Proceedings of the 2000 Hydrogen Program Review
NREL/CP-570-28890

# Hydrogen-Enriched Natural Gas Bus Demonstration

**Ranson Roser**
**NRG Technologies, Inc.**
**681 Edison Way**
**Reno, NV 89502**

## Abstract

This paper provides a project overview of a recently awarded contract for the development of a hydrogen-enriched natural gas engine and its demonstration in up to six heavy-duty transit buses. The purpose of the project is to demonstrate the applicability and benefits of hydrogen as a contributing automotive fuel in a heavy-duty bus application. NRG Technologies, Inc. in Reno, Nevada will build an engine to its specifications using off-the-shelf components suitable for transit bus operation. Engine components will be selected based on engine output goals as well as the need for high durability and efficiency to meet the expectations of heavy-duty engine users. The electronic engine management system employed will provide the sophistication required to fully realize the low-emissions potential of hydrogen-enriched natural gas. The project will evolve through sub-systems experimentation, engine dynamometer emissions and power development, field demonstration of one engine in a bus, and finally the demonstration of up to six buses in the City of Las Vegas' transit fleet. No engine data, field data, or conclusions are presented here due to the embryonic status of project.

## Introduction

Supplementation of hydrogen into natural gas (herein HCNG) extends the lean-burn, or charge-dilution limit of combustion in engines. Extremely low oxides of nitrogen (NOx) and carbon monoxide (CO) emissions can be achieved when a combined lean-burn and exhaust gas recirculation (EGR) combustion strategy is employed with HCNG. The excess air from lean-burn can be used to reduce CO and non-methane hydrocarbons with an oxidation catalyst. The EGR is intended to be the primary charge dilution agent to reduce peak combustion temperatures thus leading to extremely low $NO_x$ emissions. Without the hydrogen enhancement, natural gas would not be able to combust with the amount of charge dilution necessary to achieve the targeted $NO_x$ reductions without unacceptable sacrifices in fuel consumption, torque fluctuation, and hydrocarbon emissions. Hydrogen itself is not considered a low-$NO_x$ fuel. Due to higher combustion temperatures than natural gas at equivalent air/fuel ratios, hydrogen actually produces higher $NO_x$ emissions. It is important that the hydrogen supplementation be significant enough to extend the charge-dilution limit to levels sufficient to reduce $NO_x$ emissions beyond what is capable with three-way catalyst technology at stoichiometric air/fuel ratios. It has been the experience of NRG staff that it takes at least $30_{vol}$% hydrogen to consistently achieve impressive improvements in $NO_x$ emissions compared to natural gas alone with catalytic exhaust aftertreatment.

NRG Technologies, Inc. has been co-funded by the Department of Energy and the Gas Research Institute to develop an engine platform to demonstrate the advantages of hydrogen-enriched natural gas (HCNG) in heavy-duty transit bus applications. This is the natural extension of previous success NRG has had demonstrating HCNG in a light-duty vehicles. The scope of the three-year project is intended to progress through three major phases; engine development, single-bus demonstration, and muti-bus demonstration. The transit buses for the field demonstration will be new 26-passenger, 30 ft coaches being procured by the City of Las Vegas. The buses will be delivered to the City of Las Vegas with commercially available Cummins 5.9L 195 HP natural gas engines. The OEM engine will be removed by NRG and replaced with an HCNG engine built to its specifications and thoroughly tested on an engine dynamometer in Phase I. The intent at this time is to operate the engine on an HCNG mixture of 30% hydrogen by volume. However, NRG may use up to 60% hydrogen supplementation if it enhances the technical achievements of the engine and boosts the Department of Energy's hydrogen efforts in Las Vegas as a whole. In Phase II the HCNG repowered bus will be emissions tested at an independent CARB/EPA certified laboratory to document the emissions reductions achievable with HCNG fuel. Finally, the bus will be delivered back to Las Vegas and integrated into the City of Las Vegas transit operations for field evaluation.

Assuming the Phase II single-bus field demonstration is generally successful over an eight month evaluation period, the project will expand to include up to six total HCNG buses for Phase III. Any engine improvements deemed necessary as a result of the first evaluation phase, whether they be for hardware components or the electronic engine control strategy, can be incorporated into all of the engines during the demonstration expansion. Although the emissions capabilities of the HCNG engines are a primary driver for the project, they will not undermine the importance of the transit fleet operator's acceptance of the technology as its performance, fuel consumption, and reliability is compared to their existing diesel and natural gas powered buses.

It is important to note that the demonstration of these HCNG buses will provide benefits to the Department of Energy's Hydrogen Program and the interests of the "Hydrogen Community" in general. It will introduce fleet managers, safety regulators, air quality agencies, and the public at-large to hydrogen as a transportation fuel. It will also exercise the hydrogen generation and refueling infrastructure being constructed in Las Vegas for this and other demonstrations of hydrogen technologies.

# DISCUSSION

## Engine Platform Selection

### *Matching Performance*

The performance goal of the HCNG demonstration project is to match the engine performance that is normally expected by the bus market. This criteria alone is too vague since fleets with hills need more powerful engines than fleets servicing flat geographies. For the Las Vegas project it is most appropriate to simply look at the power and torque specifications on the natural gas engine that the transit district ordered and deemed appropriate for its needs. NRG will build an engine to those same specifications in order to achieve a seemingly transparent shift in fuel technology.

Originally it was expected that the OEM CNG engine of choice was going to be a 250 hp John Deere 8.1L natural gas engine. The John Deere performance specifications, shown in Figure 1, show it to be capable of 800 lb-ft peak torque at 1350 rpm and 250 hp at 2200 rpm. This became the original performance target to base engine development around, although it will be evident in the report that the engine target eventually changed to a lower output Cummins model.

