EPA/AA/CTAB-88-05

Technical Report

Emissions, Fuel Economy, and Performance of Light-Duty CNG and Dual-Fuel Vehicles

by

Robert I. Bruetsch

June 1988

NOTICE

Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Emission Control Technology Division
Control Technology and Applications Branch
2565 Plymouth Road
Ann Arbor, Michigan 48105

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

June 28, 1988

MEMORANDUM

SUBJECT: Exemption From Peer and Administrative Review

FROM: Karl H. Hellman, Chief KH
Control Technology and Applications Branch

TO: Charles L. Gray, Jr., Director
Emission Control Technology Division

The attached report entitled "Emissions, Fuel Economy and Performance of Light-Duty CNG and Dual-Fuel Vehicles," (EPA/AA/CTAB/88-05) describes MVEL testing of AGA and Ford compressed natural gas vehicles and trucks.

Since this report is concerned only with the presentation of data and its analysis and does not involve matters of policy or regulations, your concurrence is requested to waive administrative review according to the policy outlined in your directive of April 22, 1982.

Concurrence: ______________________ Date: ________
Charles L. Gray, Jr., Dir., ECTD

Nonconcurrence: ______________________ Date: ________
Charles L. Gray, Jr., Dir., ECTD

cc: E. Burger, ECTD

EPA/AA/CTAB-88-05

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I. Background

Natural gas has been proposed as an alternate transportation fuel for some applications, especially in metropolitan areas requiring additional carbon monoxide (CO) emission control.

Because of its very low energy density, natural gas must be compressed (CNG) or liquified (LNG) to store onboard a vehicle; even then the energy density does not match that typically achieved with gasoline. The results achieved to date with natural gas as a vehicle fuel place constraints on operating range, fuel storage volume, and load-carrying capacity.

U.S. natural gas reserves, while extensive, are being depleted. In addition, the capacity of the current gas pipeline network to handle the distribution of significant additional natural gas for vehicular use is somewhat limited.[1]* Natural gas prices vary widely across the United States. To recover the cost of vehicle conversion and the added cost of compression equipment for refueling stations, natural gas must be very favorably priced (compared to gasoline) to achieve enough in fuel-cost savings to recover the capital equipment cost within a short payback period.

For the reasons described above, natural gas tends to be used today in niche markets (such as certain fleet operations), where vehicle range and/or load-carrying capacity are not limiting factors, where fuel can be purchased at relatively low cost in commercial-level quantities, and where centralized refueling can be utilized.

CNG fuel system technology is developed, but the capability of CNG vehicles generally lags behind that of gasoline-fuel systems. CNG at its present stage of development is best for centrally fueled fleet vehicles that have ample storage volume and payload and that follow daily routes of less than 100 miles.

Most CNG fuel systems are completely mechanical in operation and control, and are designed for use as "second" fuel systems--in addition to the gasoline systems. Although this results in a vehicle capable of using two separate fuels (a "dual-fuel" vehicle as distinguished from a "flexible-fuel" vehicle), operational performance with either fuel may be compromised.

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* Numbers in brackets denote references at end of paper.

Because CNG is a gaseous fuel, it displaces air, which otherwise could be used in the combustion process, and this can reduce the engine's maximum power output. CNG fuel systems also impose penalties on the vehicle in weight and fuel storage volume. All of this reduces vehicle performance, payload capability, and overall fuel economy.

The cost to convert an existing vehicle to use CNG as a fuel is typically in the range of $1,000 to $1,500, depending on the number of storage tanks. Dual-fuel operation is usually maintained. Dedicated CNG vehicles (single-fuel vehicles) could be produced by the automobile manufacturers for less of a differential, but some incremental cost increase is inevitable because CNG storage tanks are much more expensive than gasoline storage tanks. The cost of compressing natural gas to 2,400 pounds per square inch is significant. The operating and maintenance cost of compression are in the range of $0.10 to $0.20 per equivalent gallon of gasoline. The capital cost of the compressors must be added to this cost to arrive at a total, delivered cost of CNG.[1]

CNG-fueled vehicles have not been tested by EPA for emissions, fuel economy and performance for the past seven years. EPA representatives attended a gas industry meeting in Indianapolis in September 1987 to view state-of-the-art post-1981 dedicated and dual-fueled CNG light-duty vehicles and trucks. The intent of this visit was to develop a cooperative test program to acquire emission data on updated CNG vehicles.

Previous EPA data [2] have shown reductions in carbon monoxide and non-methane hydrocarbon emissions of pre-1981 retrofit CNG-fueled vehicles compared to operation on gasoline. NOx emissions and vehicle performance were somewhat degraded from these same vehicles compared to the gasoline baseline. The significant changes in gasoline engine and vehicle technology brought about by the much more stringent passenger car emission standards that took effect in 1980 and 1981 have changed the context in which natural gas and other alternative fuels need to be considered. First, it was believed that changes in vehicle manufacturer catalyst and fuel metering technology since 1981 might have a significant effect on the exhaust emissions of in-use CNG-fueled vehicles. Second, the much lower gasoline-fueled vehicle emissions give a much lower baseline with which CNG vehicles must compete. EPA determined that it would be valuable to develop emission data on post-1981 gasoline-fueled vehicles that had been converted to dual-fuel applications. The American Gas Association (AGA) agreed to assist in this endeavor and a request for vehicles was sent to AGA.[3] A test program for both dual-fuel and dedicated fuel CNG vehicles was developed.

II. Test Program

The intent of this test program was to work with the AGA and Michigan Consolidated Gas Co., Inc. (MichCon) to obtain and test a range of late model CNG vehicles. The basic objective was a comprehensive characterization of the emissions, fuel economy and performance of CNG vehicles in order to permit a broad evaluation of the use of CNG as a transportation fuel.

In addition to obtaining an emissions database of current CNG vehicle technology, this test program was initiated to compare the test results to those of similarly equipped gasoline vehicles as well as to the applicable Federal emission standards and other vehicles in the same equivalent test weight class.[4] An additional objective was to sample the exhaust of CNG vehicles for formaldehyde (HCHO) emissions to provide first time test results of this pollutant (if emitted) from CNG-fueled vehicles. HCHO emissions from CNG vehicles have historically been assumed to be low or zero and therefore a benefit of CNG utilization, but these claims have not been based on actual test results.

The CNG test vehicles are described in Table 1. Four vehicles were supplied for this program. Limited vehicle supplier generated test data exist for these vehicles.[5,6] Three of the vehicles supplied through AGA are dual-fueled (operable on CNG or unleaded gasoline) and only one of these, the 1984 Oldsmobile Delta 88, is a high mileage vehicle. All dual-fuel vehicles are equipped with a three-way catalyst plus closed-loop air/fuel ratio control. Two of these vehicles, a 1987 Ford LTD Crown Victoria and a 1987 Chevrolet Celebrity, were tested under two different configurations as noted in the emissions results in a later section. The Crown Victoria was tested with two different engine control calibrations and the Celebrity was tested in the "as-received" and "after maintenance" configurations.

The 1987 LTD Crown Victoria was configured as a police car, but has also been suggested for taxicab application. This vehicle was originally calibrated somewhat rich to obtain improved NOx control. This calibration proved to be unacceptably rich when tested over the Federal Test Procedure (FTP). High total HC and CO emissions were measured, though low NOx numbers were obtained. The vehicle supplier recalibrated the vehicle and brought it back to be retested (on CNG only) with a leaner calibration.

The 1987 Chevrolet Celebrity exhibited vehicle driveability problems in the form of false starts and stalls and also had to be recalibrated after the first round of testing. There were also repairs to the engine control system which resolved the false start/stall problem that existed with the gasoline-fueled testing of this vehicle.

Table 1

CNG Test Vehicle Description

Model Type	Delta 88	Crown Victoria	Celebrity	Ranger
Mfr.	GM	Ford	GM	Ford
MY	1984	1987	1987	1984
Displacement	307	302	173	140
Carburetion	4	FI	FI	1
Comp. Ratio	7.9	8.9	8.9	12.8
Rated HP	140	160	125	80
Control System	EGR/PMP/OXD/3CL	EGR/PMP/OXD/3CL	EGR/3CL	EGR/PMP/OXD
No. of Cyls.	8	8	6	4
Transmission	L3-1	L4-2	L4-2	M4-1
ETW	4000	4250	3250	3000
Axle Ratio	2.41	3.27	3.33	3.45
N/V	30.2	30.0	32.4	48.0
ADHP	10.7	13.1	7.3	10.0
Fuel Type	Dual-Fuel	Dual-Fuel	Dual-Fuel	CNG-Only

Exhaust Emission Control System:

EGR = Exhaust gas recirculation
OXD = Oxidation catalyst
PMP = Air pump
3CL = Three-way catalyst + closed loop

None of the dual-fuel vehicles were tested with different spark timings for CNG than gasoline operation, although the Delta 88 was equipped with a switch for advanced timing in the CNG test mode. CNG vehicles are routinely calibrated with 10-12° more spark advance to account for the slow flame speed and reduced power output of the fuel. Higher emissions, particularly NOx, are usually the tradeoff for advanced spark timing on these vehicles. An increase of 55 percent in NOx emissions was observed in the vehicle supplier test data, though this increase was not verified by EPA as part of this test program.

One dedicated CNG-fueled Ford Ranger pickup truck, supplied by Ford Motor Company, was also tested. This truck was calibrated to have the same engine dynamometer rated power and similar (only 2 percent slower 0 to 50 mph) performance as an identically equipped gasoline-fueled 1984 Ford Ranger. A primary difference is the higher compression ratio of the CNG-fueled Ranger at 12.8:1 versus the gasoline-fueled Ranger at 9.0:1.

Test fuel for CNG vehicle evaluations was provided by MichCon in Melvindale, Michigan.[7-11] Vehicles were driven to the refueling station (usually on gasoline), CNG fuel tanks were filled to 2500 psi, and attempts were made to obtain fuel analyses of the fuel from the storage cascade for each batch EPA used. MichCon was not able to supply fuel analyses every time a vehicle was brought in for refueling. Fuel parameters of the CNG used to fuel a specific vehicle were assumed to be the same as those from the most recent fuel analysis received from MichCon prior to the time that vehicle was tested. The standard EPA emissions calculation program is not set up to handle emissions from CNG-fueled vehicles so certain MichCon fuel parameters (e.g., power heat value, density, weight percent carbon, etc.) were needed to determine estimates of exhaust emissions and fuel economy.[12,13]

Indolene (H0) test fuel was used for all non-CNG test sequences on dual-fuel vehicles as an unleaded gasoline to compare the emissions, fuel economy and performance obtained on CNG from the same vehicles. The Indolene used in the EPA lab is supplied by Howell Hydrocarbons, San Antonio, Texas.

Each vehicle was tested over the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HFET). If the vehicle was a dual-fueled test car, it was run over the FTP and HFET cycles at least twice on each fuel (CNG and Indolene) or until repeatable results were obtained. Each dual-fueled car was also tested for 5 to 60 MPH and 30 to 60 MPH performance. These accelerations were repeated five times after each vehicle FTP cycle. The dedicated CNG truck was tested over the FTP and HFET cycles on CNG only, but was not tested by EPA for acceleration performance.

