affect the robustness of the base engine. The following figure displays the steps of the dual-fuel combustion cycle.

**Figure 1 : Dual-Fuel combustion cycle**




Source: GTI

## Dual-Fuel Conversion Kit Component Description and Specifications

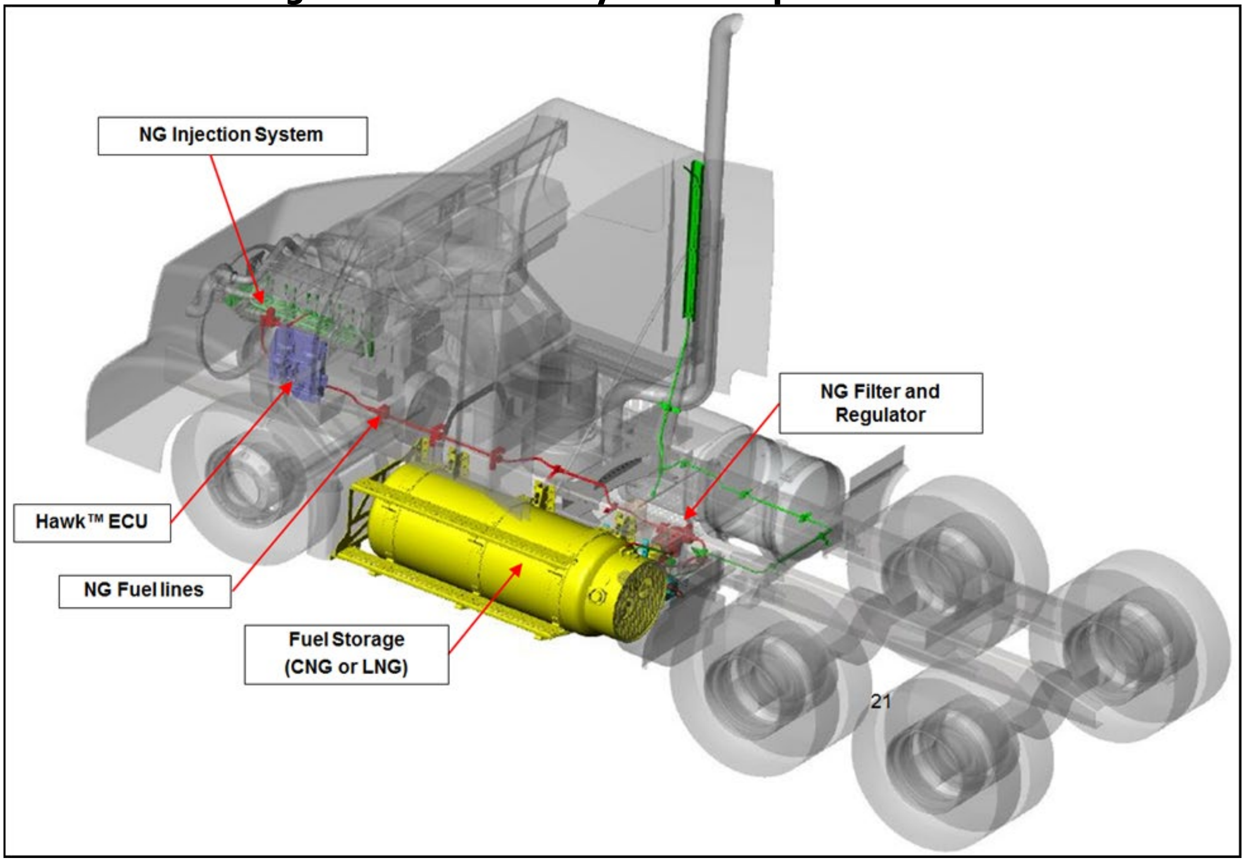
CAP's dual-fuel natural gas conversion system for the 2012 Volvo D13 and Mack MP8 requires installation of several components that enable and manage the supply of natural gas to the engine. Once converted, the system continuously monitors, evaluates, and controls the air/fuel ratio to ensure that the engine operates in the most efficient, best performing, and least emitting range of conditions.

The primary components of the conversion system include the:

- Electronic control unit (ECU).
- Dual-fuel engine harness and relay control harness.
- Natural gas inlet manifold.
- Turbocharger air bypass valve.
- Natural gas supply system.

The following figure displays how the primary components are integrated into a typical Volvo heavy-duty tractor.

**Figure 2: Dual-Fuel System Components**

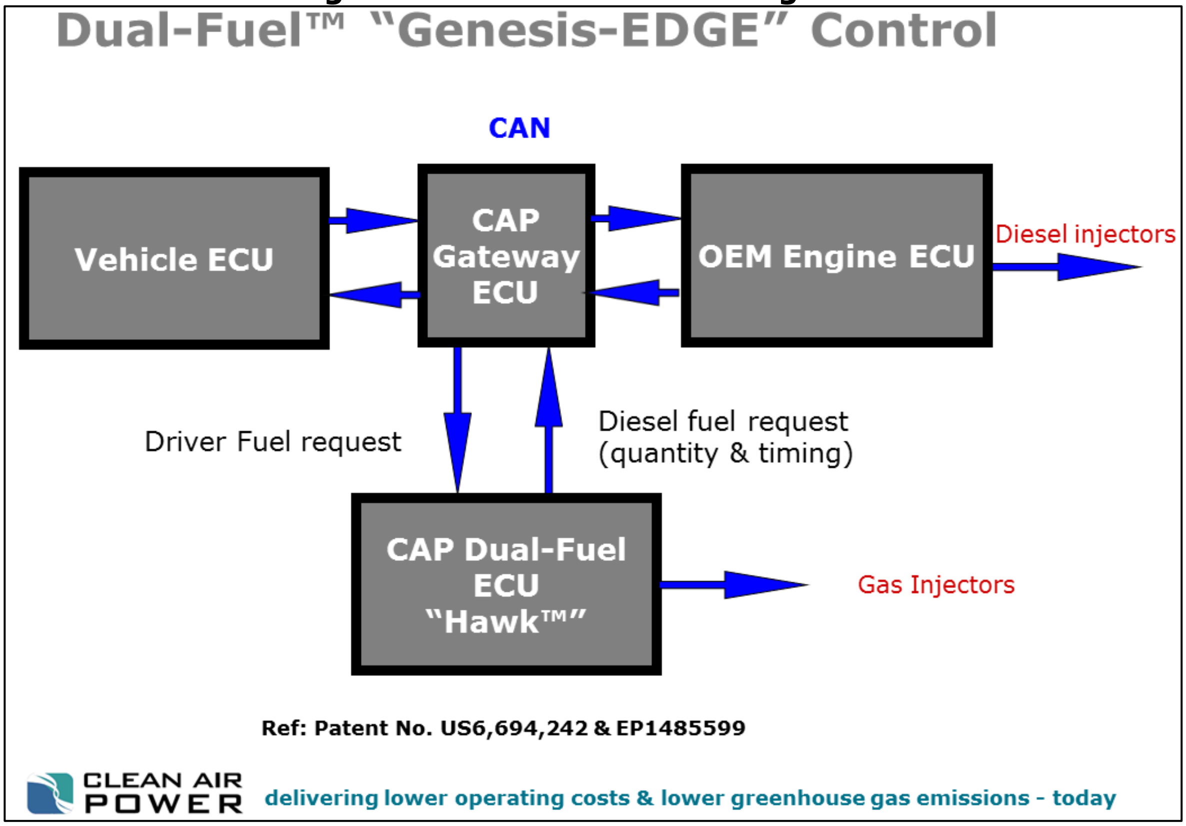



Source: GTI

## Electronic Control Unit and Electrical Harness

CAP's Hawk™ ECU manages natural gas fuel supply and controls engine operating parameters according to driver inputs and operating conditions. The Hawk™ ECU communicates with the OEM vehicle ECU and OEM engine ECU via CAP's patented Genesis EDGE™ system. Connected to the system via the OEM CAN bus, CAP's patented system allows retention of all OEM vehicle features such as cruise control, ABS, PTO, and other electronically controlled vehicle systems. Genesis EDGE ™ is also compatible with Volvo's revolutionary I-Shift (Mack mDRIVE) automated manual transmission. An overview of the communication pathways between the OEM vehicle and engine and CAP's dual-fuel conversion system is shown in the figure below.

**Figure 3: Dual-fuel control diagram**




Source: Gas Technology Institute

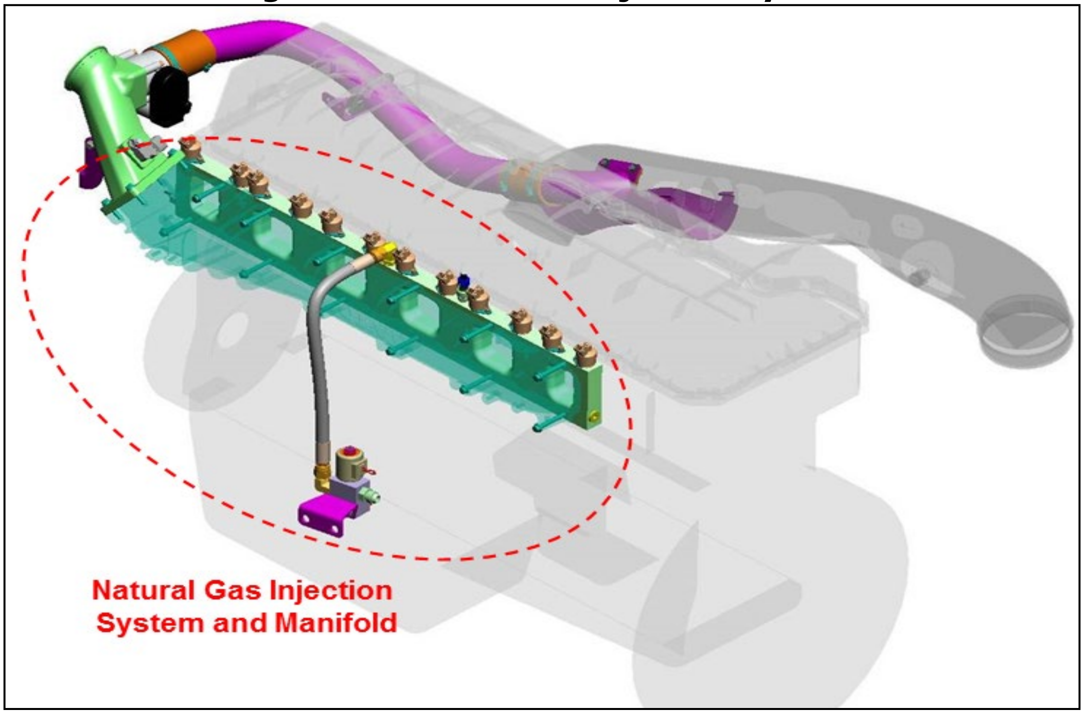
The control system is designed to interface seamlessly with the OEM's engine controller, giving ultimate control of the base engine to the dual-fuel system without compromising any features or functions of the base engine. CAP's HAWK™ ECU receives the fuel command from the Volvo engine controller. Based on this fuel command, the HAWK™ ECU recalculates the correct amount of natural gas and diesel (diesel pilot) fuels and determines the timing of the pilot injection. As a result, the appropriate volume of natural gas is injected into the intake manifold, compressed within the cylinder, and subsequently ignited by the diesel pilot injection.

Communication between the vehicle ECU and engine ECU is made possible by two harnesses specifically designed for the dual-fuel conversion system: a cab harness and chassis harness. Combined with the existing Volvo/Mack electronic system, they form the data transmission network that allows the OEM ECU to communicate with the CAP ECU. In addition, the harness relays data collected by the additional sensors to the CAP ECU to make engine operating condition adjustments.

## Natural Gas Injection System and Manifold

The natural gas injection system and manifold are installed between the OEM intake manifold and the cylinder head. The natural gas injection manifold contains 12 natural gas injectors, a natural gas shutoff valve (SOV), natural gas pressure sensors (NGP), and natural gas temperature sensors (NGT). The following figure displays how the natural gas injection system and manifold is integrated into the base engine.

**Figure 4: Natural Gas Injection System**

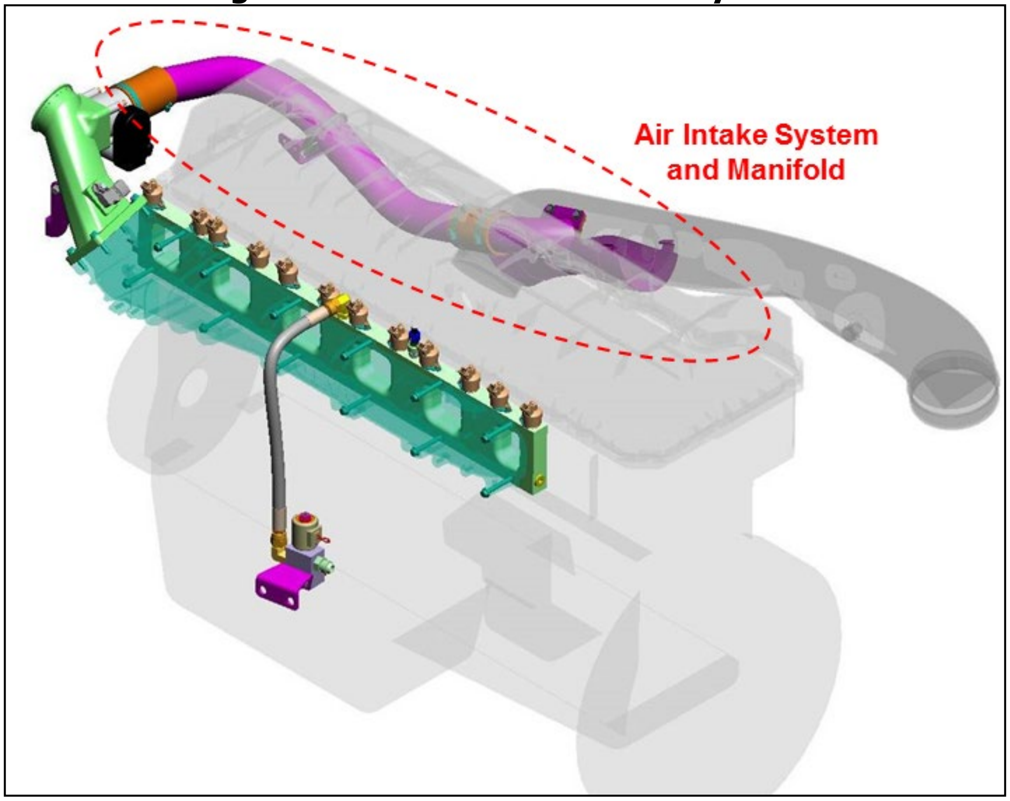



Source: Gas Technology Institute

## Air Intake System

The air intake system contains a turbocharger air bypass valve assembly that is controlled by CAP's ECU. During operation, the turbocharger air bypass opens and closes to control air/fuel ratio to ensure that the ratio for complete combustion of the natural gas is maintained. The figure below displays how the CAP air intake system is integrated into the base engine.

**Figure 5: Dual-Fuel Air Intake System**

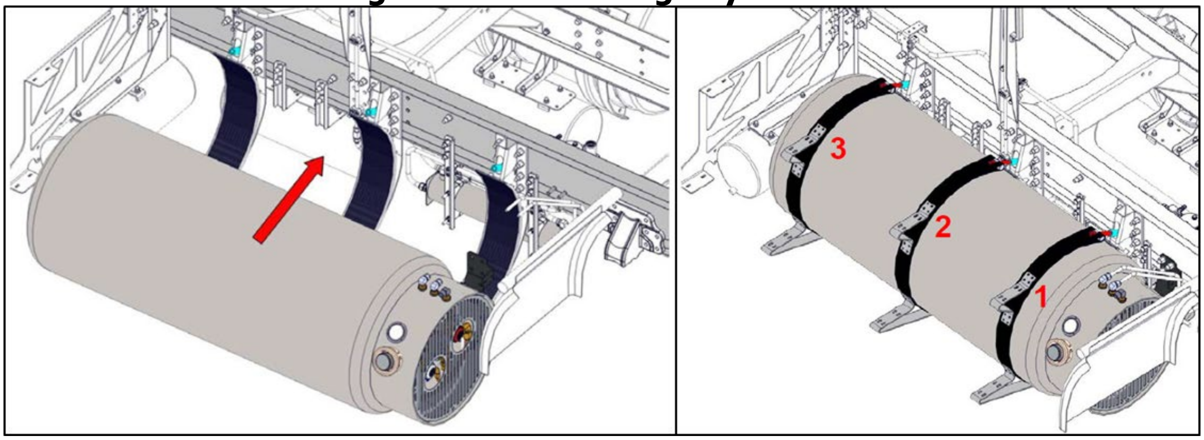



Source: Gas Technology Institute

## Natural Gas Storage and Delivery System

CAP's dual-fuel conversion system requires that a natural gas storage and delivery system be added to the vehicle chassis. During the conversion, each vehicle is equipped with a fuel storage system that consists of a cryogenic tank for the storage of liquefied natural gas (LNG) or high-pressure cylinders for the storage of compressed natural gas (CNG). The type of storage system installed depends on the operator's fuel preference. Regardless of whether the natural gas storage system is set up for LNG or CNG, the CAP system includes filters for removing oil and particulate matter from the fuel, a manual shutoff valve, and an automatic shutoff valve (SOV) to shut off gas flow when the engine is not in operation. For this demonstration, CAP collaborated with an LNG cylinder manufacturer to determine optimum tank sizes and installation procedures for the demonstration vehicles. The figure below displays the LNG tank brackets that are mounted to the vehicle chassis during installation.

