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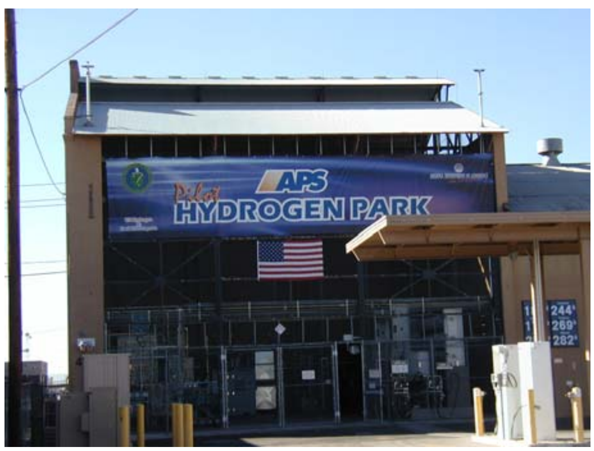
U.S. Department of Energy FreedomCAR & Vehicle Technologies Program

Hydrogen and Hydrogen/Natural Gas Station and Vehicle Operations – 2006 Summary Report



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September 2006

Idaho National Laboratory
Operated by Battelle Energy Alliance

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1. Electric Transportation Applications
2. Idaho National Laboratory

ABSTRACT

This report is a summary of the operations and testing of internal combustion engine vehicles that were fueled with 100% hydrogen and various blends of hydrogen and compressed natural gas (HCNG). It summarizes the operations of the Arizona Public Service Alternative Fuel Pilot Plant, which produces, compresses, and dispenses hydrogen fuel. Other testing activities, such as the destructive testing of a CNG storage cylinder that was used for HCNG storage, are also discussed. This report highlights some of the latest technology developments in the use of 100% hydrogen fuels in internal combustion engine vehicles. Reports are referenced and WWW locations noted as a guide for the reader that desires more detailed information. These activities are conducted by Arizona Public Service, Electric Transportation Applications, the Idaho National Laboratory, and the U.S. Department of Energy's Advanced Vehicle Testing Activity.

CONTENTS

FIGURES

TABLES

ACRONYMS

ANL	Argonne National Laboratory
APS	Arizona Public Service
AVTA	Advanced Vehicle Testing Activity
CAVTC	Clean Air Vehicle Technology Center
CH_4	methane
15% HCNG	blended fuel composed of 15% hydrogen and 85% CNG
30% HCNG	blended fuel composed of 30% hydrogen and 70% CNG
50% HCNG	blended fuel composed of 50% hydrogen and 50% CNG
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DOE	U.S. Department of Energy
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
g/mi	grams per mile
gge	gasoline gallon equivalents
GVWR	gross vehicle weight rating
HC	total hydrocarbons
HCNG	hydrogen blended with compressed natural gas
IM240	Inspection and Maintenance Driving Cycle
INL	Idaho National Laboratory
LEV	low emission vehicle
NMHC	nonmethane hydrocarbons
NMOG	nonmethane organic gases
NO_x	oxides of nitrogen
Pilot Plant	APS Alternative Fuel Pilot Plant
scf	standard cubic feet
SULEV	super ultra low emission vehicle
ULEV	ultra low emission vehicle
WOT	wide-open throttle

1. INTRODUCTION

Many energy company and government fleets have adopted compressed natural gas (CNG) as their primary alternative fuel for transportation purposes. Recent research has shown that blending hydrogen with CNG (HCNG) can result in reduced nitrogen oxides (NO_X) emissions from CNG vehicles. This ongoing research, combined with the large fleet of CNG vehicles in operation nationwide, raises the question: "Can factory CNG vehicles successfully operate long-term on a blend of hydrogen and CNG?" Collecting data to answer this question was the main focus of a testing program conducted by Arizona Public Service Company (APS), a subsidiary of Pinnacle West Capital Corporation, Electric Transportation Applications (ETA), and the U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA).

Testing was conducted in two phases. The first phase of testing involved vehicle emissions testing, fueling operations, and general vehicle operations. APS teamed with ETA and AVTA to perform testing on four vehicles, including two Ford F-150s, one Dodge Ram Wagon Van, and one Mercedes Sprinter Van.

The primary objective of the first phase of testing was to evaluate the safety and reliability of operating vehicles on 100% hydrogen and HCNG fuels. A secondary objective was to quantify vehicle emissions, cost of vehicle operation, and vehicle performance. In addition, it was speculated prior to testing that the use of HCNG fuel could extend oil change intervals, thus reducing operating costs and waste products such as used engine oil and filters. Therefore, an additional objective of the testing was to determine an acceptable oil change interval using the hydrogen and HCNG fuels. These objectives are discussed in more detail in this report.

The second phase of testing included testing 100% hydrogen and HCNG fueled vehicles operated by APS and private fleets. Testing included operating two Ford F-150 pickups on 100% hydrogen fuel, operating one Ford F-150 on 15 and 30% HCNG fuel, and operating the APS Meter Reading Fleet and private vehicles on various HCNG fuels for approximately 6 months. The initial testing of the Ford F-150 on 100% hydrogen fuel was delayed because of an engine failure necessitating extensive mechanical work.

This report is a summary of earlier hydrogen and HCNG vehicle testing activities, as well as a summary of the hydrogen station operations, which are sometimes referenced as Phase I activities. It also introduces information on the Phase II testing of 100% hydrogen fueled vehicles, fleet testing of bi-fuel and CNG vehicles operating on HCNG blends, and the destructive testing of an onboard CNG tank that was used for HCNG storage. Throughout this summary report, other reports are referenced that the reader can access for greater detail.

The Idaho National Laboratory (INL) conducts these as well as other AVTA testing activities for DOE's FreedomCAR and Vehicle Technologies Program.

2. HYDROGEN FUEL SYSTEM

2.1 APS Hydrogen Fueling Station

2.1.1 Station Description Overview

Arizona Public Service has instituted various programs to research and develop technology in the areas of renewable energy, distributed energy, remote area energy, energy storage, and alternative energy. One of the programs in the area of technology development in alternative energy is the APS Alternative Fuel Pilot Plant (Pilot Plant). The Pilot Plant is a refueling system/station consisting of hydrogen, CNG, and varying blends of HCNG. The refueling facility is shown in Figures 1 and 2.

Figure 1. Fuel Technologies Inc. fuel dispensers (CNG and hydrogen/CNG blends) used at the Pilot Plant.

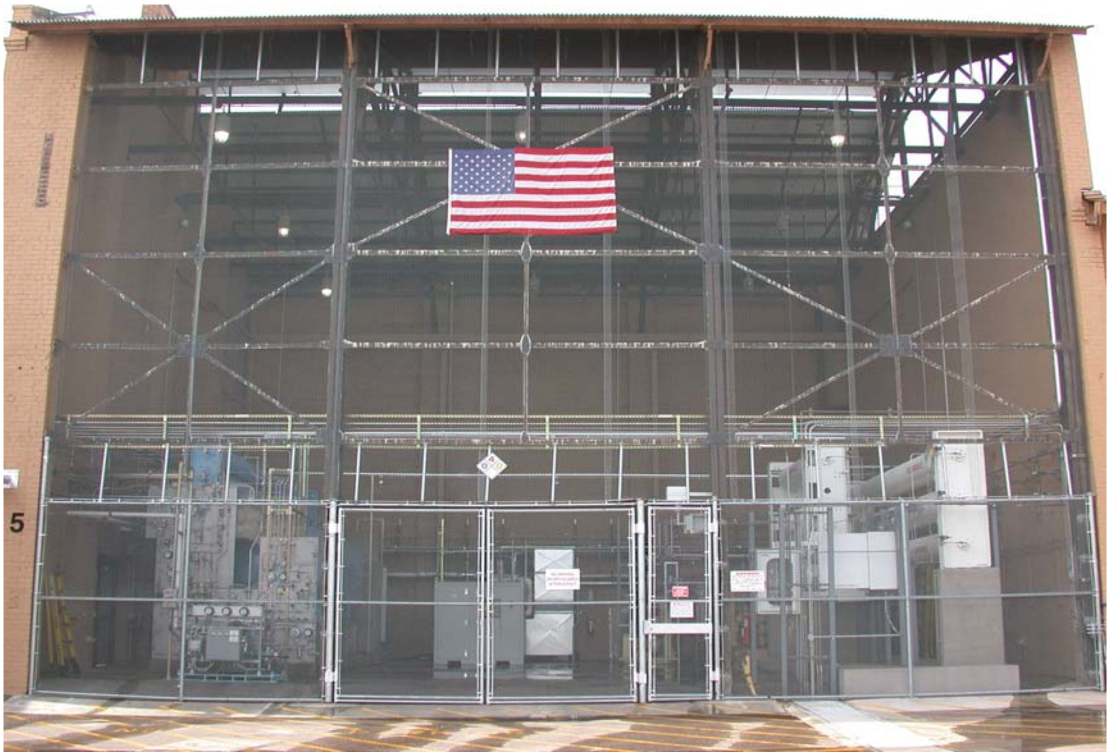


Figure 2. APS Pilot Plant fueling station.

The Pilot Plant develops experience with hydrogen as a transportation fuel and serves as the focal point for further research and development in both fuel cell and internal combustion engine technologies. Even though it has been shown over the years that existing applications of hydrogen have produced a positive safety record, further experience is required, particularly with public dispensing of hydrogen as a motor fuel, in order to fully understand the safe use of hydrogen. It is also essential to further develop methods of hydrogen production and use (such as in fuel cell and internal combustion engine technologies), to minimize production costs, and to develop methods for hydrogen infrastructure design, construction, operation, and maintenance.

Two common methods of producing hydrogen are reforming of hydrocarbons such as methane or methanol, and electrolysis of water. Reforming of hydrocarbons, which is today the most common means of hydrogen production in the United States, results in carbon dioxide as a byproduct, which is a greenhouse gas. The second method to produce hydrogen, electrolysis of water, produces only hydrogen and oxygen (when powered by renewable energy). This method is the method used to produce hydrogen in the Pilot Plant. Electrolysis is of interest to APS, particularly when the electrical energy is supplied using renewable energy and off-peak electricity. As opposed to centralized manufacturing of hydrogen and use of trucks for delivery, the electrolysis process can use the existing electric distribution system to produce hydrogen during off-peak time periods at the point of use. This provides an advantage of levelizing electric energy usage and eliminating the need for over-the-road transportation of hydrogen.