All cyclic test sequences included sampling for formaldehyde emissions as well as emissions of total hydrocarbons, methane, carbon monoxide, carbon dioxide and oxides of nitrogen. Methane sampling required the incorporation of a high range analytical span gas. Methane emissions from gasoline-fueled vehicles are relatively low (20-25 percent of a low total HC) and can be characterized fairly accurately in the low range of the instrument using a nominal 50 ppm span gas. CNG fuel and its emissions from light-duty vehicles can be from 75 to 95 percent methane requiring an instrument with measuring capacity well above a 50 ppm concentration. Therefore, a 450 ppm span gas was procured to provide more accurate measurement of high range methane analyzer concentrations. Actually, several span gases at various concentrations should be characterized to develop a true calibration curve for the methane analyzer, but complete calibration of the methane analyzer for CNG was not provided for as part of this evaluation program. Measured methane is thought to be in most cases higher than actual methane concentrations since the measured methane subtracted from the relatively well characterized total hydrocarbon concentrations yielded non-methane concentrations which were generally either zero or negative. Since negative nonmethane hydrocarbons do not represent an actual physical result, a variety of methods for estimating non-methane hydrocarbons were developed as will be discussed in more detail in the next section.

III. Exhaust Emissions and Fuel Economy Calculations

As mentioned above, the standard EPA exhaust emissions calculation computer program is not set up to determine the emissions and fuel economy of CNG-fueled vehicles. The volume of CNG testing over the years has not been high enough to justify developing subroutines for calculating and correcting for factors affecting CNG exhaust emissions and fuel economy. Therefore, the program was run assuming the test fuel used is Indolene and a separate program used to correct for the particular CNG fuel batch used in the test vehicle. The exhaust emission results are also modified by a factor which accounts for the difference in HC analyzer response to methane span gas (used as a surrogate for CNG) instead of using propane span gas which is used for Indolene.

Once a fuel analysis was obtained for a given batch of CNG used in a particular vehicle during testing, the values of heat content, molecular weight, specific gravity, weight percent carbon, and weight percent "hydrocarbon" of the fuel were determined. These fuel analyses upon which our calculations were based were performed by MichCon and referenced to 60°F and atmospheric pressure.

A. Net Heat Value

Vehicle testing was performed under laboratory conditions of 75-77°F and atmospheric pressure. Variation in the barometric pressure was negligible. The Federal Register and Code of Federal Regulations, Title 40, Part 86. 144-78, "Calculations; exhaust emissions," list densities of regulated exhaust emissions determined at 68°F and 760 mm Hg pressure.[14] Since the allowable temperature of certification specification vehicle testing is 68-86°F and the CFR densities are 68°F values, the gas analyses parameters were also converted to 68°F or were used on a mass basis (e.g., heat content) in the calculations.

The heating value reported on the MichCon Gas Analyses is the gross (high) heat value (HHV) of the natural gas and is reported on a dry basis. It is standard practice, when using fuels in engines where the exhaust water is not condensed to provide energy, to use the net (lower) heat value (LHV) of the fuel in the calculation of fuel economy. Since the MichCon gas analyses provided do not report LHV of the fuel, several gas property references were examined to see if there is a consistent LHV/HHV ratio.[15,16,17] As it turns out, this ratio is consistently very close to 0.90 in each reference cited. Since a direct measure of LHV was not available, and the gas industry could not suggest a better value or rule of thumb, the HHV numbers supplied by MichCon were multiplied by 0.90 and these values were used in the fuel economy calculations as the LHV. This way, a reasonable approximation of the LHV of the actual fuel in the test vehicle was determined, we avoided requiring additional fuel analysis for LHV by MichCon, and a separate factor for the difference between the fuel used and the "national average" CNG fuel did not have to be developed. MichCon specification requires their fuel energy HHV to be between 1000 BTU/SCF and 1050 BTU/SCF. As a result, the LHVs obtained in this calculation methodology are between 900 BTU/SCF and 945 BTU/SCF.

B. Density

Since they are thought not to affect the chemical reactions that produce photochemical oxidation, the weight percent of CO_2, He, and N_2 are deleted from the density when figuring the "total HC" and "non-methane HC" emissions from vehicles run on natural gas. EPA calculated this "HC density" based on the weight percent and molecular weight of all hydrocarbon components of the fuel (e.g., methane, ethane, propane, butane, pentane, hexane, heptane, octane, etc.).

The entire fuel composition (including CO_2, N_2 and trace He) is used in the determination of the overall "CNG density" to be used in the fuel consumption calculation. This is appropriate since the vehicle operator pays for the CO_2, He, and N_2 they get with the rest of the fuel and it is "consumed" (i.e., used) in the operation of the vehicle even if it is not consumed in the combustion process. Therefore, the density used in the fuel economy calculation will be slightly higher than that used to calculate HC emissions depending on the amount of CO_2, He, and N_2 in the fuel.

The actual values used depend on which MichCon fuel analysis is used. The weight percent carbon is reasonably consistent in the fuel analyses obtained throughout this test program at about 0.74, so this value is used as a constant. Table 2 shows a summary of the values determined from the MichCon analyses. These values are used as inputs to our calculations.

Table 2

Natural Gas Properties Used For Calculations

Date of MichCon Gas Analysis	LHV BTU/g	HC Density (g/ft^3) at 68°F and One Atmosphere For		
		CNG MPG	CNG Emissions (% Methane)	Methane
11/18/87	42.8	20.91	19.30 (96.3)	18.89
02/26/88	42.3	21.61	20.43 (91.3)	18.89
03/16/88	43.5	20.79	19.90 (94.5)	18.89
04/29/88	43.2	21.35	20.26 (93.5)	18.89
05/31/88	43.1	21.38	20.27 (93.5)	18.89

Note that although the variability of the Table 2 fuel properties are low (3 to 6 percent), individual fuel analyses were matched up with the vehicles. Properties for each fuel were used where appropriate to obtain the most accurate emissions and fuel economy estimates for each vehicle.

C. FID Correction Factor

A cursory investigation was made into the appropriateness of using propane as a span gas for the HC analyzer, a "cold" Beckman Model 400 flame ionization detector (FID), when sampling hydrocarbons from CNG-fueled vehicles. It is known that HC analyzers respond differently to different hydrocarbons.[18] Also, since CNG is largely methane, and no "standard" CNG fuel is currently used, tests were run on two methane span gases through the HC-FID to compare analyzer response to methane to the response obtained when spanning with propane.

The response to a 450 ppm methane span gas is 10 percent higher than with propane, and the response to a 50 ppm methane span gas is 12 percent higher. Taking an average, the methane response is 11 percent higher than the propane response on the analyzer. Therefore, the FID correction factor (the number to multiply the total HC concentration by to account for use of methane span gas) is 0.90 or the reciprical of 1.11. The FID correction was applied to the total HC g/mile value on each CNG test to account for the use of methane as a more appropriate "surrogate" span gas for natural gas than propane.

D. Non-Methane HC

As a result of problems encountered obtaining accurate methane measurements, different ways to calculate the non-methane HC emissions from the CNG-fueled cars were developed, because non-methane HC are very important contributors to oxidant formation.

The non-methane HC results are determined by subtracting methane measurements from total HC measurements. The methane instrument used in our laboratory was developed to measure the methane levels that are typically seen from gasoline-fueled cars, typically 0.1 grams per mile. During the development of the instrument, it was not evaluated with the high levels that are typical from the CNG-fueled vehicles. For example, a total HC value for the CNG-fueled cars of 3.5 grams per mile is not unusual to measure. This implies that the methane levels the methane analyzer sees are up to 30 times higher than the values from gasoline-fueled cars. EPA purchased a special higher range span gas for the CNG car testing. Using our existing span gas, the analyzers all read full scale when testing with CNG-fueled cars. This was discovered during testing of the first CNG vehicle, the Delta 88. It is fair to say that it is pushing these methane analyzers to read higher levels than seen heretofore. In addition, if the exhaust HC distribution is anything close to the fuel HC distribution, the analyzer is also seeing a much different HC distribution than was seen during the process of developing the instrument. The instrument may well be measuring other light hydrocarbons as methane.

When some of the preliminary calculations of the emissions from the vehicle tests were made, it was noted that some of the results from the calculation of non-methane HC computed were negative. This is a non-physical result. It would appear that the appropriate value to use would be zero when the computed result from the two different analyzers spanned on two different calibration gases is negative. The results so obtained are reported as 0.00 g/mile NMHC. This negative result may be attributable to the methane analyzer counting other light hydrocarbons as methane. Table 3 shows a summary of the NMHC calculation approaches.

Table 3

Various Methods to Compute NMHC Emissions from CNG-Fueled Vehicles

	Method 1	Method 2	Method 3*	Method 4
HC Density	16.33	16.33	Various see Table 2	Various see Table 2
Methane Density	16.33	16.33	18.89	--
FID Response	1.00	0.90	0.90	0.90
NMHC mass equals HC mass minus measured CH_4 mass?	Yes	Yes	Yes	No

---

* For the test results with gasoline as the fuel, Method 3 uses 16.33, 18.89, 1.00 and Yes.

Method 1 is the data as it comes from the computer. This assumes a density of HC equivalent to the value used for testing with Indolene. This method yields results we believe are inaccurate since they are unadjusted for CNG fuel, but may be useful for comparison to other unadjusted CNG data. Method 2 is the same as Method 1, except the FID correction factor is applied to the HC results. Method 3 is the same as Method 2 except densities of HC and methane have been adjusted as shown in Table 2.[19] Method 4 calculates non-methane HC as the total HC values (adjusted for the FID response factor) multiplied by the non-methane fraction of the CNG fuel. In other words, method 4 does not use the measured methane values.

The author places more confidence in NMHC numbers generated using method 4 than the other methods for CNG-fueled vehicles since it includes the corrections for fuel density and FID response and does not rely on methane measurements. Method 4 NMHC results may also be low since the exhaust may contain non-methane HC from burned lubricating oil and therefore higher NMHC emissions. Gasoline-fueled vehicles are best described by results from NMHC method 3, which includes the correction for the density of methane. NMHC emissions are compared in Section IV. "Test Results" and Figure 2 by using CNG results determined from method 4 versus gasoline results determined from method 3.

E. Fuel Economy

The fuel economy calculation for natural gas fueled vehicles was determined on a gasoline equivalent basis by carbon balance using the weight percent carbon and net heat value of the fuel.[20,21] The generalized expression for miles per gallon is obtained by dividing the net heat value of gasoline (BTU/gal) by the CNG energy expended per distance traveled (BTU/mile). The working equation and a sample calculation are shown below.

$$MPG = \frac{BTU/gal}{BTU/mile} = \frac{BTU/gal}{(gC/mile)(gCNG/gC)(BTU/gCNG)}$$

Where:

BTU/gal = Net heat value of Indolene = 114,132 BTU/gal

BTU/mile = BTU of energy consumed on natural gas per mile

gC/mile = Grams carbon emitted per mile (g/mile)
= (wgt. fraction C)(HC) + 0.273 (CO_2) + 0.429 (CO)

gCNG/gC = Reciprical of weight percent carbon of CNG fuel
= 1/0.74 = 1.35

BTU/gCNG = Net heat value of CNG (BTU/g). See Table 2 for values

Example Gasoline Equivalent Fuel Economy Calculation

Assume: HC = 1.62 g/mile CO_2 = 326 g/mile CO = 0.1 g/mile
LHV = 42.8 BTU/gCNG

$$GEFE = \frac{114{,}132\ (BTU/gal)}{[(0.74)(HC) + (0.273)(CO_2) + (0.429)(CO)](1.35)(42.8)}$$

$$= \frac{114{,}132\ (BTU/gal)}{[(0.74)(1.62) + (0.273)(326) + (0.429)(0.1)](1.35)(42.8)}$$

$$= \frac{114{,}132}{5{,}214}\ \frac{BTU/gal}{BTU/mile} = 21.9\ \frac{miles}{gal}$$

Generally the gasoline equivalent fuel economy of CNG-fueled vehicles is somewhat higher (about 7-12 percent) than the same vehicle operating on gasoline. Therefore, on that basis, the dual fuel vehicle is more fuel efficient on CNG than on gasoline.

