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Advanced Vehicle Testing Activity

Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150

Don Karner
James Francfort

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Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

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ABSTRACT

Federal regulation requires energy companies and government entities to utilize alternative fuels in their vehicle fleets. To meet this need, several automobile manufacturers are producing compressed natural gas (CNG)-fueled vehicles. In addition, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG (Bifuel). Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their principle alternative fuel for transportation. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can reduce emissions from CNG vehicles. However, blending hydrogen with CNG (and performing no other vehicle modifications) reduces engine power output, due to the lower volumetric energy density of hydrogen in relation to CNG. Arizona Public Service (APS) and the U.S. Department of Energy's Advanced Vehicle Testing Activity (DOE AVTA) identified the need to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To quantify the effects of using various blended fuels, a work plan was designed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck operating on 100% CNG and blends of 15 and 30% HCNG. This report presents the results of this testing conducted during May and June 2003 by Electric Transportation Applications (Task 4.10, DOE AVTA Cooperative Agreement DE-FC36-00ID-13859).

CONTENTS

1. BACKGROUND 1
1.1 Test Program 1
1.2 Test Vehicle 2
1.3 Emission Test Procedures 2
1.3.1 IM240 3
1.3.2 FTP-75 3
1.4 Acceleration and Range Test Procedures 3
2. CONDUCT OF TESTING 4
2.1 Emissions Testing 4
2.2 Acceleration Testing 6
2.3 Range and Fuel Economy Testing 9
3. TEST RESULTS 12
3.1 Emissions Testing Results 12
3.2 Acceleration Testing Results 12
3.3 Range and Fuel Economy Test Results 14
Attachment 1 - Hydrogen ICE Vehicle Acceleration Test Procedure 1
Attachment 2 - Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests 1
Attachment 3 - Hydrogen ICE Vehicle Acceleration Testing Data Sheets 1
Attachment 4 - Hydrogen ICE Vehicle Constant Speed Fuel Economy Testing Data Sheets 1
Attachment 5 - Summary Emission Test Data Sheets 1

FIGURES

Figure 1. Low-percentage blend Ford F-150 pickup. 1
Figure 2. Low-percentage blend Ford F-150 engine compartment. 2
Figure 3. Speed versus distance for the F-150 test vehicle, using 100% CNG. 6
Figure 4. Speed versus distance for the F-150 test vehicle, using 15% HCNG. 7
Figure 5. Speed versus distance for the F-150 test vehicle, using 30% HCNG. 7
Figure 6. Speed versus time for the Ford F-150 test vehicle, using 100% CNG. 8
Figure 7. Speed versus time for the Ford F-150 test vehicle, using 15% HCNG. 8
Figure 8. Speed versus time for the Ford F-150 test vehicle, using 30% HCNG. 9
Figure 10. Speed versus time for the Ford F-150 test vehicle range test, using 100% CNG. 10
Figure 11. Speed versus time for the Ford F-150 test vehicle range test, using 15% HCNG. 11
Figure 12. Speed versus time for the Ford F-150 test vehicle range test, using 30% HCNG. 11
Figure 13. Average speed versus distance for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG. 13
Figure 14. Average speed versus time for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG. 13

TABLES

Table 1. Ford F-150 original factory specifications. 2
Table 2. California LEV II emission standards. 3
Table 3. Fleet testing F-150 emissions test results (gram/mile) operating on 30% HCNG. 4
Table 4. Gasoline-fueled F-150 emission test results (gram/mile). 5
Table 5. Percentage reduction in emissions (30% HCNG fuel versus gasoline-fueled F-150). 5
Table 6. Emissions test results (gram/mile) for blended HCNG fuels and 100% CNG. 5
Table 7. Time to accelerate to 60 mph for 100% CNG, 15 and 30% HCNG. 9
Table 8. F-150 test vehicle range at a constant speed of 45 mph for 100% CNG, 15 and 30% HCNG. 10
Table 9. Emissions variations using blended fuels. 12
Table 10. Acceleration to 60 mph for various fuels. 14
Table 11. Range decrease from use of various fuels. 14

ACRONYMS

APG	Arizona Proving Grounds
APS	Arizona Public Service
ATL	Automotive Testing Laboratories
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE AVTA	U.S. Department of Energy Advanced Vehicle Testing Activity
ETA	Electric Transportation Applications
FTP-75	Federal Emissions Test Procedure
gge	Gasoline gallon equivalent
HC	Total hydrocarbons
HCNG	Hydrogen blended with natural gas
ICE	Internal combustion engine
IM240	Inspection and Maintenance Driving Cycle
kph	Kilometers per hour
LEV	Low-emission vehicles
MDV	Medium duty vehicle
mpg	Miles per gallon
mph	Miles per hour
NMCH	Nonmethane hydrocarbons
NMOG	Nonmethane organic gases
NOx	Oxides of nitrogen
psi	Pounds per square inch
psig	Pounds per square inch, gauge
kPa	Kilopascals
SULEV	Super ultra low-emission vehicle
ULEV	Ultra low-emission vehicle

Hydrogen/CNG-Blended Fuels Performance Testing in a Ford F-150

1. BACKGROUND

1.1 Test Program

Federal regulation requires energy companies and government entities to utilize alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are producing compressed natural gas (CNG)-fueled vehicles. In addition, several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG (Bifuel). Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their principle alternative fuel for transportation. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can reduce emissions from CNG vehicles. However, blending hydrogen with CNG (and performing no other vehicle modifications) reduces engine power output, due to the lower volumetric energy density of hydrogen in relation to CNG. Arizona Public Service (APS) and the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA) identified the need to determine the magnitude of these effects and their impact on the viability of using HCNG in existing CNG vehicles.

To perform this evaluation, a work plan was designed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck (Figure 1) operating on 100% CNG and blends of 15 and 30% HCNG. This work program was conducted by Electric Transportation Applications, as Task 4.10 under the DOE Cooperative Agreement DE-FC36-00ID-13859. The Ford F-150 was previously tested in fleet operation using a blend of 30% HCNG (DOE Cooperative Agreement DE-FC36-00ID-13859, Task 4.6). Results of the previous Task 4.6 testing are documented in the report: *Low Percentage Hydrogen/CNG Blend Ford F-150 Truck Operating Summary* (INEEL/EXT-03-00008, September 2002).

Figure 1. Low-percentage blend Ford F-150 pickup.