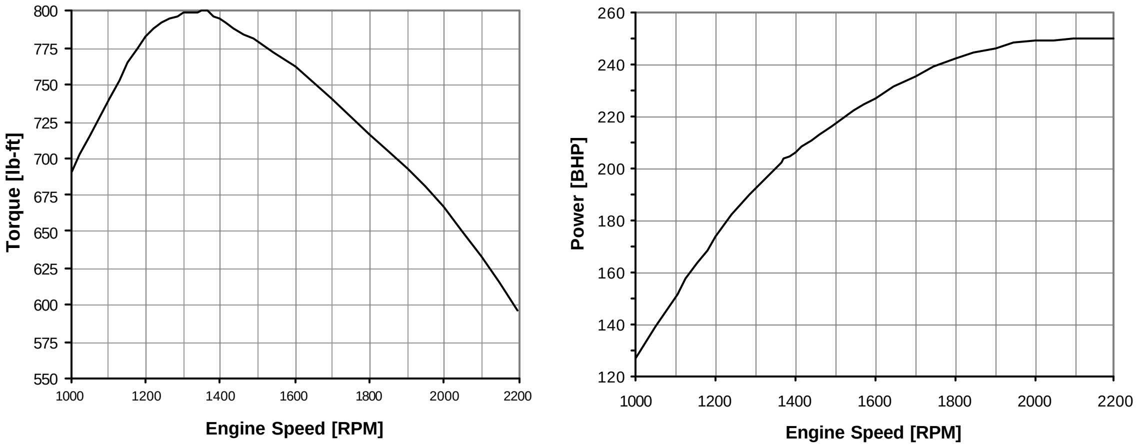

**Figure 1 – John Deere 8.1L CNG Output Specifications**

With the 250 hp John Deere in mind, NRG identified four base block and cylinder head configurations available from the racing industry suitable for evaluation as HCNG replacement candidates. These were:

- GM based 8.0L (489 $in^3$) with cast iron block and aluminum heads with stock valve and rocker positions
- Chrysler based 7.95L (485 $in^3$) with cast iron block and aluminum hemispherical four-valve heads with two spark plugs per cylinder
- GM based 9.4L (572 $in^3$) aluminum block and heads with stock valve and rocker positions
- GM based 13.2L (805 $in^3$) aluminum block and heads with stock valve and rocker positions

A spreadsheet was developed to evaluate each base configuration using reasonable assumptions regarding thermal efficiency, volumetric efficiency, expected equivalence ratios and other engine parameters to determine four general profiles for each engine configuration. The spreadsheet gave an indication of:

1. The engine speeds required to achieve power and torque specs naturally aspirated.
2. The intake air boost required to achieve power and torque specs at identical engine speeds to the peak power and torque speeds of the John Deere.
3. The engine speeds required to achieve power and torque specs with 1 atm (14.7 psi) of intake air boost.
4. The engine speeds required to achieve power and torque specs with 1.5 atm (22 psi) of intake air boost.

Table 1 shows an example of this type of spreadsheet analysis for the 572 in3 (9.4L) candidate engine platform. Careful observation of the results in Table provides insights into the trade-offs that occur with engine selection and one can draw the following conclusions from each scenario assessed for the 9.4L.

1. It would take unacceptably high engine speeds to achieve the raw performance requirements without turbocharging since frictional losses increase with engine speed. Although rated power at 4740 rpm does not represent a structural liability to the engine, it would result in a large sacrifice in fuel economy in a highly loaded heavy-duty bus application. Also, it would be more desirable to reach peak torque much before 3,900 rpm in the engine's acceleration (Scenario 1).
2. It would require undesirably high boost pressure (35 psi) to achieve peak torque at the John Deere's rated torque speed of 1350 rpm (Scenario 2).
3. A very reasonable boost pressure of 1 atm would achieve the peak torque at 2150 rpm and peak power at 3500 rpm. Each speed is reasonable for spark ignition engines. However, frictional losses and their impact on fuel consumption make rated power speeds above 3,500 rpm undesirable. The lower the speed the better for maintaining high fuel economy.
4. Finally, 1.5 atm of boost, still reasonable, achieves peak torque at 1760 rpm and peak power at 2870 with the turbo reduced to 0.8 atm of boost. This represents a very legitimate configuration and shows the 9.4L engine to be a viable platform.

