"Performance of a Ford F-150 Using Various Fuel Blends of Compressed Natural Gas and Hydrogen"

by

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Abstract

An investigation was conducted on the emissions and efficiency from hydrogen blended compressed natural gas (CNG) in light duty vehicles. The different blends used in this investigation were 0%, 15%, 30% and 50% hydrogen, the remainder being compressed natural gas. The blends were tested using a Ford F-150 truck supplied by Arizona Public Services. Tests on emissions were performed using four different driving condition tests.

Previous investigation by Don Karner and James Frankfort on a similar Ford F-150 using a 30% hydrogen blend showed that there was substantial reduction when compared to gasoline in carbon monoxide (CO), nitrogen oxide (NO_x), and carbon dioxide (CO_2) emissions while the reduction in hydrocarbon (HC) emissions was minimal.

This investigation was performed using different blends of CNG and hydrogen to evaluate the emissions reducing capabilities associated with the use of the different fuel blends. The results were then tested statistically to confirm or reject the hypotheses on the emission reduction capabilities.

Statistically analysis was performed on the test results to determine whether hydrogen concentration in the HCNG had any effect on the emissions and the fuel efficiency. It was found that emissions from hydrogen blended compressed natural gas were a function of driving condition employed. Emissions were found to be dependent on the concentration of hydrogen in the compressed natural gas fuel blend.

Introduction: The transportation sector is about 97% dependent on petroleum-based fuels and consumes about 66% of the nation's oil demand. This poses a major challenge in meeting the growing demands of the transportation sector. The average fleet efficiency is not improving because of the popularity of vans, trucks and sport utility vehicles used and the per capita mile driven has drastically increased the petroleum demand [Chalk *et al.*, 2000]. This leads to fuels shortfall, which must be met by imports. The gap between domestic production and energy use is going to increase significantly over the next decade. In 1997 itself, about 51% of the total U.S. petroleum consumption was met by imports at a cost of US $69 billion. By 2020, imported fuel is expected to account for about 73% of the fuel required and the cost will be around US $95 billion at today's prices [Chalk *et al*., 2000]. Additionally, the increasing use of fossil fuel leads to an increase of green-house gases emitted into the atmosphere. In many areas, the transportation sector is responsible for non-attainment of National Ambient Air Quality Standards (NAAQS). The atmospheric concentrations of carbon dioxide (CO_2) are now 32% higher than they were 150 years ago [Chalk *et al*., 2000].

Recently in the United States, there has been a lot of emphasis given to alternate fuels not only because of the problems associated with pollution and depletion of fossil fuel reserves, but also because of security issues associated with the import of petroleum products. The alternate fuels should not only fulfill the criteria of the abundant reserve and less pollution, but should also have better engine performance and storage properties.

Hydrogen is an ideal clean, inexhaustible fuel whereas coal is a source of greenhouse gases such as CO_2 and carcinogenic organics. Because there is no carbon in hydrogen fuel, there are no carbon monoxide or hydrocarbon emissions. However, when nitrogen in air is heated inside the internal combustion engine, nitrogen oxide is formed. While there are safety issues concerning hydrogen as fuel, it seems to be less severe when considered in the background of pollution problems and depletion of non-renewable sources such as petroleum. It will take years even by conservative estimates to convert to a hydrogen economy. Therefore, in the mean time, it seems prudent that we look for alternative fuel technologies which solve the current problem. There is currently a lot of interest in compressed natural gas (CNG) and hydrogen blended compressed natural gas (HCNG). Since natural gas is widely available and CNG and HCNG engines can easily be modified to utilize hydrogen, this seems like a reasonable alternative. However, studies need to be performed to measure the impact on air quality and to determine the economic benefits for the potential use of CNG and HCNG.

<u>Compressed Natural Gas</u>: Large amounts of carbon monoxide emissions are produced from combustion of fossil fuels which is a primary source of fuel for surface transportation. Carbon monoxide is an important Green House Gas (GHG) and any increase in the concentration of GHG causes an increase in temperature thereby contributing to global warming. Various activities linked to fossil fuel production such as fuel extraction, transport, production and distribution produce carbon monoxide in addition to the onboard combustion [Hekkert *et al*., 2003].

Natural gas, biomass, coal, hydro-wind and solar energy can be primary source of energy. A wide range of energy carriers such as gasoline, diesel, liquefied petroleum gas (LPG), liquefied natural gas (LNG), compressed natural gas (CNG), methanol, ethanol, hydrogen, electricity, etc., can be produced from the primary sources. The energy carriers can be produced from the primary sources by different methods. For example, while distillation of crude oil produces diesel fuel, it can also be produced from natural gas (NG) using the Fischer-Tropsch process [Hekkert *et al*., 2003]. In addition, fuels can also be produced centrally in large scale plants, locally at retail stations, or somewhere in between. On-board conversion of fuel is also possible. There are also alternate options to the internal combustion engine such as battery-powered vehicles, fuel cells, hybrids or different combinations of these. The above options create a wide range in alternative fuel chains.

However, employing any new fuel will require large investments and time periods to make adjustments to fuel distribution, retail stations and vehicles. Therefore, it is important to study the effects of fuel chain changes before making this transition. Additionally, the criteria of carbon emission associated with any future fuel chains is the most important aspect because of its impact on climate change. The carbon emissions can be drastically reduced either by using renewable resources or by capturing the carbon from feed stocks and storing it outside the atmosphere. However, the latter option is not possible in large scale in the near future [Turkenburg and Hendriks, 1999].

Biomass can be converted into different fuel such as biodiesel, ethanol, methanol, hydrogen and even gasoline by the Fischer-Tropsch process [Hekkert *et al*., 2003]. However, the availability of biomass and relative high costs of total fuel supply chains makes large scale use of biomass for transportation a relatively difficult option when implemented on a large scale in the short and medium term. This may change in the long term if proper infrastructure for biomass is developed [Faaij and Hamelinck, 2002].

According to Hekkert *et al*. [2003], we are currently in a transition period towards a sustainable energy system. Reducing current GHG seems to be the best strategy in the current scenario. The alternative fuel chains should however be adaptive towards future innovations in order to avoid the phenomenon of technological 'lock in'. Therefore changing from the oil-based fuel to natural gas (NG) seems to be the best way to reduce GHG emissions, meet future emissions guidelines, and have a good degree of flexibility. The NG fuels have lower carbon emissions per unit combustion energy [Hekkert *et al*., 2003]. NG can be substituted by climate friendly energy carriers such as biomass-based synthetic NG or hydrogen. Additionally, in the short term, NG has a number of other advantages in comparison to crude oil, such as fewer impurities and aromatics which reduces the amount of pollutants (like particulate matter, NO_x, and SO_x). On the basis of combustion products, it is the cleanest and most acceptable fossil fuel [Dicks, 1996]. The total recoverable NG resources are more abundant than oil resources. Also, they are more evenly distributed throughout the world and this reduces the transportation cost [Amoco, 1999]. The U.S. has NG infrastructure to transport NG via large pipeline systems. There is already significant transfer of NG between different countries [Dicks, 1996]. According to DOE, technological improvements in recovery will further increase production resulting in low costs (U.S. DOE, 2000). Therefore, in the short term, lower costs and existing infrastructure make NG the most favorable alternate primary fuel. Although NG is currently not used on a large scale in automobiles, it can be used directly as automobile fuel in the form of CNG or LPG.