1.2 Test Vehicle

The test vehicle is a model year 2000, F-150 regular cab pickup truck equipped with a factory CNG engine (Table 1) and 3600 psig carbon steel fuel tanks with an 85-liter capacity. It was modified by NRG Tech in Reno, Nevada to run on a blend of CNG and up to 30% hydrogen (by volume). NRG Tech modifications (Figure 2) include supercharging, ignition modifications, and exhaust gas recirculation. The F-150 was placed in service in the APS fleet in June 2001. Fleet testing of the vehicle was conducted from June 2001 through September 2002. Subsequent to the formal performance testing with blended fuels, the vehicle was again placed in the APS fleet. F-150 parametric performance testing with hydrogen/CNG-blended fuels was conducted in May and June 2003. At the beginning of this test program, the vehicle had accumulated 31,678 miles, operating with HCNG fuel.

Table 1. Ford F-150 original factory specifications.

Engine	5.4 L V8
Factory HP	230 HP
Curb weight	5,170 lb
GVWR	7,650 lb

Figure 2. Low-percentage blend Ford F-150 engine compartment.

1.3 Emission Test Procedures

During the previous fleet testing (Task 4.6) of the Ford F-150, emissions from the test vehicle were periodically measured. Two different emission test procedures were performed on the vehicle, the IM240 and the FTP-75.

1.3.1 IM240

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

1.3.2 FTP-75

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

Emissions tests performed under the current work program were conducted using the FTP-75 test cycle at the Automotive Testing Laboratories, Inc. (ATL) facilities, located in Mesa, Arizona. ATL is certified by the State of Arizona to conduct the Federal Test Procedure.

California emission standards are used in this report as a reference point for vehicle emissions. Currently, Low-Emission Vehicles I (LEV I) emission standards are in effect. However, a more stringent set of emission standards, LEV II, will come into effect in 2004. The California LEV II emission standards categorize emissions into the following groups: low-emission vehicles (LEVs), ultra low-emission vehicles (ULEVs), and super ultra low-emission vehicles (SULEVs). The standards are based on weight class and emissions are measured over the FTP-75 test. The F-150 test vehicle used for this work program is classified by California emission standards as an MDV3.[c] Some of the California emission standards for the MDV3 class are shown in Table 2.

Table 2. California LEV II emission standards.

	NMOG (gram/mile)	CO (gram/mile)	NOx (gram/mile)
LEV	0.09	4.2	0.07
ULEV	0.055	2.1	0.07
SULEV	0.01	1	0.02

NMOG = nonmethane organic gases.
CO = carbon monoxide.
NOx = oxides of nitrogen.

1.4 Acceleration and Range Test Procedures

Hydrogen internal combustion engine (ICE) test procedures were developed to conduct acceleration and range testing of the F-150 test vehicle, fueled using 100% CNG and blends of 15 and 30% HCNG. The acceleration test procedure (Attachment 1) requires that the vehicle be accelerated from rest to a speed of 100 mph, and speed versus time data are collected. The hydrogen ICE range test procedure (Attachment 2) requires that the vehicle be operated at a constant speed of 45 mph, and distance versus time data are collected.

[c] MDV = medium duty vehicle; MDV3 is the class of MDVs with a test weight between 5751 and 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.

2. CONDUCT OF TESTING

2.1 Emissions Testing

Emissions from the F-150 were measured at ATL using both FTP-75 and IM240 test cycles during the June 2001 through September 2002 vehicle fleet testing (Task 4.6). During this test, the F-150 was fueled exclusively with a blend of 30% HCNG. The vehicle was tested several times to validate the results. As Table 3 shows, carbon monoxide emissions from the low percentage blend F-150 averaged 0.26 gram/mile over the FTP-75 tests, well under the California SULEV standard of 1 gram/mile. Nitrogen oxide emissions averaged 0.078 gram/mile, near the California ULEV standard of 0.07. However, the first NO_x testing result (0.063) was under the 0.07 standard, which is based on emissions when a vehicle is new. Non-methane organic gases (NMOG) were not measured.

To provide an additional point of reference for F-150 emissions test results, emissions testing of a randomly selected Ford F-150 equipped with a factory gasoline engine was also conducted at ATL (Table 4).

Table 3. Fleet testing F-150 emissions test results (gram/mile) operating on 30% HCNG.

Test Date	Mileage	NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
5/2/2001	1592	0.011	0.075	0.094	0.237	0.063	440.606
5/3/2001	1613	0.019	0.084	0.118	0.249	0.094	441.442
5/4/2001	1636	0.024	0.082	0.121	0.267	0.094	437.370
5/8/2001	1657	0.017	0.099	0.133	0.257	0.084	439.940
6/14/2001	2148	0.028	0.091	0.136	0.223	0.104	435.899
8/30/2001	3890	0.028	0.074	0.116	0.348	0.051	442.515
8/31/2001	3915	0.028	0.067	0.107	0.210	0.053	437.009
Average		0.022	0.081	0.117	0.255	0.078	439.254
IM240							
5/2/2001	1592	0.062	0.050	0.124	0.135	0.040	392.720
5/3/2001	1625	0.008	0.042	0.057	0.118	0.025	402.205
5/4/2001	1647	0.014	0.054	0.078	0.146	0.023	410.147
5/8/2001	1670	0.016	0.069	0.098	0.101	0.022	411.302
8/30/2001	3901	0.014	0.054	0.078	0.077	0.089	397.635
8/30/2001	3903	0.016	0.028	0.049	0.125	0.051	402.614
8/31/2001	3928	0.013	0.045	0.066	0.101	0.019	397.634
8/31/2001	3931	0.013	0.026	0.045	0.095	0.033	396.020
Average		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

Table 4. Gasoline-fueled F-150 emission test results (gram/mile).

Test Date	Vehicle Mileage	Emission Species					
		NMHC	CH_4	HC	CO	NO_X	CO_2
FTP-75							
6/20/2001	23497	0.122	0.013	0.136	1.644	0.170	620.7
6/21/2001	23519	0.107	0.011	0.119	1.457	0.163	623.0
Average		0.115	0.012	0.128	1.551	0.167	621.9
IM240							
6/20/2001	23509	0.015	0.008	0.023	0.127	0.565	585.172
6/21/2001	23531	0.006	0.011	0.017	0.046	0.440	578.728
Average		0.011	0.010	0.020	0.087	0.503	581.95

NMHC = nonmethane Hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NO_x = oxides of nitrogen
CO_2 = carbon dioxide

Table 5 illustrates the emissions comparison between the average emissions of the F-150 during fleet testing at 30% HCNG (Table 3) and the random gasoline-fueled F-150 (Table 4). Reductions were achieved for all emission species except for methane, which is typical of vehicles operating on CNG.

