**Global Assessment of Hydrogen Technologies
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**TASK 2 REPORT
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**Comparison of Performance and Emissions from Near-Term
Hydrogen Fueled Light-Duty Vehicles**

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EXTENDED 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%, 50%, 80%, 95%, and ~100% hydrogen, the remainder being compressed natural gas. The blends were tested using a Ford F-150 and a Chevrolet Silverado 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 (CO₂) 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.

Results from the preliminary testing indicated the following:

- Hydrogen rich hydrogen methane blends show similar combustion behavior to pure hydrogen.
- Due to the lower combustion speed of methane compared to hydrogen, the spark timing has to be advanced with increased amount of methane in the blend.
- Different gas properties of methane and methane require adjustment of injection duration in order to achieve the same engine load. A curve that shows the necessary adjustments was presented.
- The NO_x emissions behavior of pure hydrogen compared to hydrogen rich hydrogen methane blends shows the same trends. Due to the lower combustion speed, the absolute level of emissions is slightly lower with increased amount of methane.
- The amount of unburned methane compared to hydrogen in the exhaust is higher relative to the composition of the feed fuel. This is supposedly due to the fact that hydrogen has a shorter quenching distance than methane and thus allows for a more complete combustion close to the combustion chamber walls.

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- Overall, only minor adjustments should be necessary in order to run an engine calibrated and tuned for operation on pure hydrogen on hydrogen rich hydrogen methane blends.

The purpose of Task 2a was to study the effects of hydrogen concentration in the HCNG fuel blend (H₂ content <50%). Results from Task 2a indicated the following:

- As observed above, there is no consistent trend in emissions or efficiency with respect to either the hydrogen concentration or the driving cycles.
- 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 CO₂ 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.

Results from Task 2b indicated the following:

- The fuel economy are quite good, NO_x emissions are not zero, but are low for all the high hydrogen content fuel blends.
- As the percentage of natural gas increased to ~20%, the fuel economy decreases. This is due to the fact that methane has a lower heating value than hydrogen.
- Since there is no carbon in the pure hydrogen fuel, the carbon containing species are likely to come from the lubricating oil.
- One of the most important lessons learned from these tests on the Ford F-150 and the Chevrolet Silverado, is that to save fuel and minimize emissions, air conditioning should not be used.

ACRONYMS

A	Flow area
AC	Alternating current
ANL	Argonne National Laboratory
APS	Arizona Public Services
BTDC	Below top dead center
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CVS	Constant volume sampler
degCA	Crank angle in degrees
DOE	Department of Energy
DOHC	Dual overhead cam
$\dot{E}$	Energy flow
ECU	Engine control unit
EPA	Environmental Protection Agency
EQMPG	Equivalent miles per gallon
EVC	Exhaust valve closed timing
EVO	Exhaust valve open timing
FTP	Federal Test Procedure
FWFET	Highway Fuel Economy Cycle
gge	Gasoline gallon equivalent

GMC	General Motors Corporation
GNG	Green house gas
GVWR	Gross vehicle weight rating
H_0	Null hypothesis
H_1	Alternate hypothesis
H_2	Hydrogen
HC	Hydrocarbon
HCNG	Hydrogen blended compressed natural gas
HP	Horse power
H_u	Lower heating value
ICE	Internal combustion engine
IM240	Inspection and maintenance driving cycle
IMEP	Indicated mean effective pressure
IVC	Intake valve closed timing
IVO	Intake valve open timing
LDT	Light duty truck
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MBT	Maximum brake torque
MIM	Motor-in-middle
NAAQS	National Ambient Air Quality Standards
NEDC	New European Driving Cycle
NG	Natural gas

NMOG	Non-methane organic gases
NO _x	Nitrogen oxide
PFI	Port fuel injector
psi	Pounds per square inch (pressure)
<i>R</i>	Universal gas constant
rpm (RPM)	Revolutions per minute
SAE	Society of Automotive Engineers
SI	Spark ignition
SO _x	Sulfur oxide
SULEV	Super ultra low emission vehicle
T	Absolute temperature
THC	Total hydrocarbon
UAB	University of Alabama at Birmingham
UDDS	Urban Dynamometer Driving Schedule
US06	EPA Supplemental Federal Test Procedure
4 WD	4 wheel drive

Greek Letters:

α	Probability of making a Type I error (in statistics)
γ	Specific heat of charge
κ	Isentropic exponent
λ	Relative air/fuel ratio
ρ	Density

1 INTRODUCTION

Hydrogen is one of several national and international entities considered the most promising future energy carrier and fuel for mobile application. The ideal long-term scenario is hydrogen as a fuel in combination with a fuel cell to convert the chemical energy into electrical energy and further into mechanical energy by using electrical motors.

In order for this ideal long-term scenario to turn into reality, several hurdles have to be overcome. These are besides the lack of hydrogen infrastructure and appropriate on-board storage devices also the high cost of fuel cells. In order to start a transition towards a hydrogen infrastructure and to be able to solve some of the issues related to hydrogen, using internal combustion engines in combination with hydrogen as a fuel is considered a short-to-midterm solution. Several publications on hydrogen powered engines and vehicles have been published in the past and national as well as foreign manufacturer have been doing ongoing development work in this field of research [Goeschel, 2003; Stockhausen *et al.*, 2002].

Additionally, hydrogen is being used to improve the combustion properties of other fuels by blending them with small portions of hydrogen. This is done with liquid fuels in combination with hydrogen as well as gaseous fuels.

1.1 Properties of Hydrogen

As a primary energy source, free hydrogen occurs only in negligible amounts. Water, ammonia, oil, and natural gas are the primary sources from which hydrogen can be produced. It is chemically very active and can readily form compounds with many other elements. Hydrogen has more energy per unit mass of fuel burned, but has a very low density on a volume basis. The low engine volumetric efficiency and poor maximum power are due to the low energy density of gaseous hydrogen. This is proving to be the main stumbling block for hydrogen becoming a major automotive fuel.

Hydrogen has a low flammability limit, which allows a lean operating mixture and a higher thermal efficiency compared to gasoline. The high thermal efficiency arises from an increase in the ratio of specific heats of charge (γ), becoming closer to that of air ($\gamma = 1.4$), and this causes lower heat loss to the engine coolant and reduced dissociation. The higher thermal efficiency leads to low peak cycle temperature and reduces NO_x emissions substantially. The comparison between different properties of hydrogen and gasoline is given in Table 1.

Table 4. Comparative properties of hydrogen and gasoline [Jamal and Wyszynski, 1994].

