Section 2

LIGHT-DUTY VEHICLES

NATURAL GAS

Fuel Description

Natural gas is a mixture of several gases (methane, propane, ethane, butane, carbon dioxide, nitrogen, etc.) with methane being the primary (typically exceeding 90% of the total) constituent. After coal, natural gas is the most abundant fossil fuel.[1] Total U.S. gas reserves exceed 1,000 trillion cubic feet, which is more than a 50-year supply at current consumption rates.[2] Natural gas is traditionally removed from wells drilled in or near oil fields. Newer reserves are being discovered using deep wells and wells tapping coal beds, as well as shale and tar sand deposits. Ninety-two percent of the natural gas used in the U.S. comes from domestic sources. The remaining eight percent comes almost entirely from Canada, which also has large reserves of natural gas.[3] Large reserves also exist outside of North America in Russia, Kazakhstan, Iran, and Indonesia.[2] Once removed from the ground, impurities (primarily water and hydrogen sulfide) and heavier hydrocarbons such as butane and propane are removed and the gas is transported by a pipeline network to where it is needed.

New York State gets its natural gas via pipelines fed primarily by gas wells in states such as Texas, Louisiana, Oklahoma, and Kansas. New York State also receives natural gas from Canada (some of which originates in the U.S.), and produces some indigenous natural gas from small pockets located mostly in the western part of the State. These indigenous sources are difficult to develop economically compared to the large natural gas fields in the major natural-gas-producing states.

Figure 2.1 shows the transmission pipeline network in New York State.[4] The natural gas used as a vehicle fuel is like the gas supplied to other customers for cooking, heating, industrial processing, etc., and is odorized so

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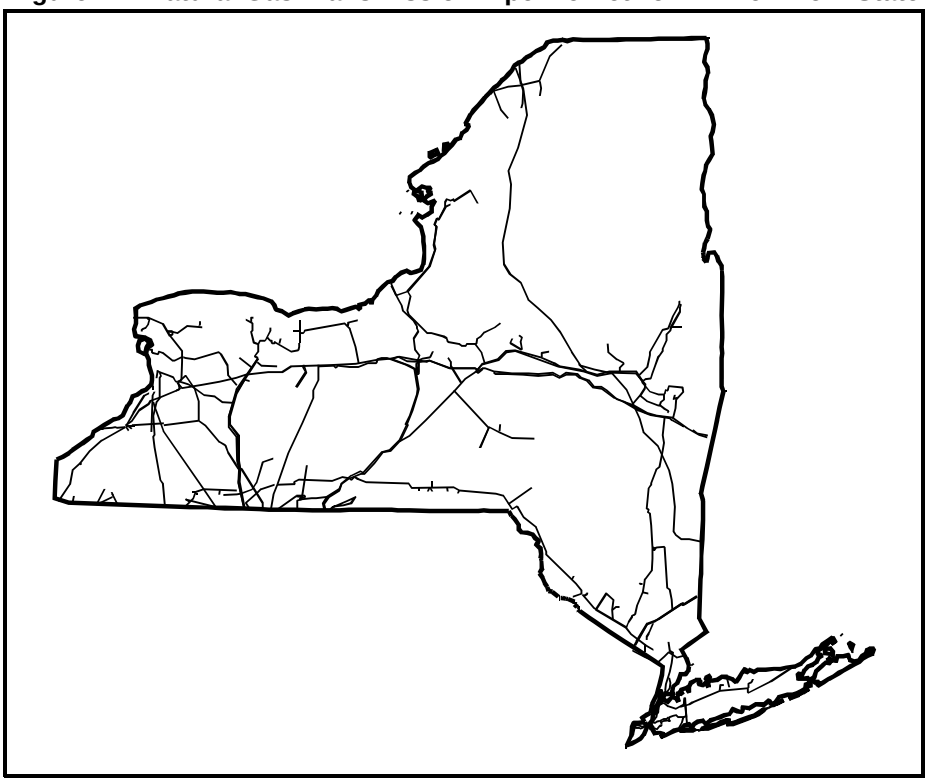
[1] Owen, Keith and Coley, Trevor, Automotive Fuels Reference Book, Second Edition, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001, 1995.

[2] Energy Planning Board, New York State Energy Plan-Volume III: Supply Assessments, October 1994.

[3] "Annual Energy Outlook - 1994 - With Projections to 2010," the Energy Information Administration of the U.S. Department of Energy, DOE/EIA-0383(94), January 1994.

[4] Map based on New York Gas Group Gas Transmission Pipelines 1989, The National Survey 1989.

Figure 2.1 Natural Gas Transmission Pipeline Network in New York State



fuel leaks are readily detectable. In the past several years natural gas use in New York State has increased with an increase in pipeline capacity. Since 1989, summer natural gas delivery capacity in New York state has increased more than 40% while winter capacity has grown 23%. Future planned pipeline expansion is expected to slow, while demand is expected to continue to increase. This should lead to a balance between supply and demand. The State Energy Plan projects supply in 2012 to be 1,436 bcf/yr (billion cubic feet per year), while demand should be between 1,301 bcf/yr and 1,436 bcf/yr.[2]

Fuel Properties

Natural gas is generally considered non-toxic, and methane, its primary constituent, is a simple asphyxiant. Coal miners inhale concentrations of up to 9% methane in air without any apparent ill effects. Natural gas has a higher percentage of hydrogen in its composition than any other hydrocarbon fuel. This high percentage of hydrogen has inherent combustion and emissions advantages. Natural gas has an octane rating of approximately 130, which is higher than that of gasoline (typically 87-93; see Table 2.1). This allows engines designed exclusively for natural gas use to have higher compression ratios, increasing overall efficiency. The high autoignition temperature of natural gas is a benefit to safety, though being a gas has both safety advantages and disadvantages.

Table 2.1 Comparison of Typical Natural Gas to Conventional Fuels

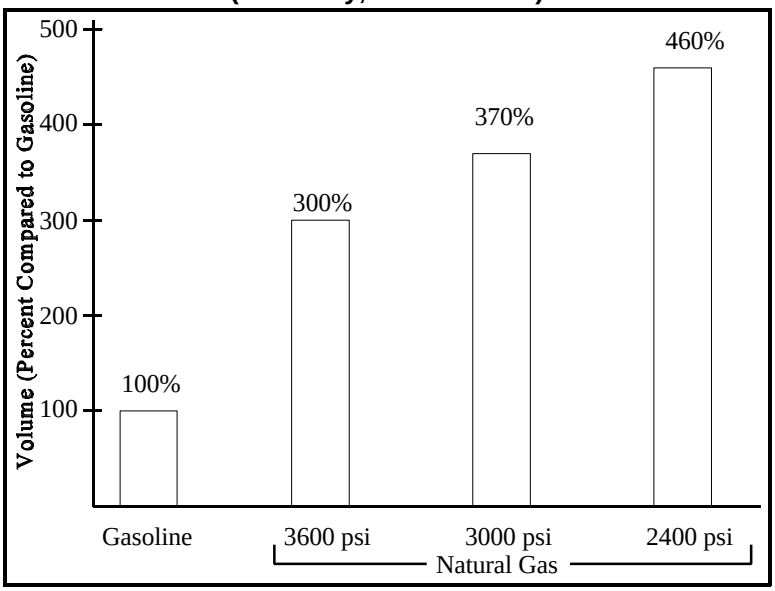
Fuel Property	Natural Gas[1]	Gasoline	Diesel
Molecular Weight	16	100 to 105	≈200
Methane Content, Percent	95 to 97[2]	0	0
Composition, Weight % Carbon Hydrogen Oxygen	 75 25 0	 85 to 88 12 to 15 0 to 4	 84 to 87 13 to 16 0
Weight, lb/gal	5.1 to 5.8[5]	6.0 to 6.5	6.7 to 7.4
Boiling Point, °F	-260	80-437	300-650
Lower Heating Value, Btu	925-950/scf[3]	109,000-119,000 per gallon	124,000-130,000 per gallon
Octane Rating, (R+M)/2	130	87-93	NA
Autoignition Temperature, °F	1004	495[4]	480[4]

[1] Assumes pure methane, except where noted
[2] Typical values for natural gas in New York State
[3] scf means standard cubic feet, the common measure for natural gas
[4] Nominal, varies with grade and composition
[5] Range of values typical for natural gas in New York State. The National Conference on Weights and Measures has proposed an equivalence of 5.66 pounds as the amount of natural gas that would take a vehicle as far as one gallon of gasoline.