Table 5. Percentage reduction in emissions (30% HCNG fuel versus gasoline-fueled F-150).

HC	CO	NO_X	CO_2
7.6%	83.5%	53.4%	29.4%

HC = total hydrocarbons.
CO = carbon monoxide.
NO_x = oxides of nitrogen.
CO_2 = carbon dioxide.

The baseline of data obtained from the previous F-150 emissions testing during the fleet testing (Tables 3 and 4) was supplemented in the current work program by conducting additional FTP-75 emissions testing for the F-150 test vehicle using fuels of 100% CNG, 15 and 30% HCNG (Table 6). 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 emissions testing was conducted by ATL using the procedures certified by the State of Arizona.

Table 6. Emissions test results (gram/mile) for blended HCNG fuels and 100% CNG.

Fuel Blend	Vehicle Mileage	Emission Species (gram/mile)					
		NMHC	CH_4	HC	CO	NO_X	CO_2
CNG	30,045	0.023	0.128	0.173	0.567	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	0.423	0.126	448.1

CO = carbon monoxide
NO_x = oxides of nitrogen
CO_2 = carbon dioxide
NMHC = nonmethane Hydrocarbons
CH_4 = methane
HC = total hydrocarbons.

2.2 Acceleration Testing

Acceleration testing of the F-150 was conducted at DaimlerChrysler's Arizona Proving Grounds (APG) in accordance with the Hydrogen ICE (Internal Combustion Engine) Vehicle Acceleration Test Procedures (Attachment 1), for fuels of 100% CNG, and blends of 15 and 30% HCNG. Tests were performed using a 2.4-mile-long straight track at the APG. For each of the three blends of fuel, two sets of acceleration runs were conducted. Each set consisted of one acceleration run in each direction (east and west) on the straight track. Data sheets from these tests (12 runs total) are presented in Attachment 3. Results of acceleration testing conducted with the F-150 test vehicle are presented as speed versus distance in Figures 3, 4, and 5 and speed versus time in Figures 6, 7, and 8 for each fuel type. Table 7 presents the times to accelerate to 60 mph for each fuel type.

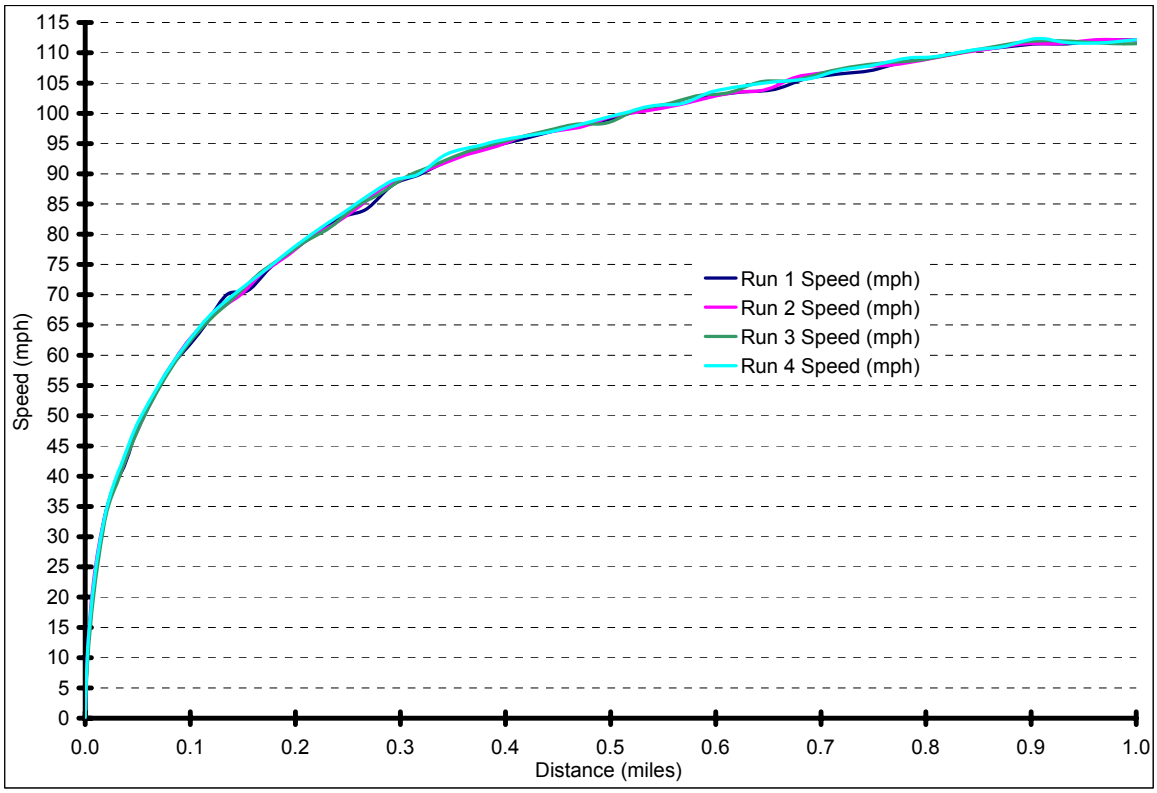

Figure 3. Speed versus distance for the F-150 test vehicle, using 100% CNG.