The Pilot Plant is located in an APS facility at 435 South Second Avenue, Phoenix, Arizona. The structure that houses the Pilot Plant was originally constructed in 1921 to house a manufactured gas plant that provided lamp gas to fire street lamps in downtown Phoenix. The structure is currently listed on the State of Arizona register of Historic Buildings. It was chosen due to its high, well-ventilated volume with an open wall to the east, one open gable end, and ridge vent. In addition, APS operates numerous fleet vehicles from this site providing the opportunity for it to serve as a fleet fueling location. This location was also chosen to gain experience with permitting a hydrogen fueling station in an urban downtown location with occupied structures in the immediate vicinity.

Because of the very small number of hydrogen refueling stations, limited standards were available to guide the design and construction of the Pilot Plant. Reliance was, therefore, placed on adhering to existing compressed gas industry standards and portions of existing building codes while working very closely with the local building inspection and safety departments, and with engineering experts having hydrogen experience.

Additional details of the hydrogen, CNG, and HCNG delivery systems are provided below.

2.1.2 Hydrogen Station Description

The hydrogen system consists of production, compression, storage, and dispensing of hydrogen. Hydrogen is produced using a proton exchange membrane that separates water into hydrogen and oxygen. The hydrogen is compressed using a diaphragm compressor and stored at pressures up to 5,800 psi in steel storage vessels with capacity totaling 17,000 scf. The oxygen is vented to the atmosphere. Hydrogen produced in the Pilot Plant is suitable for use in fuel cell-powered vehicles in which the minimum hydrogen purity goal is 99.999%.

The Pilot Plant is capable of accepting delivered hydrogen produced in central hydrogen production facilities (typically using reformation techniques). Hydrogen is delivered via tube trailer (Figure 3). The Pilot Plant is also capable of filling tube trailers.

Figure 3. Tube trailer at fueling station.

Objectives for constructing and operating the hydrogen fueling system were to:

- Ascertain safety issues associated with hydrogen production in a commercial setting
- Evaluate the adequacy of existing codes, standards, regulations, and recommended practices within a commercial setting
- Establish models for future codes and standards for distributed hydrogen generation systems within a commercial setting
- Determine performance limitations of existing technologies and components
- Evaluate the practicality of the hydrogen delivery systems in a commercial facility
- Evaluate hydrogen and blended HCNG as a potential fuel for internal combustion engines
- Develop a working model of a refueling system for fuel cell electric vehicles and internal combustion engine vehicles.

2.1.3 CNG Station Description

The CNG system uses natural gas, provided by Southwest Gas, delivered at 30 psig. The natural gas is filtered, compressed to 5,200 psig, and stored in six steel pressure vessels at three different pressure levels.

Objectives for constructing and operating the CNG fueling system were to:

- Evaluate the costs and benefits ratio of operating a natural gas fueling system
- Evaluate the safety of a natural gas fueling system
- Provide a fuel source for APS-operated CNG and HCNG vehicles.

2.1.4 Pilot Plant Monitoring System

The Pilot Plant was originally constructed with limited monitoring capabilities. To meet one of the original objectives for evaluation of the costs of alternative fuels, a project was initiated to install a Pilot Plant monitoring system to allow determination of the cost of hydrogen and HCNG fuels produced at the Pilot Plant. These cost data are used to benchmark fuel costs for operators of advanced-technology vehicles, research and development programs, and technology modelers.

The monitoring system is designed to track the quantity of hydrogen delivered to each hydrogen storage vessel and to monitor the electricity use of the major equipment required to operate the Pilot Plant and fuel dispensers. Water required for electrolysis process is also monitored. The monitoring system provides for calculation and analysis of component, subsystems, and plant operation costs to streamline plant efficiencies.

The monitoring system software uses sensor inputs to the Programmable Automation Controller. The Programmable Automation Controller also provides automatic control of hydrogen production. Monitoring system hardware, data interface, and storage and analysis tools details can be found in: *APS Alternative Fuel (Hydrogen) Pilot Plant Monitoring System,* INL/EXT-05-00502, July 2005 (http://avt.inl.gov/pdf/hydrogen/h2monitoringsystem.pdf).

Plant data show that the electricity cost per kilogram of hydrogen produced is most strongly dependent on electric rates and production plant capacity. Over the 8-month period from July 2004 through mid March 2005, 1,200 kg of hydrogen were produced at a plant capacity of

26%. Electricity costs using the APS general service plan E32 (at 2.105 cents per kWh), resulted in an electricity cost of $3.43 per kilogram of hydrogen. An ongoing focus on increasing plant capacity has improved plant capacity to a high of 49% in January of 2005. At a plant capacity of 70%, using current equipment, the cost to produce 1 kg of hydrogen (equal to 1 gasoline gallon equivalent [gge]) would drop to $2.01, which is below the 2005 DOE Hydrogen Program target of $2.47.

Monitoring system data have revealed several viable plant improvements to reduce hydrogen production costs. These include using a reverse osmosis system to recycle water, improving the electrolysis unit (HOGEN) power conversion efficiency, and replacing or modifying the current plant chillers with water-to-air heat exchangers.

2.2 Fuel Properties and GGE Values

The gge is a simple metric that allows the comparison of the energy content in any given fuel to 1 gallon of gasoline. The National Conference on Weights and Measures defined the value of 5.66 for CNG to be equal to 1 gge. There is no standard for hydrogen or for various blends of hydrogen with CNG. The provided fuel properties and gasoline gallon equivalent values in Table 1 were derived values used for various fuels and fuel mixtures.

Table 1. Fuel properties and gasoline gallon equivalents.

	Energy Content (kWh/kg)	Energy Content (kWh/gal)	GGE (lbm)	GGE (kg)
Gasoline	—	34.5	—	—
CNG	13.44	—	5.66	2.57
Hydrogen	33.90	—	2.28	1.04
15% H_2 / 85% CNG	13.85	—	5.49	2.49
30% H_2 / 70% CNG	14.32	—	5.31	2.41
50% H_2 / 50% CNG	15.56	—	4.89	2.22

2.3 Operational Results

The total product, in gge, for CNG, 15% HCNG, and hydrogen, delivered for calendar years 2003, 2004, and 2005 is shown in Table 2. The refueling system was placed in service in June 2002. To date, there have been no reported malfunctions and no reported safety issues associated with the system. A full description of the APS Alternative Fuel Pilot Plant can be found in: *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report*, INEEL/EXT-03-00976, December 2003 (http://avt.inel.gov/pdf/hydrogen/h2stationreport.pdf).

Table 2. Fuel use totals.

Fuel Type	2003 Total Motor Fuel Dispensed (gge)	2004 Total Motor Fuel Dispensed (gge)	2005 Total Motor Fuel Dispensed (gge)
CNG	4,824	7,563	11,271
15% HCNG	1,099	764	3,180
Hydrogen	32	168	256

3. DEMONSTRATION VEHICLES

Four demonstration vehicles were tested in the first phase of testing. These test vehicles include one Dodge Ram Wagon Van, one Mercedes Sprinter Van, and two Ford F-150s.

3.1 Dodge Ram Wagon Van

The 1999 Dodge Ram Wagon Van (Figure 4) was factory equipped for CNG. No modifications were performed on this demonstration vehicle prior to testing. APS began its evaluation of the Dodge Ram Wagon Van in September 2000. The van was fueled with CNG from this time until July 16, 2002, when the odometer read 30,734 miles. After this time, APS operated the vehicle on 15% HCNG (by volume) fuel. The vehicle's CNG fuel tank is rated at 3,600 psig. Other factory specifications are as follows:

Engine:	5.2 L V8
Factory HP:	150 HP
Curb weight:	5,529 lb
GVWR:	7,700 lb

Additional information pertaining to the Dodge Ram Wagon Van can be found in: *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary*, INEEL/EXT-03-00006, January 2003 (http://avt.inl.gov/pdf/hydrogen/dodgereport.pdf).

Figure 4. Dodge Ram wagon HCNG fueled van.

3.2 Mercedes Sprinter Van

The 1998 Mercedes Sprinter Van (Figure 5) was originally equipped with a 2.4-liter gasoline internal combustion engine. The German government converted the engine to operate using 100% hydrogen fuel. The conversion included adding three hydrogen tanks (total of 115 liters), constant volume injection, and a spark ignition modification. APS received this demonstration vehicle subsequent to these modifications in November 2001. The installed hydrogen storage tanks on the Sprinter operate at a maximum of 3,600 psig.

Additional information pertaining to the Hydrogen Fueled Mercedes Sprinter Van can be found in: *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, INEEL/EXT-03-00009, January 2003 (http://avt.inl.gov/pdf/hydrogen/mercedessprinterreport.pdf).

Figure 5. Mercedes Sprinter hydrogen-fueled van.

3.3 Low Percentage Blend Ford F-150 Truck

The low percentage blend HCNG demonstration test vehicle is a 2000 Ford F-150 pickup (Figure 6), originally equipped with a factory CNG engine. NRG Technologies, located in Reno, Nevada, modified this truck to operate on a blend of 30% HCNG (by volume). The modifications included adding a supercharger, making ignition modifications, and adding exhaust gas recirculation. The vehicle uses the factory-installed carbon steel CNG fuel tank, which operates at a maximum of 3,600 psig. APS began testing this vehicle in June 2001. Other vehicle specifications include:

Engine:	5.4 L V8
Curb weight:	5,170 lb
GVWR:	7,650 lb

Figure 6. Low-percentage blend Ford F-150 truck.

Additional information pertaining to the low percentage hydrogen Ford F-150 can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003 (http://avt.inl.gov/pdf/hydrogen/f150lowpercentreport.pdf).