Use of natural gas as a vehicle fuel creates challenges in vehicle and fuel station design. Methane, even when pressurized, cannot be stored as a liquid at normal temperatures (the highest temperature it can remain in the liquid state is -116°F[5]). Natural gas is usually stored on-board vehicles at between 2,400 and 3,600 psi with 3,000 psi the most common pressure used. Even with high storage pressure the volume of fuel storage needed is between three and five times that needed for gasoline, as illustrated in Figure 2.2. To contain the high pressures, heavy cylindrical tanks are used. The larger storage volume required, along with the non-conformable fuel tank shape, make it difficult to install compressed natural gas (CNG) cylinders on vehicles without a negative impact on available cargo and passenger volume. To reduce the weight of CNG tanks, manufacturers in recent years have introduced lighter materials. To store the CNG equivalent of 10 gallons of gasoline, steel-reinforced (steel wrapped with Kevlar® or similar high-strength reinforcing bands) CNG cylinders would weigh about 260 pounds, aluminum-reinforced CNG cylinders would weigh about 220 pounds, and all-composite (made from combinations of carbon fiber and other advanced materials) cylinders

[5] Compressed Gas Association, Handbook of Compressed Gases, Second Edition, 1981.

Figure 2.2 Volume Needed to Store Equal Amounts of Energy, CNG Compared to Gasoline (Fuel Only, No Hardware)



would weigh about 110 pounds. (Figure 2.3 illustrates the typical difference in CNG cylinder weight with type of material.) The cost of steel-reinforced cylinders to store the equivalent of 10 gallons of gasoline would be about $1,000, versus about $1,500 for aluminum-reinforced cylinders and about $1,250 for all-composite cylinders (see Figure 2.4). Figure 2.5 shows how a two-cylinder CNG fuel system was installed in New York State Department of Environmental Conservation (NYSDEC) Ford pickup trucks.

By comparison, the empty weight of a 10-gallon gasoline tank is only 20 to 30 pounds (depending on the shape of the tank and the material used), and its cost is relatively very low.

Figure 2.3 Typical CNG Cylinder Weights Per Gallon Storage Volume (3,600 psi Cylinders)

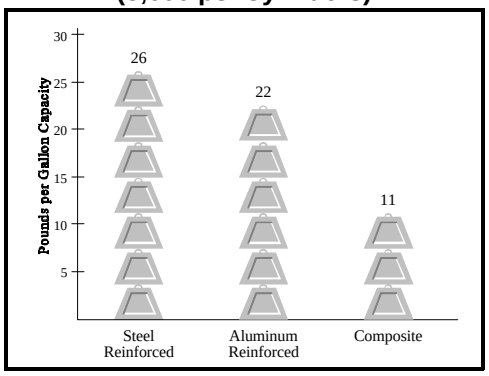


Figure 2.4 Typical CNG Cylinder Cost Per Gallon Capacity (3,600 psi Cylinders)

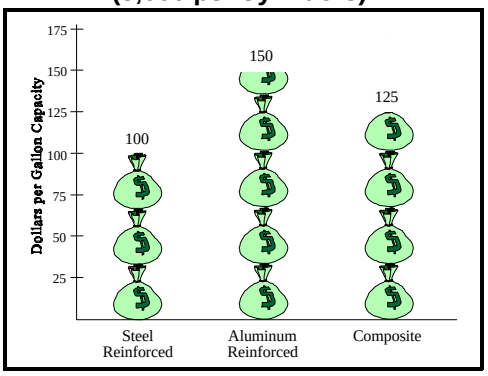
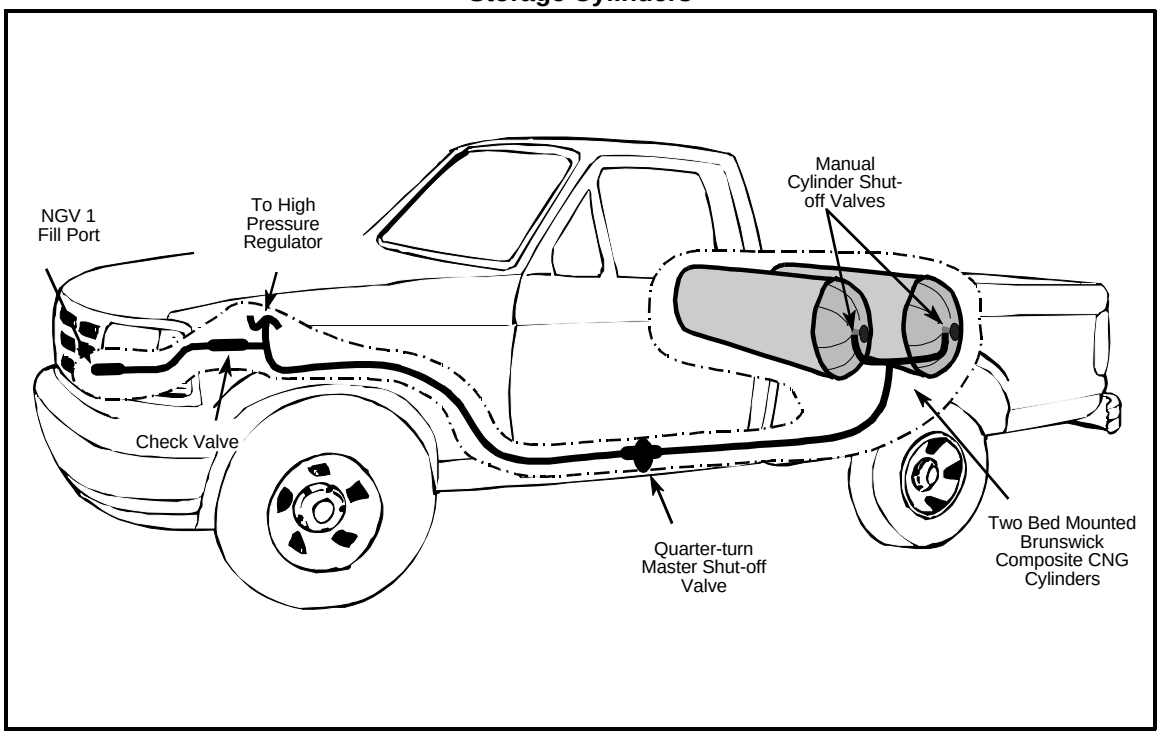


Figure 2.5 Ford F150 Pickup Truck Operated by the NYSDEC Showing Installation of Fuel Storage Cylinders



Emissions Reactivity

By itself, methane is estimated to have only about 15% of the reactivity of hydrocarbons from typical gasoline. One study has estimated that the exhaust hydrocarbon emissions from a typical gasoline automobile are capable of producing nearly twice as much ozone as those from a typical CNG vehicle.[6] In addition, evaporative, running loss, and refueling emissions of late-model gasoline vehicles are estimated to be nearly 50% higher than their exhaust hydrocarbon emissions.[7] Overall, dedicated CNG vehicles are estimated to have ozone-forming potential that is 80 to 85% lower than gasoline vehicles. Bifuel vehicles should have from one-half to three-quarters of the ozone-forming potential of gasoline vehicles, because the gasoline carried by bifuel vehicles causes evaporative, running loss, and refueling emissions.