	Property	Gasoline	Hydrogen
1	Lean limit equivalence ratio in air	0.58	0.1
2	Maximum flame speed in air, (m/s)	0.5	3.5
3	Ignition limits in air, (volume %)	10-7.6	4.0-75.0
4	Minimum ignition energy in air, (mJ)	0.24	0.02
5	Quenching distance, (mm)	2.84	0.6
6	Spontaneous ignition temperature, (°C)	280-400	574
7	Lower calorific value, (MJ/kg)	44	120
8	Net energy density, (MJ/m) (at 15°C and 101.3 kPa)	202	10.3

Because hydrogen has a very high flame speed and good ignitibility, it ensures lean operation. A stoichiometric hydrogen/air mix contains about 30% hydrogen by volume [Jamal and Wyszynski, 1994]. The lower flammability limit of hydrogen is 4% by volume and its upper limit is about 75% [Jamal and Wyszynski, 1994]. The combustion is maintained as near to constant volume as possible when operated at lean mixtures because of the higher flame speed of hydrogen, whereas the low minimum ignition energy of hydrogen helps in the rapid initiation of stable, self-sustaining flame kernels, thereby reducing cyclic variations during lean combustions. Unfortunately, the ignition energy is so low, even an extremely small spark from walking on a carpet can start a hydrogen fire [Jamal and Wyszynski, 1994].

2. BACKGROUND

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 U.S. \$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 (CO₂) 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 CO₂ 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.

2.1 Compressed Natural Gas

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,

2007]. 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.

2.2 Hydrogen Blended Compressed Natural Gas

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.

3. 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.

This task focuses hydrogen-rich hydrogen-methane-blends in a single-cylinder research engine. Combustion behavior, emissions, and performance of the engine fueled with blends of 5% methane in hydrogen and 20% methane in hydrogen are compared to operation on pure hydrogen as a baseline.

This experimental study is a baseline work to convert a hydrogen truck to blended operation on hydrogen-rich hydrogen-methane-blends. Necessary changes in the engine control unit (ECU) in order to safely operate the engine on hydrogen-methane-blends are to be identified.

4. PREVIOUS STUDIES ON EMISSIONS FROM CNG-FUELED VEHICLES

The literature indicates that the particulate emissions from CNG-fueled spark ignition engines range in size form of 0.02 to 0.06 μm . This is lower than similar emissions for diesel and even petrol emissions [Ritovski *et al.*, 2000]. However, very little data is available on particulate emissions from CNG-fueled spark ignition (SI) engines. According to Greenwood *et al.* [1996], particulate emissions from CNG-fueled engines are similar to gasoline engines and match that of diesel engines using higher loads. However, CO and NO_x emission rates of 5.53 and 3.33 g/KW/h were considerably lower than the 1997 EPA standards, and hence the spark ignition engine was considered a low emission engine.

A study by Gabele [1995] examined emissions of 11 vehicles running on CNG, LPG, methanol, and reformulated gasoline. The main purpose of this study was to investigate the ozone-forming potential of the emissions from these fuels. Reactivity weighted emission rates were calculated for each organic species and CO. The reactivity of organic emissions was an important factor as it determines the potency of ozone precursor emissions [Gabele, 1995]. Out of the three CNG vehicles, two were Dodge vans and one was a Chevy Sierra. The emissions for the CNG vehicles were 0.55, 1.46, and 5.95 g/mile for CO, 0.02, 0.6, and 0.06 g/mile for non-methane organic gases (NMOG), and 0.19, 1.48 and 0.39 g/mile for NO_x. From this, it can be seen that there are large variations in results. Further investigations showed that emissions were more a function of vehicle condition than of fuel type [Gabele, 1995].

Black *et al.* [1998] measured emissions of CO, NO_x, and speciated organic compounds for a range of vehicles using different fuels. The results indicated that ozone potential decreased by more than 90% with CNG compared to reformulated gasoline, and that toxic emissions (benzene, formaldehyde, acetaldehyde, and 1,3-butadiene) were lower for CNG than for gasoline. Exhaust NMOG emissions were 0.006 g/mile, CO₂ emissions were 0.124 to 0.320 g/mile, and NO_x emissions were 0.019 g/mile.

5. BACKGROUND

5.1 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 2 below.

Table 2. 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 3 below.

Table 3. 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 4.

Table 4. 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%

6. OBJECTIVES

6.1 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 were used in the simulation and evaluation of technology for hydrogen light duty vehicles [University of Alabama at Birmingham, 2002] and were also utilized in the comparison of deployment potential of four hydrogen-fueled light-duty vehicle technologies [University of Alabama at Birmingham, 2002].

7. TASKS

7.1 Task 2. Comparison of Performance and Emissions from Near-Term Hydrogen-Fueled Light-Duty Vehicles

This task was divided into the following three subtasks.

7.1.1 *Subtask 2a: Performance and Exhaust Emissions Testing of Hythane (20% hydrogen, 80% methane) Vehicles*

Emissions, performance, and drivability tests on hythane-powered vehicles from the Argonne fleet will be performed. The vehicles evaluated were Ford F-150 trucks designed for dedicated compressed natural gas operation (CNG). A control CNG-powered vehicle was monitored and the results compared to the hythane-powered counterpart. Emissions testing measured total hydrocarbons, carbon monoxide, and carbon dioxide, but emphasized changes in emissions of nitrogen oxides. All emissions testing was performed in the new four-wheel drive dynamometer facility at Argonne National Laboratory (ANL). This facility was designed to be hydrogen and CNG capable and employs the latest SULEV-level emissions testing equipment. The test facility is one of the premier chassis dynamometer emissions facilities in the country.

7.1.2 *Subtask 2b: Performance and Exhaust Emissions Testing of Hydrogen-Powered ICE Vehicle*

Contacts with Ford Motor Company were established through Argonne National Laboratory in an attempt to arrange to test Ford's P2000 hydrogen-fueled ICE-powered prototype vehicle in the ANL chassis dynamometer test facility. There were significant challenges in testing the emissions and efficiency of hydrogen-fueled ICE-powered vehicles because existing equipment and procedures have been developed for vehicles burning fossil fuels. There are potentially significant amounts of nitrogen oxides produced due to the high temperature of hydrogen combustion depending on fuel-to-air equivalence ratio. In addition, standard safe test procedures for determining the emissions and efficiency of hydrogen-fueled ICE-powered vehicles are required because existing equipment and procedures have been developed for vehicles burning fossil fuels. Additional instrumentation to measure hydrogen fuel flow and specific exhaust species will be required to perform these tests. Instrumentation will be purchased to enable accurate measurement of hydrogen engine emissions.