3.4 High-percentage Blend Ford F-150 Truck

The high-percentage blend test vehicle is a 2001 Ford F-150 truck (Figure 7). The truck was originally equipped with a factory 5.4-L V8 gasoline engine.

NRG Technologies, located in Reno, Nevada, modified the truck to run on a blend of 50% HCNG. Vehicle modifications performed by NRG Technologies included the addition of Ford high performance (SVO) cylinder heads, a Supercharger, and intercooler and exhaust gas recirculation. Ignition modifications were also made, and the truck was equipped with three hydrogen tanks manufactured by Quantum Technologies. The hydrogen tanks use an inner polymer liner that is not prone to hydrogen embrittlement, a carbon fiber reinforced shell, and a tough external shell that enhances damage protection. The tanks have a maximum allowable working pressure of 4,400 psig and a service pressure of 3,600 psig.

Other vehicle specifications include:

Engine:	5.4 L V8
Factory HP:	260 HP
Curb weight:	5,600 lb
GVWR:	6,300 lb

Figure 7. High-percentage blend Ford F-150 truck.

The truck arrived for testing at APS on January 6, 2002. Subsequently, APS operated the vehicle on 30% HCNG for approximately 5 months. On June 1, 2002, the engine was retuned by NRG Technologies to operate on a 50% hydrogen blend (by volume). APS operated the vehicle on the 50% blend for the balance of the test period.

Additional information pertaining to the high-percentage hydrogen Ford F-150 can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003 (http://avt.inl.gov/pdf/hydrogen/f150hipercentreport.pdf).

4. DEMONSTRATION VEHICLE FLEET OPERATING SUMMARY

4.1 Vehicle Operating History

4.1.1 Dodge Ram Wagon CNG Van

The Dodge Ram Wagon Van operated a total of 22,816 miles during Phase I testing. For the initial 13,160 miles of testing, the van was operated on CNG fuel. After that, it was operated on 15% HCNG.

This vehicle suffered no mechanical problems during the testing period, and therefore no repair costs were incurred. This vehicle did receive two oil changes using Mobil 1 synthetic oil at a total cost of $180.00. This results in a maintenance cost of 0.7 cents per mile.

Additional details concerning the operation of the Dodge Ram Wagon Van are provided in: *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary*, INEEL/EXT-03-00006, January 2003, (http://avt.inl.gov/pdf/hydrogen/dodgereport.pdf).

4.1.2 Mercedes Sprinter Van

The Mercedes Sprinter van operated 6,864 kilometers (4,263 miles – the odometer is in kilometers) on pure hydrogen fuel during Phase I testing.

Minor operational problems were reported during this time. The drivers of the Sprinter reported “rough” operation and a “dead spot” in the accelerator. However, no repairs were performed, and no repair related expenses were incurred for this reporting period. At an odometer reading of 6,719 kilometers (4,173 miles), an oil change using Mobil 1 synthetic oil was performed. The resulting maintenance cost for the Sprinter van during this reporting period was 2.2 cents per mile.

Additional details concerning the Mercedes Sprinter Van operation are provided in: *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, INEEL/EXT-03-00009, January 2003, (http://avt.inl.gov/pdf/hydrogen/mercedessprinterreport.pdf).

4.1.3 Low Percentage Blend Ford F-150 Truck

During Phase I testing, this demonstration vehicle was driven 16,942 miles. The vehicle was operated on 30% HCNG.

No mechanical problems occurred during the test period, therefore, no repair expenses were incurred. The oil was changed using Mobil 1 synthetic oil twice during the testing period at a total cost of $180.00. Therefore, the maintenance cost for this demonstration vehicle during the reporting period was 1.1 cent per mile.

Additional details concerning the operation of the low percentage hydrogen Ford F-150 can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003, http://avt.inl.gov/pdf/hydrogen/f150lowpercentreport.pdf).

4.1.4 High-percentage Blend Ford F-150 Truck

The high-percentage blend Ford F-150 was driven a total of 4,695 miles operating on up to 50% HCNG fuel for the entire period.

As no mechanical problems occurred during the reporting period, there were no associated repair costs. When the vehicle was new (odometer reading was 9 miles), the oil was changed to Mobil 1 synthetic oil at a cost of $90.00. An oil analysis was conducted on the drained oil to serve as a baseline for future oil analysis. The vehicle maintenance cost, during the 4,695-mile test period, was 1.9 cents per mile.

In 1998, Michelin held the first Challenge Bibendum as a challenge to car manufacturers to pave the way for the future of vehicles to clean the air and conserve natural resources. Since 1998, the Challenge Bibendum has been held a total of five times. The first two Challenges were held in Europe. The 2001 Challenge took place between Los Angeles and Las Vegas. The next year it moved back to Europe, and in 2003, it was held in the San Francisco area. The 2003 Challenge Bibendum was open to car manufacturers, bus manufacturers, truck manufacturers, universities, public or private companies, and research institutes who wished to participate with either production or prototype vehicles. (Note: a “Production Vehicle” is defined as a vehicle, which is available for retail purchase or lease at an authorized dealer as of September 22, 2003.)

The High-percentage Blend Ford F-150 truck (Figure 8) participated in the 2001 Challenge Bibendum, while fueled with a 50% HCNG blend, and was evaluated in several different performance categories, including emissions, noise, acceleration, braking, and slalom (handling). Each category was graded on a scale from “A” to “D” with a grade of “A” being the best grade available in a given performance category. The F-150 received the following grades:

Emissions:	B
Noise:	D
Acceleration:	C
Braking:	D
Slalom:	C

Figure 8. High-percentage F-150 while participating in 2001 Michelin Challenge Bibendum.

Two other Challenge Bibendum performance categories, efficiency and range, were not evaluated for the F-150. Additional information about the Michelin Challenge Bibendum can be reviewed at www.challengebibendum.com.

Additional details concerning the operation of the high-percentage blend Ford F-150 can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003, (http://avt.inl.gov/pdf/hydrogen/f150hipercentreport.pdf).

4.1.5 Conclusions

The four blended fuel vehicles tested were driven over 51,000 miles, with more than 37,000 miles driven on 15% or greater hydrogen. No mechanical problems were encountered with any of the test vehicles; therefore, no repair costs were incurred. The only vehicle maintenance performed during the Phase I testing were oil changes. Thus, the average vehicle maintenance cost, during the test period, was 1.4 cents per mile.

4.2 Oil Use Reduction

The objective for the Oil Use Reduction portion of the testing was to determine if oil change intervals could be extended when a blend of HCNG was used to fuel the vehicles. This determination was to be made using oil samples taken from the vehicles and analyzed at various mileage intervals. Two of four demonstration vehicles were tested at these intervals.

Because of the limited mileage during Phase I testing, the high-percentage blend Ford F-150 and the Mercedes Sprinter received only an initial oil analysis. Therefore, no conclusions on oil change extension can be made on these vehicles.

The Dodge Ram Van (CNG for the low mileage interval oil analysis and 15% HCNG at the 15,000-mile interval oil analysis) and the low percentage Ford F-150 truck were tested at various mileages (Table 3). For both of these vehicles, at the 15,000-mile range the silicon levels were in the abnormal range, indicating a contaminant source in the oil. As a contaminant, the presence of silicon can indicate that sand, dirt, dust, or similar type of abrasive was ingested into the system. Also, at the 15,000-mile interval, the oil analyses indicated wear metals (e.g., copper, iron, lead, and tin) in the oil for both vehicles. It is presumed that the presence of these wear metals is directly linked to the silicon contamination in the oil. Based on these limited results, oil change intervals on the vehicles tested is governed by contamination from dust and should not be extended to 15,000 miles. Table 3 provides the oil analyses results for all four vehicles tested in Phase I.

Table 3. Oil analyses results.

Miles on oil	Iron (ppm)	Chromium (ppm)	Lead (ppm)	Copper (ppm)	Tin (ppm)	Aluminum (ppm)	Nickel (ppm)	Silver (ppm)	Boron (ppm)	Sodium (ppm)	Magnesium (ppm)	Calcium (ppm)	Barium (ppm)	Phosphorus (ppm)	Zinc (ppm)	Molybdenum (ppm)	Titanium (ppm)	Vanadium (ppm)	Potassium (ppm)	Fuel (%vol)	Silicon (ppm)	Water (% vol)
DODGE RAM VAN																						
7,000	40	3	25	18	NR	5	NR	NR	NR	NR	1936	1318	NR	954	1155	28	NR	NR	NR	NR	24*	0.0
11,000	32	2	15	8	NR	2	NR	NR	NR	NR	1671	825	NR	1170	962	10	NR	NR	NR	NR	14	0.0
15,000	66	6	51*	27*	20*	7	6	0	30	17	1778	1238	1	1112	1338	26	0	0	0	NR	26*	0.0
6,000	47	4	17	15	10	7	4	0	64	17	300	2516	0	1004	1184	81	0	0	0	<1	23	0.0
7,000	63	4	28	15	12	6	4	0	71	19	367	2527	0	1008	1136	72	0	0	0	<1	20	0.0
12,000	105*	5	30	15	22	10	5	0	98	13	107	3378	0	1225	1206	112	0	0	0	<1	21	0.0
9,000	58	2	24	11	0	6	0	0	60	10	37	3000	0	1105	1392	107	0	0	0	<1	17	0.0
MERCEDES SPRINTER																						
2,583	21	1	2	3	NR	4	NR	NR	NR	NR	2421	1552	NR	1092	1258	2	NR	NR	NR	NR	4	0.0
3,218	15	1	1	3	NR	3	NR	NR	NR	NR	1448	902	NR	918	825	1	NR	NR	NR	NR	2	0.3*
8,802	34	2	4	6	0	6	0	0	73	3	1358	758	0	806	842	0	0	0	0	<1	1	0.2*
LOW % BLEND FORD F-150																						
6,000	40	1	6	24	NR	5	NR	NR	NR	NR	1751	1098	NR	813	987	4	NR	NR	NR	NR	53*	0.0
7,000	39	1	2	13	NR	2	NR	NR	NR	NR	1681	830	NR	1177	957	1	NR	NR	NR	NR	39*	0.6*
2,000	64	3	12	35*	0	7	0	0	15	58	1428	932	1	982	1142	5	0	0	0	N/A	53*	0.0
9,000	34	2	12	14	2	5	0	0	99	25	259	3115	1	1134	1210	81	0	0	0	<1	22	0.0
8,000	98*	3	8	24	0	9	0	0	46	37	273	2766	0	999	1078	89	0	0	0	<1	33*	0.0
13,000	63	2	5	14	0	8	0	0	57	31	80	3079	0	1105	1277	106	0	0	0	<1	21	0.0
6,000	28	2	0	12	1	8	0	0	111	15	30	2659	0	1094	1228	99	0	0	0	<1	26	0.0
HIGH % BLEND FORD F-150																						
1,388	61	1	13	15	NR	4	NR	NR	NR	NR	1658	1194	NR	894	999	16	NR	NR	NR	NR	143*	0.0
6,400	51	4	2	14	0	9	0	0	90	17	1138	1337	1	992	1074	33	0	0	0	<1	91*	0.0