<u>Hydrogen Blended Compressed Natural Gas</u>: HCNG is a type of blended CNG which can be used as a motor fuel, since NO_x emissions from the ICE can be significantly reduced by using these mixtures. NO_x emissions are a function of peak combustion temperature, and thus by introducing large amount of heat capacity that do not participate in combustion reaction, peak combustion temperature can be reduced, thereby, reducing NO_x emissions. This principle is called charge dilution and can be accomplished by lean burn, dilution with exhaust gas recirculation, or by water injection [Collier Technologies Inc., undated (b)].

In conventional fuels, all of these charge dilution methods are already used. However, conventional fuels reach misfire condition (incomplete combustion) before NO_x values can be reduced below the current and future regulations. The combustion regime can be extended to afford efficient combustion with large values of charge dilution by addition of hydrogen. In the past, hydrogen was considered to be a fuel additive and was limited to only 20% by volume. As a result of this, the NO_x reduction was not sufficient when compared to other emission reduction techniques.

All other factors being equal, addition of hydrogen increases $NO_{x.}$ However, for hydrogen concentration above 10% of volume, the reduction in nitrogen oxide emissions was shown to be better than or equal to NG. The minimum hydrogen content to reach the point of diminishing returns was found to be about 30% [Collier Technologies Inc., undated (b)]. It was also observed for hydrogen concentration above 30%, though the lean limit is extended considerably, it does not result in substantial nitrogen oxide reduction [Collier Technologies Inc., undated (b)].

HCNG can be an important fuel option that will allow heavy duty transportation fuels to meet 2010 EPA emission requirements. The two main advantages of HCNG are relatively easy addition of hydrogen to existing fueling stations and the absence of available practical technology to meet 2010 heavy duty emission standards. It is predicted that with the increase in HCNG fueling infrastructure, this fuel will also be adapted by light duty vehicles [Collier Technologies Inc., undated (a)]. The use of this fuel may also increase the demand of pure hydrogen vehicles in the future.

Statement of the Problem: The main objective of this research was to investigate whether hydrogen concentration in the compressed natural gas fuel had any effect on the emissions and fuel efficiency. Additionally, we also wanted to investigate whether driving conditions had any effect on the emissions and efficiency while using different blends of compressed natural gas.

Background Studies: In May and June 2003, testing was performed by Arizona Public Services (APS) on a Ford F-150 with hydrogen/CNG blended fuels (30% hydrogen and 70% CNG). The test vehicle was a MY2000 F-150 regular cab with a factory fitted CNG engine. It had a 3600 psig carbon fuel steel tank which can hold up to 85 liters (22.5 gallons) of fuel. The modifications which included supercharging, ignition timing modifications and exhaust gas recirculation were performed by NRG Tech of Reno, Nevada (Karner and Francfort, 2003). This vehicle was placed in the Arizona Public Service fleet in June 2001. This vehicle was fleet tested from June 2001 through September 2002. The vehicle was used for fleet testing by the APS for 31,678 miles on HCNG fuel prior to this 2003 testing. The emission test procedures used were the IM240 and FTP-75 methods. FTP-75 is a cold start test while IM240 is used for emission testing of in-use light duty vehicles in inspection and maintenance program implemented in a number of states. The vehicle specifications are listed in Table 1 below.

Table 1. Vehicle characteristics of Ford F-150 used in 30% HCNG testing [Karner and Francfort, 2003].

Vehicle Specification	5.4 L V8
Curb Weight	5600 lb
Factory HP	260 HP
GVWR	6300 lb

The test results for the IM240 and FTP-75 cycle are given in Table 2 below.

Table 2. Test results of F-150 using 30% hydrogen and 70% CNG (Karner and Francfort, 2003).

Test	NMHC, (g/mile)	CH_4, (g/mile)	HC, (g/mile)	CO, (g/mile)	NO_x , (g/mile)	CO_2, (g/mile)
FTP-75#1	0.122	0.013	0.136	1.644	0.170	620.71
FTP-75#2	0.107	0.011	0.119	1.457	0.163	623.02
Average	0.114	0.012	0.127	1.551	0.166	621.86
IM240#1	0.015	0.008	0.023	0.127	0.565	585.17
IM240#2	0.006	0.011	0.017	0.046	0.440	578.73
Average	0.011	0.009	0.020	0.087	0.503	581.95

The percent reduction in emissions of HCNG when compared to a gasoline fueled Ford F-150 is given in Table 3.

Table 3. Percent reduction in emissions of HCNG compared to gasoline [Karner and Francfort, 2003].

HC	CO	NO_x	CO_2
3.5%	43.3%	97.0%	16.7%

Research Objective: This research work evaluated various blends of compressed natural gas on their emission performance and efficiency. Nominal fuel blends included 0%, 15%, 30% and 50% hydrogen with the balance being compressed natural gas. Emission performance and fuel economy were determined for cold and hot UDDS (urban driving), HWFET (highway driving), US06 (aggressive driving), and NEDC (city driving). Emissions analyzed included carbon monoxide, carbon dioxide, nitrogen oxide, and total hydrocarbon content. The results from this task will be used in the simulation and evaluation of technology for hydrogen light duty vehicles [University of Alabama at Birmingham, 2002] and will also be utilized in the comparison of deployment potential of four hydrogen-fueled light-duty vehicle technologies [of Alabama at Birmingham, 2002].

Experimental Setup and Procedure:

1) *Burke E. Porter 4 WD Chassis Dynamometer*

The testing was conducted using the 4 WD Chassis Dynamometer Test Facility located in Building 371 of Argonne National Laboratory located in Argonne, Illinois. The dynamometer can be used to test front, rear and 4-wheel drive, hybrid electric, non-hybrid electric, or all electric vehicles for exhaust emissions, fuel economy, and performance under varying operating conditions which are normally encountered on roads and highways. The dynamometer allows precise, dynamic, variable and repeatable simulations of road load conditions for evaluation of vehicles. This chassis dynamometer is an alternative method for highway or test track testing.

The motor-in-middle (MIM) style chassis dynamometer model 6592-6055 is a heavy duty machine capable of testing emissions and certification of vehicles. The machine has two roll sets and each roll set is rated at 250 HP. Each roll set is driven by AC vector electric motors/absorbers that provide road load simulation using a solid state power supply controlled by digital logic in the pit below the floor. The vehicles are driven or pushed onto the rollers, centered and held in place with a vehicle restraint system. A view of different components of test cell is shown in the Figure 1 below.