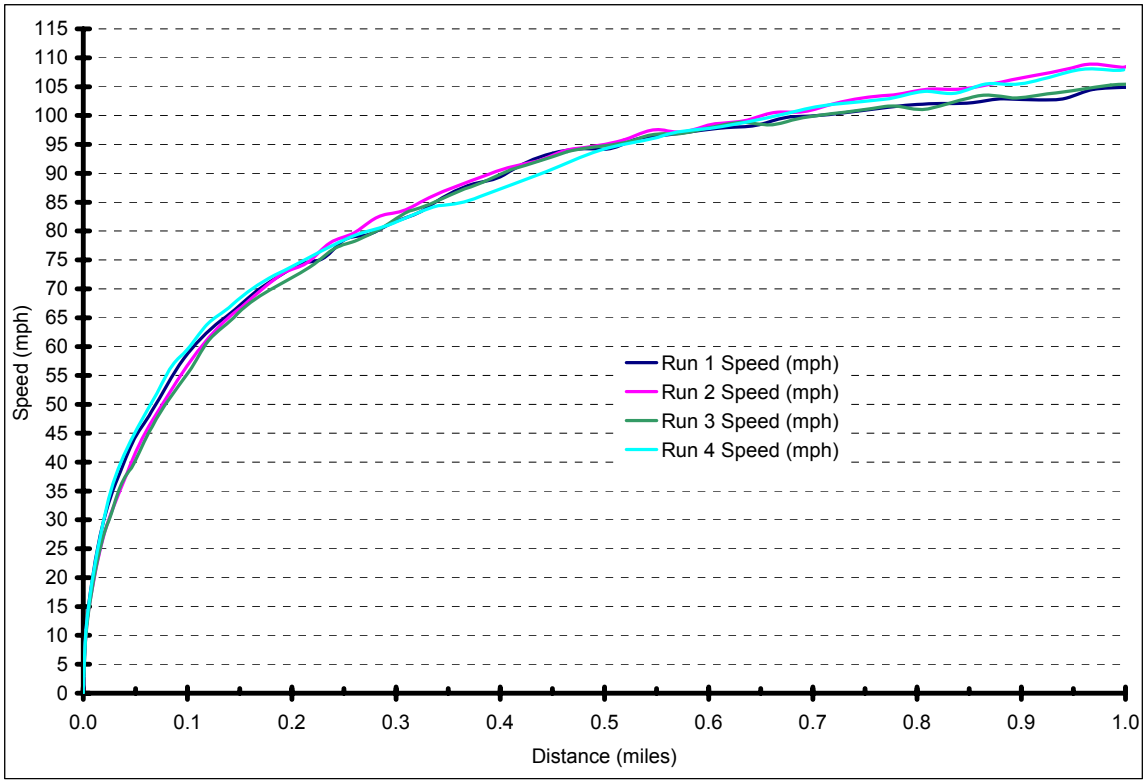

Figure 4. Speed versus distance for the F-150 test vehicle, using 15% HCNG.

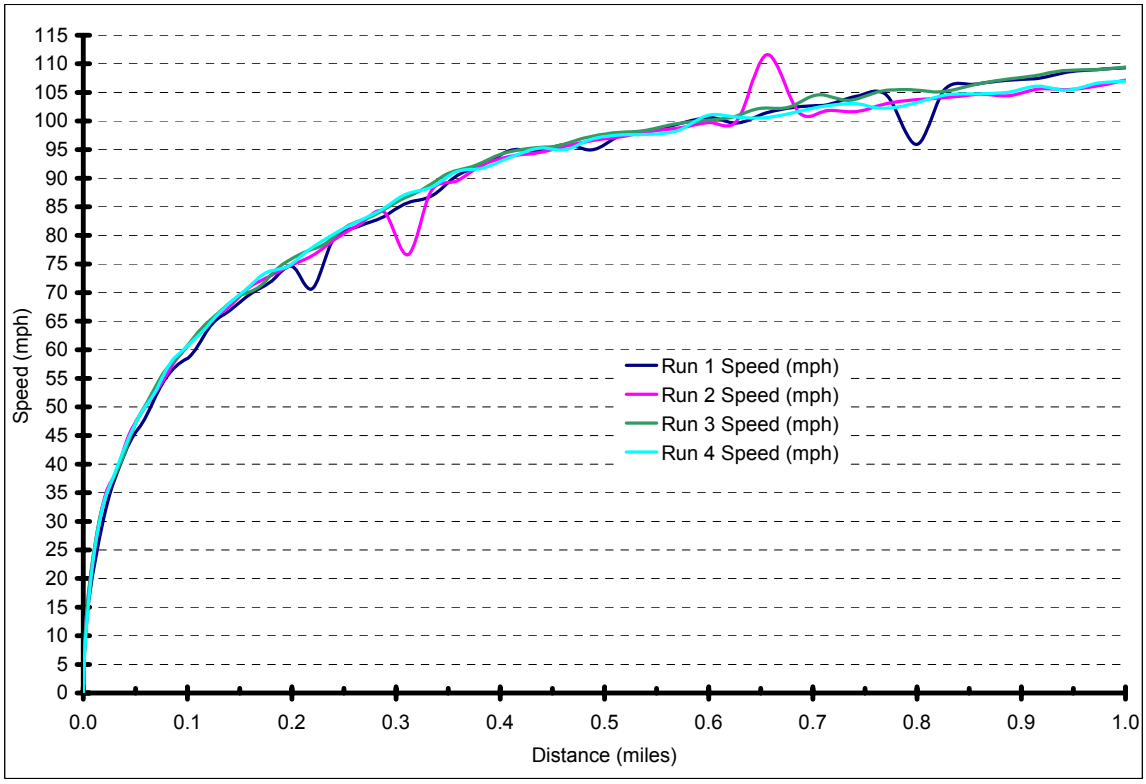

Figure 5. Speed versus distance for the F-150 test vehicle, using 30% HCNG.