* Abnormal level. Usually noted as abnormal by the test lab if the level is significantly higher than a previous test level. See PuraDYN Oil Bypass Filter System Evaluation Test Plan report, Appendix B, at http://avt.inl.gov/pdf/oilbypass/oilbypass_testplan.pdf for general wear limits. NR = Not Reported

4.3 Emissions Performance

4.3.1 Emission Test Procedures

Two different emission test procedures were performed on the demonstration vehicles referenced in this report, IM240 and FTP-75. The FTP-75 procedure is a more comprehensive evaluation, and this report treats the FTP-75 results as the true emissions values. The IM240 procedure was performed for informational purposes, and the results are listed only for completeness. Details of each test procedure are provided in the following discussion.

IM240

The Inspection and Maintenance Driving Cycle (IM240) is used by several states for the emissions testing of light duty vehicles. The test consists of a single phase, spans 240 seconds, represents 1.96 miles of travel, reaches a top speed of 56.7 mph, and an average speed of 29.4 mph. The test fails to account for cold starts where automobile emissions are typically the highest.

FTP-75

The Federal Test Procedure (FTP-75) is a more thorough emissions test than the IM240. The test consists of three phases, spans 1,874 seconds, represents 11.04 miles of travel, and an average speed of 21.2 mph. The three phases include: a cold start phase, a transient phase, and a hot start phase that occurs 10 minutes after the completion of the transient phase.

4.3.2 Emissions Test Facilities

The emissions data assembled in this report were obtained at two facilities, Automotive Testing Labs and the Clean Air Vehicle Technology Center (CAVTC). Information about each test facility is provided in the following discussions.

Automotive Testing Labs

Automotive Testing Labs (ATL) is located in Mesa, Arizona. The majority of the emissions testing conducted during this testing period was performed at ATL. The laboratory is capable of performing a variety of standard emissions tests including the FTP-75 and the IM240.

Clean Air Vehicle Technology Center

The CAVTC is located in Hayward, California. At the time testing was performed, CAVTC was the only testing center in the United States capable of performing the FTP-75 test while eliminating the effects of ambient pollution. This feature of CAVTC makes it particularly well suited to measure emissions from very low emission vehicles.

4.3.3 Emission Standards

This report makes reference to the California emission standards. When testing was performed, LEV I emission standards were in effect. However, a more stringent set of emission standards, LEV II, came into effect in 2004. The California LEV II emission standards categorize emissions into the following groups; low emission vehicles (LEV), ultra low emission vehicles (ULEV), and super ultra low emission vehicles (SULEV). The standards are based on weight class and measured over the FTP-75 test.

All the vehicles in this report are classified by California emission standards as MDV3.[c] A portion of the California emission standards for MDV3 vehicles is shown below in Table 4.

Table 4. California LEV II emission standards (g/mi).

	NMOG (g/mi)	CO (g/mi)	NO_x (g/mi)
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1.0	0.02

NMOG=Nonmethane organic gases; CO=Carbon monoxide; NO_x=Oxides of nitrogen

4.3.4 Initial Emissions Tests

Dodge Ram Van

The Dodge Ram van was operated and the emissions were tested at approximately 5,700 miles, on both CNG and 15% HCNG. Table 5 provides a summary of the average emission test results for both the FTP-75 and IM240 test protocols.

The FTP-75 emission test results indicate that emission levels for total hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2) were lower when the vehicle is operated on HCNG fuel. (The emission level of non-methane organic gases was not tested.) However, the NO_x emission was significantly greater for the HCNG fuel. The percent change in emissions is shown in Table 6. This increase in NO_x emission is attributed to the fact that the engine was not specifically modified to operate on HCNG.

Table 5. Average emission test results for Dodge Ram van.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75 Vehicle Operating on CNG					
0.052	0.288	0.391	2.192	0.096	565.301
IM240 Vehicle Operating on CNG					
0.009	0.079	0.101	0.643	0.026	540.801
FTP-75 Vehicle Operating on 15% HCNG					
0.0305	0.1915	0.255	0.9785	0.1835	501.503

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x Oxides of nitrogen; CO_2=Carbon dioxide

Table 6. Percent change in emissions; CNG vs. 15% HCNG.

HC	CO	NO_x	CO_2
-34.7	-55.4	+92.1	-11.3

c MDV-Medium Duty Vehicle; MDV3 is the class of MDVs with test weight between 5751-8500 lb. Test Weight by the California definition is analogous to the federal definition of Adjusted Loaded Vehicle Weight (ALVW); Test Weight=(curb weight + GVWR)/2.

The carbon monoxide emissions of this vehicle, using the FTP-75 test protocol, while operating on CNG, were within the LEV II emission standard for an LEV vehicle. While operating on the 15% HCNG fuel blend, the carbon monoxide emissions were within the more restrictive LEV II SULEV emission standard. The average IM240 emission test results while operating the vehicle on CNG were significantly less than the results of the more stringent FTP-75 test protocol.

Additional information concerning the emission test results can be found in: *Dodge Ram Wagon Van — Hydrogen/CNG Operations Summary*, INEEL/EXT-03-00006, January 2003 (http://avt.inl.gov/pdf/hydrogen/dodgereport.pdf).

Mercedes Sprinter Van

The Mercedes Sprinter Van operates using 100% hydrogen with its only emission potential being nitrogen oxide. No emission testing was performed on this vehicle during Phase I testing.

Low-Percentage Blend Ford F-150 Truck

The emissions of the low-percentage blend Ford-150 truck were periodically tested at the ATL test facility. Table 7 provides a summary of the average emission test results for both the FTP-75 and IM240 test protocols.

The results of the FTP-75 test indicate that the vehicle was performing below the LEV II SULEV emission standard for CO. However, the NO_x emissions were, on average, greater than the LEV II emission standard for a LEV. (The emission level of non-methane organic gases was not tested.)

No significant difference in emissions was obtained from testing conducted at increasing mileages (1,592 miles and 3,915 miles). Additional information concerning the emission test results can be found in: *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00008, January 2003, (http://avt.inl.gov/pdf/hydrogen/f150lowpercentreport.pdf).

Table 7. Average emission test results for low percentage blend Ford F-150.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75					
0.022	0.081	0.117	0.255	0.077	439.254
IM240					
0.019	0.046	0.074	0.112	0.037	401.285

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide

High-percentage Blend Ford F-150 Truck

The emissions of this vehicle were tested when the truck was first converted (87 miles). The vehicle was using a 30% hydrogen blend at the time of emissions testing. Because of the low emission levels expected from this vehicle, the emissions testing was performed at the CAVTC test facility. Table 8 provides the emission test results for the FTP-75 test protocol.

Table 8. Emission test results for high-percentage blend Ford F-150.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
FTP-75					
0.0014	0.108	0.123	0.879	0.005	518.100

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide

The results of the FTP-75 test indicate that the vehicle was performing below the LEV II SULEV emission standards for CO and NO_x. (The emission level of nonmethane organic gases is not tested.) Additional information concerning the emission test results can be found in: *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, INEEL/EXT-03-00007, January 2003, (http://avt.inl.gov/pdf/hydrogen/f150hipercentreport.pdf.

4.3.5 Follow-Up Tests

Additional emissions and performance testing was performed on the high-percentage blend Ford F-150 truck by Argonne National Laboratory (ANL) and on the low-percentage blend Ford F-150 truck by ATL. Results of this testing is reported in Sections 5 and 6.

4.4 Demonstration Vehicle Conclusions

4.4.1 Vehicle Operating History

All vehicles in the initial test fleet operating on CNG, HCNG, and pure hydrogen performed with no safety issues. The only mechanical difficulties encountered were with the starting of the Mercedes when the fuel system was not completely sealed. The overall performance of the vehicles was good with no operational issues identified. With no major mechanical repairs necessary, the only associated operational costs, other than fuel, were oil changes. Based on the results of Phase I testing, hydrogen can be a viable and safe fuel for use in internal combustion engine-powered vehicles.

4.4.2 Oil Use Reduction

Based on the preliminary results of the oil analysis of the two vehicles tested, additional validation will be required to allow oil change intervals to be extended to 15,000 miles when using synthetic oil.

4.4.3 Emissions Performance

Emissions testing was conducted for three of the four demonstration vehicles using the FTP-75 emissions test. The Mercedes Sprinter Van was not tested for emissions, because it operates on 100% hydrogen. Emissions of the tested vehicles, on all percentages of fuels, were within the LEV II Low

Emission Vehicle emission standards. Table 9 shows the average FTP-75 emission test results for the three tested demonstration vehicles.

As shown in Table 9, when hydrogen was introduced into the Dodge Ram Van the carbon monoxide (CO) emissions decreased. The decrease in CO emissions is presumed to be the result of more complete combustion. The more complete combustion, however, also results in increased NO_x as a result of increased combustion temperatures. Vehicles modified with exhaust gas recirculation to achieve complete combustion without increasing combustion temperature, achieve reductions in both CO and NO_x.