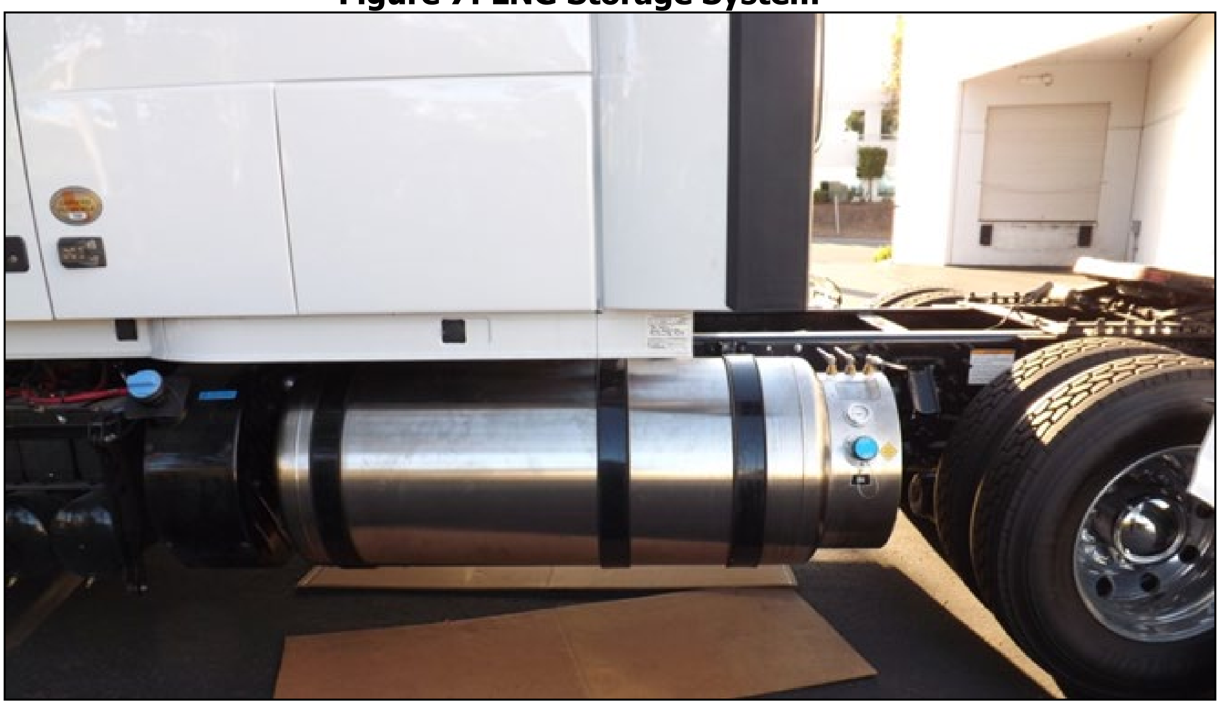
**Figure 6: LNG Storage System**




Source: Gas Technology Institute

The figure below displays the LNG storage tank installed on a demonstration vehicle within the test group.

**Figure 7: LNG Storage System**



Source: Gas Technology Institute

## Dual-Fuel Conversion Process and Requirements

The dual-fuel conversion is relatively straightforward and can be performed by a typical Volvo or Mack technician upon completion of CAP's technical training program. An installation manual, specific to each vehicle platform, will be included for each installation partner and provides the technician with the necessary steps, sequence, and specifications required to perform the conversion. The manual provides step-by-step instructions that should be followed from receipt of vehicle through commissioning of the dual-fuel system. For the demonstration vehicles included in the test group, CAP performed the first three vehicle conversions, and TEC of Fontana performed the remaining nine conversions.

## Pre-conversion Requirements and Considerations

While it is physically possible to install CAP's dual-fuel conversion system at most diesel repair shops, initial installations will take place only at OEM dealer network locations. This will ensure that installation quality is maintained during the earlier stages of commercialization. Operators will be able to purchase the conversion system only through a select Volvo/Mack dealer network that has been trained and certified by CAP's technical team.

Before starting the dual-fuel conversion, each demonstration vehicle was inspected for defects and to confirm that it was in good running order. A predelivery inspection (PDI) evaluated the physical condition of the demonstration vehicles and control system to verify that no active faults were displayed by the OEM ECU. CAP requires all dealers to maintain a record of the PDI with the build folder that is generated with each installation. In the event that the PDI identifies that the candidate vehicle has any defects, the defects must be rectified before starting the dual-fuel conversion, and the corrective actions must be recorded and stored in the build folder. The following information must be recorded upon receipt of the vehicle:

- Vehicle registration number
- Vehicle identification number
- Engine serial number
- Odometer reading
- Customer details

Upon completion of the steps above, the candidate vehicle will be immobilized for a period of about one week while the conversion is completed.

## Dual-Fuel Conversion Kit Calibration

Upon completing installation of CAP's dual-fuel conversion system, the coolant system of the engine must be refilled and the batteries charged and installed. A series of steps (also referred to as the *commissioning process*) must be taken before starting the engine for the first time. This process is critical to insuring that the installation was performed correctly and the system is properly configured for dual-fuel operation. The following table captures the commissioning process and the steps taken with each newly converted dual-fuel vehicle.

**Table 2: Commissioning Process**

| Major Steps in CAP Dual-Fuel Commissioning Process | | |
|---|---|---|
| **#** | **Activity** | **Description/Comments** |
| 1 | Program dual-fuel ECU | |
| 2 | Program gateway ECU modules | |
| 3 | Power-up checks | |
| 3.a | Switch on vehicle ignition and observe mode lamp | |
| 3.b | Connect and start CAP diagnostic tool | |
| 3.c | Sensor readings on "Engine Parameters" screen | |
| 3.d | Diagnostic tool tests ('Tests' menu on diagnostic tool) | ➢ 12 gas injectors in turn<br>➢ TAB Test<br>➢ SOV Test<br>➢ LOV Test<br>➢ Power Relay Test<br>➢ Lamp Test<br>➢ LNG Gauge Test |
| 3.e | Enter dealer settable parameters with diagnostic tool | ➢ Calibration - Enter parameter values for SAFR, HV, and MN as advised<br>➢ Assign injector codes and sequence |
| 3.f | Fault code checks | |
| 4. | Perform start-up checks | |
| 5. | Switch off the engine and top up coolant if required | |
| 6. | Fill LNG tank for the first time | |
| 7. | Dual-fuel start-up checks | ➢ Leak test<br>➢ SOV test<br>➢ Injector test<br>➢ Perform short test drive |

| Major Steps in CAP Dual-Fuel Commissioning Process | | |
|---|---|---|
| **#** | **Activity** | **Description/Comments** |
| 8. | Leak tests | ➢ Inspect tank pipework and chassis pipework |
| 9. | Test drive with loaded trailer | |
| 10. | Prepare for handover | ➢ Record test results and save in build folder |

Source: GTI

# CHAPTER 3: Demonstration and Field Trials

## In-Use Demonstration Test

CAP conducted an in-use demonstration test designed to monitor, characterize and optimize the in-use performance of 12 vehicles integrated with CAP's dual-fuel conversion system. As described in Chapter 1, the primary objective of the in-use test was to demonstrate the ability to achieve substitution, efficiency and performance adequate for commercial acceptance. A secondary objective was to obtain critical customer feedback and marketing information that would be used to make additional adjustments and enhancements before commercialization. Achieving these objectives would result in a heavy-duty dual-fuel engine capable of providing superior environmental and economic performance at a price that can be supported in the market.

Once all the required permits and approvals were obtained, CAP initiated the in-use demonstration test by identifying and selecting fleets that would operate the CAP dual-fuel vehicles.

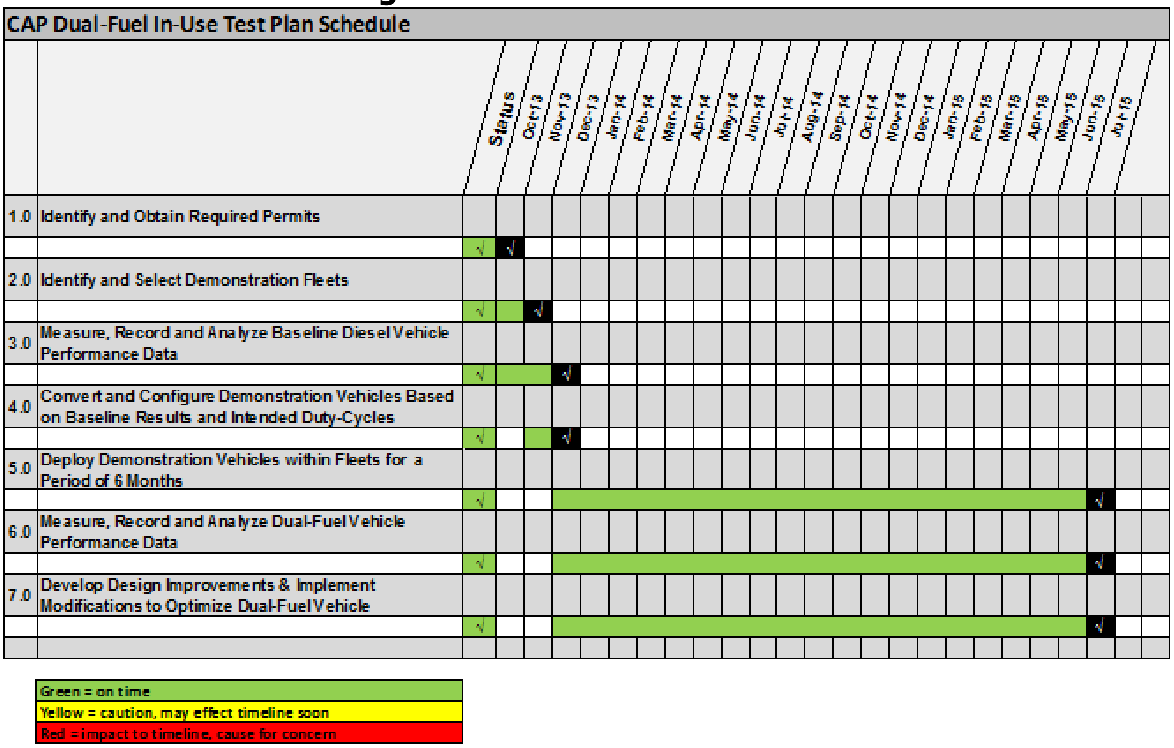
With the fleets selected, CAP evaluated a comparable conventional diesel vehicle (baseline vehicle) that represented the duty cycles that the dual-fuel demonstration vehicles will be placed into. The baseline vehicle evaluation measured, recorded, and analyzed operating parameters such as fuel consumption, engine load, engine speed, and other performance metrics that characterize the typical operating environment. These metrics were then used as a reference point for which the dual-fuel demonstration vehicles will be evaluated.

Following the baseline vehicle characterization, CAP's demonstration partners placed 12 dual-fuel demonstration vehicles into similar operational environments representative of the baseline vehicle duty cycles. Throughout the demonstration, CAP measured specific performance data and obtained operator feedback. This continuous feedback provided CAP with valuable information that was used to optimize the system before commercialization and completion of CARB certification. Similarly, the in-use performance data were analyzed throughout the demonstration. Because of this feedback, CAP's engineering team modified control system strategies to optimize vehicle and engine operating performance.

The figure below displays the 22-month timeline for the in-use demonstration. The first three months of the timeline comprised the upfront activities necessary to secure the required permits, select demonstration fleets, evaluate baseline vehicles, and convert 12 fleet vehicles with CAP's dual-fuel conversion system.

Following completion of the conversions, the demonstration vehicles operated in real-world conditions for about 20 months.

**Figure 8: Test Plan Schedule**




Source: GTI

## In-Use Demonstration Test Permits or Approvals

CAP secured the test permits and approvals necessary to conduct the in-use demonstration. A CARB experimental permit was required to operate the converted demonstration vehicles legally on California roadways. Under the provisions of Health and Safety Code Section 43014, an entity planning to test a technology that has not been certified by CARB must obtain an experimental permit from CARB’s Aftermarket, Performance, and Add-On Parts Section.[1] CARB issues experimental permits after an entity submits an experimental permit application containing technical information, demonstration test plans, and the alterations/modifications that will be made to the originally certified engine or vehicle. Experimental permits are valid for a one-year period but can be extended for an additional year to complete the testing, subject to CARB’s approval.

[1] California Air Resources Board, “Aftermarket, Performance and Add-On Parts,” (http://www.arb.ca.gov/msprog/aftermkt/aftermkt.htm#additional.)

Upon review of CAP's experimental permit applications, CARB issued Executive Orders C-318-10, C-318-11, and C-318-12 permitting the testing of CAP's demonstration vehicles. The CARB experimental permits are included with this report as APPENDIX A.

## Baseline and In-Use Demonstration Test Fleet Selection

Fleet selection is critical for a successful baseline vehicle evaluation and demonstration of CAP's dual-fuel system. For this reason, CAP selected fleets that would expose the demonstration test vehicles to a variety of real-world operating conditions. Of equal importance was the willingness of each fleet manager to cooperate throughout the demonstration period by providing feedback that would guide product optimization before commercialization. CAP contacted and evaluated several potential fleets representing applications across a range of duty cycles. CAP also considered the proximity of each candidate fleet to available fueling infrastructure, suitability of available fueling infrastructure to the vehicles characteristics, routes, and vehicle operating conditions. This was important because CAP's technical team regularly collected data, implemented performance improvement and corrective actions, and responded on short notice to assist demonstration partners with any malfunctions or issues that arose during the demonstration.

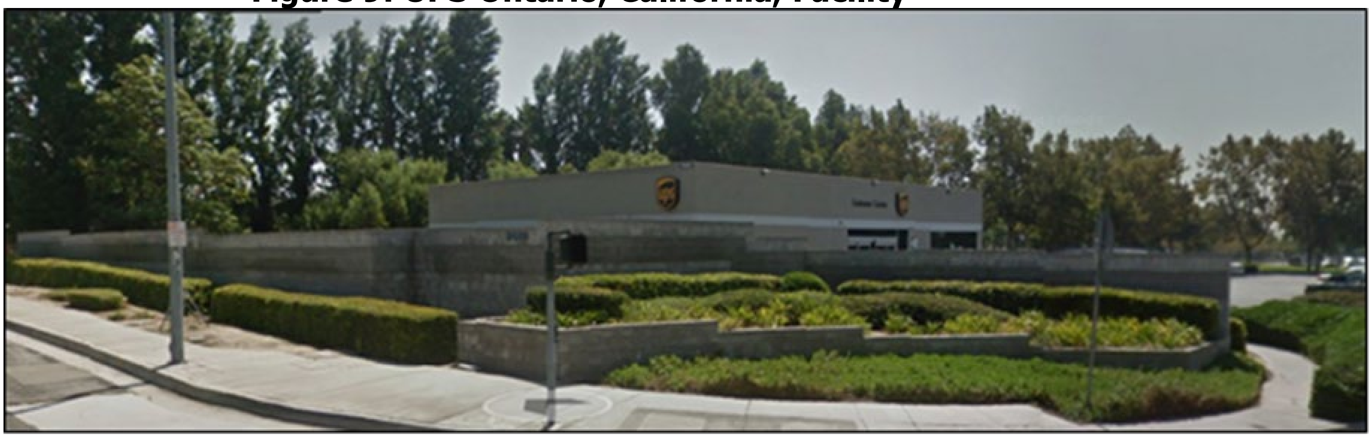
### UPS Baseline and In-Use Demonstration Test Fleet

United Parcel Service (UPS) was selected to demonstrate vehicles integrated with CAP's dual-fuel conversion system. Among the many reasons for selecting UPS as a demonstration partner was UPS's commitment to exposing the test vehicles to a variety of duty cycles and operating conditions. Moreover, UPS possesses significant experience demonstrating new technologies and has a deep understanding and comfort level with natural gas vehicle technologies. For these reasons, CAP selected UPS to evaluate baseline vehicles and demonstrate 10 vehicles during the demonstration period.

Throughout the test program, UPS operated 10 Mack MP8-powered tractors in a variety of duty cycles, which include mountainous, flat highway, desert, and city traffic conditions. The vehicles were operated under a variety of load conditions, ranging from an empty trailer to a fully loaded trailer operating at the legal full gross vehicle weight (GVW) limit of 80,000 lbs. For each driving shift, the UPS driver completed a data sheet indicating the number of miles driven, the gallons of diesel fuel, natural gas and diesel exhaust fluid (DEF) consumed, the load carried, and the trip destination. CAP's technical team collected and analyzed these data sheets weekly. CAP and UPS identified vehicle route schedules that accumulated nearly 390 miles per day and operated six days per week. CAP established this operating target to achieve a goal of accumulating one million miles during the demonstration period. The vehicles were inspected by CAP personnel regularly, and data were recorded and collected using CAP's dual-fuel system performance and diagnostic capabilities.

UPS's Ontario Air Hub served as the base location for the demonstration vehicles. The following figure displays the main entrance of UPS's Ontario Air Hub located at 10445 E. Jurupa St., Ontario (San Bernardino County).