However, the results obtained on CNG were with vehicles that did not match the performance obtained on gasoline. Our performance tests of the vehicles operating on CNG showed substantially reduced performance, measured as the time to accelerate between two speeds on the chassis dynamometer. This loss in performance was 25 to 35 percent.

In order to make the fuel efficiency comparisons at constant performance, two avenues are possible. One would be to adjust the fuel economy data on CNG to account for the loss in fuel economy that would be expected from an increase in performance to match the performance on gasoline. The other approach is to adjust the fuel economy result obtained on gasoline to the gain in fuel economy that would be expected to result from making the gasoline-fueled configuration perform the same as on CNG. We chose the latter since there is much more information about the performance and fuel economy relationships for gasoline-fueled vehicles.

Based on previous work [22], the sensitivity is 0.454 or,

$$\% \Delta MPG = (0.454) \% \Delta T$$

Where:

$\% \Delta MPG$ = Percent change in fuel economy

$\% \Delta T$ = Percent change in 0 to 60 MPH acceleration time (seconds)

If, for example, CNG gasoline equivalent fuel economy is ten percent higher than the same vehicle on gasoline (say 17.6 MPG on CNG and 16.0 MPG on gasoline), but the CNG 5 to 60 MPH test took 14 seconds while the same test took only 11 seconds using gasoline as the fuel, what would the fuel economy difference between CNG and gasoline be at constant performance?

Making the gasoline-fueled vehicle performance equivalent to the CNG vehicle performance is a 27 percent increase in acceleration time. Assuming that the sensitivity based on 5-60 accelerations is the same as the sensitivity for 0-60 accelerations the 0.454 value can be used. Using the above equation, this translates into a 12.3 percent increase in fuel economy for the gasoline-fueled vehicle, or 18 MPG. Therefore, at constant performance the vehicle would exhibit about 2 percent better fuel economy (18/17.6 = 1.02) when run on gasoline than when run on CNG.

IV. Test Results

The exhaust emission and fuel economy test results obtained in this test program are displayed in Figures 1 through 6 and Table 4. The data in Table 4 include the fuel analysis information used in the calculations, results of the four NMHC (g/mile) methods calculated, the total HC, CO, CO_2, NOx and HCHO results, and the gasoline equivalent fuel economy for each test sequence. Ford Ranger CNG results are compared to Ford-generated 1984 gasoline-fueled Ranger emissions and fuel economy. Figures 1 to 6 show the FTP emissions and fuel economy results of CNG versus gasoline operation. Data points are displayed relative to the line of equality between the two fuels. In the discussion of these test results, emphasis is placed on the four data points that represent the latest vehicle test configurations though the test results for the original Crown Victoria and Celebrity calibrations are also included.

The total HC results shown in Figure 1 indicate that when fueled with CNG the vehicles emit between 4 to 10 times more total HC than when fueled with gasoline. All the tests on CNG exceed the level of the 0.41 gram per mile total HC standard.

The results for non-methane HC shown in Figure 2 show a different trend than that seen for total HC. The NMHC emissions when CNG is the fuel are lower than with gasoline.

Carbon monoxide results are mixed as the data in Figure 3 show. The initial calibrations on the Crown Victoria and the Celebrity were worse on CNG than on gasoline. In fact, it was these results that prompted the vehicle developers to modify the vehicles. After the vehicles were modified their CO emissions were lower, but the initial emission tests were the only indication that vehicle modification was needed. Vehicle operation did not signal a need for adjustment or maintenance. One vehicle, the Crown Victoria version 1, exceeded the 3.4 gram per mile CO standard on CNG. The Delta 88 exceeded the 3.4 CO standard on gasoline.

NOx emissions were also mixed, but in this case it was one vehicle, the Crown Victoria, that provided results counter to the expected trend of higher NOx on CNG. The Celebrity exceeded 1.0 gram per mile NOx standard on both calibrations on CNG. The Delta 88 also exceeded the 1.0 gram per mile NOx level on CNG. The Crown Victoria exceeded the 1.0 gram per mile NOx standard when using gasoline. Since the Ranger is a light-duty truck, it did not have to meet the 1.0 gram per mile standard.

In reference [23] EPA provided some guidance for estimating the emissions of CNG-fueled vehicles. The guidance in [23] were prepared before this test program was run. To compare those values to the ones in this report, the average results on CNG were divided by the average result on gasoline fuel for each vehicle tested on both CNG and gasoline. The resulting averages are shown in Table 5 along with the guideline values.

Figure 1

HC Emissions
(g/mile)

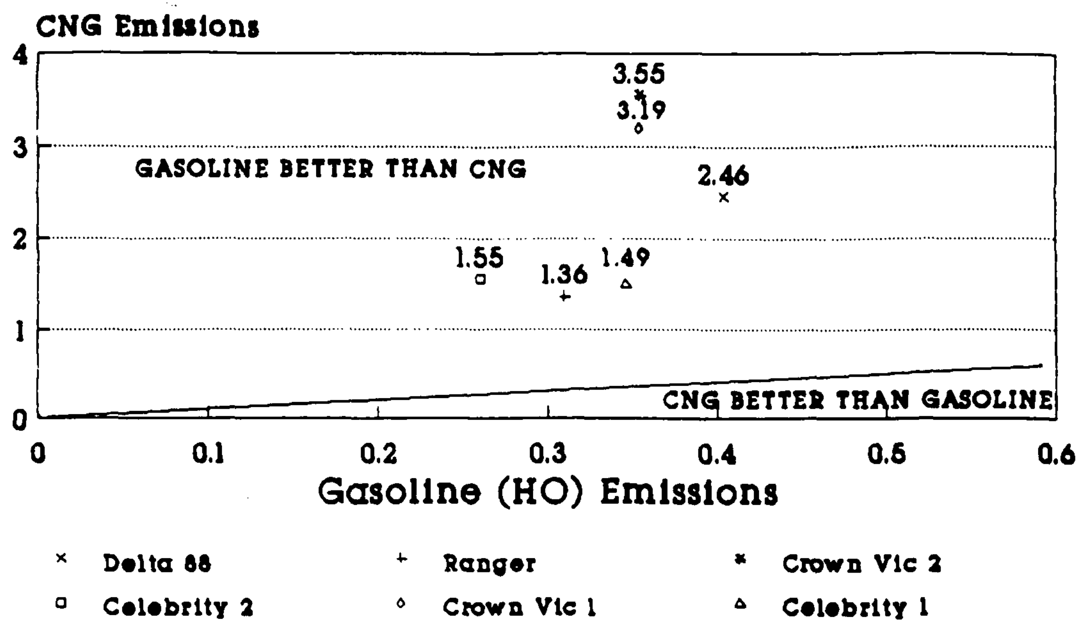


Figure 2

NMHC Emissions
(g/mile)

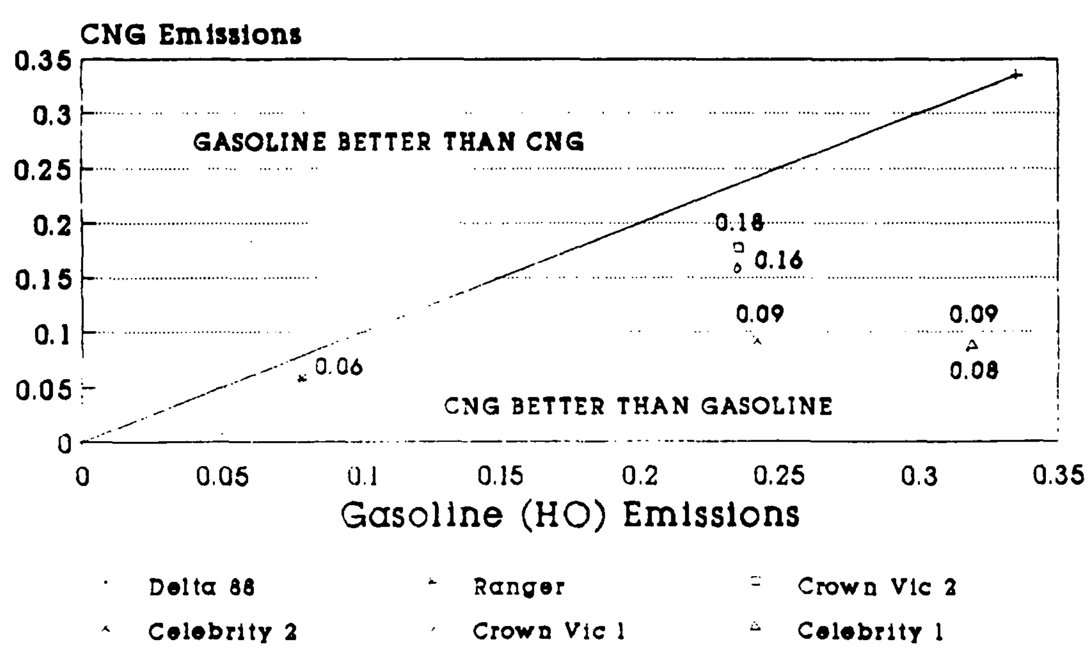


Figure 3

CO Emissions
(g/mile)

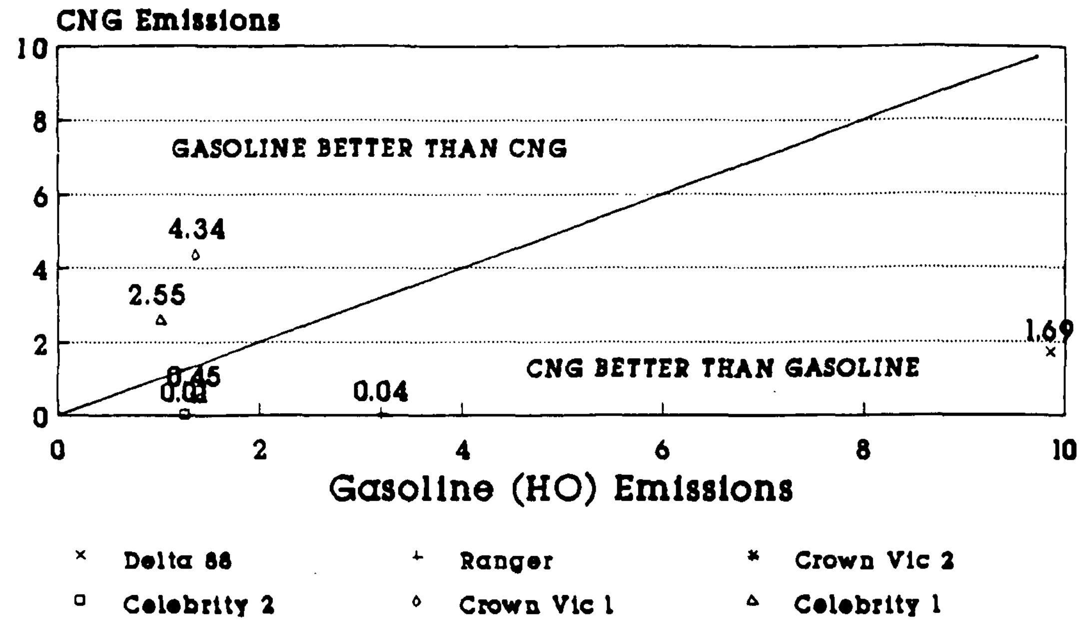


Figure 4

NOx Emissions
(g/mile)