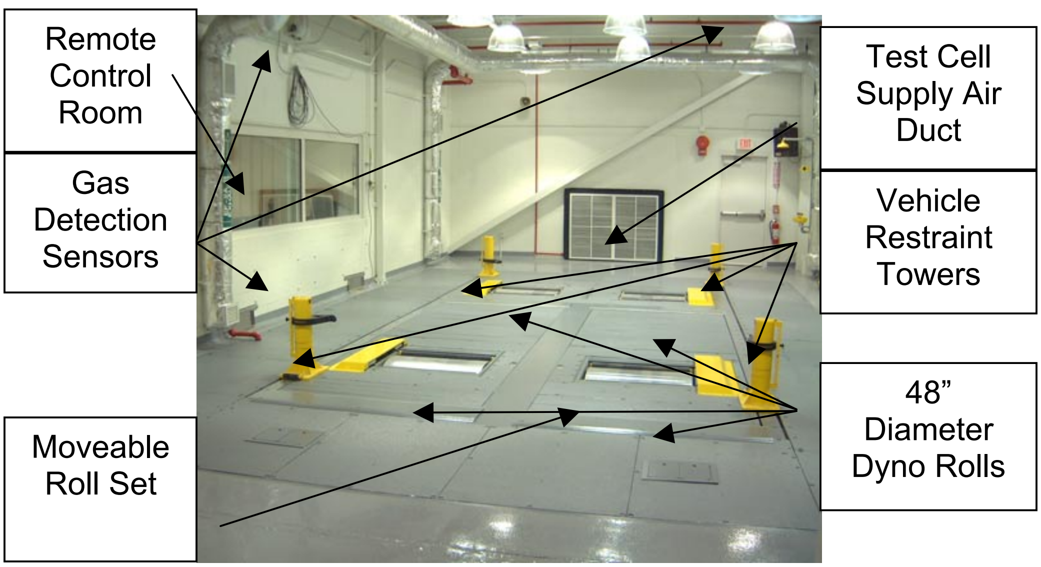


Figure 1. Different components of the dynamometer test cell [Shimcoski and Ng, 2004].

The control system of the dynamometer is programmable to compute the various forces exerted by the surface of the rollers. The digital controls of the dynamometer roller to accurately simulate road load conditions. The digital controls can also be altered by assigning different values of road load factors.

The chassis dynamometer system consists of five units, as follows.

1) Motor/Roller Assembly: Each of the two 250 HP motor and roller assemblies consist of a trunion mounting system, AC motor/absorber, AC vector motor drive, large diameter rollers and support bearings and roller brakes. The roller assembly also has two 48" diameter, hard chrome plated steel rollers which are mounted to motor shaft extension using friction collars. The roller has a designed capacity of 340 Kg single tire load and rotational speed of less than 1000 rpm.
2) Movable Motor/Roll Assembly: Mounted to a two piece sub-base assembly on a set of precision linear bearing rails is the movable motor/roller unit. A wide variety of vehicles having different wheelbase can be accommodated using a ball screw drive. The shaft rotation sensors which are mounted on both sides monitor system malfunction and shut down the drive when the two sides are not traveling at the same speed.
3) Automatic Floor System: The automatic floor system covers the roll assembly and has a capacity of 250 kg/m^2 of uniformly distributed live load or 3400 kg of concentrated load on a 260 cm^2 area. This is essentially a safety measure which prevents the operator from walking on the spinning wheel.
4) Control System: There are two computers which interface with the front and the rear rollers individually. The rear roller set is the master control unit for the dynamometer system and it also controls wheel adjustment. The Ethernet communication network supports the whole system. The rear roller control system controller communicates between the dynamometer and other parts of the overall system where as the front roller control system only manages the front roller.
5) Motor Control/Drive Cabinets: The dynamometer drive system of the front and rear roller sets is located on the mezzanine level. There are two cabinet enclosures; the left hand cabinet enclosure houses the variable speed drive, line reactor and filter while the right hand cabinet houses the dynamometer controller, control relays, various motor starters, circuit breakers, fuses, and lighting for the cabinet.

2) *Test Cell Instrumentation*

The test cell instrumentation consists of five basic components as described below.

A) Emission Bench: This Peirburg AMA 4000 system which collects and measure emissions in real time of THC, CH_4, NMHC, CO, and CO_2 and has lower detection limit of 0.01 ppm. This data is then fed into the data acquisition system.
B) Fast Nitric Oxide Measurement System: The fast nitric oxide measurement system measures the nitric oxide coming out of the engine and tailpipe. The fast nitric oxide measurement system has 0.01 ppm as the detection limit. There were two sampling probes mounted in the exhaust pipe, one before the catalyst and one after the catalyst. This allows the study of the conversion efficiency of catalyst during testing with 5 ms response time.
C) Heated Bags: Each bag collects the entire sample for a particular cycle and the bag contents are analyzed after the test. The data are reported in the output printout under the title of summary information.
D) Particulate Bench: The particulate bench was used only during the CNG testing (not for the CNG/H_2 fuel blend). The CVS mixing T, previously used for all HCNG tests was replaced by the dilution tunnel and the tail pipe was heated to 125°C. Part of the diluted exhaust was passed through two pre-weighed particulate filter papers continuously during the test. The particulate matter was collected on filter paper which was then sent out for analysis. It has a 99% retention typical for 0.3 μm aerosols and larger.

E) Multiple Venturi CVS: This system consists of several venturi which allows a wide range of air flow rates as required by the vehicle for diluting the raw exhaust. The diluted mixture can then be fed in to the emission and particulate benches. The background emission of the air is measured and the difference between the background and the sampled diluted exhaust gives the emission value from the exhaust.

3) *Vehicle Specification*

The vehicle used for testing was a Ford F-150 truck equipped with a 5.4 liter V8 engine which produces 230 HP. It has a curb weight of 5170 lbs and gross weight vehicle rating (GVWR) of 7650 lbs. The engine was modified to run on CNG and blended CNG. A view of the engine of the Ford F-150 is shown in Figure 2.

Figure 2. Ford F-150 used for testing.

4) *Fuels*

There were eight compressed gas cylinders each of 0% (100% CNG), 15% (85% CNG) and the 30% (70% CNG) hydrogen. The compressed gas cylinders were stored on site. The cylinders were used in pairs and the average value of the eight cylinders was taken as the standard for calculation. From Table 4, it can be seen that the composition of the fuel used in testing was consistent. Hence, for curve fitting calculations, we used the average values of 0%, 15%, and 30%, respectively.

It should also be noted that the fuel efficiency (fuel consumption) was calculated from fuel composition and carbon containing species measured in the exhaust. There was no direct measurement of fuel consumption.