**Figure 9: UPS Ontario, California, Facility**



Source: GTI

Fueling of the UPS demonstration fleet was performed at UPS's LCNG fueling station at 1735 S. Turner Ave. Ontario. The demonstration vehicles departed and returned to the UPS Ontario Air Hub each operating cycle. As a return-to-base fleet, the demonstration vehicles fueled primarily at this location with only a few fueling events being performed off-site. UPS's LCNG fueling station has been in operation for more than 12 years. The following table figure displays additional details on UPS's LCNG fueling station.

**Figure 10 : UPS LNG Station Information**

| **UPS Demonstration Fleet Fueling Location(s)** | | |
|---|---|---|
| **Station Name:** | UPS Ontario LCNG Station |  |
| **Street Address:** | 1735 S. Turner Ave. | |
| **City, State:** | Ontario, CA | |
| **Public/Private** | Public | |

Source: Gas Technology Institute

**TEC Leasing In-Use Demonstration Test Fleet**

As a complement to the varied duty cycles to which the UPS demonstration fleet would be exposed, CAP selected TEC Leasing as its second demonstration partner. TEC Leasing was selected to demonstrate two vehicles converted with CAP's dual-fuel conversion system. The vehicles were operated in short-term (one- to two-week) demonstrations with a variety of fleets during the test period. The small test group exposed the demonstration vehicles to varying operational environments, conditions, driving schedules, driving characteristics, duty cycles, and loading conditions. The data and experience provided valuable performance and operator feedback that complemented the results of the UPS demonstration. The short-term demonstrations were conducted with the partners listed in Table 5.

**Table 3: TEC Leasing Demonstration Fleets**

| **TEC Leasing Fleet Partners** | | | | |
|---|---|---|---|---|
| **Fleet Name** | **Application** | **Street Address** | **City, State** | **CAB *** |
| Quality Custom Distribution (QCD) | Food Distribution | 1497 Piper Ranch Rd. | San Diego, CA | SC |
| Rust and Sons | Reefer, Agricultural, Dry Van | 15353 Old Highway 80 | El Cajon, CA | SC |
| Miramar Transportation | Government Contracting, General Freight | 9340 Cabot Drive, Ste. I | San Diego, CA | SC |
| Sysco Los Angeles, Inc. | Food Distribution | 20701 E. Currier Road | Walnut, CA | DC |
| * SC: Sleeper Cab, DC: Day Cab | | | | |

Source: Gas Technology Institute

Fueling for the two vehicles participating in the demonstration fleet took place at a variety of public LNG stations throughout Southern California. The following table contains details for the public stations that provided LNG to the two TEC Leasing demonstration vehicles. Specific fueling locations depended on the routes selected by each fleet.

**Table 4: TEC Leasing Fueling Locations**

| TEC Leasing Fleet Fueling Location(s) | | | |
|---|---|---|---|
| **Station Name** | **Street Address** | **City, State** | **Public/ Private** |
| Otay Mesa Pilot - 343 | 1497 Piper Ranch Rd. | San Diego, CA | Public |
| Port of Long Beach | 3400 East I St. | Wilmington, CA | Public |
| Carson | 2045 Carson St. | Carson, CA | Public |
| City of Commerce | 5940 Sheila St. | Los Angeles, CA | Public |
| LA County Sanitation | 3212 Workman Mill Rd. | Whittier, CA | Public |
| Fontana Truck Stop | 14226 Valley Blvd. | Fontana, CA | Public |
| Riverside – Agua Mansa | 1830 Aqua Mansa Rd. | Riverside, CA | Public |
| UPS Ontario | 1735 S. Turner Ave. | Ontario, CA | Public |

Source: Gas Technology Institute

**In-Use Demonstration Test Technical Metrics**

The following technical metrics were measured and recorded by CAP's dual-fuel ECU during each vehicle operating cycle.

**Table 5: Technical Metrics**

| **Basic Information** | |
|---|---|
| VIN | |
| Date and Time of Operating Cycle | |
| **Malfunction Indicator Events During Operating Cycle** | |
| SPN Code and # of Occurrences | |
| FMI Code and # of Occurrences | |
| **Conditions Under Which Malfunction Would Be Detected and Recorded** | |
| Engine Percent Load | Engine Hours at Last Occurrence |
| Engine Speed | RMAP |
| Boost Pressure | Supply Voltage |
| Coolant Temperature | Requested Fuel |
| Intake Air Temperature | Lambda Reading |
| Gas Pressure | Lambda CNG Actual |
| Gas Temperature | Lambda CNG Desired |
| Gas Injection Angle | Engine State |
| Diesel Injection Angle | Skip Count |
| Diesel Dwell | Qnet ($mm^3$) |

| | |
|---|---|
| Gas Dwell | TBDC Corrected |
| Engine Hours at First Occurrence | |

Source: Gas Technology Institute

**In-Use Demonstration Test Operator Checklist and Subjective Metrics**
The following operator data were collected during each vehicle operating cycle.

**Table 6: Demonstration User Checklist**

| | |
|---|---|
| **Basic Information** | |
| Operator's Name | |
| Date | |
| Route | |
| **Start of Operating Cycle** | |
| Odometer Mileage | DEF Gauge |
| Fuel Gauge – Diesel | Vehicle Load % |
| Fuel Gauge – LNG | Trailer Length |
| **During Operating Cycle** | |
| Fueling Events – Diesel | |
| Fueling Events – LNG | |
| Fill Events – DEF | |
| **End of Operating Cycle** | |
| Odometer Mileage | DEF Gauge |
| Fuel Gauge – Diesel | Vehicle Load % |
| Fuel Gauge – LNG | Trailer Length |
| **Throughout Operating Cycle** | |
| Did CAP dual-fuel light illuminate during operating cycle? | |
| • Location where light illuminated | |
| • Mileage at which light illuminated | |
| • Driving conditions under which light illuminated | |
| Did vehicle run out of LNG during operating cycle? | |
| • Location where LNG ran out | |
| • Mileage at which LNG ran out | |
| • Conditions under which LNG ran out | |
| Did vehicle operate as expected? | |
| Miscellaneous operator comments | |

Source: Gas Technology Institute

## Description of Test Procedure, Data Collection, and Metrics

Throughout the demonstration, two methods were used to collect demonstration data. Vehicle and engine performance was measured, recorded, and stored using CAP's dual-fuel system ECU and sensors integral to the conversion system. As discussed above, CAP's dual-fuel conversion system is positioned in the middle of the communication path between the OEM vehicle ECU and OEM engine ECU. This positioning allows CAP's dual-fuel system to receive and transmit data to and from the OEM vehicle and engine ECUs to manage vehicle and engine performance. This is important to point out because the signals received from the engine and vehicle ECUs were stored by CAP's dual-fuel ECU. CAP's engineering team regularly collected and analyzed the critical performance and system operating data.

The second method in which data were collected during the demonstration period was directly from vehicle operators. Operators were asked to complete a short checklist at the beginning and end of each operating shift. In addition, providing real-world operating data, feedback from vehicle operators provided an avenue for obtaining subjective feedback. Correcting issues identified through this method of feedback enabled CAP to implement corrective actions for issues that might otherwise hinder commercialization.

### In-Use Maintenance and Data Collection Procedure

CAP's engineering team regularly performed maintenance on, and collected demonstration data from, each vehicle. Engineers visited the UPS site weekly. Due to UPS's schedule, it was typical that only half of the demonstration units were available for each visit. This resulted in all vehicles being addressed at least once over a rolling monthly period. The following figure illustrates how this was tracked.

**Figure 11: Example Tracking Form**

| Inspection Performed | Vehicle(s) Affected | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Data Download | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Data Download | ● | ● | ● | | ● | | | ● | ● | ● |
| Data Download | ● | ● | ● | ● | | | ● | | ● | |
| Data Download | ● | ● | ● | | ● | ● | ● | ● | ● | |
| Data Download | ● | ● | ● | ● | ● | ● | ● | ● | ● | |
| Full Technician Inspection | ● | ● | | | ● | | | | ● | ● |
| Full Technician Inspection | | | ● | ● | | ● | ● | ● | | |
| Data Download | ● | ● | ● | ● | ● | ● | | ● | ● | ● |
| Data Download | | | ● | ● | ● | ● | ● | | | |
| Data Download | ● | ● | | | | | | ● | ● | ● |
| Data Download | | ● | ● | ● | | | ● | | | ● |
| Data Download | ● | ● | ● | ● | ● | | | ● | ● | |
| Data Download | ● | ● | ● | ● | | ● | | | ● | ● |

Source: Gas Technology Institute

Maintenance was performed under the following conditions:

- Dual-fuel system fault codes present
- OEM fault codes present
- Adverse driver feedback
- Observance of failed component(s)
- DOT or periodic requirement

The data collected were as defined in Chapter 3. These data were then aggregated, or gathered, into a master tracking spreadsheet, which was reviewed on a weekly basis by the CAP project team. This review identified issues requiring attention and resolution to support the final commercialization of the product.

# CHAPTER 4: Test Results

## Baseline Vehicle Test Results

Working with UPS, CAP selected a baseline vehicle to install a data logging device for better understanding the operating metrics of a conventional vehicle in the environment that the demonstration test vehicles would be deployed. Moreover, the baseline vehicle evaluation served to identify parameters that must be adjusted on the dual-fuel vehicles before the start of the demonstration.

### Identification and Description of Baseline Vehicle(s) and Test Procedure

It was envisioned that several vehicles would be required for the baseline vehicle testing. However, discussions between CAP and UPS determined that data logging a single baseline vehicle would provide sufficient data representative of the vehicle types and duty cycles in which the dual-fuel vehicles will be placed. This was determined because UPS would operate the baseline vehicle on different routes with different drivers for each day that baseline data were collected. The table below displays general information for the baseline vehicle and engine.

**Table 7: Baseline Vehicle Identification**

| Baseline - In-Use Demonstration Test Vehicles | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | • Fleet Information | | Vehicle Information | | | | Engine Information | | | |
| | Name | Unit # | MY | Make | Model | VIN | MY | Make | Model | ESN |
| 1 | UPS | 273878 | 2012 | Mack | CXU613 | | 2012 | Mack | MP8 | |

Source: Gas Technology Institute

With the baseline vehicle selected, CAP technicians installed an Influx Technologies' Rebel xt[2] data logger to collect and record performance data. The Rebel data logger was equipped with GPS capabilities to better understand how the performance characteristics correlated to specific duty cycles or routes. Data were collected from the baseline vehicle via J1939 interface. The following fields were imported from the Rebel data logger

[2] Influx Technologies, Rebel xt, (http://www.influxtechnology.com/rebel.html.)

**Table 8: Data Logger Fields**

| Baseline Vehicle Performance Metrics | | |
|---|---|---|
| **Parameter** | **Units** | **PID** |
| Driver engine demand | | 61 |
| Engine torque | % | 64 |
| Engine speed | RPM | 0C |
| GPS | | |

Source: Gas Technology Institute

Once data were retrieved from the data logger, they were checked for quality, and outliers were purged from the dataset. Using engine speed and driver engine demand, instantaneous fuel injection was preliminarily calculated. These data were then used to calculate incremental fuel injection and, subsequently, total fuel injection. Using total fuel injection and distance, obtained from the GPS data, fuel economy was calculated for the operating cycles of each baseline vehicle. Lastly, GPS Visualizer[3] was used to overlay the GPS data collected on maps to better understand the operating cycle.

## Baseline Vehicle Operating Data and Test Summary

The 2012 Mack CXU613 baseline vehicle was placed into service for three weeks. Beginning on August 1, 2013, and ending on August 22, 2013, the baseline vehicle was evaluated over 18 days in operation. During this period, vehicle performance characteristics identified in the section above were measured, recorded and analyzed. The three-week test exposed the baseline vehicle to the eight unique routes shown in the following table.

**Table 9: Baseline Vehicle Routes**

| Baseline Vehicle Test Routes | | |
|---|---|---|
| **Starting Location** | **Delivery/Pickup Destination** | **End Location** |
| Ontario | Moreno Valley | Ontario |
| Ontario | Wasco | Ontario |
| Ontario | Mission Viejo | Ontario |
| Ontario | Wasco | Los Angeles |
| Los Angeles | Wasco | Los Angeles |
| Los Angeles | Coalinga | Los Angeles |
| Los Angeles | Moreno Valley | Los Angeles |
| Los Angeles | San Bernardino | Ontario |

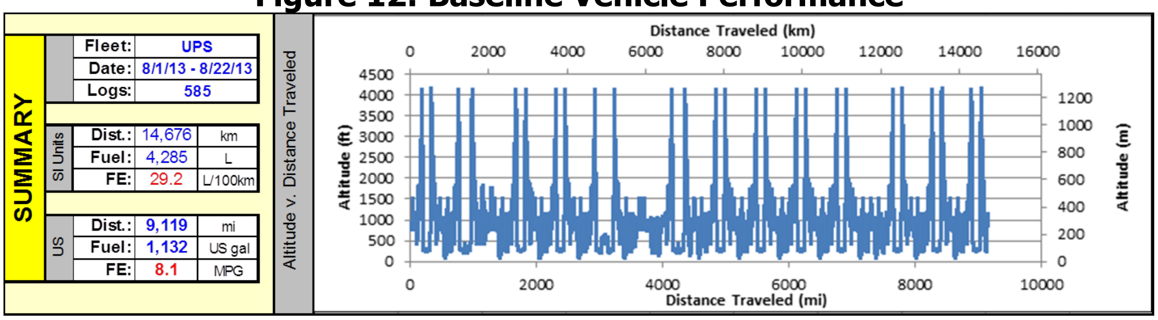
Source: Gas Technology Institute

3 GPS Visualizer, (http://www.gpsvisualizer.com/.)

The baseline vehicle began and ended daily operations at either UPS's Ontario or Los Angeles service centers. Eleven of the operating days began and ended at the same location, while the remaining seven days either began in Ontario and ended in Los Angeles or began in Los Angeles and ended in Ontario. As is typical for daily operating cycles of UPS's tractor trailers, the baseline vehicle started and ended operations wherever required and traveled to UPS locations in Moreno Valley, Wasco, Mission Viejo, Coalinga, and San Bernardino. In addition to being exposed to varying distances, the baseline vehicle experienced significant variations in altitude. For example, during trips to Wasco and Coalinga, the baseline vehicle traveled on Interstate 5, where a specific stretch of road, commonly known as the Grapevine, reaches an elevation of nearly 4,200 feet.

During the baseline evaluation period, the conventional diesel vehicle accumulated 9,119 miles and consumed 1,132 gallons of diesel fuel, achieving an overall fuel economy of 8.1 miles per gallon. On average, the baseline vehicle traveled nearly 500 miles and consumed 62.9 gallons of diesel per day. As discussed in the section above, fuel consumption was calculated, and a plot of the route was generated using GPS data. The figure below summarizes the performance and elevation profile of the conventional vehicle over the 18-day test.

**Figure 12: Baseline Vehicle Performance**




Source: Gas Technology Institute

The following table displays distance, fuel consumption, and fuel economy for each operational day during the test period. The shortest daily distance traveled during the test occurred on August 1, when the baseline vehicle travelled 59.8 miles during a round trip from Ontario to Moreno Valley. The longest daily distance traveled during the test occurred on August 8, when the vehicle travelled 720.2 miles during a round trip from Los Angeles to Coalinga. A daily summary and elevation versus distance plot are included with this report as APPENDIX B.

**Table 10: Baseline Vehicle Performance**

| Baseline Vehicle Performance Evaluation - August 2013 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1-Aug** | **2-Aug** | **4-Aug** | **5-Aug** | **6-Aug** | **7-Aug** | **8-Aug** |
| Distance (mile) | 59.8 | 580.5 | 429.5 | 477.6 | 587.8 | 618.8 | 720.2 |
| Fuel Consumed (gallon) | 8.8 | 74.1 | 60.5 | 57.7 | 73.8 | 73.7 | 87.5 |
| Fuel Economy (mile/gallon) | 6.8 | 7.8 | 7.1 | 8.3 | 8.0 | 8.4 | 8.2 |
| | **9-Aug** | **10-Aug** | **12-Aug** | **13-Aug** | **14-Aug** | **15-Aug** | **16-Aug** |
| Distance (mile) | 343.8 | 194.1 | 648.0 | 632.7 | 675.1 | 638.0 | 640.9 |
| Fuel Consumed (gallon) | 45.2 | 23.7 | 77.5 | 77.5 | 79.8 | 77.2 | 77.3 |
| Fuel Economy (mile/gallon) | 7.6 | 8.2 | 8.4 | 8.2 | 8.5 | 8.3 | 8.3 |
| | **19-Aug** | **20-Aug** | **21-Aug** | **22-Aug** | **Total** | **Avg.** | |
| Distance (mile) | 255.8 | 582.6 | 663.6 | 370.3 | **9,119.1** | **506.6** | |
| Fuel Consumed (gallon) | 32.6 | 74.2 | 82.9 | 48.0 | **1,132.0** | **62.9** | |
| Fuel Economy (mile/gallon) | 7.8 | 7.9 | 8.0 | 7.7 | | **8.1** | |

Source: Gas Technology Institute

## In-Use Demonstration Test Results

Upon completion of the baseline vehicle performance evaluation, the in-use demonstration test of CAP's dual-fuel technology commenced. UPS and TEC Leasing set out to demonstrate the dual-fuel technology in a variety of in-service applications. Aside from limiting the demonstration vehicles to routes with adequate natural gas fueling infrastructure or those with daily return-to-base operations, the demonstration partners subjected the vehicles to a variety of duty cycles, loading conditions, and operators. An example would be that truly longer haul operations within UPS were not considered as those trucks could leave the Ontario facility and not return for weeks. Within California this concern is limited, but there are certainly routes where users would run some days inside California, and then other days outside and extended for as much as a week. This section describes the demonstration test activities that were ultimately selected and the successes and challenges experienced.