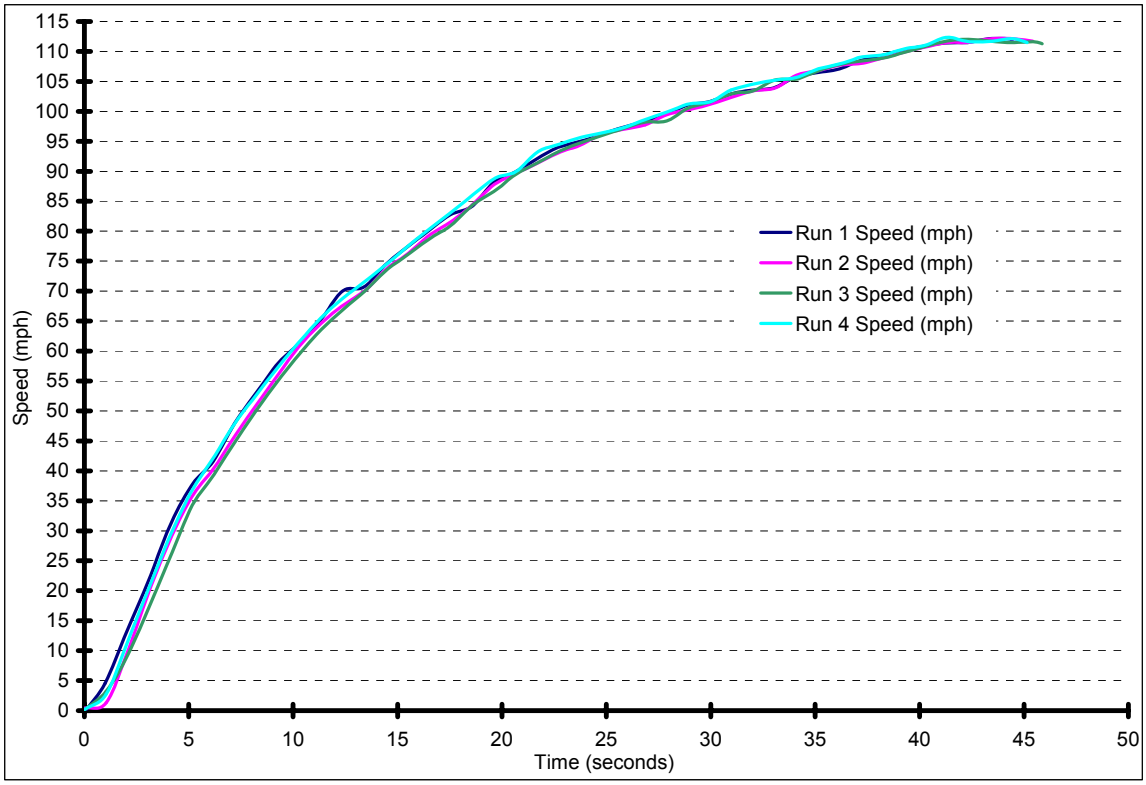

Figure 6. Speed versus time for the Ford F-150 test vehicle, using 100% CNG.

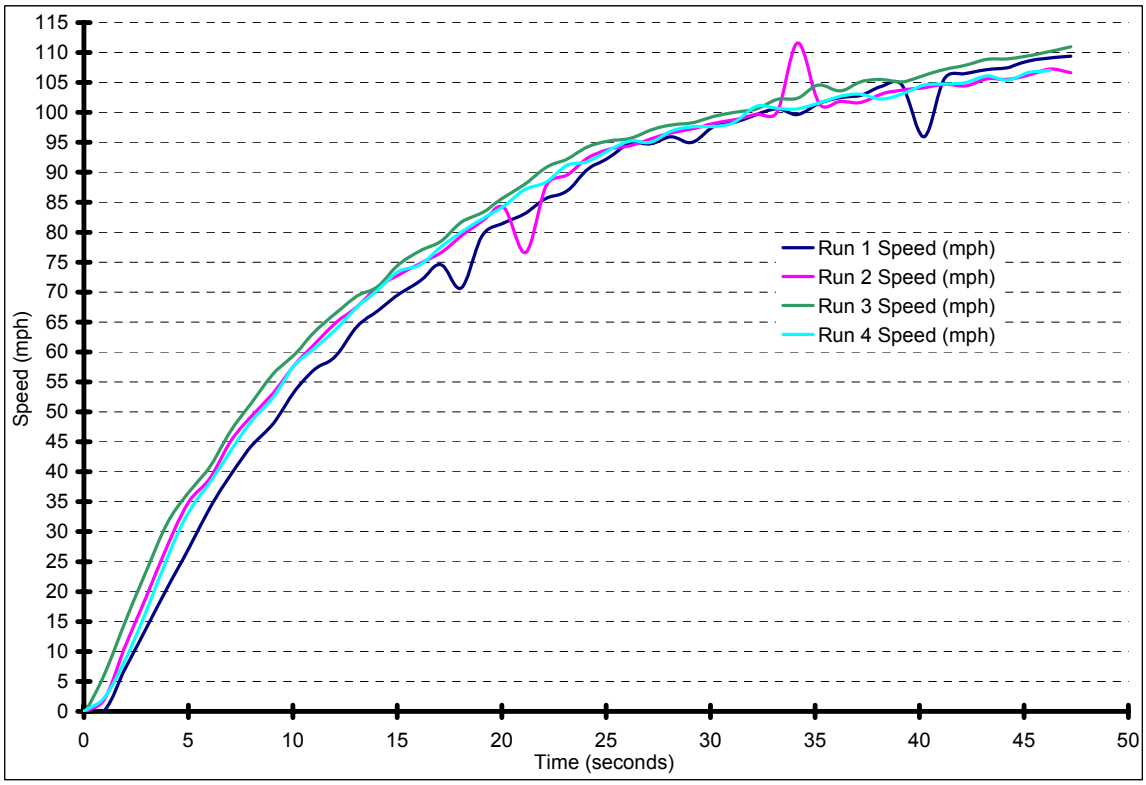

Figure 7. Speed versus time for the Ford F-150 test vehicle, using 15% HCNG.