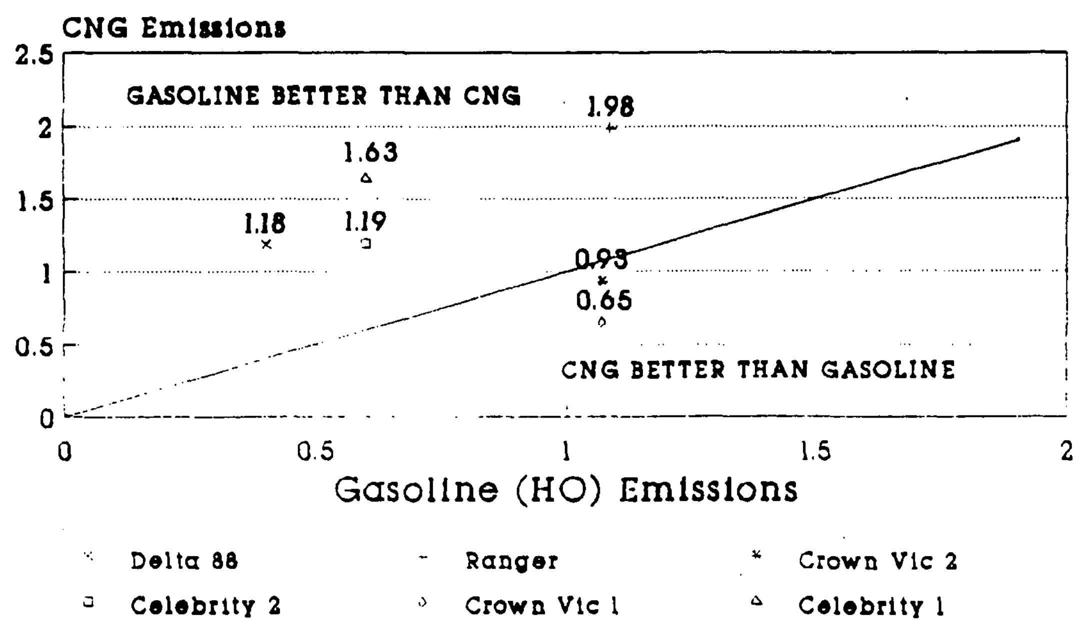


Figure 5

HCHO Emissions
(mg/mile)

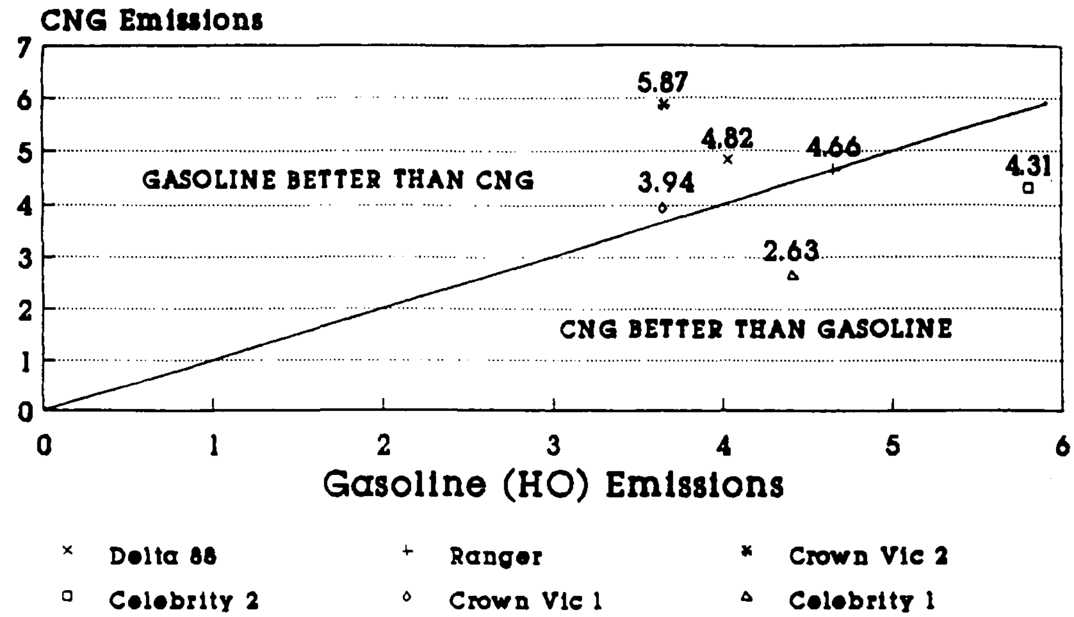


Figure 6

Fuel Economy
Gasoline Equivalent
(miles/gallon)

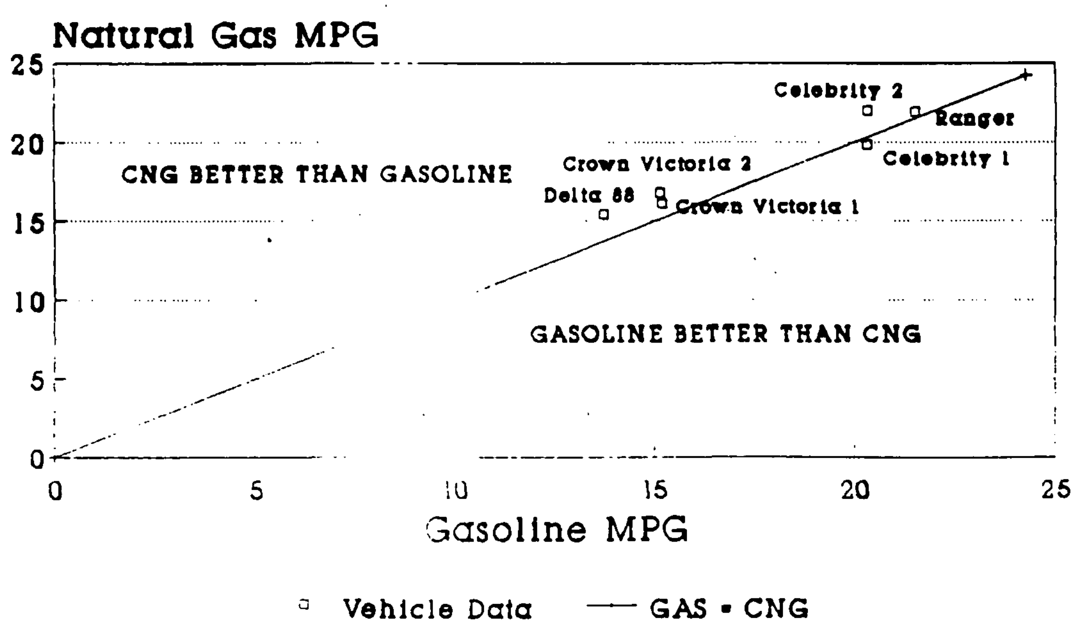


Table 4

Exhaust Emissions and Fuel Economy of
Dedicated CNG and CNG/Gasoline Dual-Fuel Vehicles

Test Number	Date	*Vehicle	Test Type	BTU/g	HC Den for MPG	HC Den (emiss)	Methane percent	Methane Density	Total HC (g/mi)	Nonmethane HC Method 1	Method 2	Method 3	Method 4	HCHO (mg/mi)	CO (g/mi)	CO_2 (g/mi)	NOx (g/mi)	GEFE MPG
Avg.	HO	Delta 88	FTP						0.404	0.259		0.317		4.03	9.84	632	0.40	13.67
Avg.	HO	Crn Vic	FTP						0.354	0.251		0.235		3.65	1.35	582	1.07	15.15
Avg.	HO	Celebrity1	FTP						0.346	0.322		0.319		4.41	1.01	435	0.60	20.30
Avg.	HO	Celebrity2	FTP						0.260	0.250		0.242		5.80	1.25	434	0.60	20.30
Avg.	11/18/87	Delta 88	FTP	42.8	20.9	19.3	96.3	18.89	2.456	0.000	0.000	0.000	0.082	4.82	1.69	464	1.18	15.30
Avg.	03/16/88	Crn Vic 1	FTP	43.5	20.8	19.9	94.5	18.89	3.191	0.027	0.000	0.000	0.158	3.94	4.34	429	0.65	16.02
Avg.	03/16/88	Crn Vic 2	FTP	43.5	20.8	18.9	94.5	18.89	3.550	0.147	0.000	0.002	0.176	5.87	0.45	417	0.93	16.66
Avg.	04/29/88	Celebrity1	FTP	43.2	21.3	20.3	93.5	18.89	1.493	0.015	0.000	0.000	0.087	2.63	2.55	354	1.63	19.83
Avg.	05/31/88	Celebrity2	FTP	43.1	21.4	20.3	93.5	18.89	1.550	0.100	0.050	0.090	0.090	4.31	0.00	324	1.19	21.90
Avg.	11/18/87	Ranger	FTP	42.8	20.9	19.3	96.3	18.89	1.362	0.191	0.082	0.119	0.057	4.66	0.04	328	1.98	21.83
Avg.	HO	Delta 88	HFET						0.082	0.059		0.055		7.43	1.89	349	0.29	25.15
Avg.	HO	Crn Vic	HFET						0.063	0.034		0.029		1.66	0.10	456	0.67	19.45
Avg.	HO	Celebrity1	HFET						0.015	0.012		0.011		0.72	0.02	335	0.63	26.46
Avg.	HO	Celebrity2	HFET						0.020	0.020		0.012		1.01	0.10	342	0.30	25.90
Avg.	11/18/87	Delta 88	HFET	42.8	20.9	19.3	96.3	18.89	0.838	0.000	0.000	0.000	0.028	7.41	1.19	267	1.13	26.69
Avg.	03/16/88	Crn Vic 1	HFET	43.5	20.8	19.9	94.5	18.89	1.545	0.027	0.000	0.000	0.076	1.87	5.55	339	0.40	20.23
Avg.	03/16/88	Crn Vic 2	HFET	43.5	20.8	19.9	94.5	18.89	2.073	0.148	0.000	0.046	0.103	5.97	0.00	365	1.54	19.23
Avg.	04/29/88	Celebrity1	HFET	43.2	21.3	20.3	93.5	18.89	0.719	0.009	0.000	0.003	0.042	0.90	2.62	252	2.08	27.78
Avg.	05/31/88	Celebrity2	HFET	43.1	21.4	20.3	93.5	18.89	0.780	0.000	0.000	0.000	0.050	1.62	0.00	250	2.20	28.50
Avg.	11/18/88	Ranger	HFET	42.8	20.9	19.3	96.3	18.89	0.782	0.127	0.049	0.074	0.026	1.38	0.01	251	2.47	28.64

*The Crown Victoria and Celebrity vehicles were each tested with two different calibrations.

Table 5

CNG Emissions Comparison

Pollutant	CNG/Gasoline This Report	CNG/Gasoline Reference [23]
NMHC	0.46	0.60
CO	1.25	0.50
NOx	1.83	1.40

Formaldehyde emissions were also measured during this test program. Formaldehyde, due to its photochemical reactivity and carcinogenicity, is of great interest for both standard and alternate fuel vehicles. The results in Figure 5 show that formaldehyde is emitted from CNG-fueled vehicles and that the results are about the same as the formaldehyde emissions from the tests using gasoline as a fuel.