### Identification and Description of In-Use Demonstration Test Vehicles

Throughout the period, test data were collected and used to optimize the hardware and control system for readying it for commercialization and CARB certification testing. The following table provides details of the vehicles that participated in the in-use demonstration test.

The 10 UPS vehicles were model year 2013 Mack CXU613 heavy-duty Class 8 truck chassis equipped with 2012 Mack MP8 heavy-duty diesel engines. The UPS demonstration vehicles were all-day cabs. Before placing the vehicles into service, CAP worked with UPS to configure the converted vehicles to meet the needs of the fleet. These configurations included adjusting maximum vehicle speeds, engine fuel rates, and other settings that matched the performance characteristics of the demonstration vehicles to those of UPS's conventional fleet. Figure 12 displays a UPS demonstration vehicle postconversion.

**Table 11: Demonstration Vehicle Identification**

| CAP Dual-Fuel - In-Use Demonstration Test Vehicles | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| # | Fleet Information | | Vehicle Information | | | | Engine Information | | | |
| | Name | Unit # | MY | Make | Model | VIN | MY | Make | Model | ESN |
| 1 | UPS | 273669 | 2013 | Mack | CXU613 | 032212 | 2012 | Mack | MP8 | 1006317 |
| 2 | UPS | 273673 | 2013 | Mack | CXU613 | 032216 | 2012 | Mack | MP8 | 1006338 |
| 3 | UPS | 273726 | 2013 | Mack | CXU613 | 032269 | 2012 | Mack | MP8 | 1007114 |
| 4 | UPS | 273670 | 2013 | Mack | CXU613 | 032213 | 2012 | Mack | MP8 | 1006320 |
| 5 | UPS | 273727 | 2013 | Mack | CXU613 | 032270 | 2012 | Mack | MP8 | 1007122 |
| 6 | UPS | 273675 | 2013 | Mack | CXU613 | 032218 | 2012 | Mack | MP8 | 1006350 |
| 7 | UPS | 273671 | 2013 | Mack | CXU613 | 032214 | 2012 | Mack | MP8 | 1006323 |
| 8 | UPS | 273674 | 2013 | Mack | CXU613 | 032217 | 2012 | Mack | MP8 | 1006342 |
| 9 | UPS | 273672 | 2013 | Mack | CXU613 | 032215 | 2012 | Mack | MP8 | 1006328 |
| 10 | UPS | 273728 | 2013 | Mack | CXU613 | 032271 | 2012 | Mack | MP8 | 1007125 |
| 11 | TEC | YAGZ412 | 2013 | Volvo | VNL670 | 139833 | 2012 | Volvo | D13 | 1003972 |
| 12 | TEC | YAHA343 | 2013 | Volvo | VNL300 | 143457 | 2012 | Volvo | D13 | 1008078 |

Source: Gas Technology Institute

**Figure 13: UPS Dual-Fuel Vehicle**


Source: Gas Technology Institute

As indicated above, the two TEC Leasing vehicles that participated in the demonstration test include a Volvo VNL670 and a Volvo VNL300. The VNL670[4] is a long-haul tractor that comes equipped with a sleeper cab. The VNL300[5] is a short-haul/regional-haul tractor equipped with a day cab. Both vehicles are equipped with 2012 Volvo D13 heavy-duty diesel engines certified alongside the 2012 Mack MP8 diesel engine. The VNL 670 uses Volvo's I-Shift transmission, while the VNL 300 uses a 10-speed manual transmission. Demonstrating the performance of CAP's dual-fuel conversion system mated to two types of transmissions on comparable vehicles ensured versatility once the systems are commercially available. In addition, validating performance across a multiple transmissions ensured that the system would reach the widest range of potential end users once commercialized. The figures below display both TEC Leasing demonstration vehicles postconversion.

[4] Volvo Trucks – United States, VNL670, (http://www.volvotrucks.com/trucks/na/en-us/products/vnl/VNL670/Pages/vnl670.aspx.)

[5] Volvo Trucks – United States, VNL300, (http://www.volvotrucks.com/trucks/na/en-us/products/vnl/vnl300/Pages/vnl300.aspx.)

**Figure 14: TEC Dual-Fuel Vehicle**


Source: Gas Technology Institute

**Figure 15: TEC Dual-Fuel Vehicle**


Source: Gas Technology Institute

## UPS In-Use Demonstration Test Summary

The 10 UPS vehicles were demonstrated for roughly 18 months, from December 2013 to June 2015. During this time, the test group accumulated 1,544,990 miles of service. The test group achieved an average substitution rate of 52 percent while sustaining an average fuel economy of 7.57 miles per DGE. The following table summarizes the performance of the UPS test group.

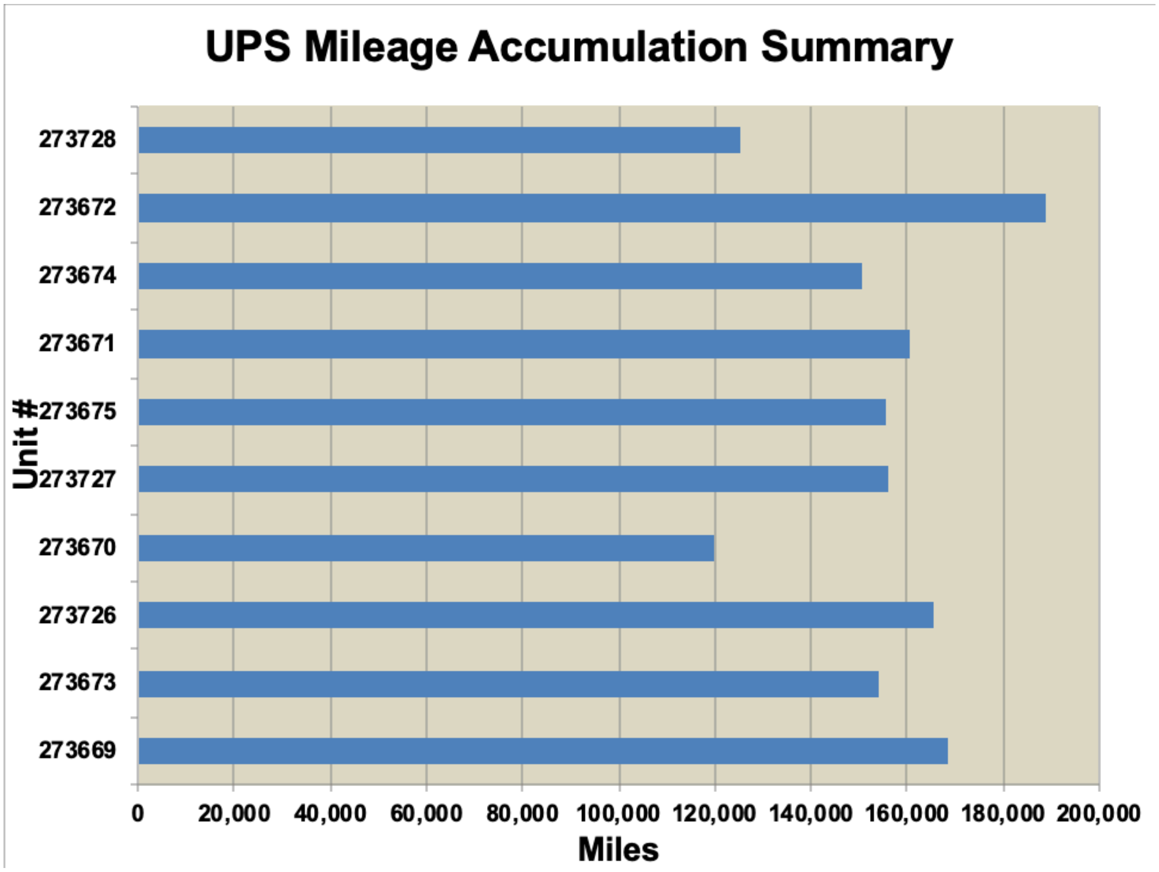
**Table 12: UPS Test Group Summary**

| UPS Test Group Demonstration Summary | |
|---|---|
| **Test Group Demonstration Summary** | |
| Total Days in Service | 5,400 |
| Total Miles Accumulated | 1,544,990 |
| Avg. Fuel Economy (miles/DGE) | 7.57 |
| **Test Group Dual-Fuel Summary** | |
| % Time in Dual-Fuel Mode | 77% |
| % Substitution | 52% |
| Total Natural Gas Consumed (DGE) | 75,562 |
| Dual-Fuel Diesel Consumed (gallons) | 70,999 |
| Total Diesel Consumed (gallons) | 123,225 |

Source: Gas Technology Institute

Each vehicle in the UPS test group entered service in December 2013 and continued to operate through June 2015. The performance of each vehicle was measured and recorded throughout the demonstration period. Operating on a variety of routes throughout California, mileage accumulation for the test group ranged from a low of 93,524 miles to a high of 174,957 miles, with an overall average of 154,499 miles. The following figure displays the mileage accumulated for each vehicle in the test group.

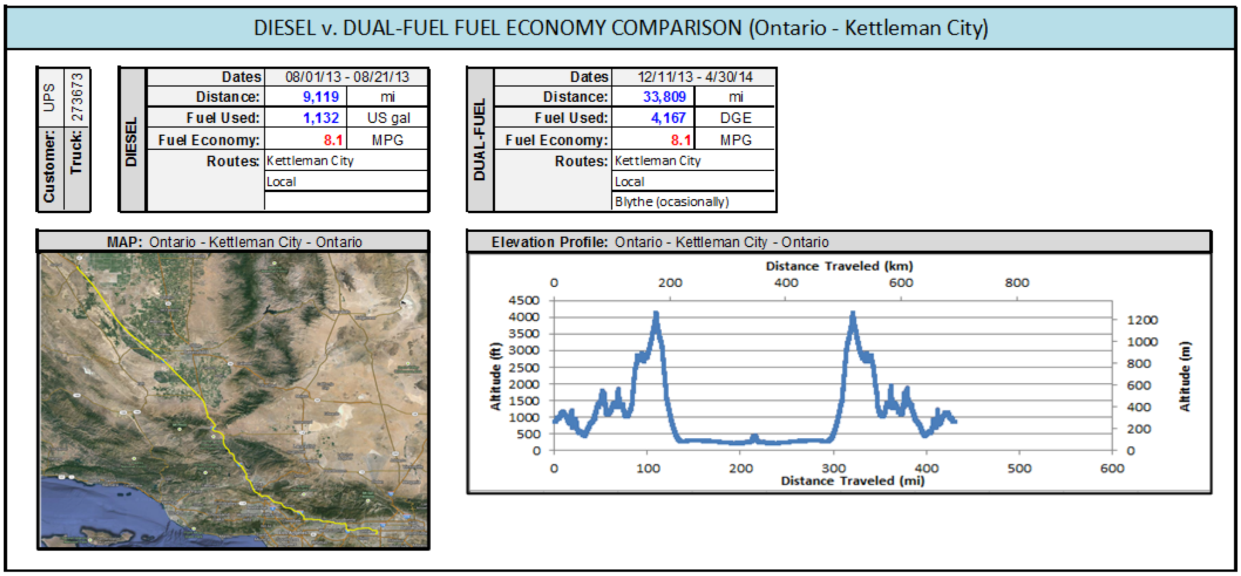
**Figure 16: UPS Mileage Accumulation**




Source: Gas Technology Institute

As discussed above, the test group achieved an average fuel economy of 7.57 miles per DGE. Within the group, fuel economy varied from a low of 7.04 to a high of 8.17 miles per DGE, which is in the range of what would be expected given the wide range of duty cycles experienced by the test group. This fuel economy compares to the baseline vehicle fuel economy of 8.1 miles per diesel gallon. However, this vehicle experienced a narrower duty-cycle variation and was the only vehicle, with one driver, over a relatively short baseline test period of 9,119 miles, in summer only. To gain confidence that the fleet MPG was comparable to the baseline vehicle, a specific subset of the UPS fleet data was extracted to compare the diesel baseline performance and the dual-fuel performance, when operated by only one vehicle on the same routes. (See Figure 16 below.)

## Figure 17: UPS Fuel Economy Comparison




Source: Gas Technology Institute

This analysis shows a fuel economy of 8.1 miles per gallon in both modes, substantiating the conclusion of comparability. See the following table.

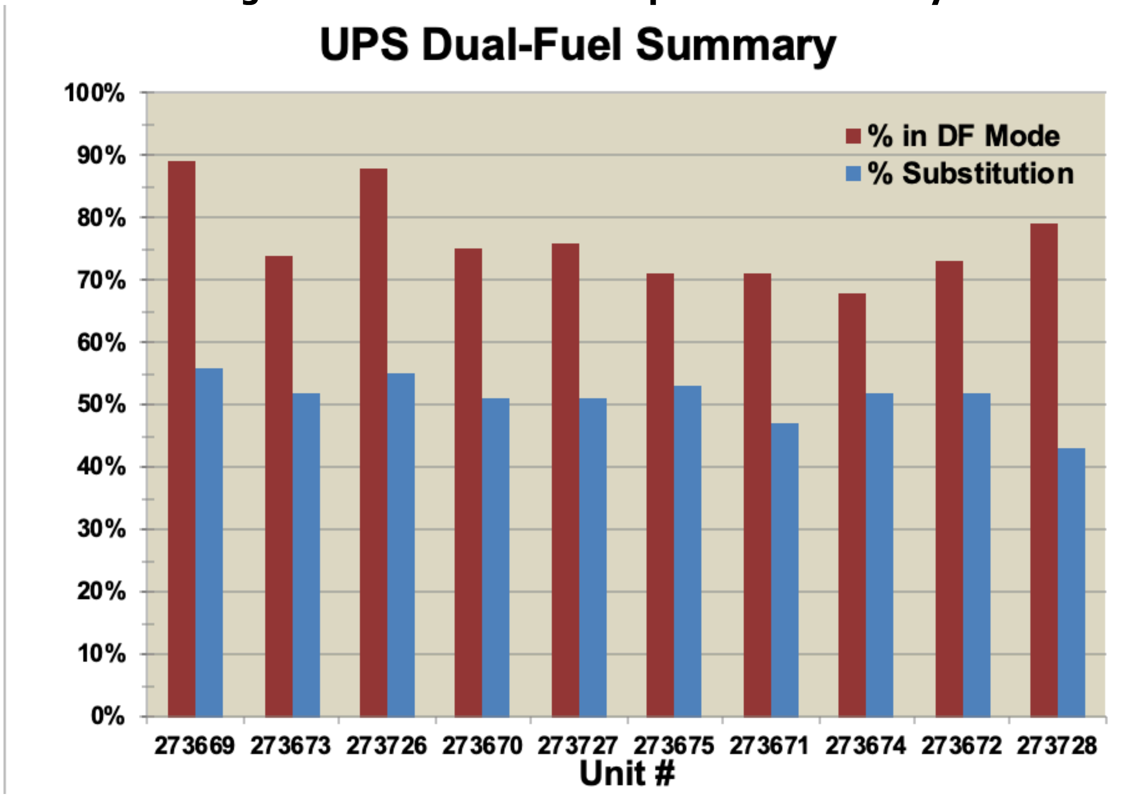
**Table 13: UPS Fuel Economy Comparison**

| Truck | Miles | Diesel Used | NG Used | MPG |
|---|---|---|---|---|
| UPS Demonstration Fleet | 1,544,990 | 123,225 | 75,562 | 7.57 |
| Baseline | 9,119 | 1,132 | - | 8.1 |
| UPS Unit 273673 subset | 33,809 | 2,467 | 1,700 | 8.1 |

Source: Gas Technology Institute

The test group substituted 52 percent of the fuel (DGE) consumed with natural gas. Within the test group, the substitution rate ranged from a low of 43 percent to a high of 56 percent, which is in the range of what would be expected given the wide range of duty cycles experienced by the test group. Equally important to the evaluation of substitution rates is the amount of time that the vehicles spent in dual-fuel mode. Recall that the dual-fuel system substitutes diesel with natural gas only when the desired operating conditions are met. For this reason, increasing the time that the system spends in dual-fuel mode will increase the total natural gas consumed during a particular duty cycle. Therefore, optimizing both the amount of time a vehicle spends in dual-fuel mode and the substitution rate achieved are critical to commercial acceptance of the conversion system. During the demonstration, the test group spent an average of 77 percent of the operating time in dual-fuel mode. For the demonstration vehicles, the average ranged from a low of 68 percent to a high of 89 percent. The following figure displays the substitution rate and percentage of time spent in dual-fuel mode for each demonstration vehicle.

**Figure 18: UPS Dual-Fuel Operation Summary**




Source: Gas Technology Institute

On May 21, 2015, a "final handover" meeting was held with personnel from the Ontario UPS facility. Present were representatives from upper management, local fleet management, local technician management, and driver representatives. Comments received were very positive, and Clean Air Power received especially high praise for product support. When asked specifically about driver opinion, the consensus was that the drivers were satisfied with the performance of the product.