# Table 1 – Engine Power Analysis Scenarios

| **Engine Power Estimator** | **Chevy 572 ci aluminum block platform** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ***Inputs*** | **Scenario 1** | | **Scenario 2** | | **Scenario 3** | | **Scenario 4** | |
| Engine Displacement [in3]: | 572 | 572 | 572 | 572 | 572 | 572 | 572 | 572 |
| Engine Speed [rpm]: | 3900 | 4740 | 1350 | 2200 | 2150 | 3500 | 1760 | 2870 |
| Gear Ratio: | none | none | none | none | 1.592 | 1.592 | 1.303 | 1.303 |
| Shaft Speed [rpm]: | | | | | 1350 | 2200 | 1350 | 2200 |
| Fuel: | 30% H2 | 30% H2 | 30% H2 | 30% H2 | 30% H2 | 30% H2 | 30% H5 | 30% H6 |
| Fuel LHV [Btu/lb]: | 23007 | 23007 | 23007 | 23007 | 23007 | 23007 | 23007 | 23007 |
| Stoichiometric AFR: | 18.03 | 18.03 | 18.03 | 18.03 | 18.03 | 18.03 | 18.03 | 18.03 |
| Lambda: | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| Brake Efficiency: | 34.0% | 34.0% | 34.0% | 34.0% | 34.0% | 34.0% | 34.0% | 34.0% |
| Volumetric Efficiency: | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| Altitude [ft above sea level]: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Air Temperature [C]: | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Intercooling medium: | none | none | ATAAC | ATAAC | ATAAC | ATAAC | ATAAC | ATAAC |
| Cooling medium termperature [C]: | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 |
| Intercooler Effectiveness: | 0 | 0 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| Boost Pressure [psi]: | **0** | **0** | **35.2** | **21** | **14.7** | **6.6** | **22** | **11.6** |
| T. Exhaust [C]: | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 700 |
| P. Exhaust [kPa]: | 107 | 107 | 107 | 107 | 107 | 107 | 107 | 107 |
| Compressor Efficiency: | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 |
| ***Calculations*** | | | | | | | | |
| Atmospheric pressure [kPa]: | 101.4 | 101.4 | 101.4 | 101.4 | 101.4 | 101.4 | 101.4 | 101.4 |
| $\rho_{amb}$ [lb/ft$^3$]: | 0.0740 | 0.0740 | 0.0740 | 0.0740 | 0.0740 | 0.0740 | 0.0740 | 0.0740 |
| Atm. Power CF: | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| T. Charge (compressed) [C]: | 25.0 | 25.0 | 214.4 | 155.9 | 124.4 | 75.7 | 160.5 | 107.0 |
| T. Charge (compressed & cooled) [C]: | 25.0 | 25.0 | 77.6 | 63.0 | 55.1 | 42.9 | 64.1 | 50.8 |
| Pressure Ratio: | 1.00 | 1.00 | 3.39 | 2.43 | 2.00 | 1.45 | 2.50 | 1.79 |
| Density Ratio: | 1.00 | 1.00 | 2.89 | 2.15 | 1.82 | 1.37 | 2.21 | 1.65 |
| Air Flow Naturally Aspirated [cfm]: | 516 | 628 | 179 | 291 | 285 | 463 | 233 | 380 |
| Air Flow Naturally Aspirated [lb/min]: | 38.20 | 46.43 | 13.22 | 21.55 | 21.06 | 34.28 | 17.24 | 28.11 |
| Air Flow Boosted [cfm]: | 516 | 628 | 516 | 627 | 517 | 633 | 514 | 626 |
| Air Flow Boosted [m$^3$/sec]: | 0.244 | 0.296 | 0.243 | 0.296 | 0.244 | 0.299 | 0.243 | 0.295 |
| Air Flow Boosted [lb/min]: | 38.20 | 46.43 | 38.15 | 46.42 | 38.26 | 46.86 | 38.04 | 46.29 |
| Corr. Comp Map Air Flow [lb/min]: | 36.01 | 43.77 | 35.96 | 43.76 | 36.06 | 44.17 | 35.86 | 43.64 |
| Mitsub. Corr. Comp Map Air Flow [kg/sec]: | 0.272 | 0.331 | 0.272 | 0.331 | 0.273 | 0.334 | 0.271 | 0.330 |
| Exhaust Flow [cfm]: | 1642 | 1996 | 1640 | 1995 | 1644 | 2014 | 1635 | 1990 |
| Exhaust Flow [m$^3$/sec]: | 0.775 | 0.942 | 0.774 | 0.942 | 0.776 | 0.950 | 0.772 | 0.939 |
| Power Output [hp]: | 205.7 | 250.0 | 205.4 | 249.9 | 206.0 | 252.3 | 204.9 | 249.3 |
| **Engine Output [kw]:** | **153.4** | **186.4** | **153.2** | **186.4** | **153.6** | **188.1** | **152.8** | **185.9** |
| Engine Output BMEP [psi]: | 73.0 | 73.0 | 210.7 | 157.3 | 132.7 | 99.8 | 161.2 | 120.3 |
| **Deere Target Output [kw]:** | **153** | **186** | **153** | **186** | **153** | **186** | **153** | **186** |
| | Peak Torque | Peak Power | Peak Torque | Peak Power | Peak Torque | Peak Power | Peak Torque | Peak Power |

One of these power analyses was performed for each engine. The analyses also provided the means for assessing appropriate compressor and turbine wheel selections for turbocharger assemblies. Ultimately it was determined that all four candidate engines were capable of meeting power and torque requirements with varying levels of turbocharging and engine speed.

The next consideration process was to look at the whole engine, its component availability, cost, and level of technical risk for a heavy-duty bus demonstration. The intent of evaluating the four candidate engine designs was to maximize the likelihood of achieving the performance and emissions goals with an engine that is commercially viable. It is important during the strategic development of the project to make sure the demonstration is a test of HCNG and high level of charge dilution and not a test of the reliability of specialty engine components. To replace the John Deere engine, NRG had concluded that the GM based 9.4L engine was the platform of choice after assessing the compromises between each of the factors mentioned above. However, the engine target changed.

In June 2000, it was announced that the engines to be supplied with the buses were going to be the 5.9L 195 hp natural gas engines manufactured by Cummins. Figure 2 shows the performance characteristics of the Cummins 5.9-195G. Notice that the performance target compared to the John Deere became much easier and the reduced requirement created more flexibility into the engine platform selection process. The new criteria was input into each engine profile in NRG's power analysis spreadsheets and new trade-off relationships were examined. In the end, NRG chose the 8.0L GM based engine with an aluminum block and cylinder heads, and two valves per cylinder with stock valve and rocker arm orientation. The power analysis showed that the 8.0L could achieve the Cummins 5.9-195G power specifications at the same rated speeds with no more than 1 atm of boost at peak torque. The 8.0L represents a very nice solution because it is the smallest of the candidate engines, it is compatible with friction-reducing cylinder coatings, and the fact that the power specifications could be met at the same engine speeds as the Cummins eliminated the need for an additional gear box.

## AUTOMOTIVE ENIGNES AND DURABILITY

Whereas the Cummins natural gas engine was originally derived from a diesel based engine, the NRG HCNG engines will be built from what are generally considered to be automotive gasoline components. The following discussion addresses the issue of durability that may arise regarding this strategy. The discussion of durability here and throughout the scope of the project will remain largely qualitative due to the fact that both 500,000 miles of real world mileage accumulation and expensive accelerated engine fatigue testing are both beyond the scope of this project.