As discussed previously the gasoline equivalent fuel economy using CNG was slightly better than the results using gasoline. Gasoline equivalent fuel economy is generally improved on CNG operation relative to gasoline operation by 7 to 12 percent. These results, though on an energy equivalent basis, are somewhat misleading relative to vehicle performance. The 5 to 60 MPH performance measured on these dual-fueled vehicles was significantly degraded by about 29 percent on CNG relative to gasoline operation. Using the equation for fuel economy as a function of performance this translates into 4 percent higher fuel economy on gasoline at equivalent performance. On the road in actual use, both CNG and gasoline MPG are compromised on dual-fuel vehicles due to the added weight of having two fuel systems. We did not account for this weight penalty in our tests.

The city, highway and composite gasoline equivalent fuel economy for each vehicle are listed in Table 6. These data are compared to measured MPG on gasoline for the dual-fueled cars and the certification gasoline fuel economy for all vehicles using data from similarly equipped same model year vehicles on the EPA Test Car List.[24,25] The measured CNG and gasoline fuel economy are also compared to: 1) the fuel economy of all vehicles in the same inertia weight class (IWC) from the appropriate model year test car list; and 2) the applicable MPG standard for the same particular gasoline vehicle (or truck) class as the CNG or dual-fuel vehicle.

As mentioned above, the measured CNG fuel economy on an energy equivalent basis is 7 to 12 percent higher than the same vehicle operating on gasoline. The CNG gasoline equivalent fuel economy is 7 to 15 percent lower than the comparable certification gasoline-fueled vehicle mileage for the dual-fueled vehicles, and essentially the same as the certification light-duty truck mileage for the dedicated CNG Ranger. Measured CNG fuel economy is low compared to certification gasoline-fueled vehicles in the same inertia weight class for the Delta 88, Ranger, and Celebrity, and higher for the Crown Victoria. Measured CNG fuel economy are lower than the applicable model year MPG standards for all dual-fueled vehicles and 20 percent higher for the 1984 dedicated CNG Ranger.

Table 7 shows the performance data measured on CNG and gasoline for all dual-fueled vehicles in this test program. The dedicated CNG Ranger was not tested for performance on natural gas, but judging from the rated power of the CNG engine and estimates provided by Ford, the performance of this truck can be expected to be nearly equivalent to that of a similarly-equipped 1984 gasoline-fueled Ranger truck. The reduced power output of the dual-fuel vehicles operating on CNG is evident, however, with 23 to 33 percent slower 5 to 60 MPH acceleration times and 29 to 36 percent slower 30 to 60 MPH acceleration times on CNG relative to gasoline operation.

The relationship of changes in MPG with changes in performance is shown in Figure 7. These data agree with the historical gasoline data, but show higher increases in performance times for a given increase in MPG with CNG operation. For the vehicles fueled on CNG to have better constant performance fuel economy than on gasoline their data points would have to lie above the line on Figure 7. None do.

V. Interpretation of Test Results

One must be careful in interpreting the test results obtained in this CNG evaluation program. Only three dual-fueled vehicles and one dedicated CNG truck were evaluated. Two of the dual-fueled vehicles, the Crown Victoria and the Celebrity, had to be recalibrated for better emissions and driveability before being retested. The other dual-fuel vehicle, the Delta 88, was not tested with advanced ignition timing, though the vehicle was equipped with a switch to advance the spark 10 to 12 degrees. This vehicle may also have not been tested in its optimum form since the advanced timing would be expected to compensate for CNG's slower flame speed and improve performance. However, data supplied by the vehicle supplier indicate higher HC, CO, and NOx emissions with the spark advanced. The Ranger truck appeared to be calibrated properly as received, but showed markedly different fuel economy than the results obtained by Ford. Also, it represents only one data point for dedicated CNG vehicles.

Table 6

Test Vehicle Fuel Economy Comparisons

Test Vehicle	Delta 88	Ranger	Crown Victoria 1	Crown Victoria 2	Celebrity 1	Celebrity 2
CNG City (MPG)**	15.3	21.8	16.0	16.7	19.8	21.9
CNG Highway (MPG)**	26.7	28.6	20.2	19.2	27.8	28.5
CNG Composite (MPG)**	18.9	24.4	17.7	17.7	22.7	24.4
HO City (MPG)	13.7	15.0[+]	15.5		20.3	20.3
HO Highway (MPG)	25.2	25.6[+]	19.4		26.5	25.9
HO Composite (MPG)	17.2	18.4[+]	17.0		22.7	22.5
Cert City (MPG)*	17.3	21.5	17.2		22.0	
Cert Highway (MPG)*	25.9	29.5	26.0		35.6	
Cert Composite (MPG)*	20.3	24.5	20.3		26.6	
IWC City (MPG)*	17.3	23.5	13.1		21.6	
IWC Highway (MPG)*	26.8	31.9	19.8		31.9	
IWC Composite (MPG)*	20.6	26.7	15.4		25.3	
Applicable MPG Standard	27.0	20.3	26.0		26.0	

* From EPA Test Car List.
** Gasoline equivalent fuel economy.
\+ Ford fuel economy data.

Table 7

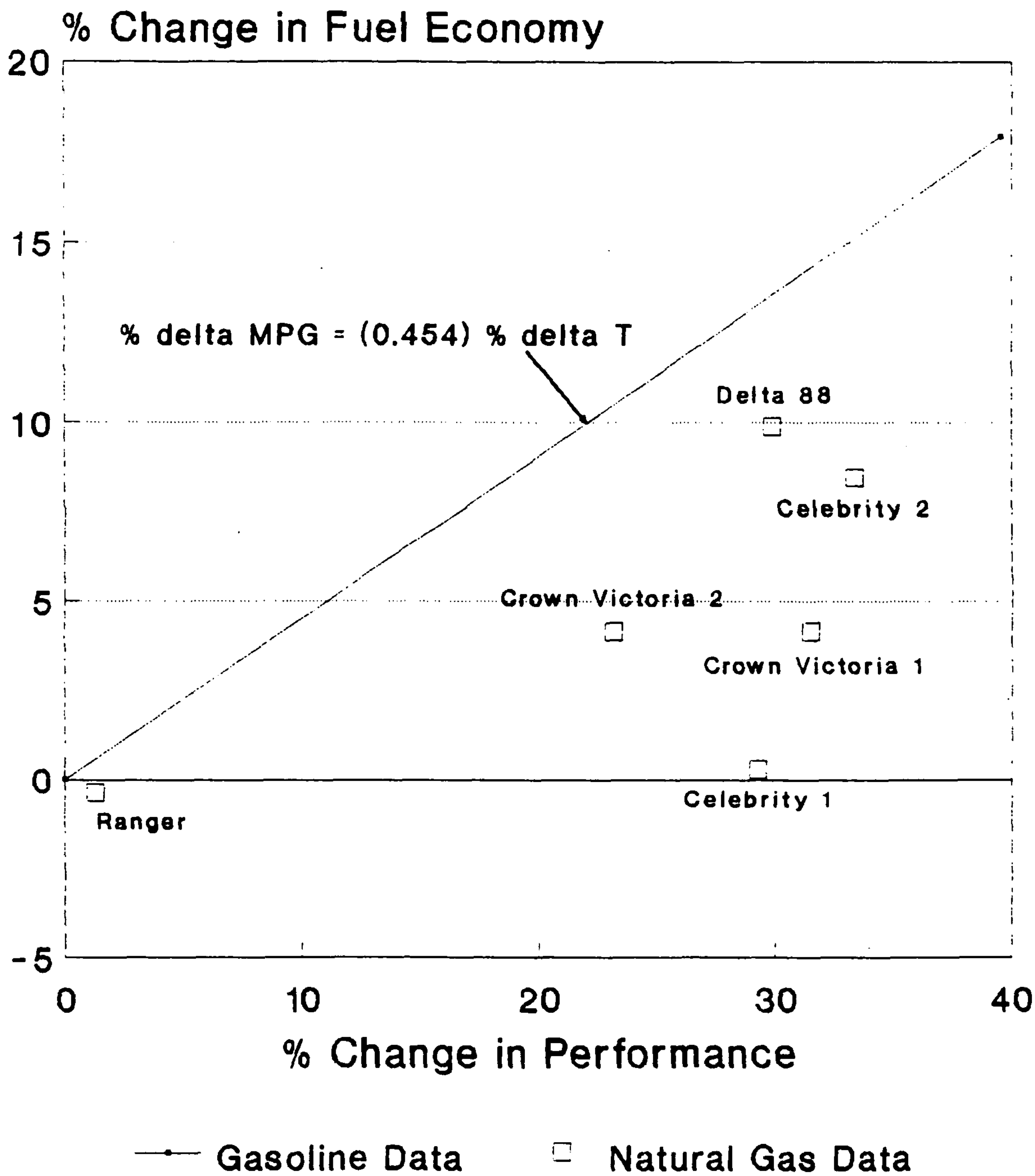
Test Vehicle Performance Data

Acceleration Times (Seconds)

Vehicle	Fuel	5-60 MPH	30-60 MPH
Delta 88	Gasoline	11.4	8.1
	CNG	14.8	10.8
	% slower on CNG	30	33
Crown Victoria	Gasoline	10.8	7.6
	CNG 1	13.3	9.9
	CNG 2	14.2	10.3
	% slower on CNG 1	23	29
	% slower on CNG 2	31	36
Celebrity	Gasoline 1	10.6	7.8
	Gasoline 2	10.5	7.7
	CNG 1	13.7	10.6
	CNG 2	14.0	10.5
	% slower on CNG 1	29	36
	% slower on CNG 2	33	36

Figure 7.

Fuel Economy Vs. Performance



The emissions, fuel economy and performance data suggest the need for further work in the optimization of dual-fuel vehicle calibration. Clearly, CNG dual-fuel vehicles have the potential to provide very large CO emission reductions, but perhaps at the expense of increased NOx emissions and decreased performance and engine power output. Vehicle compression ratios and ignition timings need to be chosen carefully or may need to be variable in order to not significantly degrade the emissions, efficiency, and performance of the vehicles on either fuel. For example, compression ratios typical of current practice using gasoline (generally about 9:1) are much lower than the optimum for CNG operation which may be closer to 13:1. Conversely, optimum CNG spark timings may be too advanced for efficient gasoline combustion. The development of more advanced technology, electronic fuel metering systems, and optimized, dedicated, CNG vehicles would undoubtedly enhance the clean use of CNG.[26]

The measurement and analytical procedures for the accurate determination of methane and formaldehyde emissions of CNG-fueled vehicles may need further development. As mentioned earlier, the characterization of the methane analyzer response to high concentrations of exhaust methane needs to be performed in order to place more confidence in the measured levels seen from CNG-fueled vehicles. Interpretation of these methane measurements as being representative of CNG vehicle methane levels yields NMHC estimates which are very low. Problems were encountered in the sampling and analysis of formaldehyde emissions throughout this program which may have added to the variability of measured HCHO results by unknown quantities. The consistency of the results of these particular HCHO tests and their levels, i.e., below 5 mg/mile and similar for both CNG and gasoline, indicate that these HCHO results are relatively accurate, particularly for comparison of CNG formaldehyde to HCHO from vehicles using other fuels.

VI. Conclusions

This CNG vehicle test evaluation program was useful in the characterization of late model CNG vehicle emissions, fuel economy and performance for comparison to vehicle operation on other fuels. Some of the more significant findings of this study are listed below:

1. CNG vehicle calibration techniques are critical to low emission performance. For example, the Crown Victoria in its as received condition was calibrated by the supplier and yet had CO emission levels much higher than expected on CNG, so high that they exceed the current CO standard. The vehicle exhibited no overt driveability problems while operating in this condition. The vehicle was recalibrated on an emission test chassis rolls and in its second configuration demonstrated a reduction in CO over the gasoline emission level.