The following are direct quotes from the group: "I have heard no complaints on power, and I would" and "I don't hear any complaints." Both were direct responses to driver satisfaction questions.

### TEC Lease In-use Demonstration Test Summary

To ensure the robustness and performance of the dual-fuel system, two TEC Leasing vehicles were placed into service with local fleets. The TEC Leasing vehicles were demonstrated over four months, from March 2015 to June 2015.

During this time, the test group accumulated 5,651 miles of service. The test group achieved an average substitution rate of 48.2 percent while sustaining an average fuel economy of 7.49 miles per DGE. The lower substitution rate achieved by the TEC Leasing test group was to be expected given that the demonstration partners had less time operating the vehicles. Additional detail discussing these results will be provided later in the section. The following table summarizes the performance of the TEC Leasing test group.

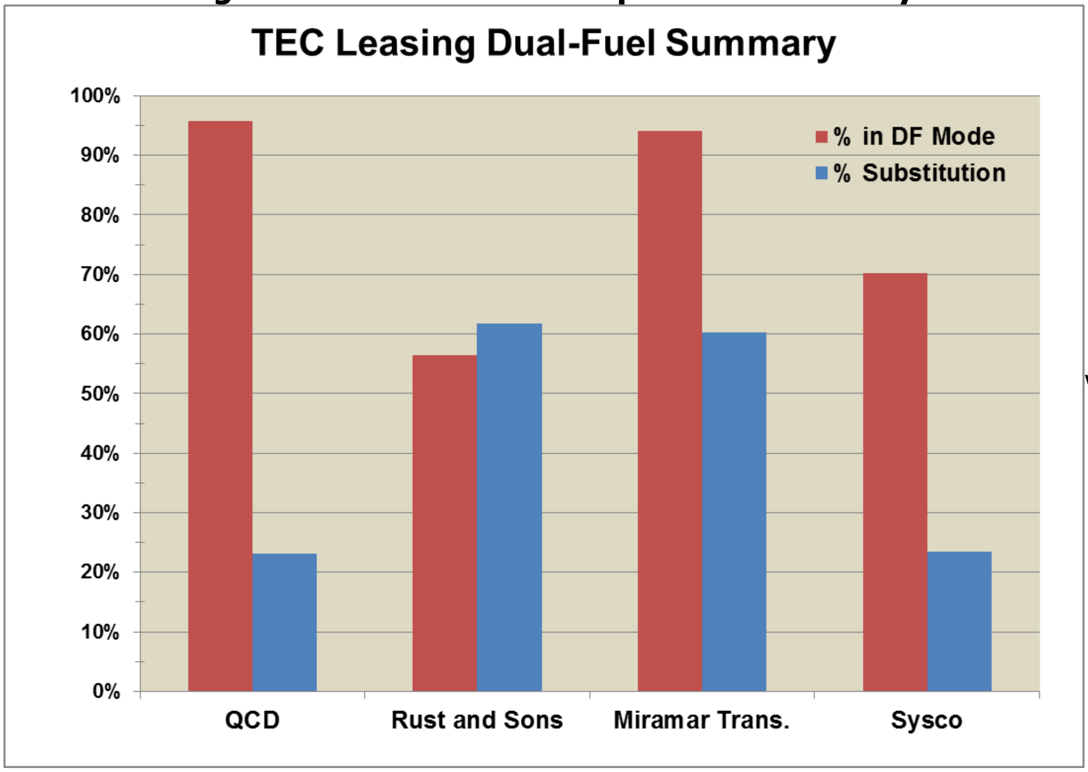
**Table 14: TEC Demonstration Vehicles Summary**

| **TEC Leasing Test Group Demonstration Summary** | |
|---|---|
| **Test Group Demonstration Summary** | |
| Total Days in Service | 20 |
| Total Miles Accumulated | 5,651 |
| Avg. Fuel Economy (miles/DGE) | 7.49 |
| **Test Group Dual-Fuel Summary** | |
| % Time in Dual-Fuel Mode | 76.2% |
| % Substitution | 48.2% |
| Total Natural Gas Consumed (DGE) | 319 |
| Dual-Fuel Diesel Consumed (gallons) | 342 |
| Total Diesel Consumed (gallons) | 532 |

Source: Gas Technology Institute

For the demonstration partners, the substitution rate ranged from a low of 23.1 percent (QCD) to a high of 61.8 percent (Rust and Sons). The percentage of time spent in dual-fuel mode ranged from a low of 70.3 percent (Sysco) to a high of 95.7 percent (QCD). The low substitution indicated by the QCD trial was due to an anomaly with the Volvo I-Shift transmission not experienced with the manual transmissions of the UPS vehicles. Time in mode was higher in both cases due to later versions of software and product maturity developed during early UPS operation. The following figure displays the substitution rates and percentage of time spent in dual-fuel mode for each demonstration partner:

**Figure 19: TEC Dual-Fuel Operation Summary**




Source: Gas Technology Institute

Further examination of the performance and experiences of each demonstration partner provided additional insight into the results displayed in the figure above.

Hauling a gross combined vehicle weight (GCVW) of more than 70,000 pounds, Rust and Sons achieved a substitution rate that was comparable with what would be expected. However, the percentage of time spent in dual-fuel mode was disproportionately low, which prompted further investigation. Discussions with the vehicle operator at the end of the demonstration period revealed that operator did not fuel the vehicle with natural gas after being notified that the tank was empty. Because the system detected that the LNG tank was empty, the conditions for dual-fuel mode were not met. Had the driver fueled with LNG, analysis indicates that the percentage of time spent in dual-fuel mode would have surpassed 95 percent. Assuming the operator commits to fueling with LNG whenever notified that the tank is empty, CAP's dual-fuel technology would provide Rust and Sons with significant cost savings once commercially deployed.

Miramar Transportation's demonstration of CAP's dual-fuel system provided further evidence of commercial acceptance once CARB-certified. Miramar Transportation achieved a substitution rate of 60.2 percent while operating 94.1 percent of the time in dual-fuel mode. Unlike Rust and Sons, Miramar Transportation hauled a relatively light load of just over 55,000 pounds. This is encouraging in that substitution rates typically suffer in light-load applications.

Feedback from the operator stated that the system was quieter and experienced less vibration than a comparable diesel vehicle. The driver also mentioned that a slight lack of power was experienced while in dual-fuel mode under certain operating conditions. Analyzing the performance data and operator feedback revealed that the lack of power occurred under high loads when the engine was operating at very low speeds. Because the torque band changes when operating in dual-fuel mode, it is recommended to maintain engine speeds greater than 1,400 revolutions per minute (rpm) to avoid any power loss. This feedback reaffirmed the importance of operator training with each deployment.

Both Sysco's and QCD's demonstrations of CAP's dual-fuel system indicated that their operations would not be an ideal fit. The combination of relatively low load weights and low duty cycles were not sufficient for the system to provide significant benefits. Upon completion of the demonstration, discussions revealed that Sysco does have routes and load conditions that would be better fit for CAP's system. Sysco and CAP agreed to investigate the opportunity to conduct additional demonstrations.

The TEC Leasing demonstration proved to be invaluable to the future commercial acceptance of the technology. The importance of accurately evaluating the operations of a fleet prior to deploying the technology within a particular fleet was evident. As a result, CAP has improved its fleet qualification process. Additional changes have been made to the CAP training material and fleet introduction communication. Route selection has become less critical in the latest versions of the control software.

Before the demonstrations of these two tractors with TEC Leasing, Clean Air Power's engineering team used the vehicles for drivability and performance development. During that period, one tractor was operated for 24,333 miles and the other for 34,482 miles for a total of 58,815 miles. These tests were performed with a 53-foot trailer at varied loads to simulate real-world conditions. A detailed report on fuel efficiency and substitution that resulted from CAP engineering staff observations is included with this report as APPENDIX C.

## Operator Feedback During In-Use Demonstration Test

Operator feedback was obtained throughout the demonstration period. The feedback provided was important to improving the dual-fuel system, as well as refinements made to fleet and operator training plans.

Feedback was collected in several ways. Initially, UPS test vehicle operator forms were filled out (Shown in Chapter 3 and Table 8). As the trial progressed, operators became less likely to complete the forms. CAP then transitioned to verbal interviews with drivers during data download sessions. At the completion of each of the TEC trials, there was a meeting held with management representatives at each fleet. This meeting included feedback from drivers. As mentioned, a formal management handover meeting was held with UPS at the conclusion of the demonstration period.

The following are examples of feedback obtained during the demonstration period:

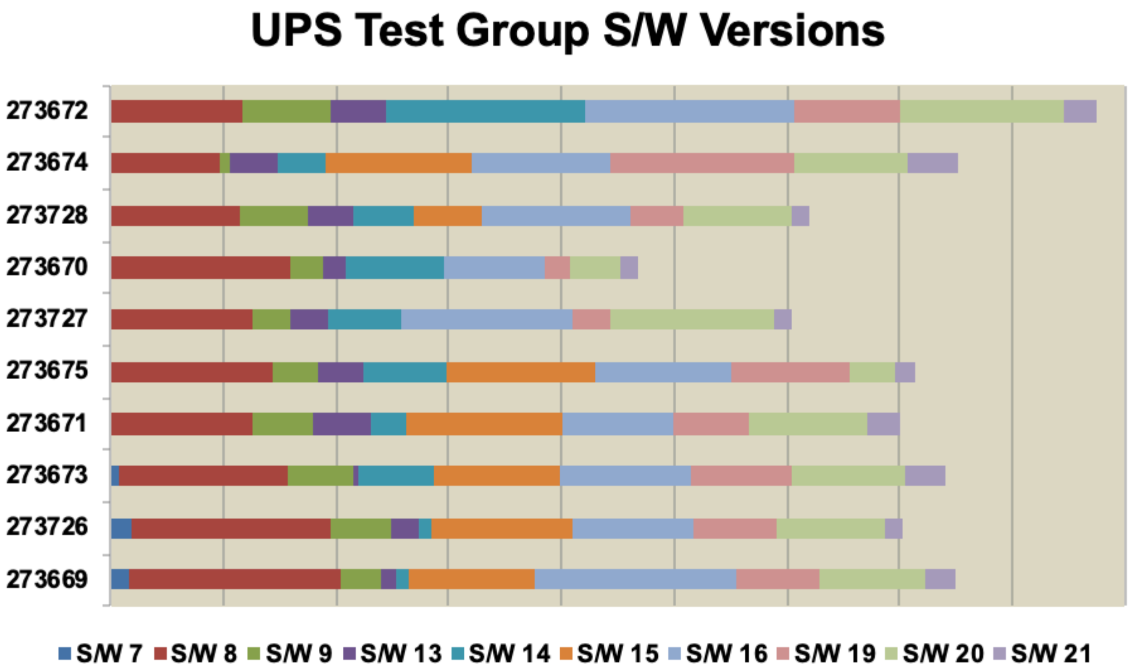
- Operators were pleased with the quietness of the engine when operating in dual-fuel mode.
- Operators were pleased with diesel-like drivability.
- Operators described instances of low power when in dual-fuel mode under high loads and low engine speeds.
- Operators expressed concerns over LNG fueling availability and fueling times.
- Operators gave positive feedback regarding diesel fallback capability.
- These meetings and operator feedback provided valuable input to the research team's hardware and software change process.

## Software Modifications/Upgrades during In-Use Demonstration Test

Throughout the demonstration, CAP engineers continuously evaluated vehicle performance data to optimize dual-fuel performance. This optimization was an iterative process that resulted in several modifications to the CAP ECU software. CAP engineers implemented 10 versions of software, which was performed by re-flashing the CAP ECU during routine retrieval of vehicle operating data. The software upgrades enhanced engine performance and emissions performance, added features, improved natural gas substitution rates, and provided beneficial features to aid product demonstration and commercialization. After each version of software was implemented, CAP engineers evaluated performance to determine if each corrective action achieved the intended result. The following figure displays the relative time accumulated under each version of software by unit.

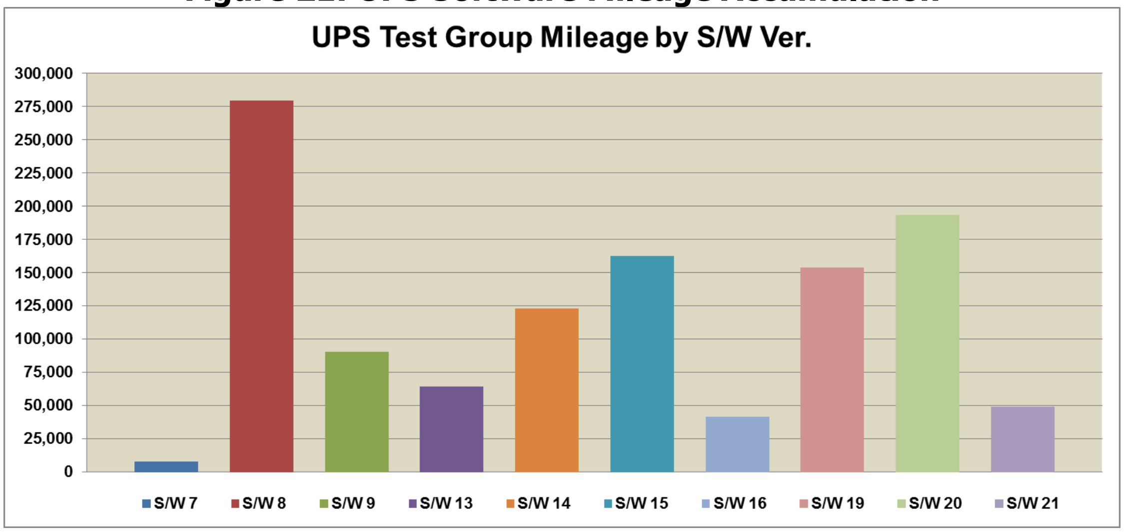
New versions of software were implemented in a phased approach. For example, the original software (Version 7) was implemented on three vehicles, Units 273669, 273726, and 273673. After delivery of the first three vehicles, CAP engineers evaluated vehicle performance prior to delivery of the remaining vehicles in the test group. During this time, the evaluation identified corrective actions that would improve dual-fuel performance and drivability. This led to the development of software Version 8, which was implemented prior to subsequent vehicle deployments. Furthermore, some software versions were rejected after initial evaluation in the test cell. Shown in the figure below are only those versions that actually accumulated mileage on the road within the UPS test group.

**Figure 20: UPS Software Versions**




Source: Gas Technology Institute

**Figure 21: UPS Software Mileage Accumulation**




Source: Gas Technology Institute

### Hardware Modifications/Upgrades During In-Use Demonstration Test

CAP engineers implemented 10 hardware upgrades throughout the demonstration to enhance driver convenience and protection, extend equipment life, increase operability ranges, and provide additional beneficial features to aid product demonstration and commercialization. No significant mechanical failures or problems were observed during the demonstration.

## Commercial Readiness

Clean Air Power uses a product development process for each new product the company offers. The process consists of five major gateway reviews by CAP senior management. Each gateway consists of reviewing the evidence that the phase of the project has been completed satisfactorily. The five phases are:

- Planning.
- Product design and development.
- Process design and development.
- Product and process validation.
- Production.

The product development process is based on automotive industry standard quality practices. The in-use demonstration project described in this final report contributed greatly to meeting the required deliverables in all phases of the overall product development project. Specifically, results from a customer trial fleet are required by the product development process before product launch, along with successful problem resolution. Also, the fabrication of the 12 demonstration vehicles produced valuable process documentation and validation. The data gathered from the in-use demonstration allowed CAP to confirm that the finished product conformed to the initial functional objectives, thus confirming commercial readiness.

# CHAPTER 5: Findings and Conclusions

Based on the results of the in-use testing, the project team's primary conclusion is that the Clean Air Power natural gas version of the Volvo Group D13/MP8 engine is successfully demonstrated as providing acceptable performance at an economically competitive cost. Further, the team can draw a series of more detailed conclusions based on both the specific objectives of the program and additional learning points encountered throughout the project time frame.

## Viability

The 13-liter Dual Fuel™ compression ignition engine utilizes an average as high as 60 percent of natural gas ignited by a pilot quantity of diesel, while meeting the U.S. EPA/CARB 2010 on-highway emission standards, and thus proves a viable commercial offering for operators of the equivalent diesel vehicle. The CARB certification obtained for this engine during this project enhances viability and commercialization.

## Acceptability

With a peak power rating of 425 hp, and 1,550 lb-ft of torque, the drivability of the compression-ignited engine was shown to be similar to the equivalent diesel engine and gained strong levels of operator acceptance, filling an existing gap in the alternative fuel engine marketplace.

## Efficiency

Typical heavy-duty natural gas engines demonstrate as much as a 20 percent energy efficiency penalty as compared to the contemporary diesel counterparts. Competitive heavy-duty natural gas engines typically employ Otto cycle combustion as is used in a gasoline-powered light-duty vehicle. This compromise minimizes the benefit of lower-cost natural gas as more total fuel is burned for the same work, eliminating much of the operating cost savings.