Table 9. Average FTP-75 emission test results for the demonstration vehicles.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
Dodge Ram Van Operating on CNG					
0.052	0.288	0.391	2.192	0.096	565.301
Dodge Ram Van Operating on 15% Hydrogen/85% CNG					
0.0305	0.1915	0.255	0.9785	0.1835	501.503
Low Percentage Blend Ford F-150 (28% Hydrogen/72% CNG)					
0.022	0.081	0.117	0.255	0.077	439.254
High-percentage Blend Ford F-150 (30% Hydrogen/70% CNG)					
0.0014	0.108	0.123	0.879	0.005	518.100

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x Oxides of nitrogen; CO_2=Carbon dioxide

5. HIGH-PERCENTAGE BLEND (50% HCNG) FORD F-150 SPECIAL TESTING

5.1 Argonne National Laboratory Testing

ANL is a nonprofit laboratory operated by the University of Chicago for DOE located near Chicago, Illinois. The ANL Advanced Powertrain Research Facility (APRF), is equipped with a four-wheel drive (4WD) chassis dynamometer. The APRF was designed for the testing of new vehicle technologies. Specifically, vehicles with reduced emissions and increased fuel economies.

As part of the AVTA work, the high-percentage blend Ford F-150 truck was transported to ANL to use the APRF for dynamometer and emissions testing. The vehicle was tested using a 50% HCNG blend. California Air Resources Board (CARB) fuel specifications were used for the CNG component of fuel to ensure repeatable tests.

During ANL testing, the emissions and fuel economy were measured using the Federal Test Procedure (FTP), and the highway fuel economy test (HWFET) drive cycles. Testing was also conducted using the US06 drive cycle and a modified New European Driving Cycle (NEDC) cycle. The FTP and HWFET results were very repeatable. On the average, the emissions levels of carbon monoxide from the FTP testing were within the LEV II SULEV standard of 1 g/mi. The emissions level for NO_x from the FTP testing, however, on the average, was greater than the LEV II SULEV standard of .02 g/mi, but within the LEV II ULEV standard of .07 g/mi. Table 10 provides a summary of the average of the three FTP-75 emission test results.

The fuel economy average of three FTP tests and two HWFET was 14.3 and 21.6 miles per gge, respectively. Results of the ANL testing are presented in a report prepared by ANL, Spring 2004 in: *CTR Exploring Hydrogen-Fueled Internal Combustions Engines* (http://www.transportation.anl.gov/transtech/v4n1/hydrogen-fueled.html).

Table 10. Average ANL FTP-75 emission test results for the 50% Hydrogen/50% CNG Ford F-150.

HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
0.1844	0.8639	0.0326	373.850

6. LOW PERCENTAGE BLEND FORD F-150 PARAMETRIC TESTING

6.1 Test Program Description

Blending hydrogen with CNG (HCNG) for fueling vehicles (and performing no other vehicle modifications) reduces engine power output because of the lower volumetric energy density of the hydrogen compared to CNG. The low percentage blend Ford F-150 (Figure 9) was tested to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To perform this evaluation, procedures were developed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck operating on CNG, and blends of 15% and 30% HCNG. A summary of the test results is provided in the following sections. Additional details of the parametric testing, test procedures, and test results, see: *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150*, INEEL/EXT-03-01313, November 2003, (http://avt.inl.gov/pdf/hydrogen/30percentf150.pdf).

6.1.1 Acceleration and Range Test Procedures

Special procedures were developed to conduct testing of the F-150 test vehicle's acceleration and range when using CNG and blends of 15% and 30% HCNG. The acceleration test procedure required that the vehicle be accelerated from rest to a speed of 100 mph and speed versus time data collected. The range test procedure required that the vehicle be operated at a constant speed of 45 mph, and distance versus time data collected.

Figure 9. Low-percentage F-150 during parametric testing.

These test procedures are provided as appendixes to: *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150*, INEEL/EXT-03-01313, November 2003, (http://avt.inl.gov/pdf/hydrogen/30percentf150.pdf).

6.2 Testing Results

6.2.1 Acceleration Testing Results

Acceleration testing of the F-150 was conducted at the Arizona Proving Grounds (APG) of DaimlerChrysler, in accordance with the test procedures for fuels of CNG and blends of 15% and 30% HCNG. Tests were performed using a 3-mile long straight track at the APG. Two sets of acceleration runs were conducted. Each set consisted of one acceleration run in each direction on the straight track. Table 11 presents the 0 to 60 mpg acceleration times for each fuel type.

Table 11. Acceleration time, 0 to 60 MPH for various fuels.

Fuel Blend	Vehicle Mileage	Time (sec) To 60 mph
CNG	32,452	10.10
15% HENG	31,943	10.97
30% HCNG	31,679	12.68

As expected, the performance (in terms of acceleration) of the F-150 test vehicle degrades with increasing amounts of hydrogen in the fuel (and no other compensating changes). However, much of the performance loss arises from the initial switch from a liquid fuel (gasoline) to a gaseous fuel (CNG) as shown in Table 12. The degradation in acceleration resulting from use of hydrogen in the fuel does not have a significant impact on the drivability until blends approaching 30% hydrogen are used. At a blend of 15% HCNG, the F-150 test vehicle acceleration was within 10% of that when operating on CNG.

Table 12. Acceleration to 60 MPH for various fuels.

Fuel Blend	Time to 60 mph (seconds)	Degradation From CNG F-150	Degradation From Gasoline F-150
Gasoline	8.6 [a]		Base
CNG	10.10	Base	17.4 %
15% H_2	10.97	8.6 %	27.6 %
30% H_2	12.68	25.5 %	47.4 %

a. 2001 Ford F-150 with 5.4-L V-8 engine and automatic transmission as reported by Edmunds.com.

Degradation of acceleration can be remedied by either increasing the amount of fuel and air entering engine cylinders or by directly injecting hydrogen into the cylinder to avoid the displacement of air by the hydrogen fuel. However, this requires additional vehicle modifications and is not practical for introducing blended fuel into existing CNG fleets.

6.2.2 Range and Fuel Economy Testing Results

The range of the F-150 test vehicle was tested in accordance with the test procedures for CNG and blends of 15% and 30% HCNG. The tests were performed at a constant speed of 45 mph using a 2-mile long high-speed oval track at the APG. The vehicle was driven 60 miles on each fuel, and the amount of fuel used was determined through the mathematical relationship between pressure, temperature, and mass for a perfect gas. From these calculations, the fuel economy in gasoline gallon equivalents was determined (Table 13). Using the fuel economy and the capacity of the fuel tanks (85 liters) filled to 3,600 psig, the range of the F-150 test vehicle for each type of fuel was calculated (Table 13).

Table 13. Range at constant speed of 45 mph for various fuels.

Fuel Blend	Vehicle Mileage	Fuel Economy (miles/gge)	Range (miles)
CNG	32,465	23.3	122
15% HCNG	31,951	22.6	110
30% HCNG	31,769	23.5	102

As shown in Table 14, degradation of vehicle range was significant with the 30% HCNG fuel. The decrease in range between CNG and 30% HCNG will require a 16.4% increase in onboard fuel storage to maintain vehicle range similar to that achievable with CNG. In the case of the F-150 test vehicle, this will require the addition of a 14-liter fuel tank. With a fuel of 15% HCNG, the range degradation was less than 10%. This should have a negligible impact on vehicle utility in fleet operation.

Table 14. Range decrease from use of various fuels.

Fuel Blend	Range (miles)	Decrease from CNG
CNG	122	Base
15% HCNG	110	9.8 %
30% HCNG	102	16.4 %

No significant change in efficiency (within the accuracy of the test methods) was noted for the fuels tested. Fuel economy for the constant speed of 45 mph range test was 23.3 miles/gge for CNG, 22.6 miles/gge for 15% HCNG, and 23.5 miles/gge for 30% HCNG.

6.2.3 Emissions Test Results.

The baseline emission test results from the initial fleet emission testing was supplemented in this portion of the test program by conducting a single FTP-75 emission test on the vehicle using fuels of CNG, 15% HCNG, and 30% HCNG. Each time fuel was changed in the test vehicle, it was driven at least 100 miles using the new fuel to allow the engine management computer to make any automatic adjustments necessary to optimize use of the new fuel. The FTP-75 test cycle emission testing was conducted by ATL using the procedures certified by the State of Arizona. Table 15 provides the emission results at the different fuel blends.

To provide an additional point of reference for the Ford F-150 emission test results, emission testing of a randomly selected Ford F-150, at approximately 23,500 miles, equipped with a gasoline engine was also conducted at ATL. Results of this testing are provided in Table 16.

The exhaust emissions using CNG, 15% HCNG, and 30% HCNG showed significant emission reductions over gasoline in NMHC, CO, NO_x, and CO_2. However, CH_4 and HC increased with the introduction of the methane-based CNG. Percentage changes are shown in Table 17.

Table 15. Blended fuel FTP-75 emission test result comparisons for the low percentage blend Ford F-150.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
Low Percentage Blend Ford F-150 (28% HCNG) at < 4,000 miles					
0.022	0.081	0.117	0.255	0.077	439.3
CNG at 30,045 miles					
0.023	0.128	0.173	0.567	0.110	473.1
15% HCNG at 29,915 miles					
0.025	0.132	0.179	0.467	0.124	452.2
30% HCNG at 28,814 miles					
0.013	0.138	0.175	0.423	0.126	448.1

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Table 16. Gasoline fueled Ford F-150 FTP-75 average emission test results.

NMHC (g/mi)	CH_4 (g/mi)	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	CO_2 (g/mi)
0.115	0.012	0.128	1.551	0.167	621.9

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Table 17. Emissions variations using blended fuels.

	Percentage Change in Emission Species					
Fuel Type	NMHC	CH_4	HC	CO	NO_X	CO_2
Gasoline	Base	Base	Base	Base	Base	Base
CNG	-80	+967	+35	-63	-34	-24
15% HCNG	-78	+1000	+40	-70	-26	-27
30% HCHG	-89	+1050	+37	-73	-25	-28

NMHC=Nonmethane hydrocarbons; CH_4=Methane; HC=Total hydrocarbons; CO=Carbon monoxide; NO_x=Oxides of nitrogen; CO_2=Carbon dioxide.