2. Further work in the optimization of dual-fuel vehicle calibration is needed for the efficient, clean, and effective use of both fuels in light-duty vehicles. Effective feedback fuel metering using CNG may be necessary.

3. Methane analyzer calibration using a series of span gases could improve the results. Constructing such a multipoint calibration curve would make methane analysis more like the analysis used for the other gaseous pollutants.

VII. Acknowledgements

The author would like to acknowledge Jeff Seisler (AGA), Roberta Nichols (Ford), Rich Polich (Consumers Power), James Magan (Total Fuels), Chris Bruch (Garretson), Tom Minerick (Wisconsin Gas) and Bill Lampert (MichCon) for their assistance and cooperation in vehicle and CNG fuel acquisition required for this test program. The author also wishes to recognize Ernestine Bulifant, Bob Moss and Ray Ouillette for their efforts in administering the vehicle tests and assisting with the sampling and analysis of emissions test data, and Marilyn Alff for assisting in the report preparation.

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IX. APPENDIX

Test Number	GAS ANL DATE	Vehicle	Test Type	BTU/g	HC Den for MPG	HC den (emiss)	Methane percent	Density	Total HC	<--- Method 1	NON METHANE HC Method 2	Method 3	---> Method 4	HCHO mg/mi	CO g/mi	CO2 g/mi	NOx g/mi	GEFE mpg
881059	11-18-87	DELTA 88	FTP	42.8	20.9	19.3	96.3	18.89	2.41				0.08	2.46	1.3	525	1.1	13.6
881061	11-18-87	DELTA 88	FTP	42.8	20.9	19.3	96.3	18.89	3.07				0.10	7.63	2.0	435	1.1	16.2
881125	11-18-87	DELTA 88	FTP	42.8	20.9	19.3	96.3	18.89	1.89				0.06	4.38	1.8	431	1.3	16.5
AVG.	11-18-87	DELTA 88	FTP						2.46				0.08	4.82	1.7	464	1.2	15.3
881060	11-18-87	DELTA 88	HFET	42.8	20.9	19.3	96.3	18.89	0.64				0.02	7.42	0.8	268	1.0	26.7
881062	11-18-87	DELTA 88	HFET	42.8	20.9	19.3	96.3	18.89	1.03				0.03	7.40	1.6	266	1.2	26.7
AVG.	11-18-87	DELTA 88	HFET						0.84				0.03	7.41	1.2	267	1.1	26.7
881034	HO	DELTA 88	FTP						0.45	0.38		0.37		4.54	12.1	666	0.3	12.9
881032	HO	DELTA 88	FTP						0.24	0.16		0.15		3.17	2.4	573	0.6	15.4
881126	HO	DELTA 88	FTP						0.52	0.44		0.43		4.38	15.1	657	0.3	13.0
AVG.	HO	DELTA 88	FTP						0.40	0.33		0.32		4.03	9.8	632	0.4	13.7
881032	HO	DELTA 88	HFET						0.12	0.09		0.09		7.46	2.5	351	0.2	25.0
881033	HO	DELTA 88	HFET						0.05	0.03		0.03		7.40	0.9	346	0.3	25.5
881147	HO	DELTA 88	HFET						0.08	0.05		0.05		7.42	2.3	351	0.3	25.0
AVG.	HO	DELTA 88	HFET						0.08	0.06		0.06		7.43	1.9	349	0.3	25.2
881584	11-18-87	RANGER	FTP	42.8	20.9	19.3	96.3	18.89	1.38	0.25	0.12	0.16	0.05	--	0.1	333	2.0	21.5
881585	11-18-87	RANGER	FTP	42.8	20.9	19.3	96.3	18.89	1.36	0.23	0.10	0.14	0.05	3.73	<0.1	330	2.0	21.7
881598	11-18-87	RANGER	FTP	42.8	20.9	19.3	96.3	18.89	1.36	0.23	0.09	0.14	0.05	8.46	<0.1	327	2.0	21.9
881730	11-18-87	RANGER	FTP	42.8	20.9	19.3	96.3	18.89	1.36	0.24	0.10	0.15	0.05	7.08	0.1	326	2.0	21.9
881731	02-26-88	RANGER	FTP	42.3	21.6	20.4	91.3	18.89	1.34	0.00	0.00	0.00	0.11	4.01	<0.1	326	1.9	22.2
AVG.	11-18-87	RANGER	FTP						1.36	0.19	0.08	0.12	0.06	4.66	<0.1	328	2.0	21.8
881586	11-18-87	RANGER	HFET	42.8	20.9	19.3	96.3	18.89	0.78	0.13	0.05	0.07	0.03	0.56	<0.1	250	2.5	28.7
881632	11-18-87	RANGER	HFET	42.8	20.9	19.3	96.3	18.89	0.79	0.13	0.05	0.07	0.03	2.20	<0.1	251	2.4	28.6
AVG.	11-18-87	RANGER	HFET						0.78	0.13	0.05	0.07	0.03	1.38	<0.1	251	2.5	28.6
882636	03-16-88	CRN VIC 1	FTP	43.5	20.8	19.9	94.5	18.89	3.68	0.04	0.00	0.00	0.18	6.03	6.7	432	0.6	15.7
882658	03-16-88	CRN VIC 1	FTP	43.5	20.8	19.9	94.5	18.89	2.68	0.00	0.00	0.00	0.13	3.16	2.5	433	0.6	16.0
882660	03-16-88	CRN VIC 1	FTP	43.5	20.8	19.9	94.5	18.89	3.22	0.04	0.00	0.00	0.16	2.63	3.8	422	0.7	16.3
AVG.	03-16-88	CRN VIC 1	FTP						3.19	0.03	0.00	0.00	0.16	3.94	4.3	429	0.7	16.0
882637	03-16-88	CRN VIC 1	HFET	43.5	20.8	19.9	94.5	18.89	1.71	0.05	0.00	0.00	0.08	1.08	6.9	337	0.3	20.2
882659	03-16-88	CRN VIC 1	HFET	43.5	20.8	19.9	94.5	18.89	1.38	0.00	0.00	0.00	0.07	2.65	4.2	341	0.5	20.3
AVG.	03-16-88	CRN VIC 1	HFET						1.55	0.03	0.00	0.00	0.08	1.87	5.6	339	0.4	20.2
882863	03-16-88	CRN VIC 2	FTP	43.5	20.8	19.9	94.5	18.89	3.52	0.12	0.00	0.00	0.17	5.79	0.6	419	0.9	16.6
882865	03-16-88	CRN VIC 2	FTP	43.5	20.8	19.9	94.5	18.89	3.77	0.20	0.00	0.01	0.19	6.62	<0.1	418	0.9	16.6
882866	03-16-88	CRN VIC 2	FTP	43.5	20.8	19.9	94.5	18.89	3.53	0.15	0.00	0.00	0.17	5.31	1.1	415	1.0	16.7
883073	03-16-88	CRN VIC 2	FTP	43.5	20.8	19.9	94.5	18.89	3.38	0.11	0.00	0.00	0.17	5.74	0.1	416	0.9	16.7
AVG.	03-16-88	CRN VIC 2	FTP						3.55	0.15	0.00	0.00	0.18	5.87	0.4	417	0.9	16.7
882864	03-16-88	CRN VIC 2	HFET	43.5	20.8	19.9	94.5	18.89	2.08	0.16	0.00	0.06	0.10	8.18	<0.1	371	1.6	18.9
883046	03-16-88	CRN VIC 2	HFET	43.5	20.8	19.9	94.5	18.89	2.07	0.14	0.00	0.03	0.10	3.76	<0.1	358	1.5	19.6
AVG.	03-16-88	CRN VIC 2	HFET						2.07	0.15	0.00	0.05	0.10	5.97	<0.1	365	1.5	19.2

Test	GAS ANL	Vehicle	Test	BTU/g	HC Den	HC den	Methane		Total	<---	NON METHANE HC		--->	HCHO	CO	CO2	NOx	GEFE
Number	DATE		Type		for MPG	(emiss)	percent	Density	HC	Method 1	Method 2	Method 3	Method 4	mg/mi	g/mi	g/mi	g/mi	mpg
882678	HO	CRN VIC	FTP						0.35	0.26		0.25		2.78	1.2	587	1.1	15.0
882676	HO	CRN VIC	FTP						0.33	0.24		0.22		2.80	1.2	580	1.1	15.2
883072	HO	CRN VIC	FTP						0.38	0.26		0.24		5.36	1.7	579	1.1	15.2
AVG.	HO	CRN VIC	FTP						0.35	0.25		0.23		3.65	1.4	582	1.1	15.1
882734	HO	CRN VIC	HFET						0.06	0.03		0.03		1.69	0.1	456	0.7	19.4
882677	HO	CRN VIC	HFET						0.07	0.04		0.03		1.62	0.1	455	0.6	19.5
AVG.	HO	CRN VIC	HFET						0.06	0.03		0.03		1.66	0.1	456	0.7	19.4
883243	04-29-88	CELEBRTY1	FTP	43.2	21.4	20.3	93.5	18.89	1.38	0.00	0.00	0.00	0.08	3.30	8.0	331	0.7	20.6
883245	04-29-88	CELEBRTY1	FTP	43.2	21.4	20.3	93.5	18.89	1.28	0.00	0.00	0.00	0.07	1.74	2.0	326	1.1	21.6
883510	04-29-88	CELEBRTY1	FTP	43.2	21.4	20.3	93.5	18.89	1.40	0.00	0.00	0.00	0.08	3.86	0.1	327	1.5	21.7
883527	04-29-88	CELEBRTY1	FTP	43.2	21.4	20.3	93.5	18.89	1.91	0.06	0.00	0.00	0.11	2.85	0.1	430	3.2	16.5
AVG.	04-29-88	CELEBRTY1	FTP						1.49	0.01	0.00	0.00	0.09	2.94	2.6	354	1.6	19.8
883244	04-29-88	CELEBRTY1	HFET	43.2	21.4	20.3	93.5	18.89	0.83	0.04	0.00	0.01	0.05	0.00	9.3	251	0.6	26.8
883246	04-29-88	CELEBRTY1	HFET	43.2	21.4	20.3	93.5	18.89	0.64	0.00	0.00	0.00	0.04	0.61	1.1	256	2.4	27.6
883511	04-29-88	CELEBRTY1	HFET	43.2	21.4	20.3	93.5	18.89	0.70	0.00	0.00	0.00	0.04	2.60	<0.1	251	2.7	28.3
883528	04-29-88	CELEBRTY1	HFET	43.2	21.4	20.3	93.5	18.89	0.72	0.00	0.00	0.00	0.04	2.08	<0.1	250	2.6	28.5
AVG.	04-29-88	CELEBRTY1	HFET						0.72	0.01	0.00	0.00	0.04	1.32	2.6	252	2.1	27.8
883247	HO	CELEBRTY1	FTP						0.43	0.41		0.40		4.85	0.6	439	0.6	20.1
883249	HO	CELEBRTY1	FTP						0.26	0.24		0.23		3.96	1.4	430	0.6	20.5
883541	HO	CELEBRTY1	FTP						0.35	0.33		0.32		5.44	0.7	436	0.7	20.2
AVG.	HO	CELEBRTY1	FTP						0.35	0.32		0.32		4.41	1.0	435	0.6	20.3
883248	HO	CELEBRTY1	HFET						0.01	0.01		0.01		0.38	<0.1	335	0.7	26.5
883250	HO	CELEBRTY1	HFET						0.01	0.01		0.01		1.04	<0.1	334	0.5	26.5
883542	HO	CELEBRTY1	HFET						0.02	0.01		0.01		0.74	<0.1	336	0.7	26.4
AVG.	HO	CELEBRTY1	HFET						0.02	0.01		0.01		0.72	<0.1	335	0.6	26.5
883848	HO	CELEBRTY2	FTP						0.29	0.26		0.26		5.54	1.4	433	0.6	20.3
883852	HO	CELEBRTY2	FTP						0.23	0.23		0.23		6.06	1.1	435	0.6	20.3
AVG	HO	CELEBRTY2	FTP						0.26	0.25		0.24		5.80	1.25	434	0.6	20.3
883849	HO	CELEBRTY2	HFET						0.02	0.02		0.01		1.20	0.1	342	0.3	25.9
883853	HO	CELEBRTY2	HFET						0.01	0.01		0.01		0.82	0.1	342	0.3	25.9
AVG.	HO	CELEBRTY2	HFET						0.02	0.02		0.01		1.01	0.1	342	0.3	25.9
883920	05-31-88	CELEBRTY2	FTP	43.1	21.4	20.3	93.5	18.89	1.48	0.00	0.00	0.00	0.09	3.66	<0.1	325	1.2	21.8
883966	05-31-88	CELEBRTY2	FTP	43.1	21.4	20.3	93.5	18.89	1.56	0.29	0.14	0.28	0.09	4.62	0.0	323	1.2	22.0
883967	05-31-88	CELEBRTY2	FTP	43.1	21.4	20.3	93.5	18.89	1.62	0.00	0.00	0.00	0.09	4.65	0.0	323	1.2	21.9
AVG.		CELEBRTY2	FTP						1.55	0.10	0.05	0.09	0.09	4.31	0.0	324	1.2	21.9
883921	05-31-88	CELEBRTY2	HFET	43.1	21.4	20.3	93.5	18.89	0.79	0.00	0.00	0.00	0.05	0.90	0.0	250	2.1	28.5
884051	05-31-88	CELEBRTY2	HFET	43.1	21.4	20.3	93.5	18.89	0.76	0.00	0.00	0.00	0.04	2.34	0.0	250	2.2	28.5
AVG.		CELEBRTY2	HFET						0.78	0.00	0.00	0.00	0.05	1.62	0.0	250	2.2	28.5