7.1.3 *Subtask 2c: Performance and Exhaust Emissions Testing of Hydrogen-Powered Fuel Cell Vehicle*

A fuel cell-powered Ford F-150 was evaluated for efficiency, performance, and exhaust emissions in simulations involving PSAT modeling. Although this prototype vehicle may not be representative of production fuel cell vehicles, it none-the-less has a state-of-the-art fuel cell stack and electric propulsion system. Note: The University of Alabama at Birmingham and Argonne National Laboratory were unable to secure a fuel

cell-powered vehicle. As a result, performance was assessed through computer simulations (see task report for Task 1).

8. RESULTS AND DISCUSSION

8.1 Preliminary Testing

This task focused hydrogen-rich hydrogen-methane-blends in a single-cylinder research engine. Combustion behavior, emissions, and performance of the engine fueled with blends of 5% methane in hydrogen and 20% methane in hydrogen were compared to operation on pure hydrogen as a baseline.

This experimental study is a baseline work to convert a hydrogen truck to blended operation on hydrogen-rich hydrogen-methane-blends. Necessary changes in the engine ECU in order to safely operate the engine on hydrogen-methane-blends are to be identified.

8.1.1 Engine Test Cell and Research Engine

The engine used to run these investigations is an automotive-size, spark-ignited single-cylinder research engine. The engine is located in a designated hydrogen engine test cell at Argonne National Laboratory that features a hydrogen metering and leakage monitoring system as well as a hydrogen emissions analyzer in addition to the standard emissions equipment. The main specifications of the engine are summarized in Table 5. A more detailed description of the engine test cell and the engine configuration can be found in Ciatti *et al.* [2006]. For these tests the engine was fueled from high-pressure cylinders that already contained the premixed blends.

Table 5. Research engine specifications.

Engine manufacturer	Ford Motor Company
Cylinders	1
Displacement (L)	0.5
Compression ratio	11.4:1
Valve train	4V Dual Overhead Cam (DOHC)
Intake Valve Timing	IVO = +345, IVC = -145
Exhaust Valve Timing	EVO = +140, EVC = -350
Max Torque (Nm)	30
Speed range (rpm)	800-6000
Injector	(6 bar) Quantum PFI
Hydrogen Measurement	Micro-Motion Coriolis Meter

8.1.2 Comparison of Fuel Properties

The fuels used are pure hydrogen (100% H₂), a blend of 5% methane in hydrogen (5% CH₄) and a blend of 20% methane in hydrogen (20% CH₄). Although both base components are gaseous under ambient conditions, the specific fuel properties differ quite significantly. As shown in Wallner *et al.* [2007], the lower heating value of pure

hydrogen (120 MJ/kg) is more than twice as high as that of pure methane (50 MJ/kg). Due to the large difference in molar mass [Wallner *et al.*, 2007], the mass-based composition of the blends is considerably different from the volume-based composition, as indicated in Figure 1. The gas properties of the tested blends are compared to those of the base gases in Table 6.

Figure 12. Influence of composition on fuel properties [Wallner *et al.*, 2007].

Table 6. Gas properties of base gases and blends.

Parameter	Unit	H ₂	5% CH ₄	20% CH ₄	CH ₄
Density	kg/m ³	0.089	0.12	0.22	0.72
Molar mass	kg/kmol	2.016	2.72	4.82	16.04
Lower heating value	kJ/kg	120000	99339	73419	50000
Stoichiometric air demand	kg _{air} /kg _{fuel}	34.3	29.3	22.9	17.2
Laminar flame speed	cm/s	200			40

The fuel properties result in a mixture calorific value in hydrogen port injection of $H_2 \sim 3.2 \text{ MJ/m}^3$ and about 3.4 MJ/m^3 for pure methane. This results in a small advantage of blended fuels in terms of power density, although the mixture calorific values are still significantly lower than those of gasoline or diesel ($\sim 3.8 \text{ MJ/m}^3$) [Eichlseder *et al.*, 2002].

8.1.3 Test Program

The three different fuels were tested at two engine speeds (2000 rpm and 4000 rpm). For each speed spark sweeps were performed at several load points in order to identify MBT (maximum brake torque) spark timing. Due to the wide ignition limits, pure hydrogen allows to run the engine unthrottled in a wide operating range. In order to assess the combustion properties of the blends in comparison to pure hydrogen, all operating points were run unthrottled.

The results at speeds of 2000 and 4000 rpm show identical trends, thus the data presented could be concentrated on selected operating points at a speed of 2000 rpm.

8.1.4 Engine Efficiency and Combustion Behavior

In Figure 13, the indicated efficiencies for engine loads of approximately 2, 4, and 6 bar IMEP are plotted versus spark timing at an engine speed of 2000 rpm. Solid black lines refer to pure hydrogen, dotted dark grey lines refer to a mixture of 5% methane in hydrogen, and dotted and dashed light grey lines represent results for 20% blends of CH_4 in H_2 . As all operating points were taken in unthrottled condition, higher engine loads result in fuel-richer mixtures. The flame speed for those gases is highly dependent on the air/fuel ratio with a maximum close to stoichiometric. Thus, higher engine loads result in higher combustion speeds and therefore require less spark advance. Furthermore the flame speed for hydrogen is very high compared to other fuels [Eichlseder *et al.*, 2003]. In a stoichiometric mixture the laminar flame speed of hydrogen is 5 times higher than that of methane [Wallner *et al.*, 2007]. In order to compensate for the lower combustion speed with increased amount of methane in the blend, the MBT spark timing occurs earlier for the 20% blend compared to the 5% blend or pure hydrogen.

Figure 13. Indicated efficiency versus spark timing at a speed of 2000 rpm [Wallner *et al.*, 2007].

The actual peak efficiencies for the different fuels are in a comparable range. For low engine loads pure hydrogen operation results in higher efficiencies compared to the blends. This is again due to the fact, that the combustion speed for these lean mixtures is fairly low for the methane blends. For high engine loads the blended fuels allow to achieve higher efficiencies than pure hydrogen. The extremely short combustion duration for close-to-stoichiometric pure hydrogen operation results in high combustion temperatures and thus increased wall heat losses [Wimmer *et al.*, 2005].