Table 4. Composition of the fuels used in testing.

Cylinder No.	Cylinder Code	Hydrogen, (%)	Methane, (%)	Ethane, (%)	Propane, (%)	Nitrogen, (%)	Methyl Mercaptan (ppm)
1	W197387	0	89.880	4.199	2.021	3.900	4
2	3000505	0	89.995	3.936	2.069	4.000	4
3	774218	0	89.805	4.026	2.107	4.062	4

4	2037	0	90.033	3.940	2.040	3.987	4
5	FL13709	0	90.077	3.966	2.019	3.938	4
6	SG9107741A	0	89.981	4.050	2.026	3.943	4
7	T13006	0	90.043	3.987	2.045	3.925	4
8	T1051327Y	0	90.078	3.969	2.034	3.919	4
Mean		0	89.987	4.009	2.045	3.959	
Std Dev		0	0.097	0.086	0.030	0.053	
9	SG758531	14.47	77.143	3.286	1.615	3.486	4
10	W206791	14.59	77.044	3.291	1.616	3.459	4
11	T605453	14.51	77.130	3.287	1.617	3.456	4
12	GH2945	14.82	76.987	3.281	1.617	3.295	4
13	1694757Y	14.53	77.036	3.289	1.618	3.527	4
14	SG1013457	14.60	77.023	3.313	1.615	3.449	4
15	T481495	14.60	77.187	3.292	1.618	3.303	4
16	SG26796A	14.57	77.006	3.284	1.616	3.524	4
Mean		14.586	77.070	3.290	1.616	3.437	
Std Dev		0.105	0.073	0.010	0.001	0.090	
17	SG632257	29.74	63.222	2.706	1.401	2.931	4
18	T456313	29.29	63.632	2.827	1.334	2.917	4
19	2224684Y	29.81	63.150	2.765	1.334	2.941	4
20	1467285Y	29.93	62.888	2.853	1.391	2.938	4
21	C20156	29.89	62.971	2.853	1.346	2.940	4
22	SG337995	29.74	63.011	2.869	1.391	2.989	4
23	SG839613	29.84	63.144	2.742	1.334	2.94	4
24	T1026409Y	29.82	63.101	2.768	1.359	2.952	4
Mean		29.76	63.140	2.798	1.361	2.943	
Std Dev		0.200	0.226	0.060	0.029	0.021	

5) *Testing Cycles*:

1) FTP 75: The FTP-75 is used for emission certification of a light duty vehicle in the U.S. since 2000, and is shown in Figure 3. The FTP-75 cycle is similar to the FTP-72 cycle, the only difference being a 505 sec (identical to first phase of FTP-72) being added as a third phase. The third phase starts after the engine has been stopped for 10 minutes. The entire FTP-75 cycle consists of cold start phase, a transient phase, and a hot start phase.

   Parameters: Distance traveled - 11.04 miles (17.77 km)
   Duration - 2474 seconds
   Average Speed - 21.2 MPH (34.1 km/h)

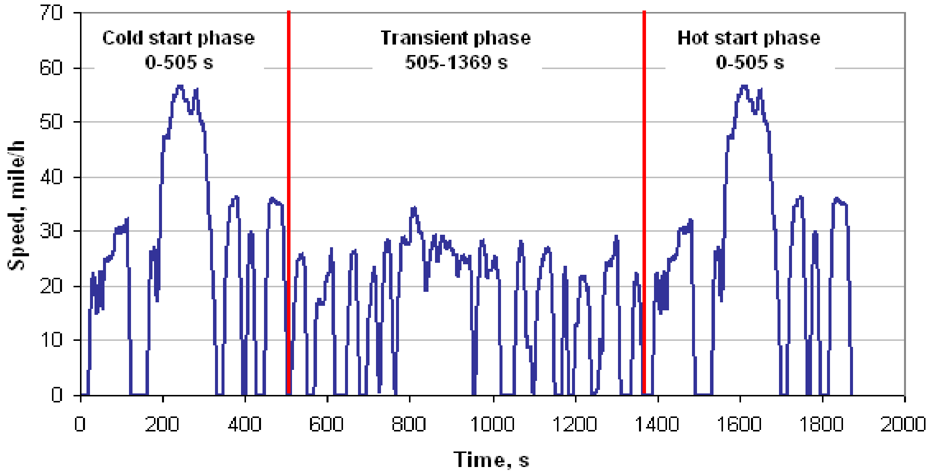


Figure 3. Speed trace of FTP-75 cycle.
[http://www.dieselnet.com/standards/cycles/ftp75.html]

2) US06: The shortcomings of the FTP-75 were addressed by the US06 Supplemental FTP (SFTP). This test represents aggressive high speed and/or high acceleration, rapid speed fluctuation and driving behavior following a startup. The speed trace of the US06 cycle is shown in Figure 4.

Parameters: Distance - 8.01 mile (12.8 km)
Average speed - 48.4 MPH (77.9 km/h)
Maximum speed - 80.3 MPH (129.2 km/h)
Duration -596 seconds

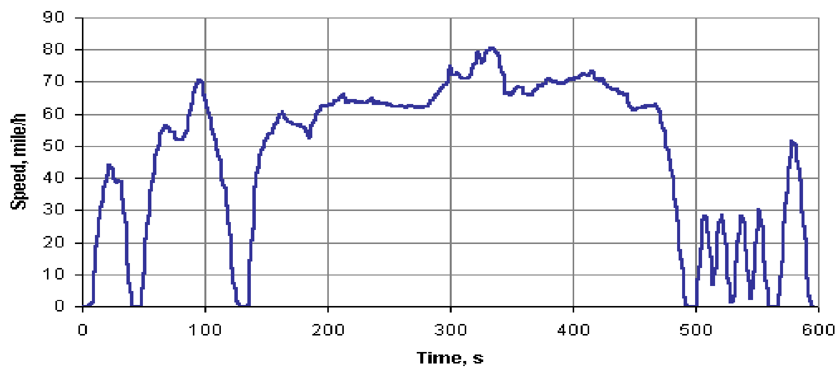


Figure 4. Speed trace of US06 cycle
[http://www.dieselnet.com/standards/cycles/ftp_us06.html]

3) Highway fuel economy cycle (HWFET): The highway fuel economy fuel test (HWFET) is a chassis dynamometer driving cycle, developed by the U.S. EPA for the determination of fuel economy of a light duty vehicle for highway driving conditions. The speed trace of the HWFET cycle is shown in Figure 5.