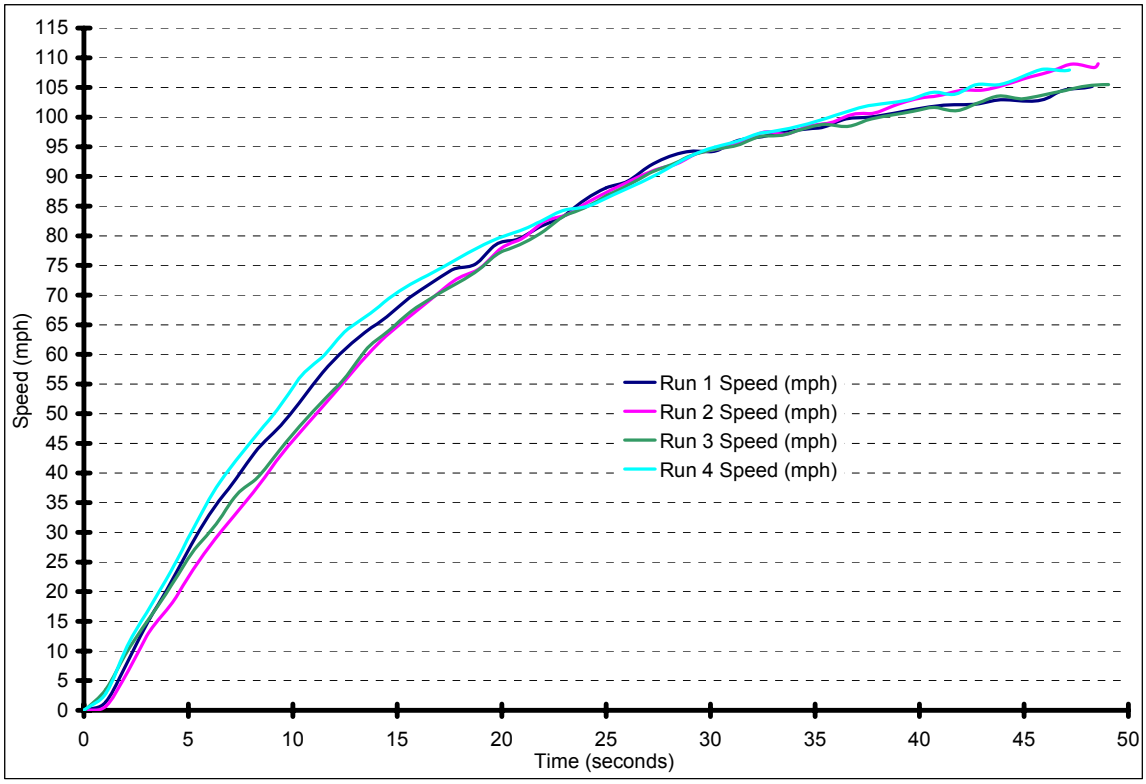

Figure 8. Speed versus time for the Ford F-150 test vehicle, using 30% HCNG.

Table 7. Time to accelerate to 60 mph for 100% CNG, 15 and 30% HCNG.

Fuel Blend	Vehicle Mileage	Time to 60 mph
100% CNG	32,452	10.10
15% HCNG	31,943	10.97
30% HCNG	31,679	12.68

2.3 Range and Fuel Economy Testing

The range of the F-150 test vehicle was also tested at the APG (Figure 9), in accordance with the Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests Procedures presented in Attachment 2, for 100% CNG and blends of 15 and 30% HCNG. Tests were performed at a constant speed of 45 mph, using the 4.2-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 (gge) was determined (see Table 8). 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, as shown in Table 8. Data sheets from these tests are presented in Attachment 4. Speed versus time testing graphs are presented in Figures 10, 11, and 12 for each fuel type. Speed was controlled manually by the driver, as the vehicle was not equipped with cruise control. Spikes in vehicle speed are the result of data acquisition system noise; they do not represent actual speed deviations.

Figure 9. Vehicle range testing at the Arizona Proving Grounds.

Table 8. F-150 test vehicle range at a constant speed of 45 mph for 100% CNG, 15 and 30% HCNG.

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

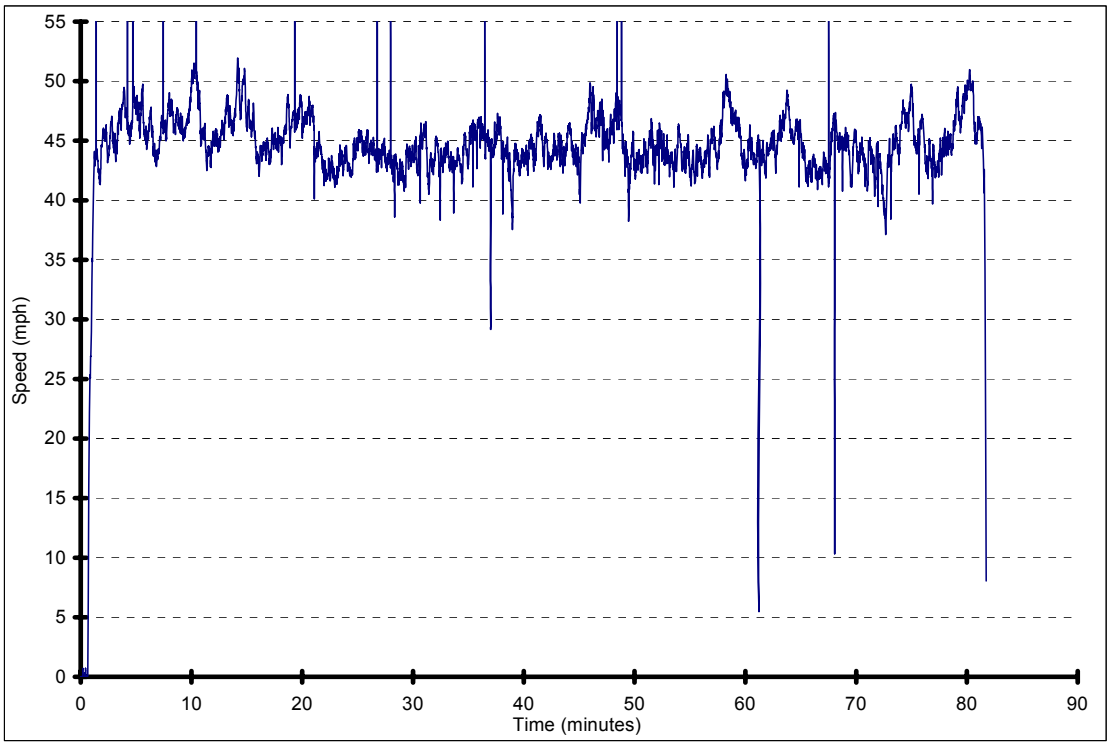

Figure 10. Speed versus time for the Ford F-150 test vehicle range test, using 100% CNG.