The physical structure of heavy-duty engines for transit buses are characterized by the compression ignition diesel engines that have historically dominated the industry. The overall structure of the block and the reciprocating components of diesel engines are more massive than those of spark ignition engines due to higher peak cylinder pressures and the market demand for durability that allows 500,000 miles of operation before major

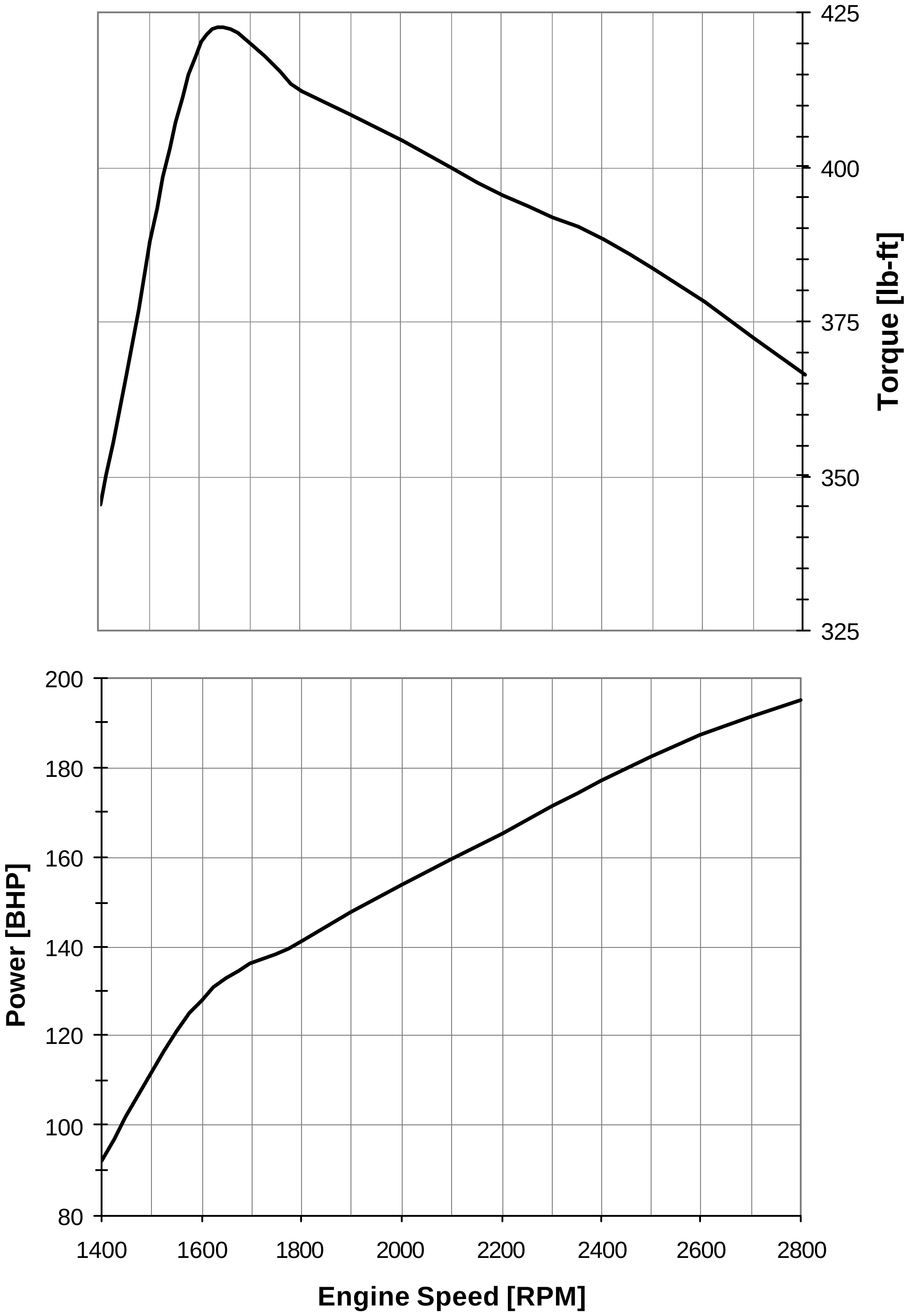

**Figure 2 – Cummins 5.9L NG Output Specifications**

engine overhauls. Fundamentally, the durability is not dictated by the massiveness of the engine components, but rather the massiveness of the diesel engine components are necessary to achieve the durability expectations in lieu of the extreme pressure induced stresses from the compression ignition process. Automotive gasoline based engines are generally thought to have less durability capabilities than diesel engines, but that judgement is heavily flawed by the consumer markets that drive their development. The heavy-duty trucking and transit industry demands, and pays the price for, durability because of the number of miles traveled per year and the high cost of down time when goods or services cannot be delivered. The automotive market, dominated by purchases for personal use, only demands 200,000 mile engine lifetimes, is far more sensitive to up front capital costs, and does not necessarily expect those engines to be rebuilt. Thus the engine manufacturers select major reciprocating components that cost less to manufacturer and are not as durable as they could be for the light-duty car and truck market. So, in most cases it is true that automotive based spark ignition engines are less durable, but it need not be true if the engine components are selected with durability as a primary consideration. The high performance racing industry is one that demands durability out of engine components under extreme conditions. The popularity of the performance industry has created an extensive aftermarket for components that have been developed with intensive engineering efforts placed on component durability for spark ignition engines. These are the components that NRG will incorporate into the HCNG engine and with far lower peak cylinder pressures than diesel engines, and even the Cummins CNG engine, it is expected that the durability of the HCNG engine could ultimately be a highlight feature of the technology.