Parameters: Duration -756 seconds
Total distance -10.26 miles (16.45 km)
Average speed - 48.3 MPH (77.7 km/h)

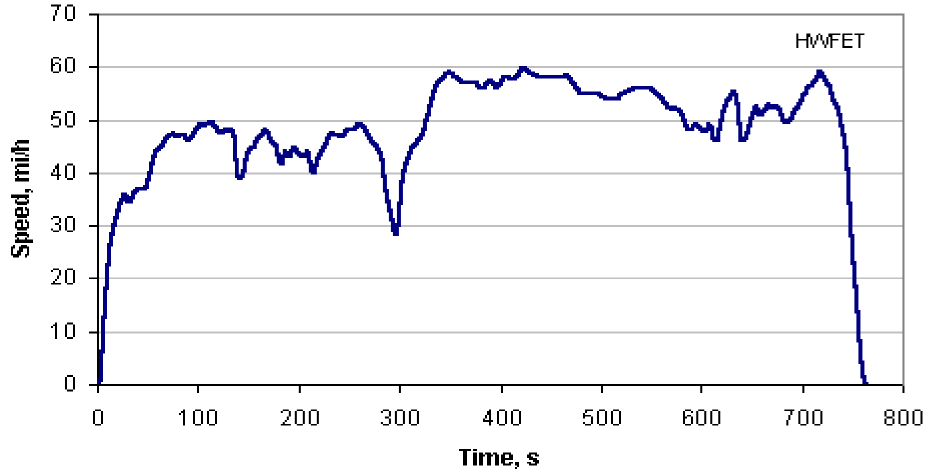
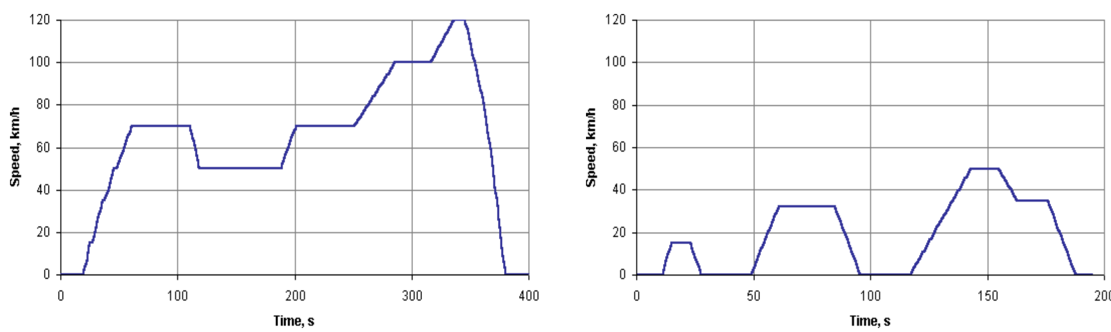


Figure 5. Speed trace of HWFET cycle.
[http://www.dieselnet.com/standards/cycles/hwfet.html]

4) New European Drive Cycle (NEDC): The ECE-15 cycle, which is also known as urban driving cycle (UDC), as shown in Figure 6a, was devised to represent city driving conditions in Paris or Rome. It is a low vehicle speed, low engine load, and low exhaust gas temperature test. The European Urban Driving Cycle (EUDC) as shown in Figure 6b has a maximum speed of 75.47 MPH (120 km/h) and accounts for more aggressive high speed driving modes. The combination of four ECE-15 cycles and a EUDC cycle is called as the New European Driving Cycle (NEDC). The testing consists of a short cycle before the actual cycle, to account for a hot start.

Parameters: Distance - 6.96 miles (11.007 km)
Duration - 1180 seconds



6(a) 6(b)

Figure 6. Speed trace of EUDC and UDC cycle.
[http://www.dieselnet.com/standards/cycles/ece_eudc.html]

Results: The results from the testing are given in Table 5.

Table 5. THC, CO, CO_2, NO_x and EQMPG for Ford F-150 (all the values are reported in g/mile except for EQMPG which is reported in miles/gallon).

THC	CSFTP	HWFET	NEDC	US06		**CO**	CSFTP	HWFET	NEDC	US06
0%	0.0634	0.0209	0.1233	0.0317		0%	0.04366	0.3189	0.3180	1.746

15%	0.0652	0.0197	0.1213	0.0359		15%	0.5066	0.2118	0.1971	1.457
30%	0.0621	0.0196	0.1088	0.0315		30%	0.4257	0.1835	0.2448	1.269
50%	0.0615	0.0870				50%	0.8633	0.0969		
CO_2	CSFTP	HWFET	NEDC	US06		**NO_x**	CSFTP	HWFET	NEDC	US06
0%	443.19	303.81	445.86	451.80		0%	0.1038	0.0724	0.0280	0.0390
15%	428.35	280.92	420.05	448.80		15%	0.1337	0.0755	0.0146	0.0270
30%	399.42	265.57	407.00	415.50		30%	0.1568	0.1028	0.0184	0.0490
50%	373.85	248.25				50%	0.0326	0.0172		
EQMPG	CSFTP	HWFET	NEDC	US06						
0%	15.47	22.59	15.84	15.08						
15%	15.25	23.60	16.07	14.51						
30%	15.32	23.06	15.53	14.67						
50%	14.28	21.58								

Particulate Matter from CNG: The particulate matter data was collected only for pure CNG testing as it was felt that with HCNG being a cleaner fuel, it would have negligible amount of particulate emissions. The assumption is justified by the results from tests using CNG which are given in Table 6.

Table 6. Particulate matter emissions from CNG fuel.

Cycle	Particulate matter, (g)	Particulate matter, (g/mile)
CSFTP	0.000996	0.000090
CSFTP	0.000476	0.000043
CSFTP	0.000016	0.000002
AVG	0.000496	0.000045
NEDC	0.000094	0.000014
NEDC	0.000300	0.000043
NEDC	NA	NA
AVG	0.000197	0.000028
HWFET	0.000059	0.000006
HWFET	0.000303	0.000030
HWFET	0.000500	0.000049
AVG	0.000287	0.000028
US06	0.000143	0.000019
US06	0	0
US06	0.000369	0.000046
AVG	0.000171	0.000021

The particulate matter emission for US06 cycle for light duty truck (LDT1) in ultra low emission vehicle category specified by EPA is 11.1 g/mile. This means that the HCNG emission (0.000021 g/mile) is negligible when compared to the current EPA standards. The emissions result for the FTP (0.000045 g/mile) is significantly less than the EPA standards for LDT1 in the ultra low emission vehicle category (0.03 g/mile).

Discussion: The t-test was used to evaluate whether the exponent in the power-law correlations used to model the emissions as a function of HCNG composition was statistically different. In the experiments, the power-law exponent functions for different cycles were compared statistically using t-tests. The power-law function was preferred over a polynomial function because it was easier to compare the exponential values of the power-law function.