COMPARISON OF PROPERTIES OF CNG, LNG, LPG, AND GASOLINE

	CNG		LNG		LPG		Gasoline	
Typical composition	Methane, 90% Ethane, 10%		Methane, 90% Ethane, 10%		Propane, 95% Propylene, 5%		C_4 to C_{12} hydrocarbons	
State of fuel as stored on vehicle	Gas		Liquid[a]		Liquid		Liquid	
Pressure as stored on vehicle, kPa (psi)	13.8	(2,000)	0.21-0.41	(30-60)	1.4	(200)	Atmospheric	
Weight as stored on vehicle, kg/liter (lb/gal)	0.1	(1.4)	0.43	(3.6)	0.50	(4.2)	0.73-0.78	(6-6.5)
Heat content as stored: mJ/liter (Btu/gal)	8.4	(30,000)	21.5	(77,000)	23.3	(83,500)	32.2	(115,800)
Specific gravity of vapor at STP (air = 1)	0.55		0.55		1.55		4.25	
Self-ignition temperature, °C (°F)	705	(1,300)	705	(1,300)	510	(950)	460	(860)
Stoichiometric A/F, by weight	17		17		15.7		15	
Octane number (RON)	100+		110+		110+		90-100	

[a]Temperature, -161°C (-258°F)

Source : DOE

A-

GAS ANALYSIS REPORT

MICHIGAN CONSOLIDATED GAS COMPANY

DATE ANALYZED: 11-18-87 RUN NO. 87-676

SAMPLE INFORMATION

LOCATION:	ALLEN RD.STA.	CYLINDER I.D.	S.LAB.
REQUESTER:	P.PAI	SAMPLE #	
DEPARTMENT:	LAB.	SAMPLE POINT:	AUTO FILL STA.
FIELD:		SAMPLE DATE@TIME:	9-15-87
CITY,STATE:	DETROIT MI	SAMPLE RECEIVED:	9-15-87
PERMIT #		ATMOSPHERIC TEMP. (F):	
FORMATION:		GAS TEMP. (F):	
SYSTEM:		GAS PRESSURE (PSIG):	1500
OWNER:		WELLHEAD PRESSURE (PSIG):	
PURCHASER:		FLOW (MMCF/DAY):	
RELATED TESTS:		SAMPLED BY:	R.LAYNG

GAS ANALYSIS

		MOL %	WT. %
NITROGEN	N_2	0.41	0.68
CARBON DIOXIDE	CO_2	1.02	2.68
HELIUM		0.00	0.00
METHANE	CH_4	96.87	93.08
ETHANE	C_2H_6	1.29	2.32
PROPANE	C_3H_8	0.21	0.55
I-BUTANE		0.05	0.17
N-BUTANE	C_4H_{10}	0.04	0.13
I-PENTANE		0.02	0.08
N-PENTANE	C_5H_{12}	0.01	0.04
HEXANES	C_6H_{14}	0.02	0.10
HEPTANES	C_7H_{16}	0.02	0.11
OCTANES		0.01	0.06
HYDROGEN	H_2	0.03	0.00
TOTAL		100.00	100.00

3.824

H/C

GROSS HEATING VALUE (BTU/SCF)

14.734 SAT / 14.650 DRY

CALCULATED	1010
DETERMINED FIELD	
DETERMINED LAB	

.........SPECIFIC GRAVITY.........

CALCULATED SP. GR.	0.577
DETERMINED FIELD	
DETERMINED LAB	

.....SULFUR (AS H2S) GR/CCF.....

HYDROGEN SULFIDE	
MERCAPTANS	
SULFIDES	
RESIDUAL	
TOTAL SULFUR	

.............OTHER.............

HYDROCARBON LIQUID (GAL/MCF)	0.12
HYDROCARBON DEW POINT (F @ PSIG)	
WATER DEW POINT (F @ PSIG)	
Lbs. WATER / MMCF	

ANALYZED BY: N.MCEACHERN
APPROVED BY: G.EVANINAGE
DISTRIBUTION: P.PAI

REMARKS: SAMPLE TAKEN THROUGH CARBON FILTER

GAS ANALYSIS REPORT

MICHIGAN CONSOLIDATED GAS COMPANY

DATE ANALYZED: 2-23-88 RUN NO. 88-69

SAMPLE INFORMATION

LOCATION:	C.N.G.OUTLET	CYLINDER I.D.	
REQUESTER:	K.CZERWINSKI	SAMPLE #	
DEPARTMENT:	TECH.DEVELOP.	SAMPLE POINT:	NORTH EAST FI
FIELD:		SAMPLE DATE@TIME:	2-22-88@9200P
CITY,STATE:	MELVINDALE MI	SAMPLE RECEIVED:	2-22-88
PERMIT #		ATMOSPHERIC TEMP. (F):	
FORMATION:		GAS TEMP. (F):	
SYSTEM:		GAS PRESSURE (PSIG):	450
OWNER:		WELLHEAD PRESSURE (PSIG):	
PURCHASER:		FLOW (MMCF/DAY):	
RELATED TESTS:		SAMPLED BY:	N.MCEACHERN

GAS ANALYSIS

	MOL %	WT. %
NITROGEN	0.94	1.54
CARBON DIOXIDE	0.51	1.31
HELIUM	0.02	0.00
METHANE	94.20	88.74
ETHANE	3.84	6.77
PROPANE	0.21	0.54
I-BUTANE	0.09	0.27
N-BUTANE	0.07	0.23
I-PENTANE	0.03	0.12
N-PENTANE	0.02	0.08
HEXANES	0.02	0.10
HEPTANES	0.03	0.17
OCTANES	0.02	0.13
HYDROGEN	0.01	0.00
TOTAL	100.00	100.00

GROSS HEATING VALUE (BTU/SCF)

	14.734 SAT / 14.650 DRY
CALCULATED	/1032
DETERMINED FIELD	
DETERMINED LAB	

........SPECIFIC GRAVITY........	
CALCULATED SP. GR.	0.588
DETERMINED FIELD	
DETERMINED LAB	

.....SULFUR (AS H2S) GR/CCF.....	
HYDROGEN SULFIDE	
MERCAPTANS	
SULFIDES	
RESIDUAL	
TOTAL SULFUR	

.............OTHER.............	
HYDROCARBON LIQUID (GAL/MCF)	
HYDROCARBON DEW POINT (F @ PSIG)	
WATER DEW POINT (F @ PSIG)	
Lbs. WATER / MMCF	

ANALYZED BY: N.MCEACHERN
APPROVED BY: G.EVANINA *GE*
DISTRIBUTION: K.CZERWINSKI

REMARKS: SAMPLED AT ALLEN RD FILL STATION

GAS ANALYSIS REPORT

MICHIGAN CONSOLIDATED GAS COMPANY

DATE ANALYZED: 3-16-88 RUN NO. 88-102

SAMPLE INFORMATION

LOCATION:	CNG ALLEN RD.	CYLINDER I.D.	S.LAB.
REQUESTER:	K.CZERWINSKI	SAMPLE #	
DEPARTMENT:	TECH.DEVELOP.	SAMPLE POINT:	LOW PRES.RUN
FIELD:		SAMPLE DATE@TIME:	3-14-88@145PM
CITY,STATE:	DETROIT MI	SAMPLE RECEIVED:	3-14-88
PERMIT #		ATMOSPHERIC TEMP. (F):	
FORMATION:		GAS TEMP. (F):	
SYSTEM:		GAS PRESSURE (PSIG):	300
OWNER:		WELLHEAD PRESSURE (PSIG):	
PURCHASER:		FLOW (MMCF/DAY):	
RELATED TESTS:		SAMPLED BY:	N.MCEACHERN

GAS ANALYSIS

	MOL %	WT. %
NITROGEN	0.66	1.10
CARBON DIOXIDE	0.39	1.02
HELIUM	0.10	0.02
METHANE	96.24	92.47
ETHANE	2.05	3.68
PROPANE	0.36	0.94
I-BUTANE	0.07	0.24
N-BUTANE	0.06	0.20
I-PENTANE	0.02	0.08
N-PENTANE	0.01	0.04
HEXANES	0.02	0.10
HEPTANES	0.01	0.05
OCTANES	0.01	0.06
HYDROGEN	0.00	0.00
TOTAL	100.00	100.00

GROSS HEATING VALUE (BTU/SCF)

14.734 SAT / 14.650 DRY

CALCULATED	[illegible]/1021
DETERMINED FIELD	
DETERMINED LAB	

........SPECIFIC GRAVITY........

CALCULATED SP. GR.	0.577
DETERMINED FIELD	
DETERMINED LAB	

.....SULFUR (AS H2S) GR/CCF.....

HYDROGEN SULFIDE	
MERCAPTANS	
SULFIDES	
RESIDUAL	
TOTAL SULFUR	

.............OTHER..............