Much of the reductions in CO, NO_x, and CO_2 emissions are achieved by switching from gasoline to CNG. Additional CO reductions are achieved with higher percentage blends of hydrogen in CNG. However, NO_x increases with the higher percentage blends. The NO_x levels measured in the current work program are significantly higher than measured during the fleet operation of the F-150 test vehicle using 30% HCNG. The fleet testing was conducted with the vehicle use between 1,500 and 4,000 miles. Testing in the current work program was conducted with the vehicle use near 30,000 miles. It is believed that aging of the catalytic converter was the cause of the increased NO_x emissions.

Based on these results, reductions in CO and CO_2 emissions can be achieved by blending hydrogen with CNG for use in CNG fleets. These emission reductions come at some cost in terms of reduced vehicle acceleration and range. However, even at 15% HCNG, the performance reductions do not have a significant impact on vehicle drivability and serve to provide an additional 10% decrease in CO and CO_2 emissions.

7. PHASE II TESTING ACTIVITIES

7.1 100 Percent Hydrogen, Four-Valve-Per-Cylinder Ford F-150

In October 2001, APS and ETA commissioned Collier Technologies to build a Ford V-8 engine to run on pure hydrogen. This project demonstrated the ability of a pure hydrogen internal combustion engine to generate equivalent power output while achieving very low emissions and high efficiency performance.

It was decided that, in order to achieve best-in-class emissions and power, the engine would require more significant modifications. However, as many off-the-shelf components were used as possible to minimize the cost of any future conversions. The engine selected for this conversion was the Ford 5.4L DOHC (double overhead cam, 4 valves per cylinder) InTech V-8 engine, as used in the Lincoln Navigator SUV. For testing, the completed converted pure hydrogen engine was installed in the high-percentage Ford F-150 truck. The specifications for the Ford 5.4L InTech engine are provided in Table 18.

Table 18. Specifications for the Ford 5.4L InTech V-8 engine.

Displacement	5.4 L/330 cu in.
Bore & stroke	90.2 mm × 105.8 mm/3.55 in.× 4.17 in.
Compression ratio	9.5:1
Horsepower	300 @ 5,000 rpm (SAE net)
Torque	355 lb-ft @ 2750 rpm (SAE net)

The DOHC design for the cylinder heads was especially important to allow for sufficient airflow into the engine to make high levels of power when running pure hydrogen as a fuel.

7.1.1 Details of Engine Conversion

Numerous modifications were made to this engine during the conversion to 100% hydrogen fuel.

Compression Ratio

In stock form, this engine has a static compression ratio of 9.5:1. The compression ratio was increased to approximately 12.8:1 in order to increase thermal efficiency. This compression ratio increase was achieved by modifying the crankshaft to increase the stroke (+4.75 mm) and by installing custom pistons that resulted in zero deck height.[d] The increase in stroke also resulted in a slight increase in displacement (from 5.4L to 5.65L) that further improved the ability to make high levels of power with the converted engine.

Cylinder Liners

Another method employed to improve efficiency was the installation of cylinder bore liners coated with Nikasil (nickel-silicon carbide). This coating reduces sliding friction between the cylinder bore and

[d] Zero deck height means that the top of the piston is flush with the cylinder deck (cylinder head mounting surface), which decreases the amount of volume above the piston when it is at the top of its stroke.

piston by up to 90%. Furthermore, there is evidence that a better cylinder bore-to-piston ring seal is achieved with the Nikasil coating, which further improves combustion efficiency.

Supercharger

In order to achieve the power output goals of this project, a supercharger was specified for the engine. There are two main contributors to the need for a supercharger. First, hydrogen requires a very low fuel-to-air mixture ratio to maintain stable combustion and to minimize the production of NO_x (lean burn). Without the supercharger, the amount of fuel delivered into each cylinder would be very small to maintain the low mixture ratio, limiting the maximum power output from the engine. Alternatively, by supplying a much greater volume of air via the supercharger, the fuel-to-air ratio can be kept low while providing sufficient fuel (hydrogen) and oxygen (from the air) to produce the power levels required for this project.

A secondary reason for using the supercharger involves the air displacement effect when using hydrogen (or any gas) as a fuel. Because the partial pressure of hydrogen is high (compared to other fuels including gasoline) and because a few hydrogen molecules occupy a relatively large volume, there is little room in a naturally aspirated cylinder for the air required for combustion. In order to maintain the low fuel-to-air ratios, the amount of hydrogen used for each combustion event is limited. By using a supercharger, the air is introduced into the cylinder at much higher pressure, reducing the volume required for the hydrogen fuel and maximizing the amount of oxygen available for combustion.

The supercharger selected for this project was a Lysholm unit, as shown in Figure 10. This screw-type supercharger is known to be more efficient than other designs, resulting in reduced power input to drive the supercharger and reduced outlet temperature.

In order to install the supercharger, Collier Technologies fabricated an aluminum intake manifold which included a water-to-air intercooler for the intake charge and a single throttle body for throttle control. This intake manifold also includes a bypass circuit that allows the supercharger to be bypassed during light-load operation, reducing parasitic loads and improving overall efficiency (see Figure 11).

Figure 10. Lysholm supercharger.

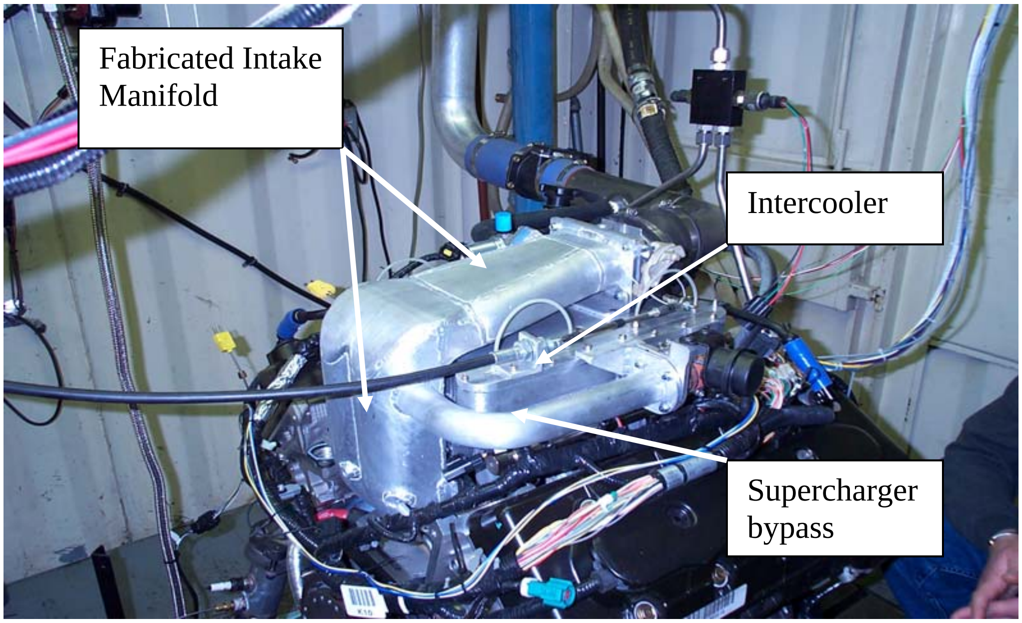


Figure 11. Fabricated intake manifold.

Water Injection

Water injection is sometimes used on high-performance engines to cool the intake charge. For this conversion, a water injection system was employed during engine testing on the dynamometer. The water for this system is taken from the exhaust gas water separator. The benefit of using this water source is twofold. First, the water is produced and stored on-board, eliminating the need to add water from a remote source. Second, the water separated from the exhaust gas is of a high purity that will minimize the buildup of contaminants over time in the combustion chamber. The water injection system is intended only for intermittent use and only when maximum power is required. Marginal benefit was attained using the water injector and this feature was not included in the engine when installed in the truck for road testing.

Crankcase Evacuation

When the engine is running, it is expected that some amount of the air/fuel mixture will blow by the piston ring sealing system and enter the crankcase volume. This is especially true with gaseous fuels such as hydrogen. To avoid accidental combustion of this fuel in the crankcase volume, a system was designed to create a vacuum inside the crankcase volume. The scavenged gases run through an oil/air separator to remove any oil vapors from the system. A Raycor oil separator (model CC4500-08L) was installed and used on the engine. The remaining gases are returned to the intake system to be burned in the combustion chamber.

For efficiency purposes, a belt-driven pump was used to generate up to 8 in. H_2O of vacuum in the crankcase during dynamometer testing. This system was not installed in the vehicle.

Engine Control

The engine employed an electronic engine control system with fuel injection. Quantum Technologies gaseous fuel injectors were used for fuel delivery. Engine control was accomplished with a MoTeC M800, 32-bit Engine Management System. This system allows for precise control of both the typical engine control functions as well as the unique systems developed specifically to run hydrogen fuel. Collier Technologies developed the fuel and spark maps, along with the control points for the other systems specifically for this development program.

Electronic control of the automatic transmission remained with the stock Ford control unit.

7.1.2 Engine Testing

The completed engine was tested on an engine dynamometer at Collier Technologies. Efficiency was measured as shown in Table 19. A peak efficiency of 40.1% was achieved. Using the same tuning parameters, a maximum horsepower of 194 was achieved.

Table 19. Engine efficiency of 4-valve hydrogen F-150 on dynamometer.