The probability of the power-law exponent being statistically constant for two sample populations was measured by using α. The value of α determined whether or not the power-law exponent for different cycles were distinguishable. The smaller value of α implies that the power-law exponents of the two sample populations are indistinguishable and the fuel blends have no effect on the emissions. Hence, when the power law exponents being compared have the value of α=0.05, it indicates that there is 95% confidence and the two power-law exponents are statistically similar. The means (X) used for comparison were the power-law exponents obtained from the experimental data. The variances were computed by taking the difference between the natural logarithm of the experimental data and natural logarithm of the predicted data squared and dividing the sum of the squared difference by the sample size. The power-law exponents were statistically tested using two hypotheses. The hypothesis H_0 (the null hypotheses) states that the two power-law exponents are equal and similar while the alternate hypothesis (H_1) states that the two power-law exponents are unequal. Due to the limited sample sizes, when the confidence level is 90% (α=0.1), we accept that the two power-law exponents are statistically different and the two power-law exponents cannot be considered to be identical.

The alternate hypothesis H_1 was accepted in cases where the value of α <0.1. This implies that in these null hypothesis cases, the power-law exponents were statistically different. When the value of α>0.1, H_0 was accepted indicating that the two power-law exponents could be considered to be the same. This means that the power-law exponents are statistically indistinguishable, however, not enough data was collected to prove it beyond doubt. The cases in which the alternate hypothesis was accepted are summarized below in the Table 7.

Table 7. Results of hypothetical testing on the value of decay rate constant.

	Emission	t value	Confidence Level	Conclusion
HWFET vs. CSFTP	CO	1.782	0.045	Accept H_1
HWFET vs. CSFTP	CO	1.804	0.044	Accept H_1
HWFET vs. CSFTP	CO	1.768	0.047	Accept H_1
HWFET vs. CSFTP	CO	1.700	0.053	Accept H_1
HWFET vs. CSFTP	CO	1.740	0.049	Accept H_1
HWFET vs. CSFTP	CO	1.751	0.048	Accept H_1
HWFET vs. CSFTP	CO	1.792	0.045	Accept H_1
HWFET vs. CSFTP	CO	1.762	0.047	Accept H_1
HWFET vs. CSFTP	CO	1.772	0.046	Accept H_1
HWFET vs. CSFTP	CO	1.701	0.052	Accept H_1

HWFET vs. CSFTP	CO	1.701	0.052	Accept H_1
HWFET vs. CSFTP	NO_x	3.292	0.002	Accept H_1
HWFET vs. CSFTP	NO_x	3.240	0.002	Accept H_1
HWFET vs. CSFTP	NO_x	3.181	0.002	Accept H_1
HWFET vs. CSFTP	NO_x	3.578	0.001	Accept H_1
HWFET vs. CSFTP	NO_x	3.434	0.002	Accept H_1
HWFET vs. CSFTP	NO_x	3.524	0.001	Accept H_1
HWFET vs. CSFTP	NO_x	3.466	0.001	Accept H_1
HWFET vs. CSFTP	NO_x	3.393	0.001	Accept H_1
HWFET vs. CSFTP	NO_x	3.519	0.002	Accept H_1
HWFET vs. CSFTP	NO_x	3.222	0.002	Accept H_1
NEDC vs. HWFET	CO	1.621	0.063	Accept H_1
NEDC vs. HWFET	NO_x	2.608	0.009	Accept H_1
NEDC vs. HWFET	NO_x	2.731	0.007	Accept H_1
NEDC vs. HWFET	NO_x	2.871	0.005	Accept H_1
NEDC vs. HWFET	NO_x	1.309	0.104	Accept H_1
NEDC vs. HWFET	NO_x	1.446	0.0857	Accept H_1
NEDC vs. HWFET	NO_x	2.281	0.017	Accept H_1
NEDC vs. HWFET	NO_x	2.050	0.027	Accept H_1
NEDC vs. HWFET	NO_x	2.125	0.024	Accept H_1
NEDC vs. HWFET	NO_x	2.485	0.011	Accept H_1
US06 vs. HWFET	CO	1.375	0.094	Accept H_1
US06 vs. HWFET	NO_x	1.460	0.084	Accept H_1
US06 vs. HWFET	NO_x	1.593	0.067	Accept H_1
US06 vs. HWFET	NO_x	1.756	0.048	Accept H_1

For the cases above, the power-law exponents are observed to be statistically different, which indicates that the CO and NO_x emissions are a function of the driving cycle. Each driving cycle has distinctive characteristics such as type of start, top speed and rate of acceleration and deceleration. Thus, for hydrogen blended CNG, the CO and NO_x emissions are a function of driving conditions. However, more testing (and data) needs to be performed to prove this observation for all driving cycles.

Relation between hydrogen concentration in CNG and emissions: From the testing data, a plot of emission versus driving cycle was made for the different fuel blends. We wanted to determine if there was a relationship between the concentration of hydrogen in the HCNG and the resultant emissions and efficiency.

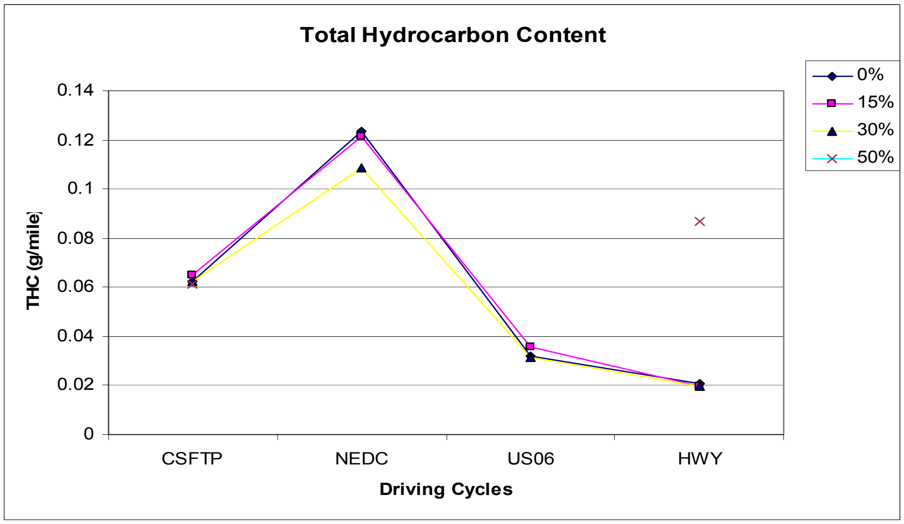


Figure 7. Total hydrocarbon emissions from different blends for different driving cycles.

From Figure 7, it was seen that 30% hydrogen blend (85% CNG) was shown to have the lowest total hydrocarbon emissions compared to the other blends for the NEDC cycle. However, for other cycles the total hydrocarbon emissions were nearly the same for all the blends except for the 50% HCNG fuel blend in the HWFET cycle.