## Engine Development on Engine Dynamometer

### *Emissions Goals*

The stated goal of the project is to demonstrate the ability of HCNG fueled heavy-duty engines to achieve a 75% reduction in HC, CO, and $NO_x$ emissions based on 1998 HDV US EPA Emissions Standards. These emissions goals, shown in Table 1, are to be met without sacrificing industry expectations in driveability or fuel economy.

**Table 1.**

| Emissions Standards and Goals | | | |
|---|---|---|---|
| | NMHC [g/bhp-hr] | CO [g/bhp-hr] | NOx [g/bhp-hr] |
| 1998 U.S. EPA Standard for HDE | 1.7 | 37.1 | 5 |
| 75% Reduction Goal | 0.4 | 9.28 | 1.25 |

### *Engine Emissions and Control Development*

Engine testing will take place on a 500 hp eddy-current engine dynamometer. First the engine will be evaluated under maximum output conditions to determine whether or not it can meet the target performance criteria at the equivalence ratios that it was designed for. If not, then hardware modifications, such as turbocharger configuration, can be made as needed. Once the engine is known to be able to meet its maximum output objectives then it will undergo an extensive array of equivalence ratio and timing mapping at various speeds and load.

Figure 3 will be used as an example maximum output Torque Vs. RPM curve for the HCNG engine. Emissions and efficiency mapping will be performed at various engine speeds at 25, 50, 75, and 100% load. At each speed/load point an equivalence sweep will be performed to determine its characteristics as a function of air/fuel ratio. Additionally, each speed/load/equivalence point will be assessed at three ignition timing intervals to map the influence of ignition timing on the system. The timing intervals will include minimum timing advance to achieve best torque (MBT), timing retard to 97.5% of maximum torque, and timing retard to 95% or best torque. The timing intervals are intended to evaluate the trade-off between NOx emissions and brake efficiency.

The goal of mapping is to characterize the trade-offs between output, emissions, and fuel consumption so "optimized" electronic engine control strategies can be defined. Once a few air/fuel ratio and timing strategies have been identified, they can be individually evaluated under further steady-state tests to develop a reasonable projection of how the engine would perform if evaluated using the official transient testing protocol for EPA and CARB emissions certification.

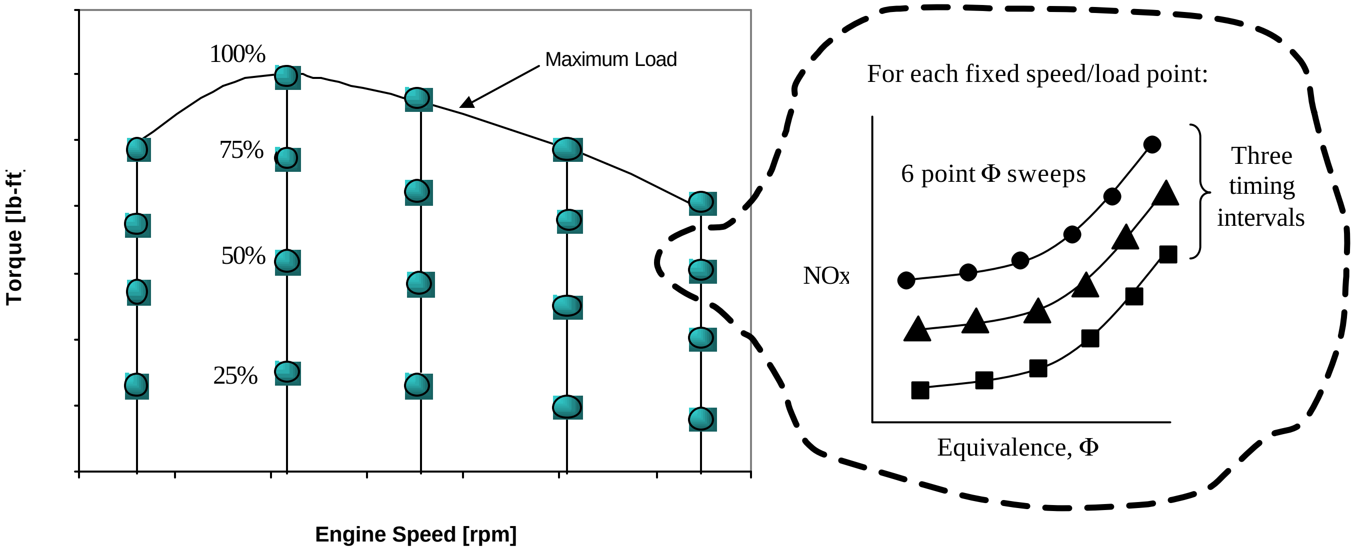

**Figure 3 – Sample Equivalence Ratio and Spark Timing Mapping**

### *Projecting FTP Emissions Using Steady-State Protocol*

The 1998 US EPA Emissions Standards and the goals set forth for this project are based on a transient testing protocol that is performed on an engine dynamometer, known as the US EPA Heavy-Duty Engine Federal Test Procedure (HD FTP) illustrated in Figure 4. The test is so time and equipment extensive that even the engine manufacturers do not use it during an engine's development phase.

Instead, the emissions are typically quantified at about eight specific steady-state conditions and then the emissions at these specific points are weighted. The final processed emissions value is intended to represent the same value that would result if the engine were to be run through the FTP. OEM engine manufacturers will typically use a weighted steady-state process that has been developed through proprietary in-house studies and has shown to provide good correlation between the final weighted steady-state numbers and actual FTP tests. A similar strategy will be used by NRG in assessing the emissions performance of the HCNG engine. NRG will use the eight-mode steady-state protocol developed by AVL (Table 2) to obtain a reasonable approximation of what the US EPA FTP emissions would be for each engine. Only $NO_X$ and THC will be evaluated with the eight-mode test. There are currently no steady-state processes that are adequate for simulating transient PM and CO. This is not expected to play a role in the evaluation process, however, because CO emissions for the HCNG engine will be practically eliminated with an oxidation catalyst and PM emissions should be consistent with natural gas technology in general.