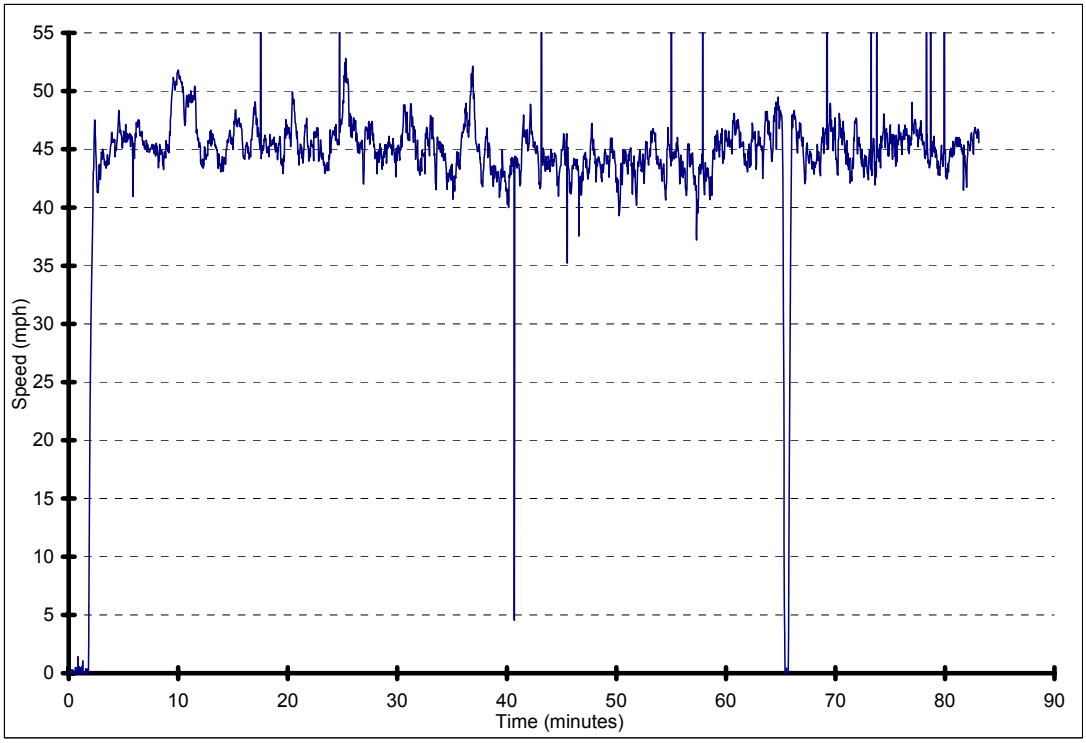

Figure 11. Speed versus time for the Ford F-150 test vehicle range test, using 15% HCNG.

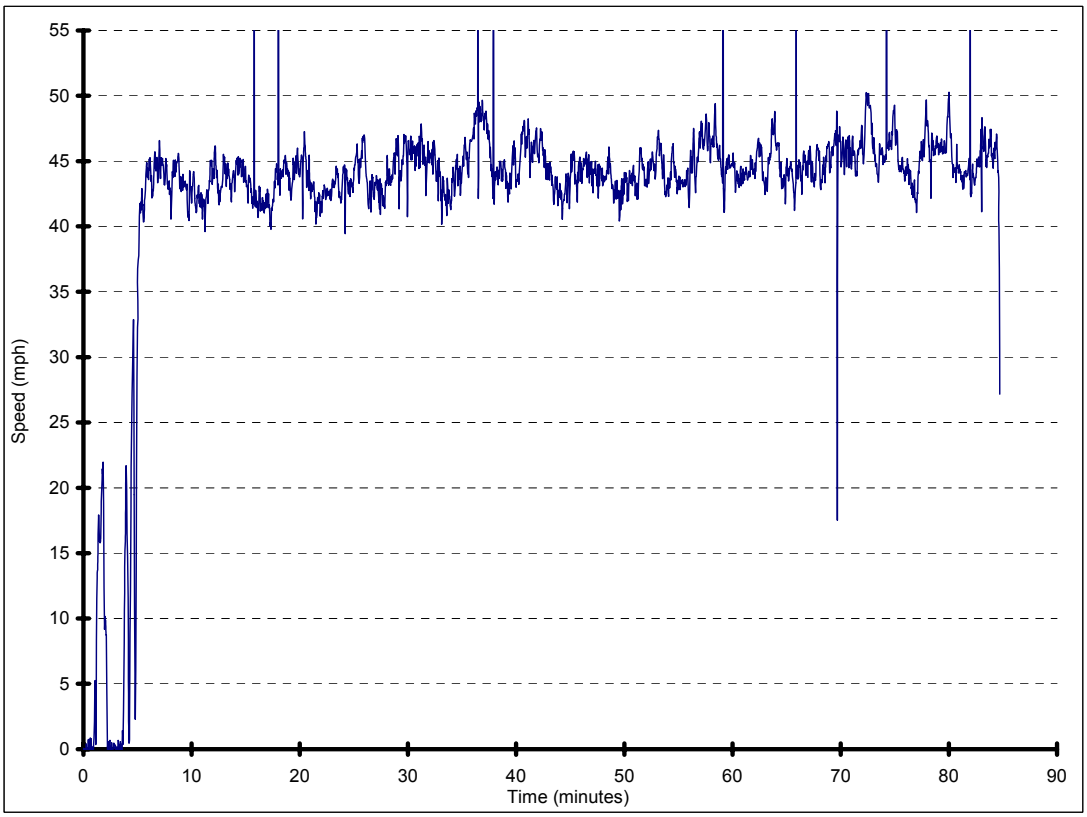

Figure 12. Speed versus time for the Ford F-150 test vehicle range test, using 30% HCNG.

3. TEST RESULTS

3.1 Emissions Testing Results

Exhaust emissions using 100% CNG, and 15 and 30% HCNG (Table 6) showed significant emission reductions over gasoline (Table 4) 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 9. Attachment 5 summarizes the test results from Automotive Testing Laboratories.

Table 9. Emissions variations using blended fuels; comparison of the results found in Tables 4 and 6.

	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% HCNG	-89	+1050	+37	-73	-25	-28

NMHC = nonmethane hydrocarbons
CH_4 = methane
HC = total hydrocarbons
CO = carbon monoxide
NOx = 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. Note that the NO_X levels measured in the current work program are significantly higher than those measured during the fleet operation of the F-150 test vehicle using a 30% blend of hydrogen in CNG. The fleet testing was conducted with between 1,500 and 4,000 miles on the vehicle. Testing in the current work program was conducted with the vehicle use near 30,000 miles. Aging of the catalytic converter was probably the cause of the increased NO_X emissions.

Based on these results, it is apparent that 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 increased CH_4 and HC emissions and reduced vehicle acceleration and range. However, even at 15% HCNG, the performance reductions do not have a significant impact on vehicle drivability and offer an additional 10% decrease in CO and CO_2 emissions.