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[6] Whitney, K.A. and B.K. Bailey, "Determination of Combustion Products from Alternative Fuels-Part I: LPG and CNG Combustion Products," SAE Paper 941903, SAE International, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001.

[7] Evaporative emissions, and running and refueling losses for late-model gasoline vehicles were estimated using the EPA MOBILE5a model.

Bifuel vehicles with open-loop CNG fuel systems tend to have poor oxides of nitrogen (NO_x) emission characteristics because they do not maintain the proper air/fuel ratio for the three-way catalyst to effectively reduce NO_x emissions. Both CO and NO_x emissions from bifuel vehicles using CNG could be improved through periodic adjustment of the fuel system. These results are indicative of CNG fuel systems that have been installed in the field without the benefit of verification on a chassis dynamometer, in which case bifuel vehicles operating on natural gas will usually have higher NO_x emissions than when operating on gasoline. Bifuel vehicles with closed-loop CNG fuel systems do better, but significant improvements over gasoline are not typical. However, original equipment manufacturer (OEM)-dedicated CNG vehicles have been able to meet the California Ultra Low Emissions Vehicle (ULEV) emissions standards, the most stringent in the U.S. for light-duty vehicles. Table 2.2 lists the ULEV emissions standards and the CNG vehicles that to date have been certified to those standards. (Several other CNG vehicles have demonstrated the capability to meet ULEV standards but have not been certified.)

Table 2.2 ULEV Emissions Regulations

Emission	NMHC[1]	CO	NO_x
gm/mi	0.04	1.7	0.2

[1] Non-methane hydrocarbons

1996 Model Year Vehicles Certified to ULEV

- Ford CNG Crown Victoria
- Chrysler CNG Minivan

Based on the wide variation in emissions observed for bifuel CNG vehicles, it is difficult to generalize about the emissions benefits for any given vehicle. Fleet managers hoping to use bifuel CNG vehicles to achieve emissions reductions should use emissions tests to verify that field-installed CNG systems are providing the desired emissions reductions.

Greenhouse Gases

Methane is one of the greenhouse gases emitted by transportation vehicles. The others are carbon dioxide (CO_2), nitrous oxide (N_2O), NO_x, CO, and ozone, which is formed from vehicle emissions. On a mass basis, methane is a greenhouse gas 70 times stronger than CO_2 (the standard against which all greenhouse gases are measured because it is the most plentiful in the atmosphere); on a mole basis it is 25 times stronger. Methane released in the atmosphere takes between 7 and 15 years to decay, compared to CO_2 which takes between 120

and 500 years to decay. Overall, methane in the atmosphere is 15 to 30 times stronger than CO_2 on a mass basis, and 5 to 10 times stronger on a mole basis.[8]

Vehicles using natural gas have an inherent advantage in CO_2 emissions compared to vehicles using gasoline. This is because natural gas contains more hydrogen and less carbon than gasoline. For vehicles of equal fuel efficiency, natural gas produces only about 75% of the CO_2 emissions. (This advantage is reduced in bifuel vehicles where CNG fuel efficiency is lower than that of gasoline.) When the entire fuel cycle from resource through combustion (full fuel cycle) is taken into account, along with the other greenhouse gases, dedicated natural gas vehicles' overall estimated greenhouse-gas impact is up to 15% less than gasoline vehicles.[9,10]

Vehicle Technology

Although natural gas is commonly used as a fuel for stationary internal combustion engines, its use as a vehicle fuel presents unique problems. In order to carry enough fuel to provide an adequate range, natural gas is stored on the vehicle at a high pressure, usually 3,600 psi, in cylinders approved by the U.S. Department of Transportation (USDOT) or most recently, certified as meeting the requirements of AGA/ANSI NGV-2 (American Gas Association/American National Standards Institute).

The pressure of the gas in the fuel tanks is reduced through a series of pressure regulators, as shown on Figure 2.6, to a lower pressure slightly above engine manifold pressure. Two methods are commonly used to mix fuel with air for use by the engine. Older style systems use a fuel mixer (in principle similar to a gasoline carburetor); newer systems use a computer-controlled fuel injection system. Aside from the fuel system, other components of a CNG engine are similar to those used in gasoline vehicles.

CNG vehicle fuel systems are sealed and do not emit any evaporative emissions. Further, they have been designed to prevent the unintended release of fuel, and to limit the volume of fuel should a release occur.

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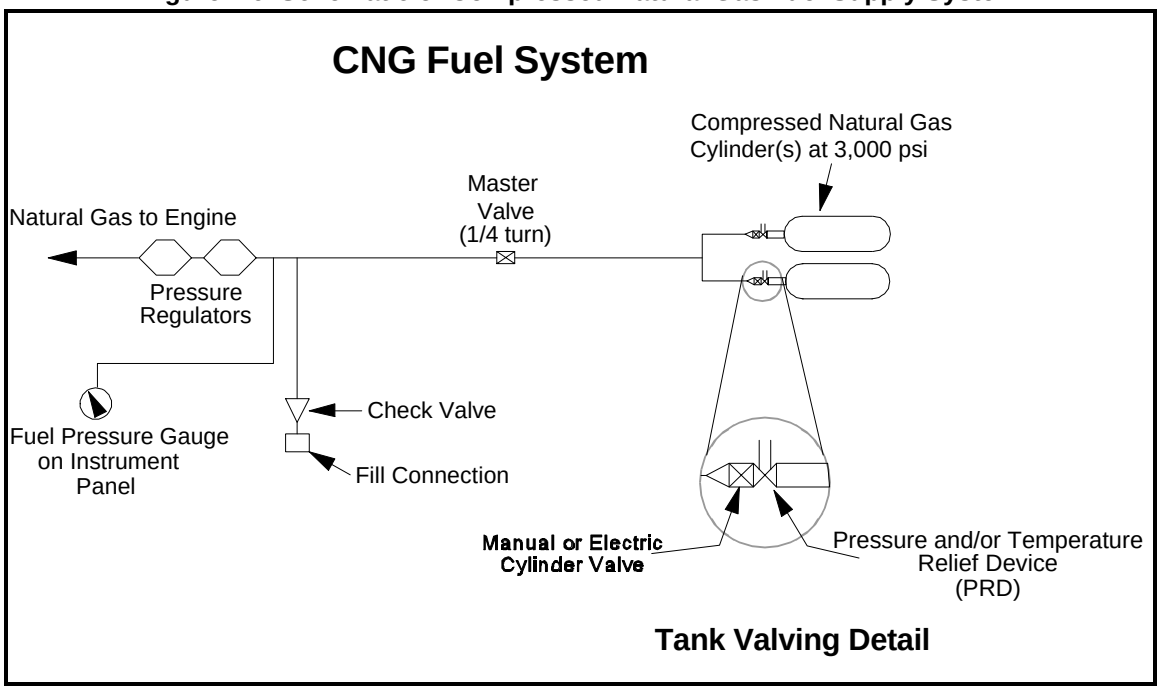
[8] Senthil, V., "Alternatives to Traditional Transportation Fuels - 1994 - Volume 2: Greenhouse Gas Emissions," U.S. Department of Energy, Energy Information Administration, Report DOE/EIA-0585(94)/2, August 1996.

[9] Ibid.

[10] Wang, M.Q., "Development and Use of the GREET Model to Estimate Fuel-Cycle Energy Use and Emissions of Various Transportation Technologies and Fuels," Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, March 1996.