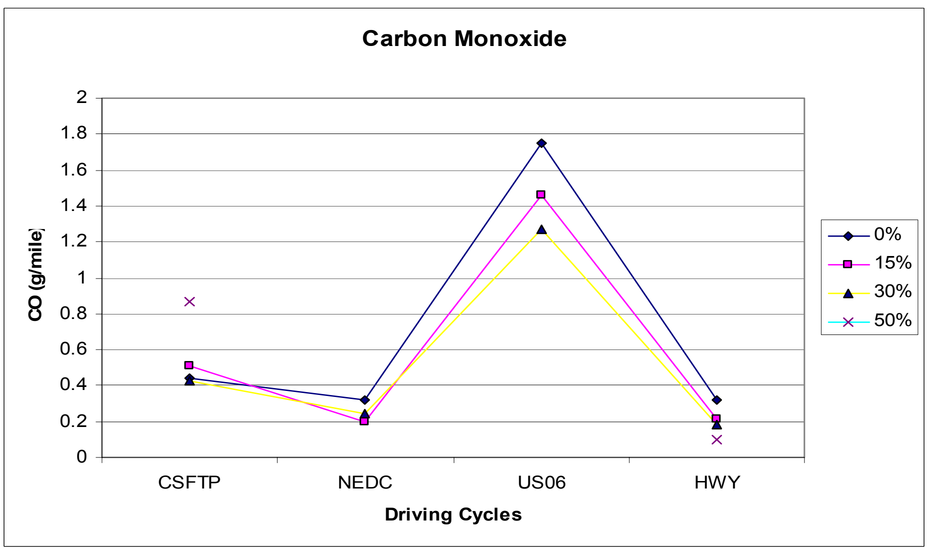


Figure 8. Carbon monoxide emissions from different blends for different driving cycles.

From Figure 8, the carbon monoxide emissions are observed to decrease as the concentration of hydrogen increases in the HCNG fuel blend for the US06 and the HWFET cycle, except for the 50% for which we do not have enough data points. However, this trend was not observed for the CSFTP and NEDC cycles.

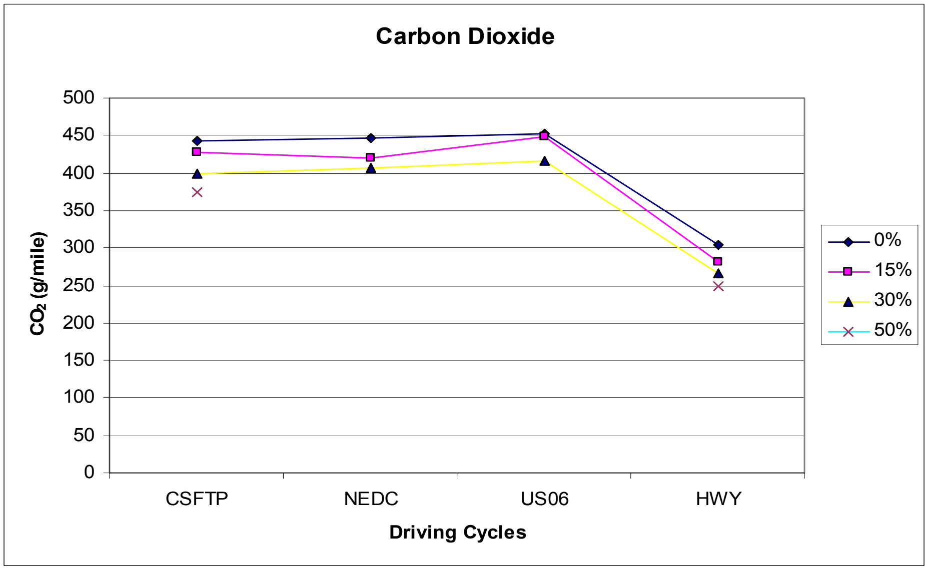


Figure 9. Carbon dioxide emissions from different blends for different driving cycles.

From Figure 9, the carbon dioxide emissions are observed to decrease as the hydrogen concentration in the HCNG fuel blend increases. This trend was seen across all the driving cycles.

The total hydrocarbon, carbon monoxide, and carbon dioxide emissions decreases with an increase in the hydrogen concentration in the HCNG blend as the corresponding carbon concentration decreases.

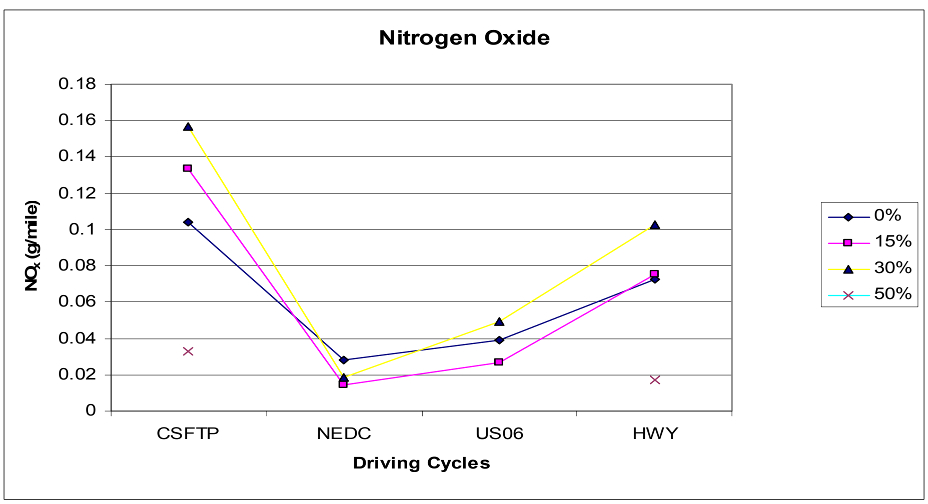


Figure 10. Nitrogen oxide emissions for different blends for different driving cycles.

In Figure 10, the nitrogen oxide emissions increased with an increase in hydrogen concentration in the HCNG for the CSFTP, US06 and the HWFET cycles. However, this trend is not seen for the NEDC cycle. The nitrogen oxide emissions for 50% HCNG blend did not follow the trend of other blends. A possible explanation could be that the vehicle used for the 50% blend had a different catalytic converter. Another possible explanation could be that there may be experimental error involved in the testing of the 50% HCNG blend. The nitrogen oxide emissions for the cold start FTP was higher as a cold engine tends to produce more nitrogen oxide emissions than a hot engine.