3.2 Acceleration Testing Results

As expected, the performance (in terms of acceleration [Figures 12 and 13] and range) of the F-150 test vehicle degrades with increasing amounts of hydrogen in the fuel. However, much of the performance loss results from the initial switch from a liquid fuel (gasoline) to a gaseous fuel (CNG), as shown in Table 10. 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 with the vehicle operating on 100% CNG (Table 10).

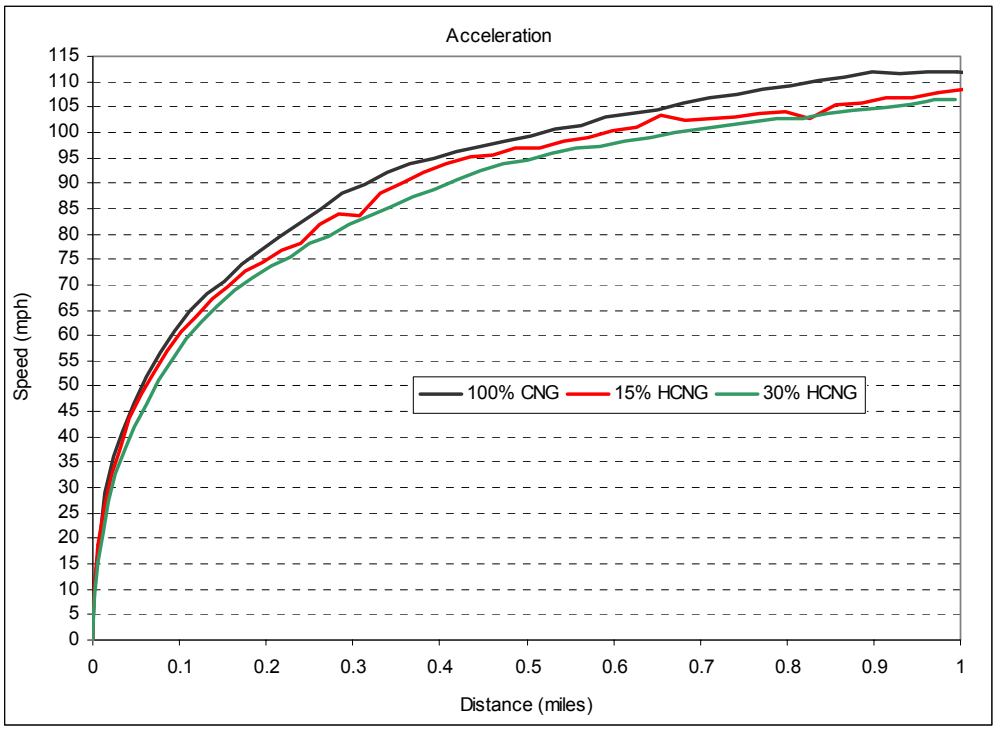

Figure 13. Average speed versus distance for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG.

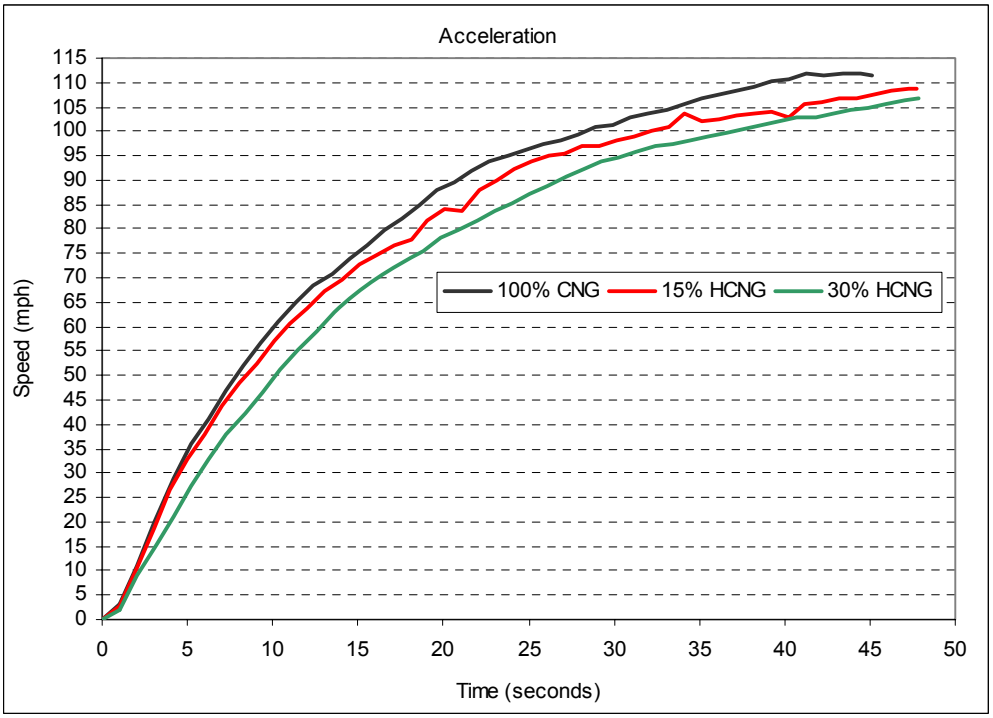

Figure 14. Average speed versus time for F-150 test vehicle range test, 100% CNG, 15% HCNG and 30% HCNG.

Table 10. 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[1]	8.6 (1)	---	Base
CNG	10.10	Base	17.4 %
15% HCNG	10.97	8.6 %	27.6 %
30% HCNG	12.68	25.5 %	47.4 %

[1] 2001 Ford F-150 with 5.4L 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 the 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, which does not appear to be economically practical for introducing blended fuel into existing CNG fleets.

3.3 Range and Fuel Economy Test Results

As shown in Table 11, degradation of vehicle range was significant with the 30% HCNG fuel. The decrease is based on the lower energy content of hydrogen when compared to CNG on a volumetric basis. The decrease in range between 100% CNG and 30% HCNG would require a 16.4 % increase in onboard fuel storage to maintain vehicle range similar to that achievable with 100% CNG. In the case of the F-150 test vehicle, this would require the addition of a 14-liter fuel tank. With a fuel of 15% HCNG, the range degradation was less than 10%, which should have a negligible impact on vehicle utility in fleet operation.

Table 11. 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 %

Note that 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 mile/gge for 100% CNG, 22.6 mile/gge for 15% HCNG, and 23.5 mile/gge for 30% HCNG.