Figure 2.6 Schematic of Compressed Natural Gas Fuel Supply System



CNG fuel systems are equipped with several safety-related valves as shown in Figure 2.6. These valves include:

- The Pressure Relief Device (PRD): These devices are valves designed to prevent catastrophic cylinder failure due to either cylinder over-pressure or over-temperature. The relief valves are designed to release the pressurized gas in a controlled manner. Filled fuel cylinders will require several minutes to completely vent fuel through the safety relief device.

- Manual Cylinder Valves: These valves isolate the gas stored in the cylinder from the rest of the fuel system (except for the PRDs). These valves would be closed whenever a vehicle's fuel cylinders are being serviced.

- The Master Valve: The main fuel line contains a main fuel shut-off (quarter-turn) valve. Before servicing a vehicle fuel system (other than those with electric cylinder valves), this valve would be closed by repair personnel. Closing this valve limits the volume of fuel that could be released while working on the fuel system.

- Electric Cylinder Valve: Some OEM vehicles have solenoid valves installed on the vehicle fuel cylinders. These valves isolate the gas stored in the cylinders from the rest of the fuel system. These valves are usually controlled in the same manner as electric fuel pumps are on conventional vehicles and would normally be closed except when a vehicle's engine is running.

The high-pressure fuel lines on the vehicle use stainless steel tubing to limit corrosion. Ferrule-type fittings are used to attach the fuel lines to valves, regulators, or pressure transducers. This allows lines to be easily repaired or serviced by qualified mechanics.

The fuel storage and delivery systems used by OEMs and vehicle converters are similar, though engine fuel systems vary significantly. Two basic aftermarket engine fuel systems are available. Mechanical carburetor-style fuel mixers with and without electronic air-fuel ratio feedback control and fully electronic fuel metering systems injecting fuel at either the throttle body or in the intake manifold runners. OEM systems generally use an electronic fuel control system.

CNG vehicles in the AFV-FDP used one of four fuel control systems: mechanical open-loop (MOL); mechanical closed-loop (MCL); electronic single-point closed-loop (ESPCL); and electronic multi-point closed-loop (EMPCL).

The MOL systems as the name implies operate without any feedback as shown in Figure 2.7. Air-fuel ratios are controlled by nozzle sizes and fuel pressure (as supplied to the fuel mixer). Typically mixtures are set at idle and at 2,500 rpm under no-load conditions.

MCL systems are similar in design to MOL systems. Mixtures are again set during installation. Electronics have been added allowing these systems to continuously adjust air-fuel ratio based on signals from the oxygen sensor(s) in the exhaust as shown in Figure 2.8. Since the air-fuel ratio is continuously adjusted, the fuel system theoretically will (within its limits of operation) adjust itself for small errors in initial setup, for drift due to mechanical wear, etc.

ESPCL systems (see Figure 2.9) electronically control fuel flow based on calculated air flow. The systems used in the AFV-FDP vehicles calculate air flow based on engine speed, intake manifold vacuum, and air temperature (speed-density). Use of fully electronic fuel control allows faster response to oxygen sensor information, tighter control of air-fuel ratio, and the ability to use one system for many vehicles by changing the control software.

Figure 2.7 Schematic of Typical Mechanical Open-Loop Fuel System

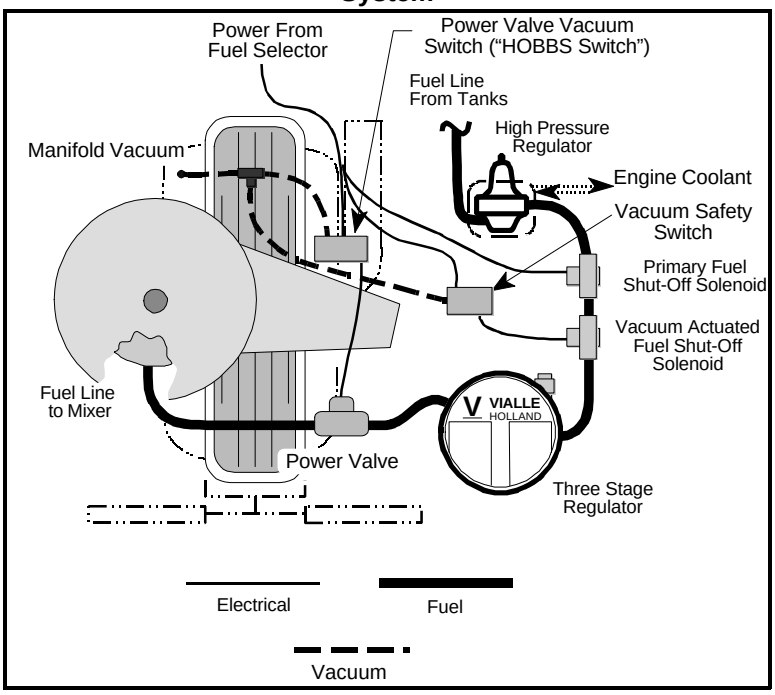


Figure 2.8 Schematic of Typical CNG Mechanical Closed-Loop Fuel System

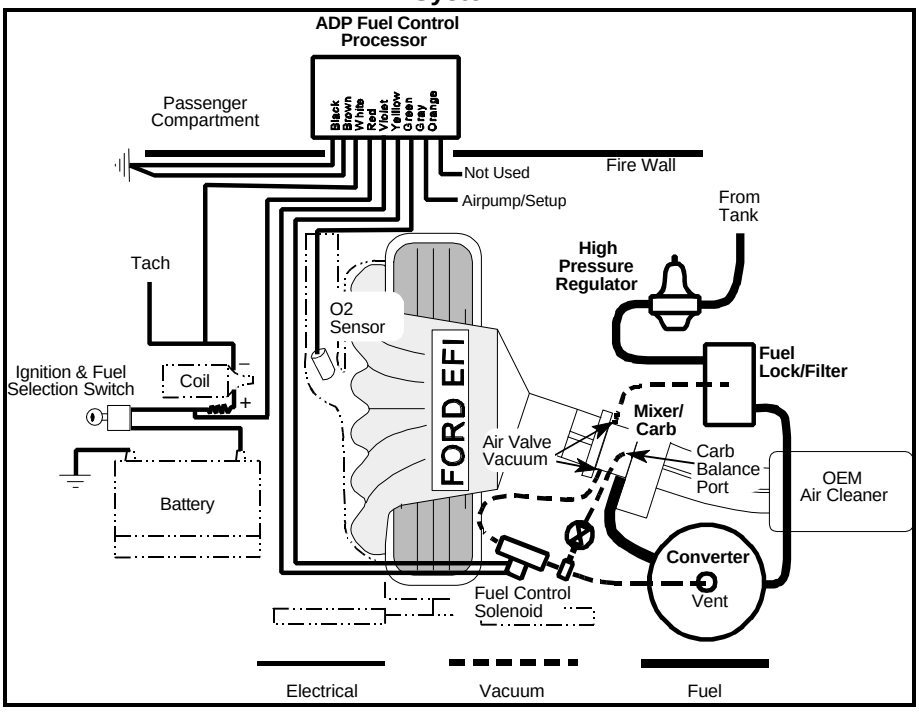
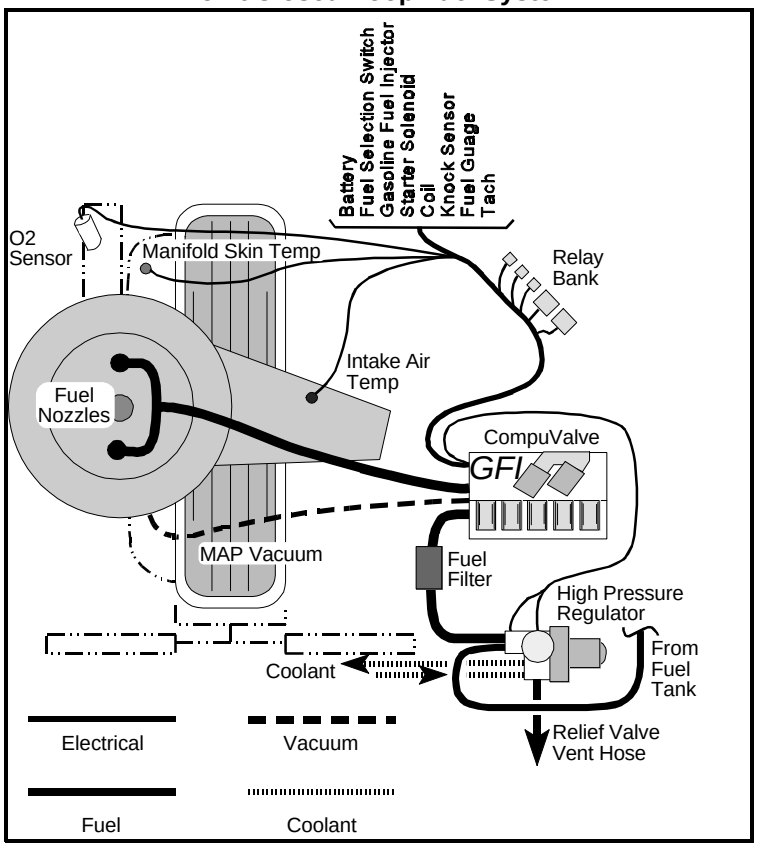