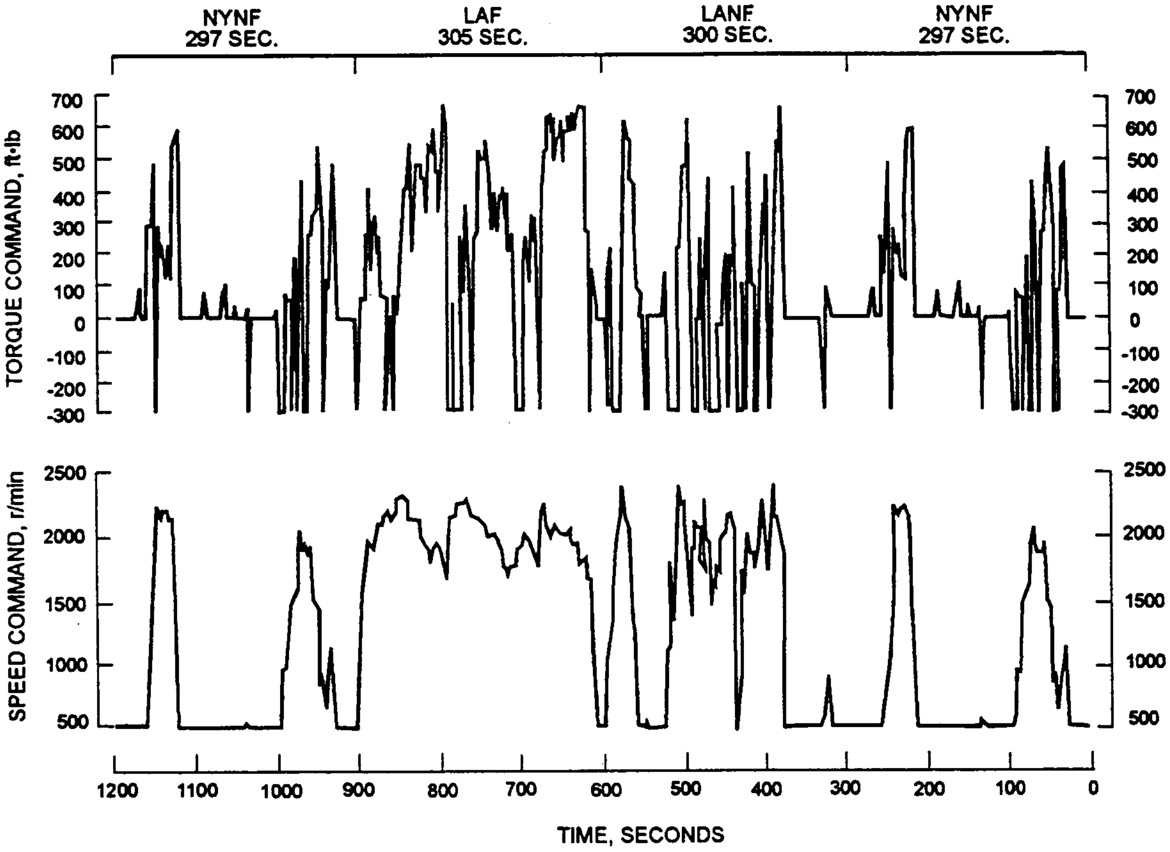

**Figure 4 – The U.S. EPA Heavy-Duty Federal Test Procedure**

The eight-mode test will be used as a development tool to define the best fuel and spark control strategy and it will provide one level of comparison between HCNG and natural gas capabilities. It will not be used, though, as the final comparison between the HCNG engine and current natural gas technology. Chassis dynamometer evaluations will be conducted under one of the heavy-duty bus driving cycles that have been developed for emissions testing purposes. This will provide an in-use comparison of NG and HCNG bus emissions. The chassis dynamometer testing process will be discussed later in this report.

### Table 2 - Eight-Mode Steady-State Protocol & Weight Factors

| AVL Eight-Mode Test For Predicting US EPA FTP Emissions | | | |
|---|---|---|---|
| Mode | Speed %(1) | Torque %(2) | Weight Factor(3) |
| 1 | 0 | 0 | 35.01 |
| 2 | 11 | 25 | 6.34 |
| 3 | 21 | 63 | 2.91 |
| 4 | 32 | 84 | 3.34 |
| 5 | 100 | 18 | 8.4 |
| 6 | 95 | 40 | 10.45 |
| 7 | 95 | 69 | 10.21 |
| 8 | 89 | 95 | 7.34 |
| (1) Speed % means percent between idle and rated | | | |
| (2) Torque % means the percent of maximum torque at a given speed. | | | |
| (3) The weight factors are not supposed to add to 100%. | | | |

### *Emissions Measurement at NRG*

Emissions of $NO_x$, CO, and THCs will be measured with the engine on NRG's 500 HP eddy-current dynamometer in Reno. $NO_x$, CO, and THC emissions will be measured using chemiluminescence, non-dispersive infra-red, and flame-ionization detection equipment, respectively . . . all manufactured by Thermo Environmental Instruments. These measurement techniques are the industry standard for automotive emissions testing. The instruments provide data in parts per million which will then be converted to g/bhp-hr. Particulate measurement will not be addressed for two reasons. First, PM measurement for automotive applications requires transient testing equipment that is outside the scope of this project. Second, PM regulations for heavy-duty engines are set at levels that reflect the state of the art of diesel fueled engines. Diesel engines produce inherently higher levels of PM because of the nature of diffusion flame combustion using a liquid hydrocarbon fuel. The PM produced by any gaseous-fueled engine comes predominately from lubricating oil, This is far less than from diesel engines and is not expected to play a role in assessing the viability of hydrogen-enriched natural gas as a fuel. The project participants can be assured that $NO_x$ reduction techniques for this project are not going to come at the expense of PM, a common trade-off relationship with diesel systems.