Conversely, dual-fuel engines are capable of maintaining the benefits of the compression-ignition, diesel combustion cycle, which explains the inherent efficiency benefit. The reason is that there is no need for an air throttle to control air/fuel ratio, and that dual-fuel engines retain the compression ratio of the parent engine. Data collected during the in-use testing demonstrate that the CAP conversion to a natural gas engine resulted in a class-leading efficiency penalty of roughly 3 percent across a series of duty cycles.

## Demonstration Process

Operation of the fleet for a significant time and distance has highlighted several opportunities to optimize the system for improved performance and operator acceptability. Without this stage and the funding that supported it, the project team believes it would be very difficult to deliver an acceptable alternative-fueled product to commercial vehicle fleets without compromising operational performance.

## System Robustness

The vehicles used in the demonstration fleet were driven by several operators across different applications, delivering reliable and variable performance, as measured by levels of utilization of natural gas and other performance data. Performance was found to improve with experience or training, and the base capability of the system to deliver was always present.

## Diesel Backup

For a new technology such as this to gain acceptance in commercial operation, it is significant that the Dual-Fuel system can operate in diesel mode in the event of unforeseen circumstances.

## Vehicle Systems

The interaction with the EMD+ technology on the base diesel vehicle and the necessity to not trigger vehicle fault messages have proven more complex than predicted, resulting in a significant amount of unplanned effort in developing the DFCI engine. This effort will be compounded with the evolution to full on-board diagnostic capability (OBD), such that a full development project would need similar financial support to deliver a commercially viable product.

## Additional Lessons Learned

Initially, the research team's proposed OEM partner was Navistar Inc. At the time of the application, the authors had just completed a concept development project with it based on its MaxxForce 13 engine. Subsequently, Navistar dropped all natural gas development projects to focus on its core diesel product due to regulatory pressures. This required Clean Air Power to select another OEM. Having previous experience with both Volvo Truck and, specifically, its D13 engine model, the research team transitioned to Volvo as the technology platform for this project. As a current supplier for its European variant, the team elected to modify that product to a U.S. example meeting EPA and CARB standards. The D13 has fundamental differences to the MaxxForce engine, which required engineering resources not originally scheduled that contributed to project delays. The change of OEM, however, gave the team the opportunity to compare different diesel engine technologies and associated performance with the team's Dual-Fuel technology. This highlighted that certain diesel engine attributes are preferential to Dual-Fuel operation.

The need to generate and compile varied diesel baseline data on multiple vehicles vs. just one diesel baseline vehicle was a lesson learned. Moreover, the authors have recognized the need for ongoing control vehicles operating within the test fleet to account for seasonal and application variations. Having multiple and reliable data logging equipment would enable future demonstration projects to obtain these critical baseline data. Recent advances in data logging technology should reduce the associated cost and improve the reliability of the data.

Having a centralized cooperative fleet partner such as UPS was critical to the success of the demonstration project. As with any new technology, there will be issues identified, and technical solutions will have to be implemented quickly to reduce fleet downtime. The facility and workforce (technicians, drivers, and dispatch and support personnel) at UPS were already familiar with using natural gas for HD commercial transportation vehicles, and this experience was very valuable and contributed to the success of this demonstration project. Also having a fleet operating 24 hours a day, six days a week generated mileage very quickly and helped give valuable feedback to Clean Air Power personnel when a change was implemented.

Another important success factor developed during this demonstration that should be included in future projects is having a disciplined problem-solving process. Each issue generated from the demonstration fleet was documented and tracked in a database until the issues were resolved. This structured problem identification and solution process was supported by Clean Air Power senior management, and responsible persons were identified and held accountable to report at a weekly meeting to review their progress toward a solution. The steps included immediate containment action, cause identification, final corrective action, and verification. More than 90 technical issues were identified and resolved during the 20-month demonstration and resulted in a more robust product ready for sale.

# CHAPTER 6: Findings and Benefits

## Technological Impacts

In its current state, the dual-fuel retrofit technology will probably not have much if any immediate effect. But as pressure mounts for alternatives to diesel-fueled freight systems, this technology may become one of the few available solutions. If nothing else, it may allow for a gradual phasing from current levels of diesel use to other fueling activities or electrification. This would be especially true if natural gas becomes increasingly abundant within the future transportation fuel mix.

## Direct Benefits

This retrofit, dual-fuel, add-on technology will have very desirable benefits once in more general use, especially at high substitution rates. At high substitution rates, diesel is used more to initiate combustion, and less as an energy contributor to combustion. As substitution rates increase, diesel exhaust, a toxic air contaminant, is gradually decreased. In addition, fuel soot content will also decrease, reducing the opportunity for PM2.5 emissions. This equates to reducing emissions of carbon black and diesel exhaust, toxic air contaminants.

At high substitution rates, the reduction in carbon dioxide emissions is estimated by CAP to be 15 percent over that for current diesel fuel combustion. If one compares the pounds of carbon dioxide produced from million Btu of diesel versus natural gas, diesel produces 161.3 pounds as compared to 117.0 for natural gas when burned separately. Diesel carbon dioxide emissions are almost 38 percent higher than for natural gas. Therefore, CAP's 15 percent estimate is credible.

With dual-fuel firing, control of emissions is accomplished with an add-on technology that is installed only once. The costs occur during installation, and there are no extra ongoing maintenance costs. Emission reductions are enabled through cleaner fuels. According to CAP, technician training and certification were not a problem that would hinder distribution of a commercialized retrofit package.

It is difficult to distinguish fuel-economy differences between dual-fuel and diesel operation. The in-use demonstration results for fuel economy and substitution rate are hard to reduce. They differ depending on test group, application, and condition of operation. If one considers just the UPS test group, the substitution rate varied from 43 to 56 percent, with an average of 52 percent. The fuel economy ranged from 7.04 to 8.17 miles per natural gas DGE and diesel combined on an energy (Btu) basis. The baseline fuel economy was 8.1 miles per gallon of diesel. The transmission of the truck makes a big difference in the performance of the dual-fuel system. With the automatic transmission, the fuel economy is improved over a manual transmission, as would be expected. The automatic transmission also has a negative impact on substitution. This is due to the dual-fuel system having to let the gear box control fueling during gear shifts and sometimes means a transition back into dual-fuel mode after a shift is missed.

Neglecting the needs to fine-tune the control technology to specific engines and work cycles, the above benefits are accomplished through the one-time addition of retrofit technology without negating the ability to fire on diesel only. Therefore, diesel can be used as either a backup or alternative fuel when not operating in dual-fuel mode. Furthermore, this ability to fire in two modes contributes to the diversification of transportation fuel sources during any shortages of either natural gas or diesel. Finally, natural gas can be used in the form of compressed natural gas or liquefied natural gas, depending on the preference of the truck owner.

Although no supporting data were provided, CAP maintains that drivability of the Volvo and Mack engines were similar for both dual-fuel and diesel firing. Based on feedback from drivers, there did not appear to be a significant loss of performance in dual-fuel mode, as would be experienced when comparing spark ignition of natural gas with compression ignition of diesel.

## Problems and Limitations

For now, future progress in developing this technology for other diesel engines will depend on the cooperation with other "fleet partners." Such partners were critical for the success of this project.

## Energy Impacts

The dual-fuel retrofit system is not yet of consequence to the current transportation fuel. However, if the technology should evolve past needing duty-cycle adaption while being adapted to more diesel engines, it could represent a major avenue to reduce diesel use within the transportation fuel mix. This is especially true if it comes as original equipment on new vehicles, not just as a retrofit device. At that point, the technology could provide a major inroad for natural gas use for local as well as long-haul trucking. This would represent a major displacement in the transportation fuel mix. Such an increase in the demand of natural gas would change roadway fuel storage to accommodate high-pressure natural gas storage and to move away from liquid tank storage for diesel.

## Health Benefits

The primary health benefit resulting from widespread use of this technology would be the reduction of diesel exhaust emissions, a toxic air contaminant. The level of benefit would depend on the substitution rate. Even at high substitution rates, some diesel would be combusted for compression ignition.

Minor criteria pollutant reductions would be associated with the reduction of lower fuel-bound nitrogen and sulfur of natural gas. Although small reductions would be expected in oxides of nitrogen and oxides of sulfur, it is less clear how particulate matter emissions would be reduced going from diesel to a diesel/natural gas combustion mix. Natural gas does not contain any significant soot when compared to diesel. As a result, particulate matter emissions may be substantially lower while firing in dual-fuel mode.

### Social Impacts

There are no anticipated social impacts of the dual-fuel retrofit technology. There may be social benefits where environmental justice issues revolve around exposure to truck exhaust. Such problems may occur where truck transportation is routed through low-income neighborhoods.

### Environmental Benefits

The dual-fuel retrofit technology does not show any increase in fuel economy. However, within a dual-fuel combustion mix, a lower carbon intensity is associated with the natural gas fuel than for the diesel fuel. As mentioned, the pounds of carbon dioxide emitted per 1,000 Btu of fuel energy are 161.3 and 117.0 for diesel and natural gas, respectively. As a result, there are substantially less emissions of carbon dioxide when firing in dual-fuel mode. This duel-fuel retrofit technology can be considered beneficial in regard to potential climate impact.

Diesel also poses another danger through carbon black emissions in the form of soot. Carbon black is recognized as a short-lived climate pollutant. The substitution of diesel with natural gas will reduce the climate impact of soot emissions from diesel combustion.

One downside to expanded natural gas use is fugitive methane emissions. Methane composes roughly 90 percent of natural gas. There is a national problem with methane emissions from the natural gas distribution system. Since methane is a GHG, any expansion of the natural gas storage and distribution system may entail increases in fugitive methane emissions. Methane is a more potent GHG than carbon dioxide. Moving to increased natural gas usage will accelerate the need to reduce fugitive natural gas emissions.

## Regulatory Impacts

The main economic motivation for purchasing a dual-fuel retrofit system would be if diesel prices were much higher than those of natural gas when compared on a Btu basis. Although environmental benefit is a buyer consideration, buyers are normally more concerned about price. As a result, governmental market incentives or direct regulation may provide a way to move buyers toward more environmentally friendly natural gas. Such regulatory incentives or regulations could be authorized as toxic air contaminant control measures to reduce diesel emissions.

### Industrial Impacts

In current form, application of the dual-fuel retrofit system is limited to retrofit applications that use data logging. Data logging is used to optimize the system for the specific duty-cycle applications. In addition, the system is available only for two makes/models of diesel engines. As time proceeds, this situation may change as the system becomes more available for larger number of diesel engine makes and models. As duty-cycle optimization becomes unnecessary, the system could become available for general application on new diesel trucks. If the duel-fuel retrofit technology is adopted in a large segment of the new diesel-truck retail sales market, this technology could be very disruptive to the truck manufacturing industry. The disruption would be even greater if buyers are motivated through economic or regulatory means.

## Economic and Market Impacts

### Cost/Benefit from Demonstration Data

Although CAP states that the dual-fuel retrofit system is cost-effective, there were no data provided demonstrating this assertion. Even with such data, one would need to account for expected changes in fuel prices. Even so, much would be gained from providing equipment labor costs for the retrofit system. Without cost data, raw or reduced, it is hard to qualitatively discuss cost and benefits of the dual-fuel retrofit system.

When considering fuel economy, there is no demonstrated difference between natural gas and diesel on a Btu basis as used for a duel-fuel engine. When considering emissions and health impact, the cost benefit of the dual-fuel retrofit provides a clear benefit for the price in reducing diesel exhaust, but it is not quantified.

Future project scopes of work should anticipate the need to evaluate the costs and benefits of projects. Ways of calculating costs and benefits for specific projects should be developed in coordination with grant recipients. In this particular case, any fixed costs (for example, retrofit system components, labor for installation, and data logging for duty-cycle adaptation) along with maintenance costs should be provided in an itemized format.

For the time being, it appears that applications will have to proceed on a case-by-case basis for the applicable Volvo and Mack engines. To expand potential applications, CAP will need to adapt the dual-fuel retrofit system to other large diesel engines. CAP had several recommendations regarding these processes, which are documented in the final project report. One is to use a disciplined problem-solving process. The second, where using in-use fleet applications, involves choosing a centralized cooperative fleet partner. More details are available in the final report.

### Potential Market Impact or Disruption

At the current stage of development, the evaluator believes there are no anticipated impacts of the dual-fuel retrofit technology on product markets. Clearly, more product development along with regulatory forcing or market incentives will be needed to achieve a substantial sales volume.

In the case that natural gas prices on a Btu basis fall significantly below those of diesel for a sustained period, there is the possibility that the retrofit of diesel trucks to a dual-fuel system would be more economically feasible. Increasing sales would then be available to develop the dual-fuel retrofit system.

### Elimination of Roadblocks or Bottlenecks

There are still obstructions to the commercial viability of the dual-fuel retrofit system. Widespread use of the system will depend ultimately on adaptability. Although particulate filters on large diesel engines are adapted to duty cycles using data logging over a trial period, the technology will be more marketable if the need for duty-cycle and seasonal adaptations can be eliminated. Once eliminated, new truck manufacturers will be able to install dual-fuel retrofit units as original equipment at the plant for general duty-cycle use.

As developers of the dual-fuel retrofit system accumulate more run-time with their product, it is entirely possible that technical issues with engine diesel engine applicability and duty-cycle adaption will gradually be overcome.

### Self-Sustainability and Potential for Substitution by Future Technology Developments

Although there are barriers to current market entry, very few competitors can provide combustion ignition performance with natural gas. This product has a high moat and could do well economically once technical barriers have been removed.

# CHAPTER 7: Conclusions and Recommendations

The primary goal of the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program, is accelerating the development of alternative transportation fuels through improvement and commercialization of existing and emerging alternative-fueled vehicles and infrastructure. This grant for developing this retrofit package appears to have been well spent in terms of bringing an innovative product closer to market. Even now the product could be deemed ready for limited commercialization. The grant provided for further technical development through in use applications that allowed the grantee to optimize a product through limited real-world conditions.

The dual-fuel retrofit system has the potential to move the transportation fuel market away from diesel and toward increasingly abundant natural gas. The combustion gases from burning diesel are considered a toxic air contaminant, while natural gas is considered a cleaner fossil fuel. This retrofit technology potentially reduces diesel combustion, including both carbon-black emissions, a short-lived climate pollutant, and diesel exhaust emissions, a toxic air pollutant.

The retrofit package is a promising technology that merits further development. This project investigated the commercial viability of the retrofit technology as applied to two diesel engine models in used for mostly local and regional delivery. Further development is warranted for adapting the retrofit package to more current diesel engine models. In addition, the retrofit package could be tested for more general uses, including long-haul trucking.

# GLOSSARY

BRITISH THERMAL UNIT (Btu)—The standard measure of heat energy. It takes one Btu to raise the temperature of one pound of water by one degree Fahrenheit at sea level. MMBtu stands for one million Btu.

CALIFORNIA AIR RESOURCES BOARD (ARB)—The "clean air agency" in the government of California whose main goals include attaining and maintaining healthy air quality, protecting the public from exposure to toxic air contaminants, and providing innovative approaches for complying with air pollution rules and regulations.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

CARBON DIOXIDE EQUIVALENT (CO2e)—A metric used to compare emissions of various greenhouse gases. It is the mass of carbon dioxide that would produce the same estimated radiative forcing as a given mass of another greenhouse gas. Carbon dioxide equivalents are computed by multiplying the mass of the gas emitted by its global warming potential.

CLEAN AIR POWER (CAP) - Clean Air Power designs, develops and delivers Dual-Fuel™ and second generation *MicroPilot* engine systems to enable heavy-duty, compression-ignited engines to run on natural gas mixed with small quantities of diesel to act as the "spark" that ignites the gas. [6]

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

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[6] Clean Air Power website (http://www.cleanairpower.com/about.html)

DIESEL EXHAUST FLUID (DEF)- is a liquid used to reduce the amount of air pollution created by a diesel engine.[7]

DIESEL GAS EQUIVALENT OR DIESEL GALLON EQUIVALENT (DGE)- The amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel gasoline.

ELECTRONIC CONTROL UNIT (ECU)- Any embedded system in automotive electronics that controls one or more of the electrical systems or subsystems in a vehicle.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GROSS COMBINED VEHICLE WEIGHT (GCVW)- The maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers, and cargo, but excluding that of any trailers.

GAS TECHNOLOGY INSTITUTE (GTI)- the leading research, development and training organization addressing energy and environmental challenges to enable a secure, abundant, and affordable energy future.[8]

LIQUEFIED NATURAL GAS (LNG)- LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

ON-BOARD DIAGNOSTIC (OBD)- A vehicle's self-diagnostic and reporting capability.

ORIGINAL EQUIPMENT MANUFACTURER (OEM)- Makes equipment or components that are then marketed by its client, another manufacturer, or a reseller, usually under that reseller's own name.

SHUTOFF VALVE (SOV)- an actuated valve designed to stop the flow of a hazardous fluid upon the detection of a dangerous event.[9]

UNITED PARCEL SERVICE (UPS)- an American multinational package delivery and supply chain management company.

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[7] DEF Wikipedia page (https://en.wikipedia.org/wiki/Diesel_exhaust_fluid)

[8] GTI Website (https://www.gti.energy/about/)

[9] Shut down valve Wikipedia page (https://en.wikipedia.org/wiki/Shut_down_valve)

UNITED STATE ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA)- A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting, and enforcement activities.