Figure 2.9 Schematic of Typical CNG Electronic Single-Point Closed-Loop Fuel System

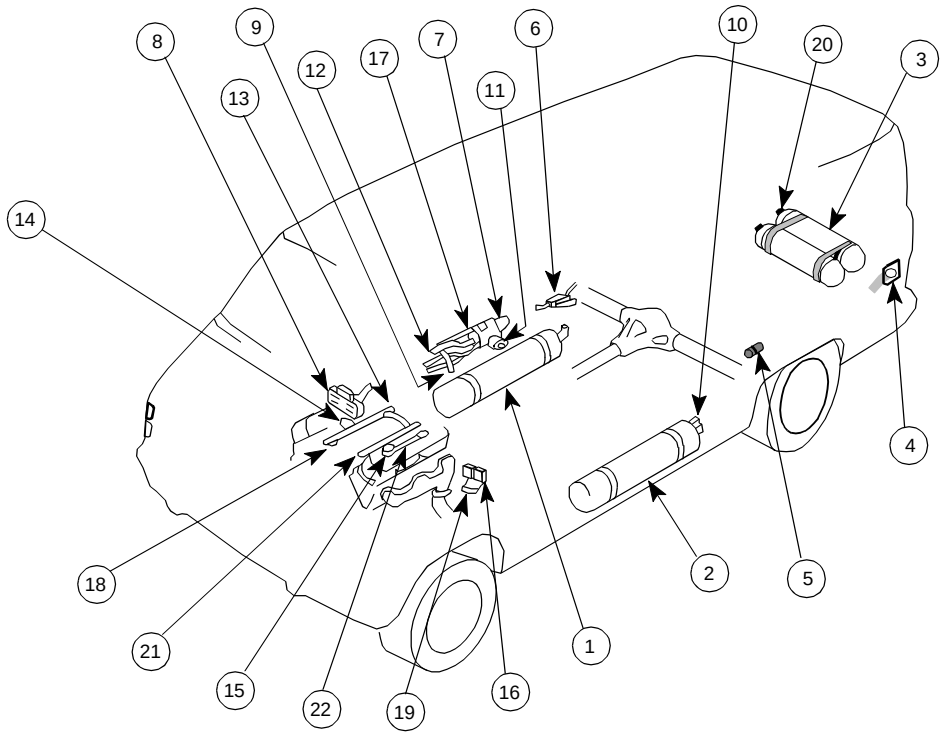


EMPCL systems use multiple fuel injectors (one per cylinder) installed in the intake port (see Figure 2.10). Fuel control is based on the mass air flow to the engine (mass air). This allows more precise control of the air-fuel ratio. This type of system was supplied by Chrysler (when they produced OEM CNG vehicles) and is currently used by Ford on their CNG Crown Victoria.

The AFV-FDP included each of these type of vehicles. Table 2.3 summarizes the number of light-duty CNG vehicles included in the AFV-FDP that were tested for emissions using each type of fuel system. Table 2.4 lists vehicle models and types, the fleet operators that used them, and the type of CNG fuel system for each of the light-duty CNG vehicles participating in the AFV-FDP.

Figures 2.11 through 2.15 illustrate several of the CNG vehicles that participated in the AFV-FDP.

Figure 2.10 Schematic of Typical CNG Electronic Multi-Point Closed-Loop Fuel System



1. FUEL CYLINDER (RIGHT-CERTAIN MODELS)
2. FUEL CYLINDER (LEFT)
3. FUEL CYLINDERS (REAR)
4. FUEL FILL RECEPTACLE
5. ONE-WAY CHECK VALVE
6. MANUAL SHUT-OFF VALVE
7. FUEL PRESSURE REGULATOR
8. POWERTRAIN CONTROL MODULE
9. PRESSURE RELIEF DISCHARGE TUBE
10. FUEL GAUGE PRESSURE SENSOR
11. HIGH PRESSURE FUEL SHUT-OFF SOLENOID
12. ENGINE COOLANT HOSES (2)
13. FUEL TEMPERATURE SENSOR
14. FUEL PRESSURE SENSOR
15. LOW-PRESSURE FUEL SHUT-OFF SOLENOID
16. HIGH PRESSURE FUEL SHUT OFF SOL. RELAY
17. PRESSURE RELIEF DEVICE
18. FUEL INJECTORS (8)
19. ASD RELAY
20. FUEL CYLINDER CONTROL VALVES (AT EACH CYLINDER)
21. FUEL RAIL
22. LOW PRESSURE FUEL LINE (TO PRESSURE REGULATOR)

Table 2.3 Summary of CNG Fuel Systems Used in Light-Duty Vehicles Participating in AFV-FDP

Fuel System Type	Number of Vehicles
MOL	45
MCL	33
ESPCL	9
EMPCL	1

Table 2.4 CNG Fuel Systems Used by Light-Duty Vehicles in the AFV-FDP

Operator(s)	Vehicle Model	Vehicle Type	Fuel System	Number
Monroe County	Ford Taurus	Passenger Car	MCL	3
NYSPSC	Chevrolet Caprice	Station Wagon	ESPCL	4
USPS	Grumman	Postal Delivery Van	ESPCL	5
USPS	Grumman	Postal Delivery Van	MOL	45
NYSDEC	Jeep Cherokee	Sport-Utility	MCL	3
City of Buffalo	Chevrolet S10	Pickup Truck	MCL	3
City of Buffalo	Chevrolet Van	Van	MCL	1
City of Buffalo	Ford Van	Van	MCL	2
NYSOMH	Dodge Van	Passenger Van	EMPCL	1
NYSOMH	Dodge Van	Passenger Van	MCL	3
Erie County	Ford Pickup	Pickup Truck	MCL	5
City of Buffalo	Ford Pickup	Pickup Truck	MCL	4
City of Buffalo	Ford Bronco	Sport-Utility	MCL	3
NYSDEC	Ford Pickup	Pickup Truck	MCL	2
Erie County	GMC K1500	Pickup Truck	MCL	2
NYSERDA	Chevrolet Blazer	Sport-Utility	MCL	1
City of Buffalo	Chevrolet Blazer	Sport-Utility	MCL	1