Speed (RPM)	Power (HP)	Fuel (g/s)	Efficiency LHV	Efficiency HHV
1300	35	0.69	31.6%	26.8%
1400	38	0.71	33.5%	28.4%
1500	43	0.74	36.0%	30.5%
1600	48	0.78	37.8%	32.0%
1700	52	0.83	39.0%	33.1%
1800	58	0.89	40.1%	34.0%
1900	63	0.99	39.5%	33.5%
2000	69	1.1	38.7%	32.8%
2100	74	1.21	37.8%	32.0%
2200	79	1.33	36.8%	31.2%
2300	84	1.42	36.6%	31.0%
2400	89	1.51	36.75	31.1%
2500	94	1.57	37.3%	31.6%
2600	99	1.64	37.4%	31.7%
2700	103	1.68	38.0%	32.2%
2800	108	1.75	38.4%	32.5%
2900	113	1.8	39.0%	33.0%
3000	118	1.87	39.0%	33.0%
3100	121	1.94	38.7%	32.8%
3200	125	2.06	37.6%	31.9%
3300	131	2.21	36.6%	31.1%
3400	137	2.37	35.8%	30.3%
3500	141	2.57	34.1%	28.9%

Speed (RPM)	Power (HP)	Fuel (g/s)	Efficiency LHV	Efficiency HHV
3600	146	2.67	33.9%	28.8%
3700	151	2.79	33.5%	28.4%
3800	154	2.87	33.2%	28.2%
3900	155	2.94	32.7%	27.7%
4000	156	3.02	32.0%	27.1%
4100	158	3.09	31.7%	26.9%
4200	162	3.22	31.2%	26.4%
4300	168	3.35	31.2%	26.4%
4400	176	3.44	31.7%	26.8%
4500	183	3.57	31.7%	26.9%
4600	189	3.68	31.8%	27.0%
4700	193	3.82	31.3%	26.5%
4800	194	3.91	30.8%	26.1%

7.1.3 Vehicle Operation and Utilization

Upon completion of dynamometer testing, the engine was installed in the chassis of the high-percentage F-150, previously used for blended fuel testing. Once the vehicle integration was complete, the vehicle was transported to Phoenix for Baseline Performance Testing in the AVTA and operation in the APS fleet. Unfortunately, the vehicle was operated for only a short period in the very high ambient temperatures of Phoenix before a severe pre-ignition event caused a catastrophic failure of the engine.

The engine was subsequently rebuilt using forged connecting rods and forged pistons to increase the strength of the engine rotating assembly. However, the compression ratio remained unchanged. The engine was again operated in the high ambient temperatures of Phoenix, Arizona, with unsatisfactory results. Continued preignition events caused the failure of ring bands on multiple pistons, requiring a second overhaul of the engine. The replacement pistons were custom machined to achieve a compression ratio of 10.25:1 to reduce the potential for pre-ignition and increase the engine drivability.

To further improve drivability, a Baumann Engineering "Baumannator" control unit was employed to control the automatic transmission. As delivered from Collier Technologies, the shift schedule using the Ford controller was awkward and resulted in very harsh shifts. Using the Baumannator unit, the shift schedule was custom tuned to allow for smoother shifts at more reasonable engine speeds.

The engine as installed in the high-percentage Ford F-150 will be tested in Baseline Performance Testing for both performance and emissions. Results of this testing will be reported separately by the INL.

7.2 100 Percent Hydrogen Two Valve Per Cylinder F-150

Because of the extensive modification and fabrication expense required with the development of the 4-valve hydrogen internal combustion engine (HICE), a decision was made to convert a smaller production engine to hydrogen fuel with a focused effort to minimize fabrication and modification costs. Collier Technologies built a Ford V-8 engine (single overhead cam engine, two valves per cylinder) to be installed in a 2003 Ford F-150 XTL sport truck. Specifications for this engine are presented in Table 20.

Experience with engine failure in the hydrogen 4-valve engine exposed potential vulnerability with production rods and pistons. To upgrade strength, prior to installing the engine in the truck, forged rods and pistons were replaced in the engine. Three 150-liter, 2,900-psi hydrogen storage tanks were installed. The tanks and pressure regulator were placed in the bed of the truck. The truck was modified with a WEH 5,000-psi fueling inlet for compatibility with the APS Pilot Plant for fueling.

Table 20. Specifications for Ford 5.4L V-8.

Displacement	5.4
Horsepower	106 @ 3,000 rpm
Torque	189 lb-ft @ 1,500 rpm

7.2.1 Ford F-150 2-Valve Vehicle Testing

As part of the U.S. Department of Energy Advanced Vehicle Testing and Evaluation Activity, the truck was evaluated as a production vehicle against the HICEV America Baseline Test objectives. These test objectives were developed for a variety of parameters and operating characteristics as well as for conformance to selected hydrogen fuel system and vehicle integration requirements established for various types of hydrogen vehicles. Performance statistics for this vehicle are presented below.

Acceleration 0-50 mph

Acceleration time: 18.1 seconds

Acceleration goal: 13.5 seconds

Maximum Speed

Speed at 1 mile: 80.9 mph

Performance goal: >70 mph

SAE J1634 Driving Cycle Fuel Economy (AC Off)

Fuel economy: 18.0 miles/gge

SAEJ1634 Driving Cycle Fuel Economy (AC On)

Fuel economy: 14.5 miles/gge

Complete vehicle specifications and test results are provided in Appendix A. No emission testing was performed.

7.2.2 Engine Modifications

After initial fleet testing for mileage accumulation, a problem with oil in the intake system was noted. Subsequent engine work resulted in discovery of erosion of the valve seats. Upgraded valves and valve seats were installed to tolerate the higher combustion temperature of hydrogen. In addition, a Magnesium Supercharger was installed to help recover power.

The truck has entered 24,000-mile accelerated reliability testing and is accumulating mileage in the Phoenix metropolitan area.

7.3 Four-Valve and Two-Valve Engine Comparison

Two engine platforms were tested, with one platform being the four-valve per cylinder 5.6-L Ford modular with a twin-screw supercharger, and the other a two-valve per cylinder 5.4-L Ford modular engine with a conventional roots-type supercharger. The compression ratios for each engine, as tested, were for the four-valve at approximately 12.5:1 and the two-valve at approximately 13.5:1.

The results of testing are shown in Tables 21 and 22. The high efficiency point is taken at 1,500 rpm while the high engine output power point is taken at 4,000 rpm. The most obvious difference between the engine platforms is the brake efficiency, 37% vs. 31% at the maximum efficiency point and 29% vs. 22% at the maximum power point. To put this in perspective, the four-valve engine will use one-third less fuel under high load conditions and 20% less fuel at moderate load conditions than the 2-valve engine.

It is not obvious from the data which of the differences between these engines were responsible for the incremental improvements in observed efficiency. However, there is a strong indication that the difference in the ability of the engine to flow air is a contributor to the efficiency improvements. By examining the boost pressures, one can see that the differences in airflow rates between engines under nearly identical manifold conditions. The four-valve engine flows considerably more air. This additional airflow allows more fuel to be combusted while maintaining the same air-fuel ratios. Therefore, the four-valve engine makes more power for the same parasitic loads on the engine. Of course, this assumes that the superchargers are of equal efficiency, which they are not, but a great deal of the efficiency differences can be attributed to the differences in breathing characteristics for the two engines.

The NO_x emissions for the four-valve engine are higher than the two-valve engine. It is believed that this is due to the higher power outputs of the four-valve engine. To demonstrate this, another data point for the four-valve is also shown. For nearly the same NO_x emissions of the two-valve engine, the four-valve engine made 183 ft-lb of torque with 35% efficiency. This compares to 126 ft-lb at 32% efficiency for the two-valve engine.

In conclusion, the comparison between engine configurations has demonstrated the importance of having engines with low parasitic losses and high volumetric efficiency when using hydrogen as the engine fuel to achieve vehicle drivability and low NO_x emissions. These tests show that merely adapting hydrogen to an existing gasoline engine will not achieve the desired results. Also, one can reasonably expect that by using a turbocharger instead of a supercharger, the four-valve engine could achieve 40% brake thermal efficiency.

Table 21. High efficiency point test results. (wot – wide open throttle).

Run Type	Speed (rpm)	Torque (ft-lb)	Power (hp)	Throttle (%)	Power Boost (psi)	Air Flow (g/s)	Calculated Equivalence	CO (ppm)	NO_x (ppm)	THC (ppm)	Brake Efficiency (%)
2-valve	1502	126	36	wot	9.8	58	0.424	3	1	--	31.1
4-valve	1500	240	69	wot	11.2	92	0.427	1	118	4	37.1
Lower NOx Point											
4-valve	1702	183	59	wot	11.6	110	0.329	1	2	3	35.0

Table 22. High power point test results.

Run Type	Speed (rpm)	Torque (ft-lb)	Power (hp)	Throttle (%)	Power Boost (psi)	Air-Flow (g/s)	Calculated Equivalence	CO (ppm)	NO_x (ppm)	THC (ppm)	Brake Efficiency (%)
2-valve	3943	131	99	wot	11.5	176	0.439	11	1	--	22.1
4-valve	4120	230	180	wot	11.6	249	0.440	4	5	7	28.9

7.4 Extended Fleet Testing of Low Percent H_2 Blended Fueled F-150

7.4.1 Test Objectives

The primary objective of the ongoing fleet testing activities for the low percentage blend F-150 was the evaluation of the safety and reliability of operating a low percentage HCNG blend vehicle. Once again, secondary objectives of the ongoing testing were to quantify vehicle emissions, cost, and performance with an additional objective of evaluating the potential for oil use reduction.

The low percentage blend Ford F-150 will continue to operate in fleet duty in the Phoenix area during the ongoing testing. It is expected that it will accumulate at least 1,000 miles per month for a 12-month period. During this service, fuel economy and cost will be evaluated and additional oil analysis will be performed.

7.4.2 Test Metrics

Formal emissions testing with the blended fuels were conducted in May and June of 2003 as outlined in Table 23. Each time the fuel was changed in the vehicle, the vehicle was driven a minimum of 100 miles to allow the engine management computer to adjust to the new fuel.

Table 23. Emissions test results (gram/mile) for blended HCNG fuels and 100% CNG. Fuel vehicle emission species (gram/mile).

Blend	Mileage	NMHC	CH_4	HC	CO	NO_x	CO_2
CNG	30,045	0.023	0.128	0.173	0567	0.110	473.1
15% HCNG	29,915	0.025	0.132	0.179	0.467	0.124	452.2
30% HCNG	28,814	0.013	0.138	0.175	0.432	0.126	448.1

CO = carbon monoxide; NMHC = nonmethane hydrocarbons
NOx = oxides of nitrogen; CH_4 = methane
CO2 = carbon dioxide; HC = total hydrocarbons.