# APPENDIX A:
# ARB Experimental Permits C-318-10, C-318-11, and C-318-12

State of California
AIR RESOURCES BOARD

EXECUTIVE ORDER C-318-10

Relating to Experimental Permits for
Vehicle Emission Control Devices

Clean Air Power

Pursuant to the authority vested in the Air Resources Board by Section 43014 of the Health and Safety Code which allows it to issue permits for the testing of experimental motor vehicle pollution control devices installed in used motor vehicles, or for the testing of experimental and prototype motor vehicles which appear to have very low emission characteristics; and

Pursuant to the authority vested in the undersigned by Sections 39515 and 39516 of the Health and Safety Code and Executive Order G-02-003;

IT IS ORDERED AND RESOLVED: That Clean Air Power be granted this permit for field testing of ten on-road heavy-duty diesel engines modified to operate on either diesel or a mixture of diesel and up to 90% natural gas.

Clean Air Power shall keep a copy of this permit with the following information in the glove compartment of the test vehicles:

| Vehicle | VIN | Engine | Engine Family | ESN |
|---|---|---|---|---|
| 2013 Mack CXU613 | 1M1AW09Y5DM032212 | 2012 Volvo | CVPTH12.8S01 | 1006317 |
| 2013 Mack CXU613 | 1M1AW09Y7DM032213 | 2012 Volvo | CVPTH12.8S01 | 1006320 |
| 2013 Mack CXU613 | 1M1AW09Y9DM032214 | 2012 Volvo | CVPTH12.8S01 | 1006323 |
| 2013 Mack CXU613 | 1M1AW09Y0DM032215 | 2012 Volvo | CVPTH12.8S01 | 1006328 |
| 2013 Mack CXU613 | 1M1AW09Y2DM032216 | 2012 Volvo | CVPTH12.8S01 | 1006338 |
| 2013 Mack CXU613 | 1M1AW09Y4DM032217 | 2012 Volvo | CVPTH12.8S01 | 1006342 |
| 2013 Mack CXU613 | 1M1AW09Y6DM032218 | 2012 Volvo | CVPTH12.8S01 | 1006350 |
| 2013 Mack CXU613 | 1M1AW09Y8DM032219 | 2012 Volvo | CVPTH12.8S01 | 1006365 |
| 2013 Mack CXU613 | 1M1AW09Y1DM032269 | 2012 Volvo | CVPTH12.8S01 | 1007114 |
| 2013 Mack CXU613 | 1M1AW09Y8DM032270 | 2012 Volvo | CVPTH12.8S01 | 1007122 |

Clean Air Power shall maintain a record of the engines, vehicles, and the specific test program. This record shall be maintained for the duration of the test program and made available at reasonable times to the Air Resources Board.

This permit is valid for one year from the date of signature. At the expiration of this permit, the engines must be rebuilt to a California-certified configuration or be shipped out of California.

No engines, vehicles, or experimental technologies in this program shall be sold to an ultimate purchaser for operation in California prior to completion of the certification procedures by the Air Resources Board.

Executed at El Monte, California this 30th day of October 2013.

Erik White, Chief
Mobile Source Operations Division

State of California
AIR RESOURCES BOARD

EXECUTIVE ORDER C-318-11

Relating to Experimental Permits for
Vehicle Emission Control Devices

Clean Air Power

Pursuant to the authority vested in the Air Resources Board by Section 43014 of the Health and Safety Code which allows it to issue permits for the testing of experimental motor vehicle pollution control devices installed in used motor vehicles, or for the testing of experimental and prototype motor vehicles which appear to have very low emission characteristics; and

Pursuant to the authority vested in the undersigned by Sections 39515 and 39516 of the Health and Safety Code and Executive Order G-14-012;

IT IS ORDERED AND RESOLVED: That Clean Air Power be granted this permit for field testing of two on-road heavy-duty diesel engines modified to operate on either diesel or a mixture of diesel and up to 90% natural gas.

Clean Air Power shall keep a copy of this permit with the following information in the glove compartment of the test vehicles:

| Vehicle | License Plate | Engine | Engine Family | ESN |
|---|---|---|---|---|
| 2013 Volvo VNL 670 | YAGZ412 | 2012 Volvo D13 | CVPTH12.8S01 | 1003972 |
| 2013 Volvo VNL 300 | YAHA343 | 2012 Volvo D13 | CVPTH12.8S01 | 1008078 |

Clean Air Power shall maintain a record of the engine, vehicle, and the specific test program. This record shall be maintained for the duration of the test program and made available at reasonable times to the Air Resources Board.

This permit is valid for one year from the date of signature. At the expiration of this permit, the engines must be rebuilt to a California-certified configuration or be shipped out of California.

No engine, vehicle, or experimental technologies in this program shall be sold to an ultimate purchaser for operation in California prior to completion of the certification procedures by the Air Resources Board.

Executed at El Monte, California this 11th day of June 2014.

Annette Hebert, Chief
Emissions Compliance, Automotive Regulations and Science Division

State of California
AIR RESOURCES BOARD

EXECUTIVE ORDER C-318-12

Relating to Experimental Permits for
Vehicle Emission Control Devices

Clean Air Power

Pursuant to the authority vested in the Air Resources Board by Section 43014 of the Health and Safety Code which allows it to issue permits for the testing of experimental motor vehicle pollution control devices installed in used motor vehicles, or for the testing of experimental and prototype motor vehicles which appear to have very low emission characteristics; and

Pursuant to the authority vested in the undersigned by Sections 39515 and 39516 of the Health and Safety Code and Executive Order G-14-012;

IT IS ORDERED AND RESOLVED: That Clean Air Power be granted this permit for field testing of ten on-road heavy-duty diesel engines modified to operate on either diesel or a mixture of diesel and up to 90% natural gas.

Clean Air Power shall keep a copy of this permit with the following information in the glove compartment of the test vehicles:

| Vehicle | VIN | Engine | Engine Family | ESN |
|---|---|---|---|---|
| 2013 Mack CXU613 | 1M1AW09Y5DM032212 | 2012 Volvo | CVPTH12.8S01 | 1006317 |
| 2013 Mack CXU613 | 1M1AW09Y7DM032213 | 2012 Volvo | CVPTH12.8S01 | 1006320 |
| 2013 Mack CXU613 | 1M1AW09Y9DM032214 | 2012 Volvo | CVPTH12.8S01 | 1006323 |
| 2013 Mack CXU613 | 1M1AW09Y0DM032215 | 2012 Volvo | CVPTH12.8S01 | 1006328 |
| 2013 Mack CXU613 | 1M1AW09Y2DM032216 | 2012 Volvo | CVPTH12.8S01 | 1006338 |
| 2013 Mack CXU613 | 1M1AW09Y4DM032217 | 2012 Volvo | CVPTH12.8S01 | 1006342 |
| 2013 Mack CXU613 | 1M1AW09Y6DM032218 | 2012 Volvo | CVPTH12.8S01 | 1006350 |
| 2013 Mack CXU613 | 1M1AW09Y8DM032219 | 2012 Volvo | CVPTH12.8S01 | 1006365 |
| 2013 Mack CXU613 | 1M1AW09Y1DM032269 | 2012 Volvo | CVPTH12.8S01 | 1007114 |
| 2013 Mack CXU613 | 1M1AW09Y8DM032270 | 2012 Volvo | CVPTH12.8S01 | 1007122 |

Clean Air Power shall maintain a record of the engines, vehicles, and the specific test program. This record shall be maintained for the duration of the test program and made available at reasonable times to the Air Resources Board.

This permit is valid for one year from the date of signature. At the expiration of this permit, the engines must be rebuilt to a California-certified configuration or be shipped out of California.

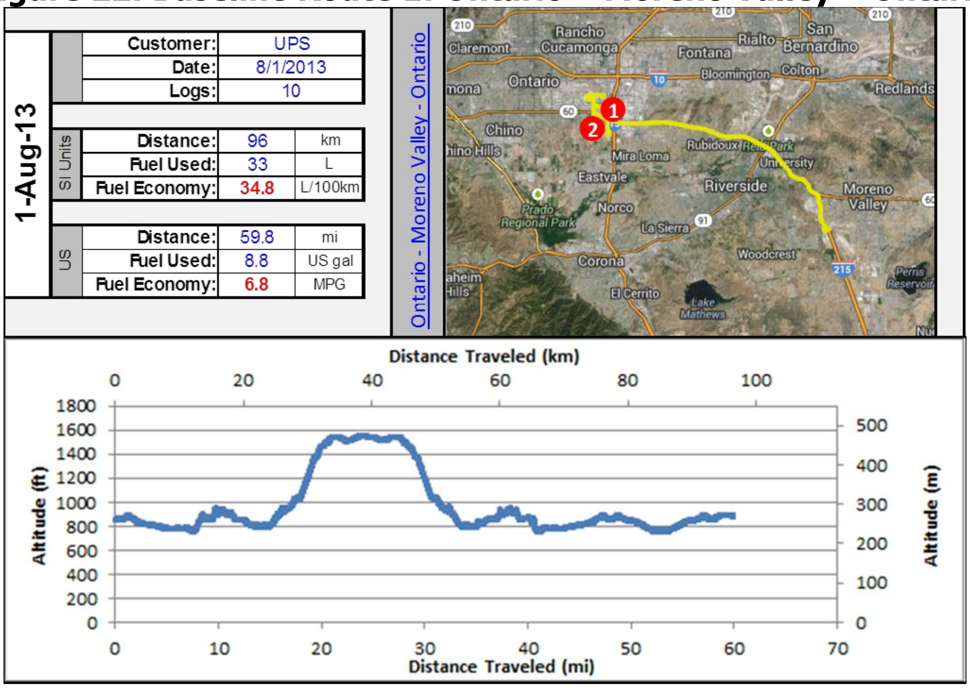
No engines, vehicles, or experimental technologies in this program shall be sold to an ultimate purchaser for operation in California prior to completion of the certification procedures by the Air Resources Board.

Executed at El Monte, California this 22 day of September 2014.

Annette Hebert, Chief
For Emissions Compliance, Automotive Regulations and Science Division

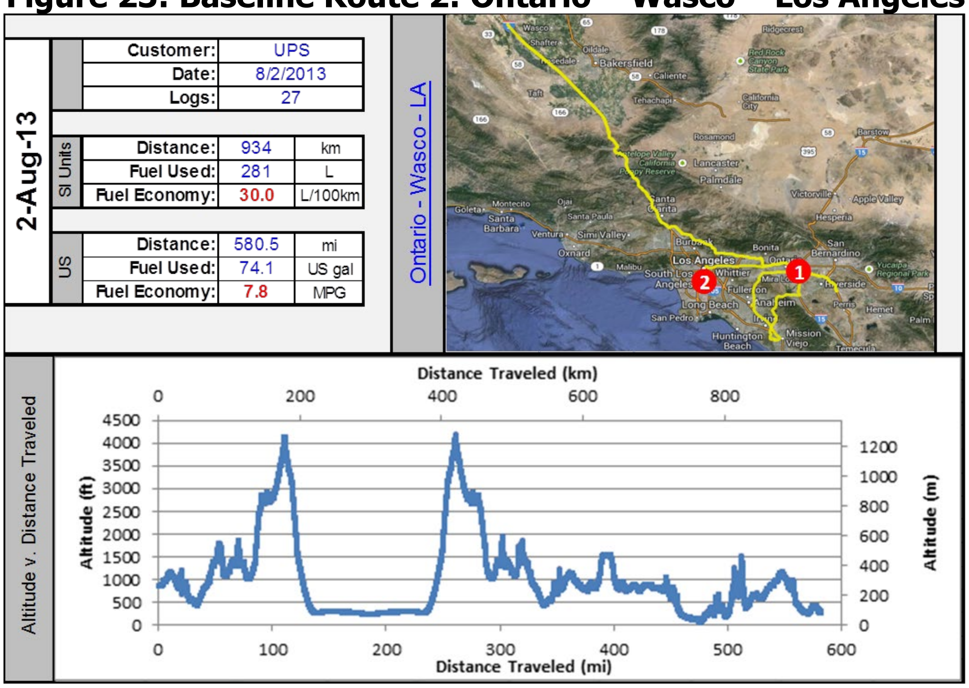
# APPENDIX B: Baseline Operations Data

**Figure 22: Baseline Route 1: Ontario – Moreno Valley – Ontario**



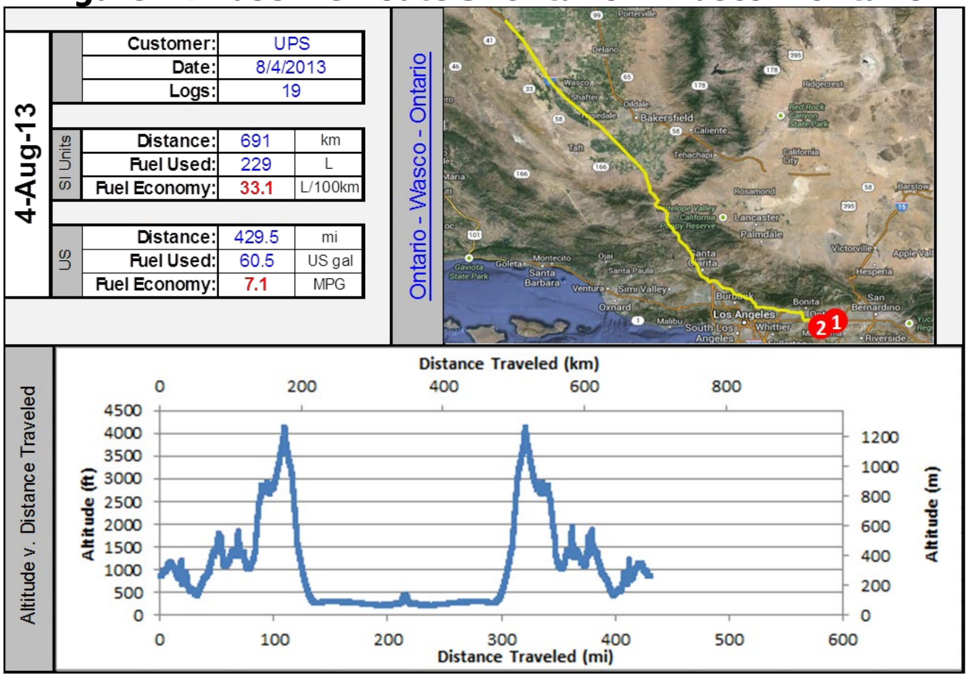

Source: Gas Technology Institute

**Figure 23: Baseline Route 2: Ontario – Wasco – Los Angeles**



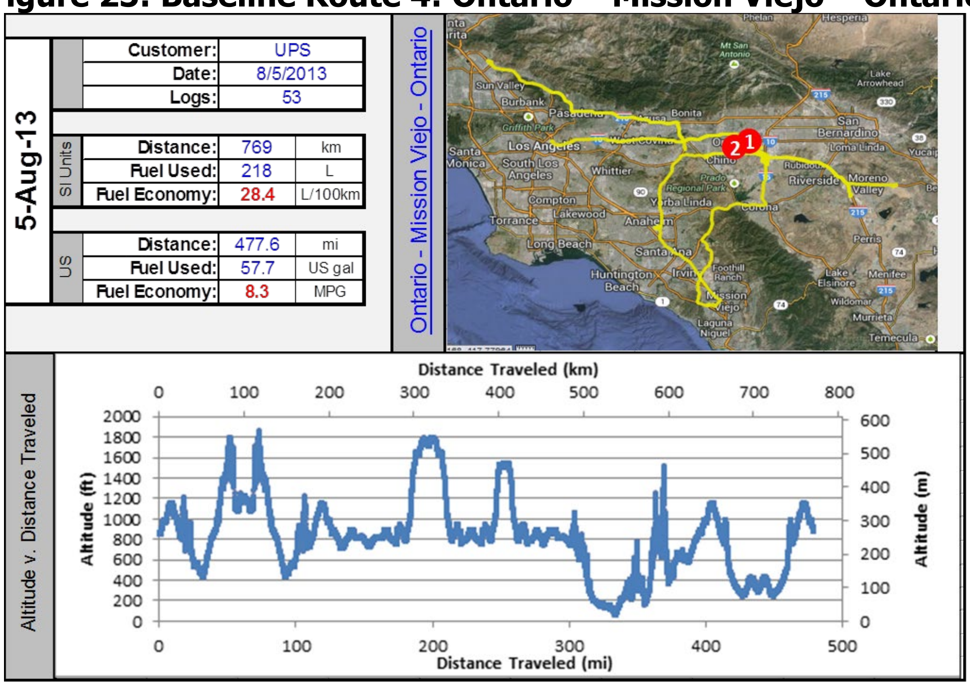

Source: Gas Technology Institute

## Figure 24:Baseline Route 3: Ontario – Wasco – Ontario




Source: Gas Technology Institute

## Figure 25: Baseline Route 4: Ontario – Mission Viejo – Ontario



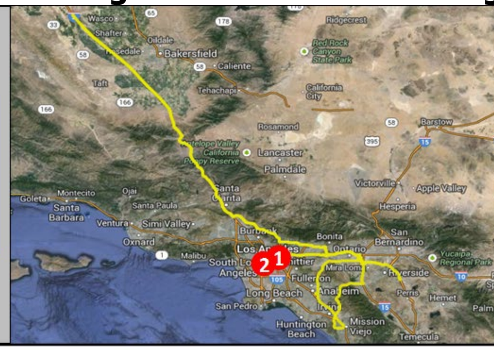

Source: Gas Technology Institute

## Figure 26: Baseline Route 5: Los Angeles – Wasco – Los Angeles

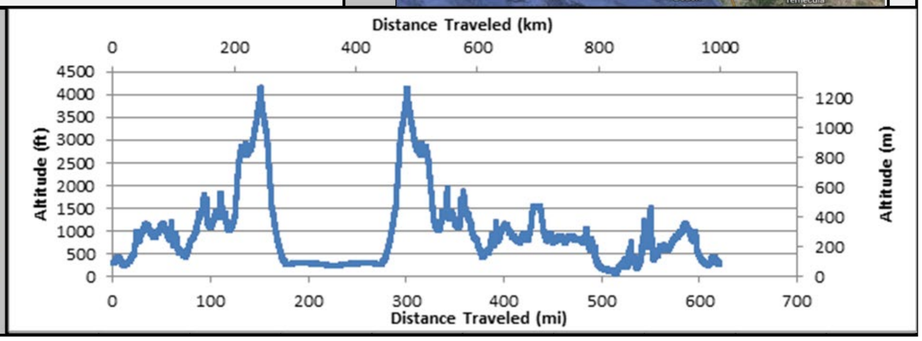
**7-Aug-13**

| | | | |
|---|---|---|---|
| | Customer: | UPS | |
| | Date: | 8/7/2013 | |
| | Logs: | 33 | |
| SI Units | Distance: | 996 | km |
| SI Units | Fuel Used: | 279 | L |
| SI Units | Fuel Economy: | 28.0 | L/100km |
| US | Distance: | 618.8 | mi |
| US | Fuel Used: | 73.7 | US gal |
| US | Fuel Economy: | 8.4 | MPG |