Figure 2.11 One of the USPS CNG Vans Being Refueled

Figure 2.12 South Beach Psychiatric Center Dedicated CNG Dodge Vans

Figure 2.13 NYSDEC Bifuel CNG Ford F-150 Pickup

Figure 2.14 Monroe County Bifuel CNG Ford Taurus Being Refueled

Figure 2.15 NYSERDA Bifuel CNG Chevrolet Blazer

Refueling Infrastructure

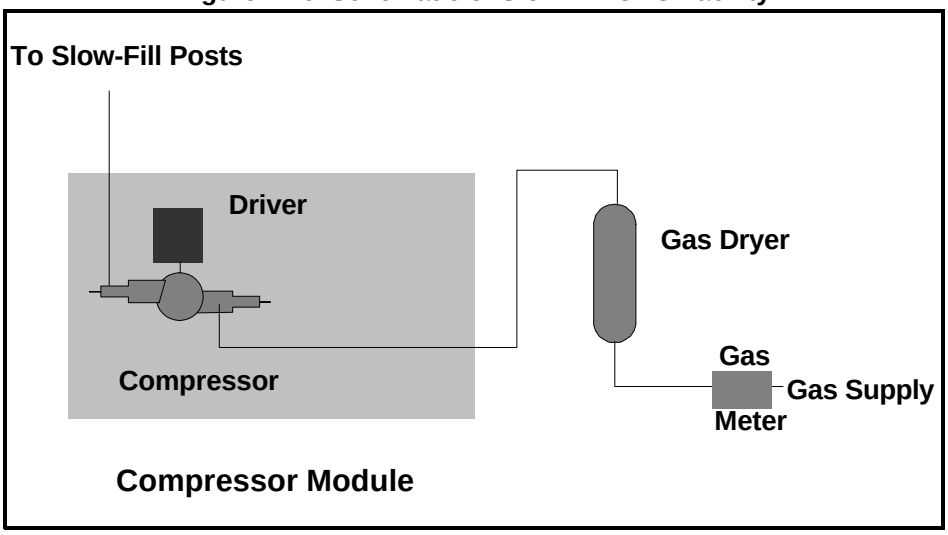
Two types of fuel delivery systems are commonly used at CNG refueling stations, slow- and fast-fill. Both types of station include compression equipment and gas dryers. Natural gas compression equipment is available from a number of manufacturers and are commonly supplied with the user's choice of electric motor drive or natural gas engine drive. Generally electric motor compressor drives have a lower initial cost, require less maintenance, and are usually quieter than engine drive units. However, natural gas engine drive compressors have the potential of lower fuel operating costs.

Desiccant inlet dryers are commonly needed to lower the moisture content of pipeline gas to help prevent condensation from forming after compression. Condensation usually consists of heavier hydrocarbons (propane, butane, etc.) and water. The water can freeze due to temperature drops associated with gas expansion (or cold weather) and block fuel passageways. In addition the water can combine with trace gases (e.g., CO_2 or hydrogen sulfide) to form corrosive liquids that can damage fuel system components. The desiccant inlet dryer is designed to lower the inlet natural gas moisture content to a safe level. Additional filters and moisture traps are commonly used to capture liquid hydrocarbons that condense out of the natural gas during compression.

Slow-Fill. Slow-fill stations refuel CNG vehicles over a several-hour period. The refueling station equipment typically includes a gas dryer, natural gas compressor, a simple set of compressor controls, and a distribution manifold with connections, referred to as posts, for each vehicle being refueled (one to several hundred). Figure 2.16 is a schematic of a slow-fill station. Vehicles are attached to the slow-fill posts at the end of the work day. Many slow-fill stations use automatic controllers so the compressor only operates late at night to take advantage of off-peak electric utility rates. Once the compressor begins operation, natural gas will flow to the vehicle with the lowest storage pressure. Eventually all of the vehicles attached to refueling ports will have the same storage pressure. Compressor operation will continue until the vehicles reach their design storage pressure at which time the station controller will automatically shut down the compressor.

Slow-fill stations' main advantage over fast-fill stations are their lower initial cost and potentially lower operating cost. Slow-fill stations do not require any gas storage (which is required to help a fast-fill station quickly refuel vehicles) and because the compressor is usually able to operate for longer periods of time than those at most fast-fill stations, a smaller compressor can be used to supply the same volume of fuel. This helps

Figure 2.16 Schematic of Slow-Fill CNG Facility



lower initial cost. Many times operating costs are reduced due to lower electric demand charges associated with a smaller compressor. In addition the slow refilling of vehicle fuel tanks allows a more complete refueling. The storage temperature of CNG cylinders after fast-filling can be significantly above ambient. This temperature increase, caused by the compression of the fuel, lessens the amount of fuel that storage cylinders can carry. Slow-filling vehicles allows the heat of compression to be dissipated as the vehicles are refueled helping to ensure a complete fill.

The disadvantages of using slow-fill stations include inconvenient refueling (hours to refill rather than minutes) and potentially high installation costs for large fleets. Since slow-fill stations are designed to refill vehicles over a long period of time, quickly refueling a single vehicle is inconvenient unless the station is designed to allow for both fast-fill and slow-fill. All vehicles complete refueling at the same time limiting usefulness for fleets that do not have a common refueling period available. Measuring the volume of fuel dispensed to individual vehicles is not currently practical. This makes it difficult or impossible to bill individual fleets for fuel use at shared facilities. Refueling a large fleet (e.g., a hundred vehicles) requires the installation of an equally large number of refueling connections. This can, in some situations, increase the station cost above that needed to provide a suitable fast-fill station.

Fast-Fill. Fast-fill stations operate, from the users point of view, similar to a conventional liquid fuel dispensing station. A refueling hose is taken from a dispenser and attached to a CNG vehicle. The vehicle is usually refueled in 5 to 10 minutes. Refueling vehicles in less than 10 minutes requires a high refueling delivery rate. However, any fast-fill station can also be configured to slow-fill vehicles. Figure 2.17 illustrates the components of a fast-fill refueling facility with capability to refuel vehicles using slow-fill.

Figure 2.17 Schematic of a Fast-Fill CNG Refueling Facility with Slow-Fill Capability

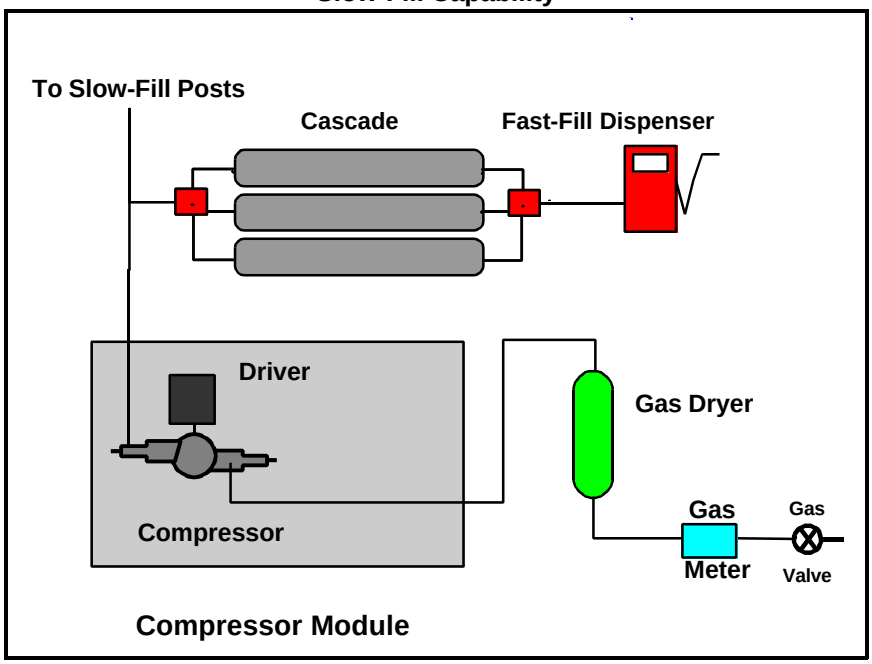


Table 2.5 shows typical refueling needs for different vehicles and refueling station flow rates required for fast-filling. These flow rates are usually achieved using gas supplied from a compressor(s) and from several pressurized storage cylinders called a cascade.