7.5 Low Percent Blended Fuel Fleet Testing of Bi-fuel CNG Vehicles

7.5.1 Test Objectives

The primary objective of the extended road testing activities remains the evaluation of the safety and reliability of operating HCNG blends in bi-fuel fleet vehicles at various percentages of hydrogen. The goal was to obtain 216,000 total miles for dual fuel (gasoline and CNG) vehicles. The drivers of the vehicles would be asked to use HCNG blended fuel. Use of all fuel types were reported and recorded. Once again, secondary objectives of the ongoing testing are to quantify alternative fuel use, driver choice of alternative fuel, and vehicle performance.

7.5.2 Low Percent Blend Bi-Fuel CNG Vehicles Fleet Testing

Two separate fleets participated in fleet service using various blends of hydrogen fuel. Predominately, 15% HCNG fuel was used; however, some users fueled with the higher hydrogen blends. All drivers were given instruction in use of the blended fuel dispenser at the Pilot Plant.

The first fleet was composed of APS utility vehicles operated for various business related purposes. However, the primary fleet function was delegated for electric meter reading in the Phoenix metropolitan area. This fleet was housed close to the fueling station, and the blended fuel was used for 64% of the overall miles accumulated.

The second fleet was composed of privately owned bi-fuel gasoline and CNG vehicles. The majority of the vehicles were utilized primarily for commuting to work in the downtown Phoenix area. Two of the vehicles were used for transportation/delivery needs associated with small businesses. The vehicles associated with a small business accumulated significantly higher monthly mileage. Of the fleet vehicles, some were OEM vehicles but the majority of the vehicles were converted bi-fuel vehicles. The 15% HCNG blended fuel was used for 86% of the accumulated miles. The mileage results are presented by vehicle in Table 24.

A total of 158,223 miles was accumulated using HCNG fuels. A total of 230,959 miles was reported, exceeding project goals. There were over 2,000 fueling events with approximately 12,000 gge of HCNG fuel dispensed.

Table 24. Fleet mileage accumulated.

Vehicle Type	Begin Odometer	End Odometer	HCNG Mileage	Total Mileage
S10	5,244	17,132	3,145	11,888
Blazer	16,230	43,081	16,446	26,851
S10	1,371	17,083	5,557	15,712
Ram Wagon	30,734	58,500	27,766	27,766
GMC Sierra	1,281	18,496	5,240	17,489
GMC Sierra	2,363	24,147	18,979	21,784
GMC Sierra	1,956	26,843	15,921	24,887
GMC Sierra	3,404	25,708	13,113	22,304

GMC Sierra	1,171	20,171	14,825	19,000
Civic GX	95,664	101,381	5,717	5,717
Ford Contour	63,977	70,245	5,626	6,268
Civic	27,552	35,067	7,515	7,515
Silverado	75,231	82,557	4,368	7,326
Civic	73,814	79,185	4,828	5,371
Tahoe	36,036	44,100	6,160	8,064
Civic	58,838	61,855	3,017	3,017
		Total Miles	**158,223**	**230,959**

7.5.3 Fleet Maintenance

One vehicle in the study reported catalytic converter failure within the first week of using the blended fuel. The failed catalytic converter was from an OEM bi-fuel vehicle that had accumulated 75,000 miles prior to participation in the study. The owner was unsure if the failure was related to the use of HCNG fuel or converter age. The catalytic converter was replaced and the participant continued in the study using the 15% blend with no further performance issues. Early in the data collection another participant felt that the HCNG fuel had affected engine performance of his personally owned converted bi-fuel vehicle. He reported increased engine noise and poor performance. He opted to discontinue participation in the study and did not report accumulated miles. The remaining participants found no significant change in engine performance using blended fuel. All vehicles received regular preventative maintenance service during study.

7.5.4 Tank Failure Testing

To determine if the use of HCNG fuels in the low percentage blend F-150 had any deleterious effects on the standard CNG fuel tanks used in that vehicle, testing was conducted on one of the fuel tanks after completion of Phase I testing. Powertech Labs, Inc. performed testing of a Type-2 CNG cylinder from the low percentage blend F-150. The investigation was to determine the condition of the steel liner as a result of exposure to the CNG/hydrogen mixture. The glass fiber hoop-wrap was removed to allow for ultrasonic scanning that could detect defects that could exceed 5% of the wall thickness. Following the examination, the liner was hydraulically pressurized to burst.

Test results revealed no defects exceeding 5% of the wall thickness. The burst pressure of the bare liner was 5,084 psi, which exceeded the ANSI/IAS NGV2-1998 design requirement of 4,500 psi. An examination of the burst initiation location did not reveal any indication of tank embrittlement.

7.6 Conclusions

The bi-fuel CNG vehicles were driven 231,000 miles, with more than 158,000 miles driven with 15% HCNG. From the extended blended fuel vehicle testing it is evident that 15% HCNG fuel can be used in CNG bi-fuel vehicles without modifications to the engine or fuel storage tank. When running hydrogen percentage mixes greater than 15% with CNG, it is necessary to tune the engine to achieve lower emission results. Without tuning the engine with the 50% blended fuel, there was actually an increase in measured emissions parameters. So to maintain the emissions benefits of alternative fuels, when using new fuel blends, the engine must be tuned to that fuel.

Our testing indicated that there are no detrimental effects on the vehicle by using 15% blended fuel in the CNG bi-fuel vehicles. There were no mechanical problems attributed to the use of the blended fuel. Routine maintenance was performed on all vehicles during the study. Both OEM and converted bi-fuel vehicles were tested without noticeable effect on engine performance. There is a potential to extend oil changes when using 15% HCNG; however, additional testing is required to validate the results under various operating conditions.

The use of blending hydrogen and CNG provided a great way to get experience with hydrogen fueling.

Appendix A – 2-Valve Engine HICEV America Test Sheet

HICEV AMERICA

US DOE ADVANCED VEHICLE TESTING ACTIVITY

2003 Hydrogen ICE[1] Truck

VEHICLE SPECIFICATIONS

CONVERSION VEHICLE
Base Vehicle: 2003 Ford F-150
VIN: 2FTRF07W73CA64601
Seatbelt Positions: Three
Features:
- 5.4L SOHC V-8
- Supercharged
- Fuel Injected
- Manual Transmission
- Power Locks and Windows
- Front and Rear Disk Brakes
- Anti-lock Brakes
- Rear Wheel Drive
- Cruise Control
- Power Steering
- AM/FM Stereo w/ 6 Disk CD Player
- Dual Airbags

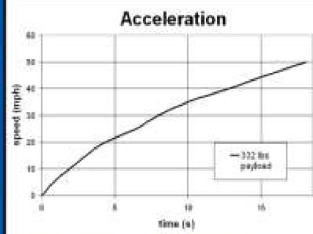
FUEL TANKS
Manufacturer: Dynetek
Model: W150H200G8
DOT Type 3[2]
Description: Carbon Fiber Wrap over Polymer Bladder
Number of Tanks: 3
Tank Liquid Volume: 150 liters
Total Liquid Volume: 450 liters
Nominal Pressure: 2900 psi
Maximum Pressure: 3625 psi
Fuel Capacity[7]: 6.52 GGE[8]
Fueling Inlet: OPW LW5000

WEIGHTS
Base Design Curb Weight: 4063 lbs
Delivered Curb Weight: 4685 lbs
Distribution F/R: 52/48%
GVWR: 6050 lbs
GAWR F/R: 2800/3500 lbs
Payload: 1365 lbs
Requirement: ≥ 400 lbs

DIMENSIONS
Wheelbase: 120.1 inches
Track F/R: 65.4/65.5 inches
Length: 207.4 inches
Width: 79.9 inches
Height: 72.6 inches
Rear Overhang: 48.6 inches
Ground Clearance: > 5.0 inches
Requirement: ≥ 5.0 inches

TIRES
Tire Mfg: BF Goodrich
Tire Model: Radial Long Trail
Tire Size: P275/60R17
Tire Pressure: 35 psi
Spare Included: Yes

PERFORMANCE STATISTICS



ACCELERATION 0-50 mph
Acceleration Time: 18.1 seconds
Performance Goal: 13.5 seconds

MAXIMUM SPEED
Speed At One Mile: 80.9[3] mph
Performance Goal: ≥ 70 mph
Speed At Quarter Mile: 57.9 mph

CONSTANT SPEED FUEL ECONOMY
Distance Traveled: 61.78 miles
Average Speed: 44.94 mph
Fuel Consumed: 2.288[4] GGE[8]
Fuel Economy: 27.0 miles/GGE[8]

SAE J1634 DRIVING CYCLE FUEL ECONOMY (A/C OFF)
Distance Traveled: 71.2 miles
Fuel Consumed: 3.956[4] GGE[8]
Fuel Economy: 18.0 miles/GGE[8]

SAE J1634 DRIVING CYCLE FUEL ECONOMY (A/C ON)
Distance Traveled: 71.0 miles
Fuel Consumed: 4.897[4] GGE[8]
Fuel Economy: 14.5 miles/GGE[8]

BRAKING FROM 60 mph
Controlled Dry: 229 feet
Controlled Wet: 263 feet
Panic Wet: 232 feet
Course Deviation: 0.0 feet

HANDLING
Average time: 70.9 seconds
Avg Gasoline ICE time: 58.3[5] seconds

GRADEABILITY (CALCULATED)
Maximum Speed @ 3%: 73.1 mph
Maximum Speed @ 6%: 54.6 mph
Maximum Grade: 34%

TEST NOTES:
1. Internal Combustion Engine.
2. 49 CFR 571.304
3. Maximum speed was determined from acceleration runs where overdrive was not used.
4. Fuel consumption was determined using the Ideal Gas Law.
5. ICE vehicle tested was a 1992 S-10 pickup with rear wheel drive with a 4.3L V-6 engine.
6. Rough Road testing showed no damage to the fuel system or any other component of the vehicle.
7. At nominal pressure and 25°C.
8. Gasoline Gallons Equivalent.

This vehicle meets all HICEV America Minimum Requirements listed on back.
Values in red indicate the Performance Goal was not met.