LA - Wasco - LA




Altitude v. Distance Traveled




Source: Gas Technology Institute

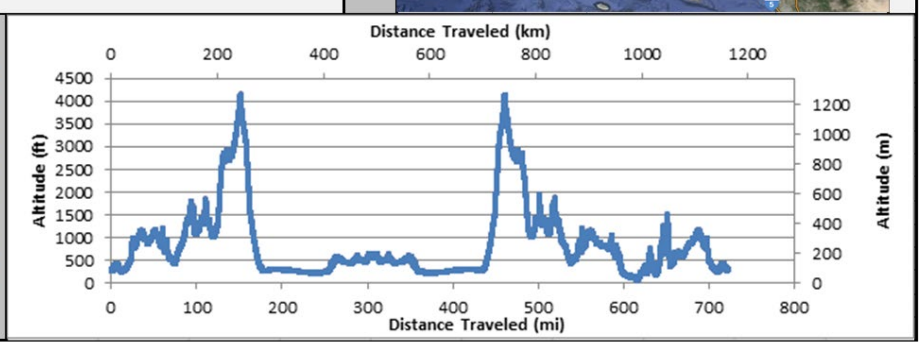
## Figure 27: Baseline Route 6: Los Angeles – Coalinga – Los Angeles

**8-Aug-13**

| | | | |
|---|---|---|---|
| | Customer: | UPS | |
| | Date: | 8/8/2013 | |
| | Logs: | 26 | |
| SI Units | Distance: | 1159 | km |
| SI Units | Fuel Used: | 331 | L |
| SI Units | Fuel Economy: | 28.6 | L/100km |
| US | Distance: | 720.2 | mi |
| US | Fuel Used: | 87.5 | US gal |
| US | Fuel Economy: | 8.2 | MPG |

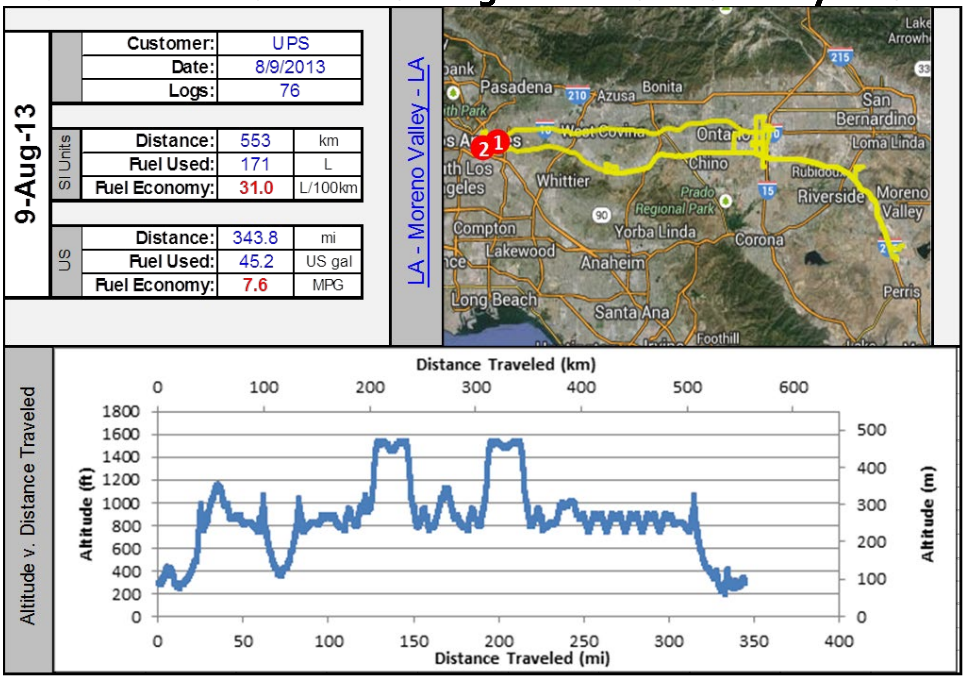
LA - Coalinga - LA


Altitude v. Distance Traveled



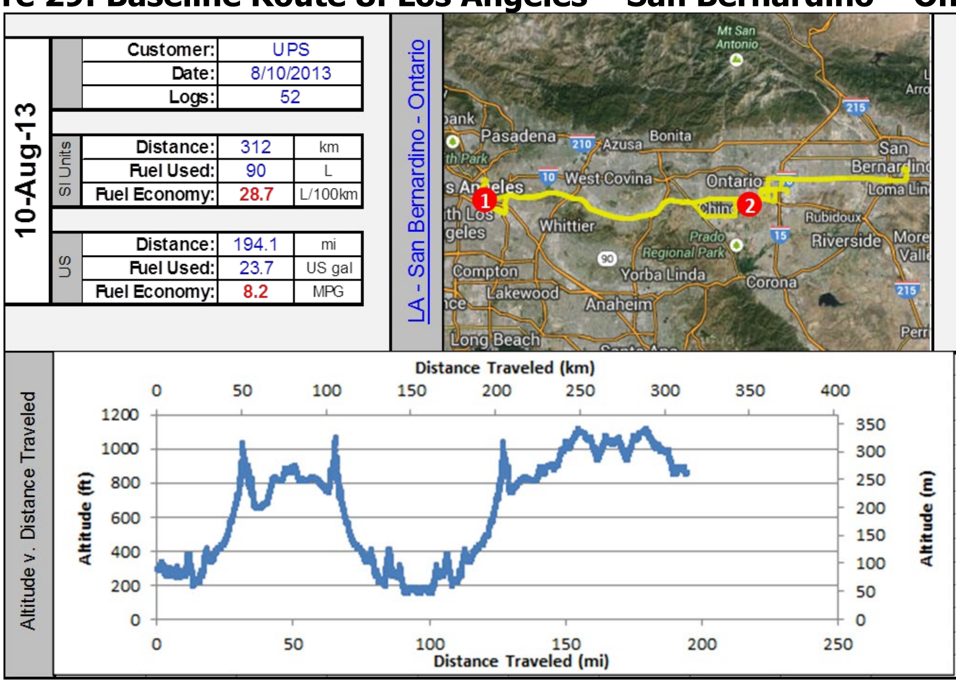

Source: Gas Technology Institute

**Figure 28: Baseline Route 7: Los Angeles – Moreno Valley – Los Angeles**




Source: Gas Technology Institute

**Figure 29: Baseline Route 8: Los Angeles – San Bernardino – Ontario**




Source: Gas Technology Institute

# APPENDIX C: Fuel Economy and Usage Report

## Executive Summary

### Performed test

1. Development Route
2. Flat Route
3. Mountainous Route
4. Controlled Test

### Test objects

1. Volvo Day Cab (manual transmission)
2. Volvo Sleeper Cab (automatic transmission)

### Results

**Table 15: Volvo Sleeper Cab – Full Load**

| Test | MPG | Substitution (%) |
|---|---|---|
| Development Route | 5.18 | 57.90 |
| Flat Route | 7.12 | 59.20 |
| Mountainous Route | 3.08 | 61.75 |

Source: Gas Technology Institute

**Table 16: Volvo Day Cab – Full Load**

| Test | MPG | Substitution (%) |
|---|---|---|
| Development Route | 4.18 | 67.80 |
| Flat Route | 5.28 | 69.65 |
| Mountainous Route | 2.44 | 74.00 |

Source: Gas Technology Institute

**Table 17: Controlled test**

| MPG | Substitution (%) |
|---|---|
| 4.62 | 67.05 |

Source: Gas Technology Institute

## Introduction

The purpose of this report is to document the fuel economy figures for the initial release of the US2010 Genesis LNG Dual-Fuel system. All subsequent releases of software or calibration for the US210 Genesis LNG Dual-Fuel system should match or improve on the fuel economy figures presented in this report.

## Objectives

Document the fuel economy figures for the US2010 Genesis LNG Dual-Fuel system in the following scenarios:

1. General operation simulated by the use of a predefined development route consisting of freeway and city running

2. Operation of the system on flat ground such as desert areas simulated by the use of a predefined route through the desert.
3. Operation of the system in mountainous areas simulated by the use of a predefined route consisting of large inclines.
4. Controlled test using the Poway engine dynamometer to remove variables encountered in on the road running.

## Test Objects

## Volvo Sleeper Cab

Vehicle Identification number: 4V4NC9EH9DN139833

Engine Model: D13 425HP ECO-Torque

Engine Serial Number: D13/1003972

Transmission: ATO2612D Volvo Auto

Transmission Number: 0710210558

Number of Axles: 3

Date of Manufacture: July 2012

## Volvo Day Cab

Vehicle Identification number: 4V4NC9EG6DN143457

Engine Model: D13 425HP ECO-Torque

Engine Serial Number: D13/1008078

Transmission: FRO-16210C, 10 Speed

Transmission Number: S0971720

Number of Axles: 3

Date of Manufacture: August 2012

## Trailer

Trailer Identification (Heavy weight):100067 Vanguard

Trailer Identification (Light weight):1324 (rented from Tec Leasing)

Number of axles: 2

## Natural Gas System

Clean Air Power Model: US2010 Genesis

Variant: LNG

Software Identification: 20_03

Calibration Identification: 16_03

## Tests

The following test procedures were used to obtain the fuel economy data for each of the scenarios. In order to get representative results an average of two or more runs for each scenario was used to form the fuel economy data. Three runs were completed in Dual-Fuel and diesel so that the Dual-Fuel fuel economy can be compared to a based diesel truck. Each test in the data set was a perfect test with no influences such as traffic or adverse weather conditions.

## Test Equipment

The following equipment was used in the testing:

- Clean Air Power Diagnostics Tool: Used to collect fueling data and trip distances.
- Plastic measuring jug – Used to measure the amount of DEF used.

## Development Route

The procedure for this test can be found in report 200736 US Development Route Validation Procedure which is stored in (C:\CAP PDM\ENGINEERING PDM DATA\PROCEDURES\TEST PROCEDURES)

## Flat Ground Route

*The procedure for this test can be found in report 200788* CAP Test Route Definition - El Centro Routes which is stored in (C:\CAP PDM\ENGINEERING PDM DATA\PROCEDURES\TEST PROCEDURES)

## Mountainous Route

*The procedure for this test can be found in report 200788* CAP Test Route Definition - El Centro Routes which is stored in (C:\CAP PDM\ENGINEERING PDM DATA\PROCEDURES\TEST PROCEDURES)

## Controlled Test

*The controlled test is run on the engine dynamometer in Poway by taking input data such as throttle position and engine speed recorded from a typical development route. This is then inputted into the dynamometer controller so that the same test conditions can be replicated very easily. This reduces the variability such as inlet air temperatures affected by the weather and eliminates variability in speed and load caused by driver inconsistency and traffic.*

## Results

In these results the trucks were measured at the following weights:

## Results for full load

Volvo Sleeper Cab: 76,960 lbs

Volvo Day Cab: 74,200 lbs

## Results for part load

Volvo Sleeper Cab: 56,750 lbs

Volvo Day Cab: 54,680 lbs

All the raw data that these results have been published from can be found in the file labelled US Fuel Economy Database in the following location: (V:\Department Data\Product Development\Product Engineering\Volvo\US 2010 Genesis\Road Testing)

## Development Route Results

**Table 18: Full Load**

| Truck | MPG | MPG delta to diesel baseline (%) | Substitution (%) | DEF usage percent total fuel (%) * | |
|---|---|---|---|---|---|
| | | | | Dual-Fuel | Diesel |
| Volvo Sleeper Cab | 5.18 | -2.21 | 57.90 | 3.0 | 3.7 |
| Volvo Day Cab | 4.83 | -7.96 | 67.80 | 2.8 | 3.4 |

Source: Gas Technology Institute

*The Diesel Exhaust Fluid data was taken from 16_00_13_02 level software however the dosing strategy didn't dramatically change in the software revisions to 20_03_16_03 and it is believed that any change in dosing would be lost in the accuracy of the measurement method used to collect the DEF data.

**Table 19: Part Load**

| Truck | MPG | MPG delta to diesel baseline (%) | Substitution (%) |
|---|---|---|---|
| Volvo Sleeper Cab | 6.35 | 1.07 | 54.00 |
| Volvo Day Cab | 5.83 | -2.42 | 65.00 |

Source: Gas Technology Institute

## Flat Ground Route Results

**Table 20: Full Load**

| Truck | MPG | MPG delta to diesel baseline (%) | Substitution (%) |
|---|---|---|---|
| Volvo Sleeper Cab | 7.12 | N/A | 59.20 |
| Volvo Day Cab | 5.28 | -11.47 | 69.65 |

Source: Gas Technology Institute

**Table 21: Part Load**

| Truck | MPG | MPG delta to diesel baseline (%) | Substitution (%) |
|---|---|---|---|
| Volvo Day Cab | 6.26 | -6.22 | 69.05 |
| Volvo Sleeper Cab | Data not available due to truck availability | | |

Source: Gas Technology Institute

## Mountainous Route Results

**Table 22: Full Load**

| Truck | MPG | MPG delta to diesel baseline (%) | Substitution (%) |
|---|---|---|---|
| Volvo Sleeper Cab * | 3.08 | 1.40 | 61.75 |
| Volvo Day Cab | 2.44 | -2.40 | 74.00 |

Source: Gas Technology Institute

*The data for the Volvo sleeper cab wasn't taken from the set route described in document 200788 CAP Test Route Definition - El Centro Routes as there wasn't truck availability to gather this data. Instead data was used from a route conducted in Denver which is described in report 200825 US Genesis Altitude Test Report located at C:\CAP PDM\ENGINEERING PDM DATA\DOCUMENTS AND REPORTS

**Table 23:Controlled Test Results**

| MPG | MPG delta to diesel baseline (%) | Substitution (%) | DEF usage percent total fuel (%) | |
|---|---|---|---|---|
| | | | Dual-Fuel | Diesel |
| 4.62 | -5.33 | 67.05 | 2.9 | 3.3 |

Source: Gas Technology Institute

*See appendix for raw data

### Conclusion

The transmission of the truck makes a big difference in the performance of the Dual-Fuel system. With the automatic transmission the fuel economy is improved over a manual transmission as would be expected however the automatic transmission also has a negative impact on substitution. This is due to the Dual-Fuel system having to let the gear box control the fueling during gear shifts and sometimes means a transition back in to Dual-Fuel after a shift is missed.

**Table 24: Controlled Test Raw Data**

| Test Number | Mode | Total Miles | Total Diesel (kg) | Total Gas (kg) | Total Fuel (DGE) | Total Work (hp-hr) | MPG | MPG Delta (%) |
|---|---|---|---|---|---|---|---|---|
| 8551 | Diesel | 64.1 | 42.06 | 0.00 | 13.20 | 265.98 | 4.86 | 0 |
| 8555 | Diesel | 64.1 | 41.80 | 0.00 | 13.12 | 269.28 | 4.89 | 0 |
| 8562 | Dual-Fuel | 64.1 | 14.45 | 26.15 | 13.81 | 277.57 | 4.64 | -4.74 |
| 8563 | Dual-Fuel | 64.1 | 14.74 | 26.32 | 13.97 | 282.82 | 4.59 | -5.77 |

Source: Gas Technology Institute

**Table 25: Controlled Test Raw Data**

| BSFC (g/hp-hr) | BSFC Delta (%) | Energy Substitution (%) | DEF Consumption (ml) | BSDEFC (Vol Based %) |
|---|---|---|---|---|
| 157.94 | 0 | 0 | 1650 | 3.03 |
| 155.04 | 0 | 0 | 1650 | 3.05 |
| 158.39 | 1.21 | 67.2 | 1500 | 2.63 |
| 157.15 | 0.42 | 66.9 | 1500 | 2.60 |

Source: Gas Technology Institute