Table 2.5 Refueling Needs and Required Refueling Delivery Rates Needed to Fast-Fill Some Typical CNG Vehicles

Vehicle Type	Typical Refueling Needs (GGE*)	Required Fuel Delivery Rate (scfm)
Bifuel Automobile	3-5	40-125
Dedicated Automobile	4-8	50-200
Bifuel Light Truck	4-8	50-200
Dedicated Light Truck	6-15	75-390
Dedicated School Bus	12-25	150-600
Dedicated Transit Bus	30-90	400-2,000

* Gasoline Gallon Equivalents

Supplying the fuel from a cascade of storage cylinders allows the use of a smaller compressor than would otherwise be required. In many fast-fill stations, refueling is essentially accomplished from the cascade, the compressor being used to recharge the cascade.

The storage cascade is usually divided into multiple banks of cylinders, which allow greater use of the stored gas. At the beginning of the day before any vehicles have been refueled all three banks of the cascade are filled to their design pressure. During vehicle refueling, natural gas flows from the first bank of the cascade into the vehicle. This increases the pressure in the vehicle tanks and at the same time decreases the pressure in the first bank of the cascade. As these two pressures begin to equalize, the flow rate will decrease. In order to maintain adequate fuel flow rates, control valves (sequential valves) automatically switch to banks with higher pressure, maintaining a minimum pressure differential, as the vehicle fills. The control valves are usually programmed to switch to higher pressure banks whenever the pressure differential (between the cascade storage pressure and the vehicle fuel storage pressure) reaches a predefined limit.

When refilling the cascade, the compressor output is directed to fill the bank with highest pressure first. Once this bank is filled output is directed by priority valves to successively lower pressure banks until all are refilled. By refilling the cascade banks in the opposite order from which they are used, it is possible to maintain pressure, in at least some of the cascade storage, above the vehicle design storage pressure. With some of the cascade at a pressure above the design vehicle storage pressure, it is possible for vehicles to receive complete refuelings.

The CNG refueling stations in Tonawanda and at the State University of New York campus in Buffalo (SUNY Buffalo) both are designed to operate in this manner. The Tonawanda station (see Figures 2.18 and 2.19), has a 74 scfm compressor supplying fuel to over 25 town vehicles and two dedicated school buses from the Kenmore-Tonawanda School District. With approximately 30,000 scf of natural gas stored in the cascade, any of the these vehicles can be refueled quickly. Slower filling can occur if insufficient time is allowed between vehicle refuelings (approximately 30 to 40 minutes is required after refueling a school bus) for the compressor to recharge the cascade.

Fast-fill CNG station designs need to balance compressor size with cascade size to meet vehicle refueling requirements while maintaining reasonable operating and installation costs. The smaller size compressor needed when cascade storage is used can help to lower operating costs by lessening electrical demand charges. One disadvantage of fast-filling is the heating of the vehicle storage tanks by the rapid

Figure 2.18 Fast-Fill CNG Facility at the Town of Tonawanda Water and Sewer Department

Figure 2.19 The Town of Tonawanda CNG Refueling Island and Dispenser

compression of the fuel already in the tanks. This temperature increase decreases the amount of fuel that can be stored on board the vehicle. After refueling, the tank will slowly return to ambient temperature and the storage pressure will be several hundred psi below the vehicle design storage pressure.

Station Costs. Two fast-fill stations were bid for installation in western New York, near Buffalo, as part of the AFV-FDP. The first was purchased and installed to serve the Town of Tonawanda. The second was bid to serve SUNY Buffalo and several public sector fleets located nearby. The primary contractor for each bid was required to supply complete compressor packages. To limit on-site construction and lower the final installed cost, all equipment was skid-mounted. The compression and storage equipment was supplied on four skids. The first consisted of the gas dryer, related filters, and controls. The second skid was composed of the storage cascade. The third was a dual hose dispenser. Since the Town of Tonawanda has a mix of vehicles with different service pressures, one hose was set-up to provide a 2,400-psi refueling and the other to provide a 3,000 psi-refueling. The last skid included the compressor, sequential valves, priority valves, computerized controls, compressor cooling system, refueling vapor return storage tank, and an annunciator panel. Total equipment cost was approximately $200,000 in 1994.

The Town provided many of the infrastructure improvements. These improvements included installing high-pressure natural gas lines from the compressor skid to the dispenser, installing curbs and paving, and supplying a fuel management system. These site preparation, infrastructure, and other installation related costs totaled approximately $60,000.

Compressor stations sized to meet the fast-fill needs of fleets with fewer than 50 to 100 light-duty vehicles will most likely be electrically driven. Large stations that require over approximately 250-500 scfm compression capacity are likely to use either natural gas engine driven compressors or electric motors. The choice will depend on the local electric and natural gas cost structure.

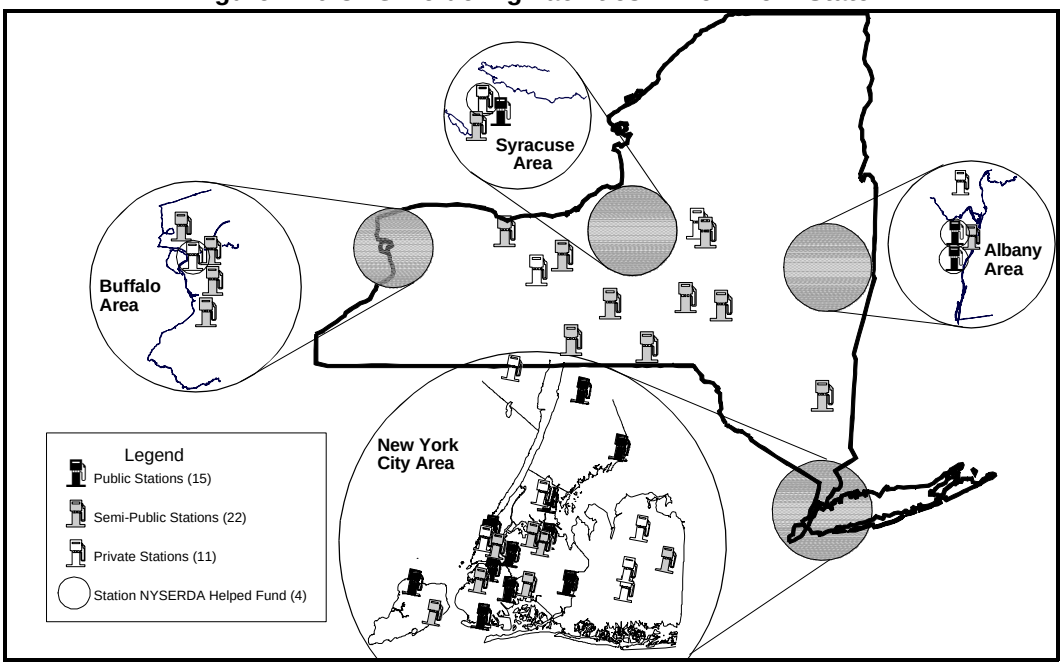
The high cost of CNG compressors and other refueling equipment is a major impediment to more widespread acceptance of CNG vehicles. It is significantly more expensive to establish a CNG refueling facility with the capability to refuel the same number of vehicles that currently use a typical gasoline refueling station. To facilitate operation of CNG vehicles in the AFV-FDP, the program helped establish CNG stations in Tonawanda, Colonie, and Glenmont, and has provided technical assistance for the station at SUNY Buffalo.