A detailed analysis of the combustion behavior was performed in order to investigate the influence of blending. Based on high-speed cylinder pressure measurements the rate of heat release was calculated. Figure 14 shows the pressure traces as well as the rates of heat release for a medium-load point (4 bar IMEP) at a speed of 2000 rpm. The spark timing was held constant at 25 degCA BTDC which allows better comparison of the actual traces. The air/fuel ratio for these operating points is between $\lambda \sim 2.5$ for the 20% CH₄ blend and $\lambda \sim 2.8$ for pure hydrogen. The difference in air/fuel ratio results from the slightly lower efficiency in blended operation (see Figure 13). Although the mixture is leaner in pure hydrogen operation, the combustion duration is still shorter for pure hydrogen than for the two blends. The maximum value of heat release is comparable for the three fuels.

Figure 14. Pressure traces and rates of heat release at medium load (2000 rpm, 4 bar IMEP).

The difference in combustion behavior and flame speed is even more distinct at higher engine loads for richer mixtures. Figure 15 shows a comparison of pressure traces and heat release rates for an IMEP of about 6 bar. This corresponds to an air/fuel ratio λ of about 1.7. The combustion in pure hydrogen operation takes only about 25 degCA, which is remarkable considering that it is still a lean mixture. In comparison, the combustion duration for the 5% CH₄ blend is about 35 degCA and the combustion duration for the 20% CH₄ mixture is distinctively longer with about 55 degCA. In addition, the maximum rate of heat release is significantly higher for pure hydrogen operation, which also results in a higher combustion peak pressure (50 bar for 100% H₂ compared to about 30 bar for the 20% CH₄ blend).

Figure 15. Pressure traces and rates of heat release at high load (2000 rpm, 6 bar IMEP).

Overall, these results show that the spark timing has to be advanced in blended operation compared to pure hydrogen mode in order to achieve maximum efficiency. For a 5% methane in hydrogen blend, the spark advance is only minor and does not significantly reduce the engine performance. For the 20% CH₄ blend, spark timing definitely needs to be adjusted for optimal results.

8.1.5 Influence of Blending on Fuel Maps

Due to the lower heating value of the blends compared to pure hydrogen, the amount (mass) of fuel to be injected to reach the same engine load increases with an increased amount of methane in the blend. On the other hand the density of methane is higher than that of hydrogen, thus blends of hydrogen/methane have an increased density with increased amount of methane in the blend. Although the mass to be injected almost doubles when a 20% CH₄ blend is injected instead of pure hydrogen, the injection duration remains nearly unchanged (see Figure 16).

Figure 16. Influence of fuel composition on injected fuel mass and injection duration.

Given identical injector flow characteristics and an isentropic critical injection event, the energy flow can be calculated as:

$$\frac{\dot{E}}{A} = H_u \times \rho \times \sqrt{\kappa \times R \times T} \quad \{\text{Equation 1}\}$$

where:

- $\dot{E}$ Energy flow, [J/s]
 A Flow area, [m²]
 H_u Lower heating value, [J/kg]
 ρ Density, [kg/m³]
 κ Isentropic exponent, [-]
 R Universal gas constant, [J/kg-°K]
 T Absolute temperature, [°K]

Figure 17 shows the trace of area related energy flow versus concentration in the blend. In addition, the relative flow compared to that of pure hydrogen is shown. Starting from pure hydrogen, the energy flow slightly decreases with a minimum relative flow of about 95% at a concentration of about 15% methane in hydrogen. For methane-rich blends (>50% CH₄ in H₂), the energy flow rises significantly. Overall, the influence of

the energy flow in the area of interest for these investigations (0% to 20% CH₄ in H₂) is minimal.

Figure 17. Energy flow versus methane concentration.

8.1.6 Emissions Behavior

The only relevant emissions in hydrogen operation are nitric oxides. NO_x emissions are highly dependent on the air/fuel ratio. In premixed operation with air/fuel ratios λ higher than 2.0, the NO_x emissions are negligible. For richer mixtures a distinct NO_x emissions peak can be observed at an air/fuel ratio of $\lambda \sim 1.3$. A further reduction of air/fuel ratio towards stoichiometric operation results in a decrease of nitric oxides [Wallner *et al.*, 2003].

As shown in Figure 18, an increase in load results in an increase in NO_x emissions. Due to the lean-operating strategy, there is only a negligible amount of NO_x emissions at an engine load of 2.0 bar IMEP. At medium engine load (4 bar IMEP), the NO_x emissions are generally still below 10 ppm. Only operating points with extremely early spark timing resulting in high combustion temperatures produce nitric oxides in an amount of up to 100 ppm. At higher engine load (6 bar IMEP), the NO_x emissions increase significantly (note the logarithmic scale). The same trend with an increase of NO_x emissions for early spark timing can be seen. Due to the faster combustion and hence higher combustion temperatures of pure hydrogen compared to the blends, the NO_x emissions are generally slightly higher in pure hydrogen operation.

Figure 18. Influence of blending on NO_x emissions.

H₂ emissions are not regulated by any standards, but it is nevertheless important to monitor and minimize these emissions because it directly affects the engine efficiency. Figure 19 shows the H₂ emissions for pure hydrogen and the two hydrogen methane blends. Very lean engine operation (IMEP~2 bar) results in a very slow combustion and thus a higher portion of unburned fuel. This trend can be seen for all three fuels, due to the even lower combustion speed with an increased amount of methane in the blend, this effect is even more significant. With increased engine load the H₂ emissions drop well under 2000 ppm. Considering that up to 30 Vol % of the initial fuel gas mixture is hydrogen, 2000 ppm (0.2 Vol %) is minimal and represents an almost negligible loss in efficiency [Wallner, 2004]

Figure 19. Influence of blending on H₂ emissions.

The second component of the blended fuels, methane, was also monitored during engine operation. The trends in CH₄ emissions are very similar to those of H₂ emissions, due to the fact that the fuels contain different amounts (or no) methane, the absolute levels of the CH₄ emissions differ significantly (see Figure 20). As expected the amount of methane emissions in pure hydrogen operation is close to zero.

Figure 20. Influence of blending on CH₄ emissions.

Given that the engine was fueled with a homogenous mixture of hydrogen, methane and air, one could expect that the ratio of unburned fuel (methane and hydrogen) should be the same as the hydrogen-methane ratio of the feed fuel. Figure 21 shows the ratio of methane to hydrogen emissions for the two different blends.

Figure 21. Traces of CH₄/H₂ emissions ratio.