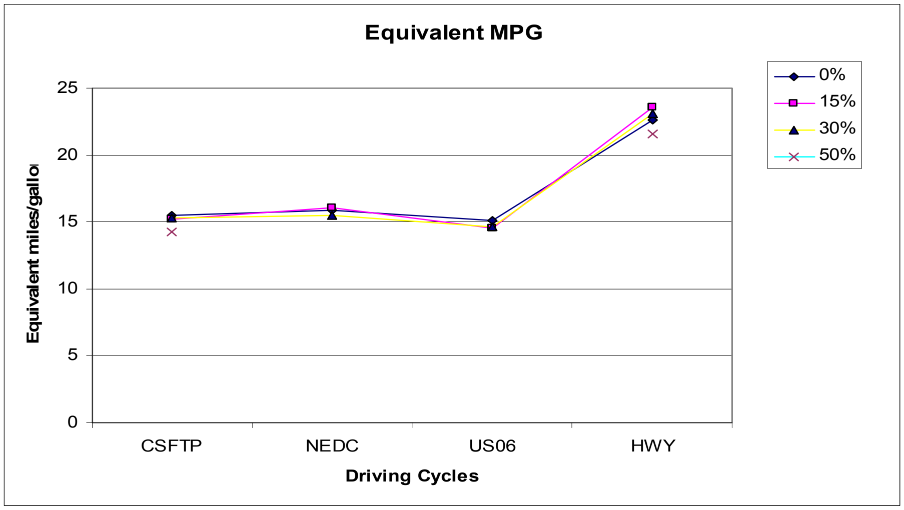


Figure 11. Efficiency (miles/gallon) for different blends for different driving cycles.

From Figure 11, it was seen that the efficiency (equivalent miles/gallon) is nearly the same for all the cycles. The concentration of hydrogen in HCNG seems to have no effect on the efficiency (equivalent miles/gallon).

From the graphs above, it was not very clear if the trace lines were overlapping each other or not. As a result, t-tests were performed to determine whether they were statistically different. From the t-test results, it can be seen that in most cases, the value of α was greater than 0.1. In these cases, trace lines cannot be considered to be statistically different and hence the emissions were not a function of the driving conditions. For the cases where the value of α was less than 0.1, the trace lines were statistically different, and hence the emissions were a function of the driving conditions.

Conclusions

The purpose of this project was to study the effects of hydrogen concentration in the HCNG fuel blend. The conclusions from this study are summarized below.

1) Total Hydrocarbon Content
   - CSFTP: 50%<30%<0%<15%
   - HWFET: 30%<15%<0%<50%
   - NEDC: 30%<15%<0%
   - US06: 30%<0%<15%
2) Carbon Monoxide
   - CSFTP: 30%<0%<15%<50%
   - HWFET: 50%<30%<15%<0%
   - NEDC: 15%<30%<0%
   - US06: 0%<15%<30%
3) Carbon Dioxide
   - CSFTP: 50%<30%<15%<0%
   - HWFET: 50%<30%<15%<0%

- NEDC: 30%<15%<0%
- US06: 30%<15%<0%

4) Nitrogen Oxide
   - CSFTP: 50%<0%<15%<30%
   - HWFET: 50%<0%<15%<30%
   - NEDC: 15%<30%<0%
   - US06: 30%<0%<15%
5) Equivalent MPG
   - CSFTP: 50%<15%<30%<0%
   - HWFET: 50%<30%<0%<30%
   - NEDC: 30%<0%<15%
   - US06: 15%<30%<0%

As observed above, there is no consistent trend in emissions or efficiency with respect to either the hydrogen concentration or the driving cycles. However, there are some significant results which are discussed below.

The carbon dioxide emissions decreased with an increase in hydrogen concentration in the CNG. This trend was consistent across all the driving cycles. For example, for the CSFTP cycle, the CO_2 emissions from the 50% blend were about 15.65% less than for the 0% blend.

The nitrogen oxide emissions increased by 51% when the hydrogen concentration in the CNG blend increased from 0% to 30%. However, the nitrogen oxide emissions for the HWFET and CSFTP cycles for 50% hydrogen blend showed some inconsistencies.

The hydrogen concentration in the CNG blend did not have a substantial effect on the fuel efficiency (EQMPG) and the total hydrocarbon emissions for all the driving cycles.

In summary, emissions and efficiency were a function of driving conditions and the concentration of hydrogen in the compressed natural gas.

References

Amoco, B.P., 1999. "Statistical Review of World Energy".
Chalk S.G., J.F. Miller and F.W. Wagner, 2000. "Challenges for Fuel Cells in Transport Applications", ***J. Power Sources***, 86(1-2): 40-51.
Collier Technologies Inc., undated (a), http://www.bestemissions.com/pdf/cti_brochure.pdf.
Collier Technologies Inc., undated (b), http://www.bestemissions.com/pdf/tech_paper.pdf.
Dicks, A.L., 1996. "Hydrogen Generation from Natural Gas for the Fuel Cell Systems of Tomorrow", ***J. Power Sources***, ***61***: 113-124.
Faaij, A.P.C., and C. Hamelinck, 2002. "Long-term Perspectives for Production of Fuels from Biomass; Integrated Assessment and R&D Priorities", *Proceedings of the 12th Conference on Biomass for Energy, Industry and Acclimate Protection, Amsterdam, Netherlands*.
University of Alabama at Birmingham, 2002. DOE Project on "Global Assessment of Hydrogen-Based Technologies".

Hekkert M.P., P.C.A. Faaij, F. Hendriks and M.L. Neelis, 2003. “Natural Gas as an Alternative to Crude Oil in Automotive Fuel Chains Well-to-Wheel Analysis and Transition Strategy Development”. *Energy Policy*, (in press) (http://www.sciencedirect.com.fetch.mhsl.uab.edu/science?_ob=ArticleURL&_udi=B6V2W-49Y9BHG-1&_user=446477&_coverDate=11%2F13%2F2003&_alid=182784570&_rdoc=1&_fmt=full&_orig=search&_cdi=5713&_sort=d&_st=4&_docanchor=&_acct=C000020378&_version=1&_urlVersion=0&_userid=446477&md5=27d94226d7cd0ea5860fc5969957af46).

http://www.dieselnet.com/standards/cycles/ftp75.html.

http://www.dieselnet.com/standards/cycles/ftp_us06.html.

http://www.dieselnet.com/standards/cycles/hwfet.html.

http://www.dieselnet.com/standards/cycles/ece_eudc.html.

Karner, D., and J. Francfort, 2003. “High Percentage Hydrogen/CNG Blend Ford F-150 Summary”, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

Shimcoski, D. A., and H.K. Ng, 2004. “Energy System Division, Environmental Safety and Health Plan”, Argonne National Laboratory, Argonne, IL.

Turkenburg, W.C., and C.A. Hendriks, 1999. “Fossiele brandstoffen in een duurzame energievoorziening: de betekenis van CO_2 – verwijdering”. Utrecht, Science, Technology and Society, Utrecht University (in Dutch).

U.S. Department of Energy (DOE), 2000. *EIA Annual Energy Outlook*. Washington, DC.

U.S. Environmental Protection Agency, 2004. http://www.epa.gov/air/urbanair/pm/hlth1.html.

U.S. Environmental Protection Agency, 2000. http://www.epa.gov/otaq/cert/veh-cert/b00001i.pdf.