### *Transient Compensation and Feedback Control Development*

The final phase of engine dynamometer development will be to define the deviations in air/fuel ratio that occur with sharp accelerations and decelerations. Once the nature of the deviations is defined, NRG will develop, test, and implement transient compensation algorithms into the electronic engine control strategy in-order-to further enhance the stability of the emissions control system. Furthermore, a feedback control system will be implemented and tested. Oxygen sensor feedback control allows tighter control of air/fuel ratio, protection against the effects of faulty or aging sensors, and protection from variations in fuel hydrogen content. The methodology of this test phase is proprietary to NRG and will not be outlined in detail. However, examples of the benefits of these compensating elements can be demonstrated from laboratory data subsequent to the development work.

At the completion of Phase I, NRG will have a 8.0L V8 engine that has been fully characterized for emissions and achieves the same performance as the Cummins 5.9 – 195G. The project will then progress into Phase II which includes integration of the engine into the bus and chassis dynamometer evaluation of the emissions at an independent laboratory.

### Initial On-Road Assessment In Reno

The NRG bus engine will have been thoroughly tested and the electronic engine control (EEC) strategies developed on NRG's engine dynamometer in Phase I. However, further EEC strategy modifications are often necessary when transitioning an engine from the dynamometer to the street. Using properly licensed NRG personnel, the bus will be evaluated for initial driver perception in Reno. If appropriate, NRG will modify the air/fuel ratio, spark advance, transient control parameters, and shifting algorithms to optimize bus accelerations and decelerations. In this fashion the bus can be delivered to the City of Las Vegas with confidence that it will be accepted by the drivers in the bus fleet.

### Chassis Dynamometer Testing

Once NRG has finalized any EEC strategy modifications for on-road driving the whole bus will be emissions tested as a system. The testing will be performed at California Truck Testing Services (CATTS) in Richmond, CA. CATTS is run by the Clean Air Vehicle Technology Center (CAVTC) and jointly owned by CAVTC and Arcadis/Geraghty & Miller (formerly Acurex Environmental). The CATTS facility's features and capabilities include the following:

- Emissions testing over any programmable drive cycle
- Electric dynamometer with tandem 48" rolls
- Vehicle weight, power, and speed: GVW from 6,000 to 85,000 lbs, power absorption up to 500 hp at rolls, speeds up to 75 mph
- Vehicle size: Up to 65 feet long with single or tandem drive axles
- Axle dead load: hydraulic simulator
- Temperature-controlled engine air supply
- Bag-dilute modal emissions analysis capabilities for CO, $NO_x$, $CO_2$, HC, and $CH_4$..
- Particulate mass measurement and size distribution capability

In the early stages of Phase II, one of the CNG buses in operation with the City of Las Vegas will be instrumented with a data logging system supplied by NRG to assist with the chassis dynamometer emissions evaluation of an HCNG bus. The purpose of the data logging system is to characterize the typical engine and bus operating characteristics within real routes of the Las Vegas transit system. Operating profiles may be generated for more than one bus route if deemed appropriate. The bus operating profiles will be compared against standard heavy-duty bus driving schedules for chassis dynamometer emissions testing. The driving protocol that best represents the real world usage of the Las Vegas buses will be used for performing chassis dynamometer emissions evaluations of the NRG HCNG engine. Examples of these heavy-duty bus driving schedules are shown in Figure 5.