For the 5% mixture, the ratio of CH₄/H₂ emissions is fairly constant with an average of about 8% and a maximum of 11%. On the other hand, the methane to hydrogen emissions ratio for the 20% blend varies quite significantly with a minimum ratio of over 30% and a maximum of almost 55%. The average ratio of CH₄/H₂ emissions for the 20% blend is almost 40%. In addition, the ratio increases with retarded spark timing, an effect that can also be seen for low load traces of the 5% blend. This indicates that towards the end of combustion close to the combustion chamber walls, hydrogen is still able to burn while the local conditions do not allow for methane to burn anymore. This effect is very likely due to the shorter quenching distance of hydrogen (0.6 mm [Goeschel, 2003]) compared to methane (2 mm [Goeschel, 2003]) [Wimmer *et al.*, 2005].

8.1.7 Influence of Blending Hydrogen and Methane on Engine Calibration

The main target of the presented investigations is to determine the necessary changes and adaptations in the engine control unit (ECU) of a hydrogen powered vehicle in order to run it on blends of hydrogen and methane. Currently the truck is operated with a lean burn strategy with a constant air/fuel ratio. Further information on the truck and the operating strategy can be found in Lohse-Busch *et al.* [2006].

8.1.8 Injection

In order to avoid operating regimes with high NO_x emissions, the truck was run on a lean burn strategy with a constant relative air/fuel ratio λ . The calibration of the ECU was performed for a relative air/fuel ratio $\lambda \sim 2.25$. Due to the changes in energy flow, adjustments of injection timing will be necessary. If only discrete blends with known composition are being used, the injection settings can be changed manually according to the dependencies shown in Figure 17. If the decision is being made that various blends or blends with unknown composition are used to fuel the vehicle, the above mentioned curve should be implemented in the ECU. This also means that a way to identify the composition of the mixture has to be developed.

8.1.9 Ignition

Due to the lower combustion speed of methane compared to hydrogen the spark timing should be adjusted for optimum engine performance. With the current engine control strategy, the engine was run with a constant air fuel ratio of $\lambda \sim 2.25$. In this air/fuel ratio range, the MBT spark timing with the 5% methane in hydrogen mixture was about 5 degCA earlier than with pure hydrogen. For the 20% CH_4 in H_2 blend, the spark timing should be about 15 to 20 degCA earlier compared to pure hydrogen. For blends with small amounts of methane (<5 Vol. %), the engine can be operated without adjusting the spark timing, which will result in only a negligible loss in engine efficiency. For blends with higher amounts of methane, the spark timing should be adjusted to maintain efficiency.

8.1.10 Other ECU Functions

The earlier spark timing when blending hydrogen with methane could possibly lead to knocking combustion. Due to the good knocking properties of methane, this does not seem very likely as in addition, the lean burn strategy itself inhibits knocking. In addition, a knock sensor could be used to prevent the engine from operating under knocking conditions.

Due to the changed composition of the feed fuel, the dependency of the air/fuel ratio on the exhaust oxygen feedback slightly changes. Figure 22 shows this dependency of exhaust oxygen content and relative air/fuel ratio in the relevant air/fuel ratio regime $1.8 < \lambda < 2.6$. As can be seen in Figure 22, a feedback of exhaust oxygen content of ~10 Vol % is equal to an air/fuel ratio λ of 2.1 in pure hydrogen operation. The same oxygen content results in a relative air/fuel ratio of 2.08 with the 5% blend and about 2.05 with the 20% blend.

Figure 22. Relative air/fuel ratio as a function of exhaust oxygen content.

Knowing that the air/fuel ratio especially in the region of $\lambda \sim 2$ has a crucial influence on the NO_x emissions behavior, the above shown effect should be taken into account. On the other hand, it could be shown in Figure 18 that blending hydrogen with methane slightly reduces the NO_x emissions level due to the slower combustion speed of methane compared to hydrogen. Overall these two effects might balance each other and lead to about the same emissions characteristics.

8.1.11 Summary and Conclusions

In order to investigate the influence of blending hydrogen with methane, several tests on a single-cylinder research engine were performed. The goal of these tests was to identify the changes necessary in an engine ECU in order to run it on hydrogen rich hydrogen methane blends. Based on the results shown, the following conclusions were drawn:

- Hydrogen rich hydrogen methane blends show similar combustion behavior to pure hydrogen.
- Due to the lower combustion speed of methane compared to hydrogen, the spark timing has to be advanced with increased amount of methane in the blend.
- Different gas properties of methane and methane require adjustment of injection duration in order to achieve the same engine load. A curve that shows the necessary adjustments was presented.

- The NO_x emissions behavior of pure hydrogen compared to hydrogen rich hydrogen methane blends shows the same trends. Due to the lower combustion speed, the absolute level of emissions is slightly lower with increased amount of methane.
- The amount of unburned methane compared to hydrogen in the exhaust is higher relative to the composition of the feed fuel. This is supposedly due to the fact that hydrogen has a shorter quenching distance than methane and thus allows for a more complete combustion close to the combustion chamber walls.

Overall, only minor adjustments should be necessary in order to run an engine calibrated and tuned for operation on pure hydrogen on hydrogen rich hydrogen methane blends.

8.2 Subtask 2a: Performance and Exhaust Emissions Testing of Hythane (20% hydrogen, 80% methane) Vehicles (testing with a Ford F-150 truck)

8.2.1 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 Figure 12.

Figure 42. 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-inch 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, CH₄, NMHC, CO, and CO₂ 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/H₂ fuel blend). The constant volume sampler (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 13.

Figure 13. 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 7, 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 7. 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 14. 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 14. Speed trace of FTP-75 cycle.

[<http://www.dieselnets.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 15.

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 15. Speed trace of US06 cycle.

[http://www.dieselnets.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 16.

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

Figure 16. 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 17a, 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 17b 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 17. Speed trace of EUDC and UDC cycle.

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

8.2.2 Results

The results from the emissions testing are given in Table 8.

Table 8. THC, CO, CO₂, 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		
CO₂	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 was justified by the results from tests using CNG which are given in Table 9.

Table 9. 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).

8.2.3 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 values of α determined using a power-law exponent equation 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 $\alpha=0.05$, it indicates that there is 95% confidence and the two power-law exponents are statistically similar. The means ($\bar{X}$) 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% ($\alpha=0.1$), 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 $\alpha < 0.1$. This implies that in these null hypothesis cases, the power-law exponents were statistically different. When the value of $\alpha > 0.1$, 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 10. Additional information on the statistical analysis is found in Dutta [2005]

Table 10. 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.

8.2.4 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 18. Total hydrocarbon emissions from different blends for different driving cycles.

From Figure 18, 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 19. Carbon monoxide emissions from different blends for different driving cycles.

From Figure 19, 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 20. Carbon dioxide emissions from different blends for different driving cycles.

From Figure 20, 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 5. Nitrogen oxide emissions for different blends for different driving cycles.