HYDROCARBON LIQUID (GAL/MCF)	
HYDROCARBON DEW POINT (F @ PSIG)	
WATER DEW POINT (F @ PSIG)	
Lbs. WATER / MMCF	

ANALYZED BY: N.MCEACHERN
APPROVED BY: G.EVANINA GE
DISTRIBUTION: K.CZERWINSKI+P.PAI

REMARKS: FILLING HIGH PRESSURE TANKS (During filling)
Filling started at 12:30 PM

GAS ANALYSIS REPORT

MICHIGAN CONSOLIDATED GAS COMPANY

DATE ANALYZED: 5-4-88 RUN NO. 88-207

SAMPLE INFORMATION

LOCATION:	CNG TANK FARM	CYLINDER I.D.	S.LAB.
REQUESTER:	B.LAMPORT	SAMPLE #	1
DEPARTMENT:	S.FUELS	SAMPLE POINT:	WIS-ERG TRUCK
FIELD:	ALLEN RD.STA.	SAMPLE DATE@TIME:	4-29-88@900AM
CITY,STATE:	MELVINDALE MI	SAMPLE RECEIVED:	4-29-88
PERMIT #		ATMOSPHERIC TEMP. (F):	
FORMATION:		GAS TEMP. (F):	
SYSTEM:		GAS PRESSURE (PSIG):	1100
OWNER:		WELLHEAD PRESSURE (PSIG):	
PURCHASER:		FLOW (MMCF/DAY):	
RELATED TESTS:		SAMPLED BY:	H.WENZEL

GAS ANALYSIS

	MOL %	WT. %
NITROGEN	0.73	1.21
CARBON DIOXIDE	0.50	1.30
HELIUM	0.01	0.00
METHANE	95.58	91.13
ETHANE	2.60	4.64
PROPANE	0.41	1.07
I-BUTANE	0.06	0.20
N-BUTANE	0.05	0.17
I-PENTANE	0.02	0.08
N-PENTANE	0.01	0.04
HEXANES	0.01	0.05
HEPTANES	0.01	0.05
OCTANES	0.01	0.06
HYDROGEN	0.00	0.00
TOTAL :	100.00	100.00

GROSS HEATING VALUE (BTU/SCF)

	14.734 SAT / 14.650 DRY
CALCULATED	/1025
DETERMINED FIELD	
DETERMINED LAB	
........SPECIFIC GRAVITY........	
CALCULATED SP. GR.	0.581
DETERMINED FIELD	
DETERMINED LAB	
.....SULFUR (AS H2S) GR/CCF.....	
HYDROGEN SULFIDE	
MERCAPTANS	
SULFIDES	
RESIDUAL	
TOTAL SULFUR	
.............OTHER.............	
HYDROCARBON LIQUID (GAL/MCF)	
HYDROCARBON DEW POINT (F @ PSIG)	
WATER DEW POINT (F @ PSIG)	
Lbs. WATER / MMCF	

ANALYZED BY: N.MCEACHERN
APPROVED BY: G.EVANINA GE
DISTRIBUTION: B.LAMPORT+K.CZERWINSKI ✓

REMARKS:

GAS ANALYSIS REPORT

MICHIGAN CONSOLIDATED GAS COMPANY

DATE ANALYZED: 6-1-88 RUN NO. 88-241

SAMPLE INFORMATION

LOCATION:	CNG TANK FARM	CYLINDER I.D.	S.LAB.
REQUESTER:	B.LAMPORT	SAMPLE #	2
DEPARTMENT:	SYS.FUELS	SAMPLE POINT:	WIS-EPA TRUCK
FIELD:		SAMPLE DATE@TIME:	5-31-88@200PM
CITY,STATE:	MELVINDALE MI	SAMPLE RECEIVED:	6-1-88
PERMIT #		ATMOSPHERIC TEMP. (F):	
FORMATION:		GAS TEMP. (F):	
SYSTEM:		GAS PRESSURE (PSIG):	1000
OWNER:		WELLHEAD PRESSURE (PSIG):	
PURCHASER:		FLOW (MMCF/DAY):	
RELATED TESTS:		SAMPLED BY:	H.WENZEL

GAS ANALYSIS

	MOL %	WT. %
NITROGEN	0.59	0.98
CARBON DIOXIDE	0.58	1.51
HELIUM	0.01	0.00
METHANE	95.67	91.19
ETHANE	2.55	4.55
PROPANE	0.43	1.12
I-BUTANE	0.06	0.20
N-BUTANE	0.05	0.17
I-PENTANE	0.02	0.08
N-PENTANE	0.01	0.04
HEXANES	0.01	0.05
HEPTANES	0.01	0.05
OCTANES	0.01	0.06
HYDROGEN	0.00	0.00
TOTAL	100.00	100.00

GROSS HEATING VALUE (BTU/SCF)

14.734 SAT / 14.650 DRY

CALCULATED	1025
DETERMINED FIELD	
DETERMINED LAB	

.........SPECIFIC GRAVITY.........

CALCULATED SP. GR.	0.581
DETERMINED FIELD	
DETERMINED LAB	

.....SULFUR (AS H2S) GR/CCF.....

HYDROGEN SULFIDE
MERCAPTANS
SULFIDES
RESIDUAL
TOTAL SULFUR

..............OTHER..............

HYDROCARBON LIQUID (GAL/MCF)
HYDROCARBON DEW POINT (F @ PSIG)
WATER DEW POINT (F @ PSIG)
Lbs. WATER / MMCF

ANALYZED BY: N.MCEACHERN
APPROVED BY: G.EVANINA GE
DISTRIBUTION: B.LAMPORT+K.CZERWINSKI

REMARKS:

December 3, 1987

CNG FUEL SYSTEMS

Consumers Power
212 West Michigan Avenue
Jackson, Michigan
49201 U.S.A.

Attention: Mr. Richard Polich

Dear Mr. Polich;

I am writing with regard to the 1984 Oldsmobile Delta 88 Royale that CNG Fuel Systems is providing for emissions testing at Ann Arbor. As you know, that vehicle is equipped with our experimental GEN II NGV fueling system. We hope it will expand the knowledge of NGV technology.

As you know, CNG Fuel Systems' Board of Directors has elected to close the company. Accordingly, we have no vested interest in the results of this test work, other than altruism.

We have performed several FTP tests on the vehicle before releasing it for these tests. While the tests were not exhaustive, they are informative, and are summarized below.

Test	Fuel	Ignition Timing	Wtd. Emissions (g/mi) Est. nmHc	HC	CO	NO_x	ENERGY USE MJ/100 Km
STD.			.39	.41	3.4	1.0	-
FTP	Gasoline	Gasoline	.10	.13	4.8	.71	504
	NGV	"	.18	.74	1.2	.58	529
HOT 505	Gasoline	"	.09	.12	8.1	.64	463
	NGV	"	.12	.48	2.2	.69	469
	NGV	NGV +12°	.17	.72	3.9	1.07	463

NOTE: NGV installations typically use the +12° timing

NOTE: Non-methane hydrocarbons (nmHC) are estimated values

These results verify several points that we have made in our recent papers.

1. Current aftermarket practice of advancing the NGV mode timing significantly increases NO_x and may cause vehicles to exceed the NO_x standard on NGV. More development work is required to learn how to advance the timing without sacrificing NO_x. Likely solutions include even better closed loop control in the NGV

2150 Steeles Ave. East, Brampton, Ontario, Canada L6T 1A7 (416) 793-3560 Telex 06-988548

mode to raise the catalyst's NO_x conversion efficiency, and a more sophisticated NGV mode ignition control system that provides less aggressive spark advance in the sensitive driving modes for urban emissions.

In order to allow the EPA to independently evaluate spark angle effects on NGV mode emissions, we have equipped the car with an underhood switch to select either gasoline or NGV mode timing. We hope the EPA will evaluate both modes.

2. The HC emissions on NGV may exceed the standard for total hydrocarbons yet be far below a non-methane standard. Ultimately, either NGV vehicles would need to be evaluated against a nmHC standard, or further development work must be performed to reduce methane exhaust emissions.

   Work that we have done indicates that very precise closed loop control about stoichiometry may be able to provide total hydrocarbon levels equal to gasoline's (i.e. well below the standard). We feel that achieving that exceptionally tight air fuel ratio control is feasible for an aftermarket system. At our current level of development, we may need refinements in the NGV metering device and closed loop control (i.e. the dynamic loop; the volatile and keep alive adaptive memories).

3. We believe that the GEN II experimental system currently can provide NGV mode emissions compatible with the U.S. emissions standards.

4. More NGV techology development is required.

The GEN II system installed on the car is a generic system aimed at aftermarket installation. This concept has a universal calibration which is further refined by the installer. Pointedly, this system would not have an engine specific "factory calibration" developed for new models. We feel that this universal concept is crucial if the NGV industry is to flourish.

If there are questions that arise on the car or our results, please feel free to contact me.

Sincerely,

Stephen A. Carter
Vice President
Conversions

cc: Mr. Jeff Allison (EPA)
Mr. Jeffery Seisler (AGA)
Mr. Peter Flynn (CNG Fuel Systems
Mr. Ulrich Oester (CNG Fuel Systems)

CNG FUEL SYSTEMS

SAC/dj

Table 1 - Ford Ranger Exhaust Emissions

(Grams Per Mile)

	HC	CO	NO_x
Federal Standards < 8500 GVW	0.8	10.0	2.3
Gasoline Ranger (1984) 1/	0.31*	3.2	1.1
Natural Gas Ranger (1984) 2/	1.20**	0.03	1.9

* Total HC emissions
** These HC's are 88% CH_4

1/ Emission levels of a typical 1984, 49 state low mileage Ranger.

2/ Single vehicle test at low mileage.

The replacement of a dirty air filter corrected one and the other was cured by the replacement of the fuel priming circuit board.

- Power steering pump rattle - One of the participants reported severe engine knock at 3500 rpm. Investigation disclosed the "knock" was due to excessive end play in the power steering pump shaft. Replacement of the pump eliminated the noise.

Proponents of natural gas powered vehicles have claimed reduced maintenance costs, especially in the areas of engine oil and spark plug life. While there is no evidence that a natural gas powered vehicle requires more maintenance, there is also no evidence that it requires less. Although natural gas leaves no lead, carbon or varnish deposits in the oil, the oil will still gradually thicken and the additives and inhibiters will break down even though it remains clear. Until conclusive tests are conducted, it is recommended that the oil be changed at the regular service intervals.

The absence of lead salts and carbon build-up from the combustion of natural gas should mean that spark plugs will last longer than in gasoline engines. However, with a current life of 48,000 km (30,000 mi), it is too early to tell, based on the lease fleet experience if spark plug life will be noticeably increased. Either way, spark plugs are not seen as a major factor in maintenance costs.

INCREMENTAL COSTS

The primary cost difference between the natural gas powered Ranger and the gasoline powered Ranger is due to the expense of the natural gas fuel cylinders. The cost savings from the elimination of the fuel tank and the carburetor from the gasoline powered engine are offset by the cost of regulator, fuel mixer and natural gas cylinder mounting brackets.

In mass production, the cost of the natural gas engine, including further refinements for natural gas operation, would be about the same as a gasoline engine. The fuel tanks are significantly more expensive than gasoline tanks and would remain one of the major cost issues with a natural gas powered vehicle. The present estimated cost for an after-market conversion of an internal combustion vehicle to operate on natural gas is $1500. It is anticipated that the cost premium for a high volume factory-engineered version could be approximately one-half as much. Based on current fuel prices, the price differential could be amortized in about three years.

CONCLUSIONS

Vehicle operation utilizing natural gas as a fuel offers the potential for substantial cost savings. Because public refueling stations for natural gas virtually do not exist at present in the United States, natural gas operation is probably confined to the fleet operator although the home refueling option utilizing residential gas is understudy. Based on Ford's experience to date with compressed natural gas vehicles it is concluded that:

- There are no unresolvable technological issues that would prevent motor vehicles from operating efficiently and economically on natural gas.
- Single fueled vehicles, optimized for compressed natural gas operation, provide better fuel efficiency and performance than dual fuel vehicles, with acceptable range for most fleet operation. The additional tank volume required for operating range reduces the vehicle carrying capacity and volume.
- In mass production, the cost of a natural gas engine would be about the same as a