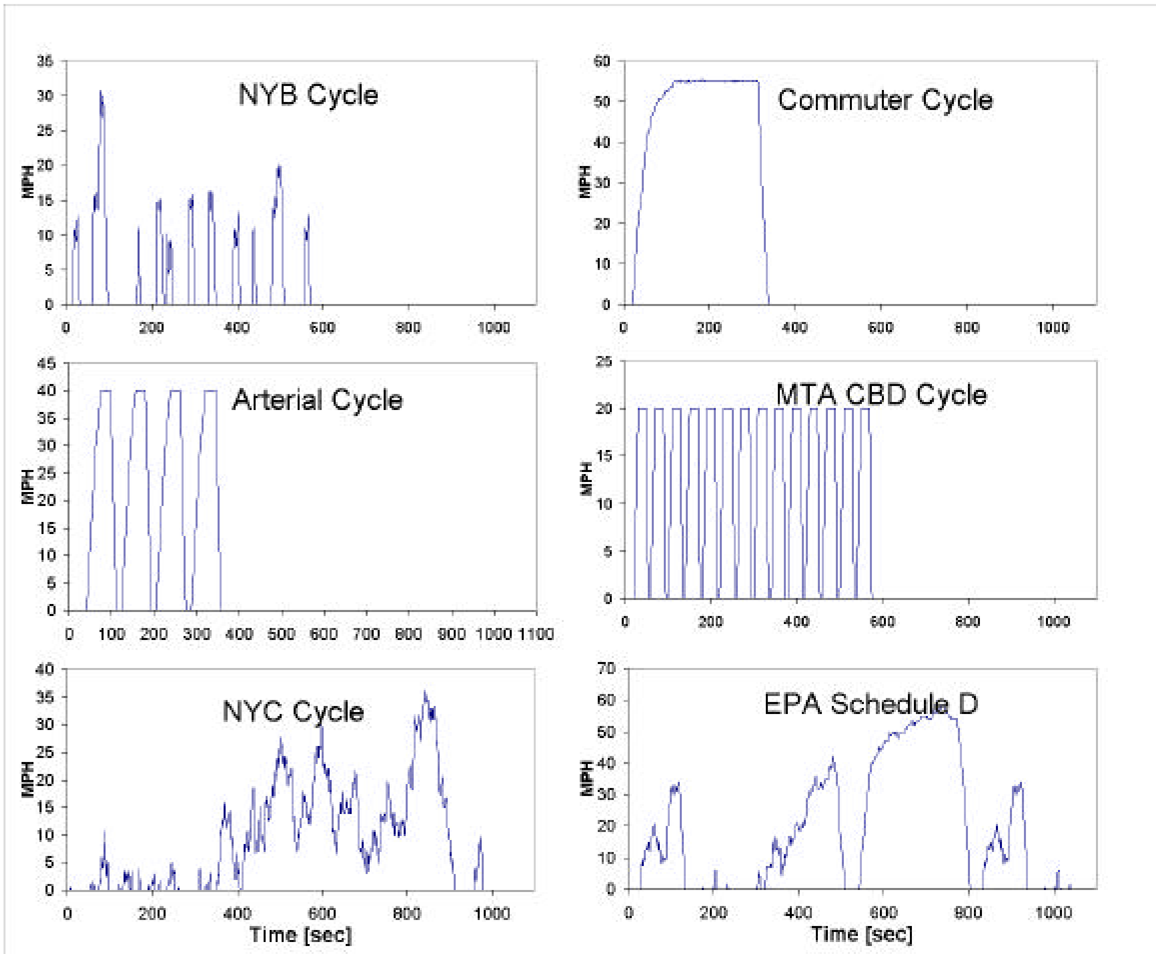

**Figure 5 – Heavy-Duty Bus Driving Cycles**

The bus with the first integrated HCNG engine will be tested on a chassis dynamometer using a driving schedule, or protocol, that will have been specified after reviewing data logging information from a real bus in the Las Vegas fleet as described. Emissions of CO, $NO_x$, and THC will be collected in tedlar bags and measured in terms of grams per mile over the whole test. Real-time emissions in parts per million will also be measured. The grams per mile data is useful for making composite comparisons of HCNG with other fuel technologies whereas the real-time ppm data is useful as a development tool for analyzing the engine's emissions performance during specific driving conditions such as cruise, accelerations, and decelerations.

The chassis dynamometer testing will give NRG the opportunity to make further EEC strategy modifications if transient emissions performance warrants such changes. The chassis dynamometer is the final forum in a controlled environment for determining the trade-offs between emissions, driveability, and fuel consumption. Once a final engine control strategy has been decided upon, then a final "official" driving cycle test will be performed for documenting the emissions reduction capability of the NRG HCNG engine. Between the NRG engine dynamometer data and CATTS chassis dynamometer data, there will be a solid characterization of the HCNG engine's emissions performance allowing a comparison between it and commercially available CNG technology.

### Las Vegas Field Demonstration

After the emissions testing is completed at CATTS, the HCNG powered bus will be operated in the Las Vegas public transit system for a period of several months. During that time detailed records will be kept on fuel usage, oil consumption, maintenance, and driver perception for evaluation before progressing with the demonstration expansion proposed for Phase III. Oil samples will be taken at regular maintenance intervals for tracking of wear metals.

NRG will install a data logging system on the bus for monitoring parameters such as oil, coolant, and intake air temperature, engine and vehicle speed, boost pressure, and throttle position. The system will be accessible remotely at NRG's facilities via an on-board modem with cellular phone access. This will allow NRG to obtain daily feedback on the engine's performance for record keeping and diagnostic troubleshooting if necessary.

It will be the responsibility of the bus operators to perform the standard maintenance as prescribed by NRG. NRG will provide training on the engine and its maintenance procedures to all appropriate personnel when the bus is delivered to Las Vegas operating on HCNG.

### Phase II Completion – Engine Teardown

At the end of the three-month field test in Las Vegas, the bus will be shipped by a commercial carrier to NRG in Reno. NRG will then remove, disassemble, and inspect the engine for abnormal wear conditions. Measurements of valve seat recession and bore wear will be made in order to begin tracking the durability of the engine during the life of the whole project. If any abnormalities are identified, then NRG will be able to make design modifications to the engine package before progressing with Phase III. Ultimately, the engine will be reinstalled into the bus as one of up to six Phase III repowers.

## PHASE III – HCNG DEMONSTRATION EXPANSION

The HCNG demonstration with the City of Las Vegas will expand to include up to six total buses running on hydrogen mixtures assuming the first bus in Phase II proved successful. Phase III will provide the more meaningful data with regards to fuel consumption and reliability because the data will become more statistical rather than singular in nature. The bus expansion will also be important for the hydrogen refueling infrastructure being developed in Las Vegas. Fast-fill gaseous fueling systems are capital intensive and it becomes important for the owners of the station to bring the equipment up to reasonable capacity as quickly as possible.

At the end of Phase III it will be up to the project participants to decide the fate of the HCNG engines. The demonstration period could be extended or the City of Las Vegas may wish to have the Cummins engines reinstalled if the fast-fill HCNG station poses long-term problems to the operation of the fleet.

## CONCLUSION

NRG Technologies, Inc. has initiated work on a three-year plan to demonstrate hydrogen-enriched natural gas in the City of Las Vegas bus fleet. The project is only in its early stages of development so no technical results are available for discussion within this paper. Based on initial engine modeling, NRG has decided to use a General Motors based 8.0L aluminum block with aluminum wedge style cylinder heads. The larger displacement compared to the base Cummins engine is necessary to maintain output goals while achieving significant emissions reductions with extreme charge dilution compared to conventional fuels. Two engine simulation software packages are also being used to optimize intake, exhaust, valve, and camshaft geometry. The project is the natural extension of previous success with HCNG fuels in light-duty demonstrations.