In Figure 21, 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 were higher as a cold engine tends to produce more nitrogen oxide emissions than a hot engine.

Figure 6. Efficiency (miles/gallon) for different blends for different driving cycles.

From Figure 22, 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.

8.2.5 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 CO₂ 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.

8.3 Subtask 2b: Performance and Exhaust Emissions Testing of Hydrogen-Powered ICE Vehicle (Testing on Chevrolet Silverado)

8.3.1 Introduction

Emissions, performance, and drivability tests on hydrogen/natural gas powered vehicles from the Argonne fleet were performed. The vehicle evaluated was a Chevrolet/GMC Truck Silverado/Sierra designed for dedicated hydrogen gas operation. This vehicle was recalibrated to operate on hydrogen/natural gas blends and emissions and performance testing performed before and after hydrogen operation. The vehicle was monitored and the results compared to their hydrogen-powered counterparts. Emissions testing measured total hydrocarbons, carbon monoxide, and carbon dioxide. The testing emphasized changes in emissions of nitrogen oxides. All emissions testing were performed in the new four-wheel drive dynamometer facility at Argonne National Laboratory (ANL). This facility has been designed as to be hydrogen and CNG capable and employs the latest SULEV-level emissions testing equipment. The test facility is one of the premier chassis dynamometer emissions facilities in the country.

In addition, the effects of air-conditioning on emissions and fuel economy of this vehicle were investigated to determine its significance.

8.3.2 Test Set Up

The vehicle tested is a Chevrolet/GMC Truck Silverado/Sierra 1500HD Crew Cab 2WD LS converted to hydrogen operation by ETEC and Roush. The standard features are summarized below in Table 11.

Table 11. Standard features of the Chevrolet Silverado truck.

Standard features	
Seat positions	6
Engine	6.0l V8
Transmission	4 speed automatic
Drive	2 wheel
Vehicle modifications	
Supercharged and intercooled	
Power train control system custom calibrated for H ₂ Fuel	
Compressed Hydrogen with electronic fuel injection	
Three 150 liter tanks, Type 3 (aluminum lined, carbon-fiber reinforced) 350 bar (5000 psi) storage pressure	
10.5 kg (10.5 gge) usable fuel	
Standard 350 bar fueling nozzle (SAE J2600)	

Weight and dimensions	
Curb Weight (est.)	6,625 lbs.
GVWR	8,600 lbs.
Wheelbase	153 in

8.3.3 Results and Analysis

Compressed H₂/natural gas fuel blends for nominal hydrogen contents of ~80%, ~95%, and ~100%, were used in the testing. Emissions tests were performed on total hydrocarbons, nitrous oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO₂), along with determinations of fuel efficiency. The driving cycles used during these tests included the cold start FTP (CS FTP), highway driving (HWFET), and urban driving (UDDC) cycles. Results obtained are listed below.

Table 12. Emissions testing results (bag results) on the Chevrolet Silverado truck using nominal hydrogen contents of 80%, 95%, and 100% with different driving cycles.

Bag data:

H ₂ , (%)	Test	Bag No.	Total Hydrocarbons, (gm/mile)	NO _x , (gm/mile)	CO, (gm/mile)	CO ₂ , (gm/mile)	Fuel Economy, (miles/kg)
99.99	CS FTP	1	0.0000	0.0878	0.0424	0.00	13.62
		2	0.0000	0.0364	0.0850	0.00	13.22
		3	0.0000	0.0730	0.1145	0.00	15.22
		FTP	0.0000	0.0579	0.0842	0.00	13.89
99.99	CS FTP	1	0.0004	0.1019	0.0132	0.00	13.69
		2	0.0009	0.0428	0.0496	0.00	13.43
		3	0.0014	0.0728	0.0882	0.65	15.33
		FTP	0.0009	0.0641	0.0528	0.19	14.03
99.99	J1634 w/o A/C	UDDS	0.0000	0.0581	0.0712	3.00	14.46
		UDDS	0.0000	0.0494	0.0658	0.00	14.48
		HWY(2)	0.0009	0.0074	0.0297	1.10	21.02
99.99	J1634 with A/C	UDDS	0.0033	0.0720	0.0987	0.00	11.93
		UDDS	0.0015	0.0678	0.0863	2.28	12.39
		HWY(2)	0.0014	0.0316	0.0722	1.71	18.23
99.99	HWY(2)	1	0.0000	0.0270	0.0478	0.00	20.57
99.99	UDDS	1	0.0000	0.0558	0.0036	0.20	14.52
94.971	CS FTP	1	0.1238	0.0638	0.5633	75.48	10.31
		2	0.1377	0.0305	0.7216	70.35	10.50
		3	0.1133	0.0386	0.4775	67.69	11.71
		FTP	0.1278	0.0400	0.6179	70.69	10.80
94.971	HWY(2)	1	0.0654	0.0236	0.3015	47.15	16.13
	HWY(2)	1	0.0717	0.0268	0.2950	48.70	15.99

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	HWY(2)	1	0.0668	0.0219	0.2949	48.48	16.18
94.971	UDDS	1	0.1303	0.0301	0.7094	67.67	11.19
	UDDS	1	0.1215	0.0340	0.5883	67.80	11.11
	UDDS	1	0.1202	0.0355	0.5731	71.54	11.11
79.84	CS FTP	1	0.7133	0.0534	3.3029	225.26	7.60
		2	0.8875	0.0442	4.1445	228.31	7.55
		3	0.6534	0.0397	2.8518	201.35	8.52
		FTP	0.7833	0.0449	3.5951	219.97	7.84
79.84	HWY(2)	1	0.3970	0.0239	1.8235	143.74	11.84
		1	0.4049	0.0271	1.8343	146.16	11.80
		1	0.4209	0.0245	1.9447	146.23	11.82
79.84	UDDS	1	0.7317	0.0362	3.3342	209.68	8.20
		1	0.7492	0.0366	3.4506	210.01	8.32
		1	0.7438	0.0350	3.4077	210.69	8.33

Modal data collected from chemical sensors are summarized below.

Table 13. Emissions testing results (modal data) on the Chevrolet Silverado truck using nominal hydrogen contents of 80%, 95%, and 100% with different driving cycles.

Modal data:

H ₂ , (%)	Test	Bag No.	Total Hydrocarbons, (gm/mile)	NO _x , (gm/mile)	CO, (gm/mile)	CO ₂ , (gm/mile)	Fuel Economy, (miles/kg)
99.99	CS FTP	1	0.0000	0.0408	0.2210	0.30	13.62
		2	0.0000	0	0.5659	0.00	13.22
		3	0.0000	0.0401	0.3810	0.00	15.22
		FTP	0.0000	0.0202	0.4393	0.07	13.89
99.99	CS FTP	1	0.0007	0.0840	0.4406	0.00	13.69
		2	0.0009	0.0359	0.8979	0.00	13.43
		3	0.0021	0.0643	0.5864	0.00	15.33
		FTP	0.0012	0.0543	0.7108	0.00	14.03
99.99	J1634 w/o A/C	UDDS	0.0000	0.0562	0.5361	0.75	14.46
		UDDS	0.0000	0.0457	0.4847	0.91	14.48
		HWY(2)	0.0011	0.0276	0	0.00	21.02
99.99	J1634 with A/C	UDDS	0	0.0661	0.4997	0.80	11.93
		UDDS	0.0011	0.0666	0.5484	0.00	12.39
		HWY(2)	0.0014	0.0365	0.3050	0.36	18.23
99.99	HWY(2)	1	0	0.0256	0.3691	0.31	20.57
99.99	UDDS	1	0	0.0522	0.6411	0.00	14.52
94.971	CS FTP	1	0.1188	0.0593	0.5573	76.39	10.31
		2	0.1325	0.0295	0.7253	73.11	10.50
		3	0.1073	0.0364	0.4817	64.59	11.71
		FTP	0.1224	0.0379	0.6198	71.39	10.80
94.971	HWY(2)	1	0.0643	0.0216	0.3102	47.77	16.13

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	HWY(2)	1	0.0681	0.0258	0.3018	48.89	15.99
	HWY(2)	1	0.0661	0.0207	0.3069	47.71	16.18
94.971	UDDS	1	0.1288	0.0306	0.7117	69.39	11.19
	UDDS	1	0.1216	0.0344	0.6078	70.45	11.11
	UDDS	1	0.1205	0.0354	0.5856	68.44	11.11
79.84	CS FTP	1	0.7057	0.0486	3.2786	230.90	7.60
		2	0.8821	0.0454	4.1295	227.18	7.55
		3	0.6509	0.0361	2.8449	205.12	8.52
		FTP	0.7783	0.0434	3.5804	221.69	7.84
79.84	HWY(2)	1	0.3959	0.0224	1.8283	145.22	11.84
		1	0.4027	0.0260	1.8302	147.22	11.80
		1	0.4187	0.0227	1.9489	145.52	11.82
79.84	UDDS	1	0.7327	0.0355	3.3473	214.77	8.20
		1	0.7490	0.0361	3.4703	211.15	8.32
		1	0.7439	0.0351	3.4135	212.63	8.33

The above results are summarized in the table below using average data results.

Table 14. Average test results on the Chevrolet Silverado truck using nominal hydrogen contents of 80%, 95%, and 100% with different driving cycles.

CS FTP Cycle:

H ₂ , (%)	Total Hydrocarbons, (gm/mile)	NO _x , (gm/mile)	CO, (gm/mile)	CO ₂ , (gm/mile)	Fuel Economy, (miles/kg)
99.99	0	0.06709	0.06624	0.105	13.9875
94.971	0.12565	0.04323	0.59508	71.0525	10.8300
79.84	0.75938	0.04555	3.47358	218.7225	7.8775

HWY(2) Cycle:

H ₂ , (%)	Total Hydrocarbons, (gm/mile)	NO _x , (gm/mile)	CO, (gm/mile)	CO ₂ , (gm/mile)	Fuel Economy, (miles/kg)
99.99	0	0.027	0.0478	0	20.57
94.971	0.06797	0.0241	0.29713	48.11	16.1000
79.84	0.4076	0.02517	1.8675	145.37667	11.82

UDDS:

H ₂ , (%)	Total Hydrocarbons, (gm/mile)	NO _x , (gm/mile)	CO, (gm/mile)	CO ₂ , (gm/mile)	Fuel Economy, (miles/kg)
99.99	0	0.0558	0.0036	0.20	14.52
94.971	0.12400	0.0332	0.6236	69.0033	11.1367
79.84	0.74157	0.03593	3.3975	210.1267	8.2833

Observations from these tests are summarized below.

The data appears to be of very high quality, and is quite reproducible from replicate experiments. The data for the highway driving cycle were always collected on the second cycle, to allow the vehicle to warm up. The bag 1 data for the cold-start tests were true cold start tests (the vehicle having not been operated since the previous day). Using the hydrogen-rich fuels, the emissions of carbon monoxide are very low. NO_x emissions are not zero, but are low due to the fact that there is no emission control device. To achieve extremely low NO_x emissions, an emission control device (with an efficiency of at least 80%) is likely required. Total hydrocarbon emissions are very low for all the driving cycles studied.

The carbon monoxide analyzer malfunctioned during the high purity hydrogen testing; the CO modal data for the high purity hydrogen tests (99.99% H₂) are somewhat questionable due to this fact. The data comparing the modal and bag data for CO emissions is presented in Figure 23, indicating that the data are not in good agreement for low CO emissions. Data for the other emissions were in good agreement between the bag and modal data determinations, an example is shown in Figure 24 for CO₂ emissions.

As the percentage of natural gas increased to ~20%, the CO₂ emissions were on the order of several hundred gm/mile. As the percentage of natural gas increased to ~20%, the fuel economy decreases. This is due to the fact that methane has a lower heating value than hydrogen.

Very good agreement was obtained for the bag analysis and the modal analysis (obtained using chemical sensors) for the 80% and 95% hydrogen-rich fuel blends. Results on the emissions of total hydrocarbons, CO, and CO₂, and fuel efficiency were comparable for the cold start FTP and urban driving (UDDC) cycles. Figures 25 and 26 below show the cases for the total hydrocarbons and CO₂ emissions.

Figure 23. Comparison of bag and modal data results for CO emissions.

Figure 24. Comparison of bag and modal data results for CO₂ emissions.

Figure 25. Comparison of total hydrocarbons emissions for the driving cycles CS FTP, HWFET, and UDDC.

Figure 26. Comparison of CO₂ emissions for the driving cycles CS FTP, HWFET, and UDDC.

Additionally, two tests employing a J1634 driving cycle were conducted, one in which no air conditioning was used, and the other case in which the air conditioning was used in the operation of the vehicle. Results from that testing are summarized below.

Table 15. Effect of air conditioning on emissions and fuel economy.

Parameter	Without Air Conditioning	With Air Conditioning	Increase/Decrease
Total Hydrocarbons, (gm/mile)	0.0003	0.00207	Increase – 6.9x
NO _x , (gm/mile)	0.0383	0.0571	Increase – 1.49x
CO, (gm/mile)	0.0036	0.6236	Increase – 173x
CO ₂ , (gm/mile)	0.0556	0.0857	Increase – 1.54x
Fuel Efficiency, (miles/kg)	16.647	14.183	Decrease – 14.8%

It is apparent from the above test results that using air conditioning increases the release of gaseous emissions of total hydrocarbons, NO_x, CO, and CO₂, and causes a reduction in the fuel efficiency of nearly 15%. A comparison of these two tests (with and without air conditioning) is shown graphically in a bar chart fashion on the following page.

Figure 27. Comparison of emissions and fuel efficiency with and without air conditioning.

8.3.4 Summary and Conclusions

Observations from these tests are summarized below.

- The fuel economy are quite good, NO_x emissions are not zero, but are low for all the high hydrogen content fuel blends.

- As the percentage of natural gas increased to ~20%, the fuel economy decreases. This is due to the fact that methane has a lower heating value than hydrogen.
- Since there is no carbon in the pure hydrogen fuel, the carbon containing species are likely to come from the lubricating oil.
- One of the most important lessons learned from these tests on the Ford F-150 and the Chevrolet Silverado, is that to save fuel and minimize emissions, air conditioning should not be used.

8.4 Overall Summary and Conclusions

Results from the preliminary testing indicated the following:

- Hydrogen rich hydrogen methane blends show similar combustion behavior to pure hydrogen.
- Due to the lower combustion speed of methane compared to hydrogen, the spark timing has to be advanced with increased amount of methane in the blend.
- Different gas properties of methane and methane require adjustment of injection duration in order to achieve the same engine load. A curve that shows the necessary adjustments was presented.
- The NO_x emissions behavior of pure hydrogen compared to hydrogen rich hydrogen methane blends shows the same trends. Due to the lower combustion speed, the absolute level of emissions is slightly lower with increased amount of methane.
- The amount of unburned methane compared to hydrogen in the exhaust is higher relative to the composition of the feed fuel. This is supposedly due to the fact that hydrogen has a shorter quenching distance than methane and thus allows for a more complete combustion close to the combustion chamber walls.
- Overall, only minor adjustments should be necessary in order to run an engine calibrated and tuned for operation on pure hydrogen on hydrogen rich hydrogen methane blends.

The purpose of Task 2a was to study the effects of hydrogen concentration in the HCNG fuel blend (H₂ content <50%). Results from Task 2a indicated the following:

- As observed above, there is no consistent trend in emissions or efficiency with respect to either the hydrogen concentration or the driving cycles.
- 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 CO₂ 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.

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- 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.

Results from Task 2b indicated the following:

- The fuel economy are quite good, NO_x emissions are not zero, but are low for all the high hydrogen content fuel blends.
- As the percentage of natural gas increased to ~20%, the fuel economy decreases. This is due to the fact that methane has a lower heating value than hydrogen.
- Since there is no carbon in the pure hydrogen fuel, the carbon containing species are likely to come from the lubricating oil.
- One of the most important lessons learned from these tests on the Ford F-150 and the Chevrolet Silverado, is that to save fuel and minimize emissions, air conditioning should not be used.

9. THESES, PUBLICATIONS, CONFERENCE PROCEEDINGS AND TECHNICAL PRESENTATIONS

Theses:

Dutta, Samrat P., 2005. “An Investigation on Emissions and Efficiency from Hydrogen-Blended Compressed Natural Gas”; M.S. Thesis completed Fall semester, University of Alabama at Birmingham, Birmingham, Alabama, 2005, (*graduated*).

Publications:

Sisiopiku, V.P., A. Rousseau, F.H. Fouad, and R.W. Peters, 2006. “Technology Evaluation of Hydrogen Light-Duty Vehicles”, *ASCE J. Environ. Engrg.*, **132**(6): 1-7.

Conference Proceedings:

Sisiopiku, V.P., R.W. Peters, and F.H. Fouad, 2007. “Emissions Associated with Various Driving Cycles for Light-Duty Vehicles”, Paper included in *Proceedings of the Huntsville Simulation Conference 2007*, Huntsville, Alabama, October 31 – November 1).

Wallner, T., H.K. Ng, and R.W. Peters, 2007. “The Effects of Blending Hydrogen with Methane on Engine Operation, Efficiency, and Emissions”, Paper No. 2007-01-0474 included in *Proc. 2007 SAE World Congress and Exhibition*, Detroit, Michigan, (7 pages).

Dutta, S., R.W. Peters, F.H. Fouad, M.J. Duoba, and H. Ng, 2004. “Performance of a Ford F-150 Using Various Fuel Blends of Compressed Natural Gas and Hydrogen”, Paper included in *Proceedings of the 2004 Annual American Institute of Chemical Engineers (AIChE) Meeting*, Topic: T3 on Fuel Cells, 19 pages, Austin, Texas, November 7–12, 2004.

Technical Presentations:

Sisiopiku, V.P., R.W. Peters, and F.H. Fouad, 2007. “Emissions Associated with Various Driving Cycles for Light-Duty Vehicles”, Paper presented at the Huntsville Simulation Conference 2007, Huntsville, Alabama, October 31 – November 1).

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Poster Paper Presentations:

University of Alabama at Birmingham (F.H. Fouad, R.W. Peters, A. Sullivan, V.P. Sisiopiku, and S. Jones) and Argonne National Laboratory (D. Hillebrand, M. Mintz, H. Ng, R. Ahluwalia, and A. Rousseau), 2005. "Global Assessment of Hydrogen-Based Technologies (TVP-13)", Poster paper presented at the DOE Hydrogen Program Review Meeting, Arlington, Virginia, (May 23-26).

Dutta, S., R.W. Peters, F.H. Fouad, H. Ng, and M. Duoba, 2005. "Comparison of Blends of CNG and Hydrogen Fuels on the Basis of Emissions and Efficiency Performance Using a Ford F-150", Poster paper presented at the 2005 Spring National American Institute of Chemical Engineers (AIChE) Meeting, Atlanta, Georgia, (April 10-14); Paper presented by J.P. Perl⁺.

University of Alabama at Birmingham (F.H. Fouad, R.W. Peters, A. Sullivan, S. Jones, and V. Sisiopiku, 2004. "Global Assessment of Hydrogen-Based Technologies", Poster paper presented at the Hydrogen, Fuel Cells, and Infrastructure Technologies Program of the U.S. Department of Energy, Philadelphia, PA, (May 24-27).

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