The high cost of CNG refueling facilities combined with the relatively small number of CNG vehicles on the road has discouraged retailers from offering CNG in New York State. The natural gas utilities serving New York State have taken the lead in establishing CNG refueling facilities. Figure 2.20 illustrates the location of

the 47 currently known CNG refueling facilities in New York State, virtually all of which are wholly or partially funded by gas utilities. For comparison, there are approximately 6,000 gasoline stations in New York State.

Until a more widespread system of CNG refueling facilities is built, CNG will tend to remain an alternative fuel best suited to fleet vehicles that stay within a limited geographical area, served by a few centrally located CNG refueling facilities.

Figure 2.20 CNG Refueling Facilities in New York State



Operations and Maintenance

Fuel Economy. Fuel economy for the AFV-FDP vehicles was calculated from fueling records kept by each fleet. Variations in these data are due to different operating conditions in different areas of the state, different types of operation, and varying accuracy of the refueling records, and do not reflect differences in fuel system performance. Fuel economies can also be calculated from dynamometer emission tests. Using the emission tests to calculate fuel economy removes the vehicle operating variables from the results and provides a better comparison of fuel system performance. Most of the vehicles were tested over three different cycles. These cycles are designed to simulate different styles of driving. They include the FTP City Cycle, the FTP

Highway Cycle, and the New York City Cycle (NYCC). Table 2.6 summarizes the average fuel economy observed of the different types of vehicles and CNG fuel systems that participated in the AFV-FDP.

Table 2.6 Average CNG Vehicle Fuel Efficiency Relative to Gasoline

Driving Cycle	Taurus		Postal Vehicle		Chev. S10	Jeep Cherokee	Ford F150	Dodge B350	
	MCL	ESPCL	MOL	ESPCL	MCL	MCL	MCL	MCL	EMPCL
City	-6.9%	-6.5%	-9.8%	-12.5%	-2.9%	-4.1%	-2.8%	-11.6%	-5.5%
Highway	-4.6%	NT*	-11.1%	-20.8%	-5.4%	NT	-1.9%	-28.5%	13.2%
NYCC	-9.8%	-10.8%	-5.6%	-6.8%	-6.8%	-5.2%	-1.6%	-18.4%	-3.6%

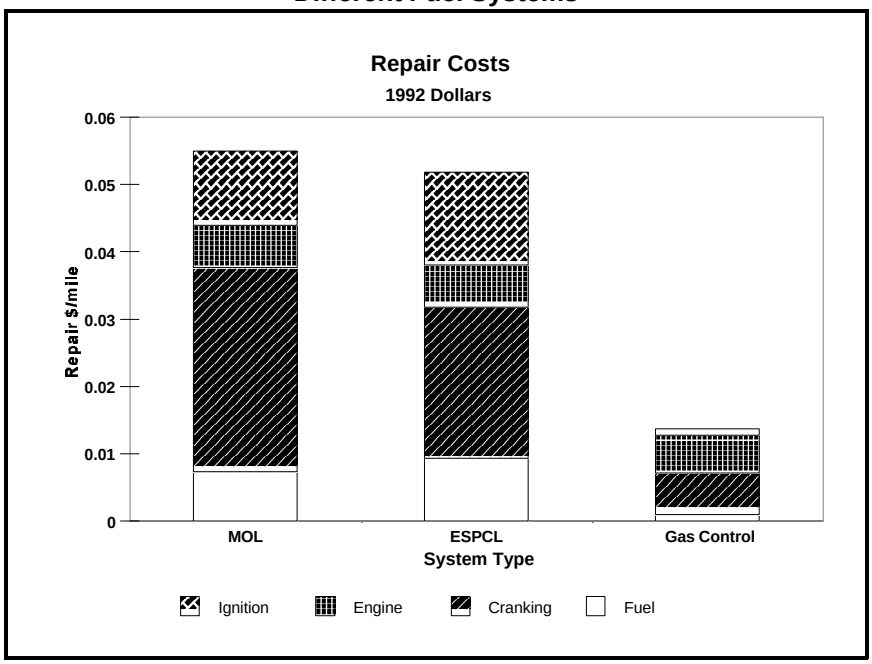
*NT = Not tested

Fuel economies on natural gas were lower than the fuel economies of the same vehicles operating on gasoline. Generally the conversion electronic fuel injection systems performed worse than either of the conversion mechanical systems. This may have been due to slightly lean initial fuel mixture settings used on the mechanical systems. The emission test results seem to confirm this (generally lower NO_x levels were found for the electronic systems than the mechanical systems). The only fuel system to show an increase in fuel economy over similar gasoline vehicles was the system supplied with the OEM Dodge van tested over the highway cycle. This is also the only vehicle whose CNG fuel and ignition system are optimized by the manufacturer. The lower fuel economies achieved by the other CNG systems is probably due to non-ideal air-fuel ratios that occur under normal (transient operation) driving conditions.

Reliability and Durability. Maintenance and repair records were kept by the fleets operating CNG vehicles. The fleets had individual methods of keeping these records so that comparisons between different fleets are not possible. Within-fleet comparisons can be made and several trends do become apparent. Two problems that reoccurred in several different fleets were starting difficulties and fuel releases. Fleets that experienced starting problems were usually able to keep the problems under control by making adjustments to the fuel system.

The USPS fleet on Staten Island keeps maintenance and repair records by accounting period (13 four-week periods each year). The records include vehicle number, parts cost, labor cost, and vehicle sub-system being repaired; for example, suspension, charging, fuel. In order to compare reliability differences between three fuel systems used (gasoline control, mechanical open-loop CNG, and electronic single point closed-loop CNG) repairs were separated into five groups: fuel system, cranking system, engine, ignition, and other. Repair costs (in 1992 dollars) on a per mile basis are shown in Figure 2.21. Costs associated with engine repairs were approximately the same for the CNG and the gasoline control vehicles. These repair costs were 11.3% higher for the mechanical CNG fuel system and 12.7% higher for the electronic CNG fuel system when compared to

Figure 2.21 Per Mile Repair Cost for CNG Postal Vehicles Using Different Fuel Systems



the gasoline control vehicles. Repair costs associated with fuel, cranking, and ignition repairs were significantly higher (263% to 1,243%) for the CNG vehicles compared to the gasoline controls. The CNG vehicles had slightly lower repair costs for other vehicle sub-systems; i.e., all repairs other than those involving the fuel, cranking, engine, or ignition systems. The lower repair costs for systems not related to vehicle starting compensated for the higher repair costs for systems affecting starting performance. Overall, the CNG vehicles with mechanical fuel control cost 2.6% more to repair, while the CNG vehicles with electronic fuel control cost 0.6% less to repair than the gasoline control vehicles. The breakdown of the percent differences between CNG vehicle repair costs and gasoline vehicle repair costs are shown in Table 2.7.

Table 2.7 Percent Difference in System Repair Costs for CNG Postal Vehicles Versus Gasoline Control Vehicles

Fuel System	Fuel System	Cranking System	Engine	Ignition System	Other Repair	Total Repair
MOL	+662%	+393%	+11.3%	+971%	-9.0%	+2.7%
ESPCL	+872%	+263%	+12.7%	+1,243%	-11.5%	-0.6%

Other repairs (not fuel, cranking, engine nor ignition related) accounted for 85% of the repair costs for the CNG vehicles and 96% of the repair cost for the gasoline controls. The reasons for the decrease in other system repairs is not known.

The CNG Chevrolet Blazer operated by NYSERDA experienced a loss in power, which was corrected under warranty by adjusting the fuel mixture strength. The vehicle also experienced difficulty starting on CNG. The difficulty starting increased and eventually the vehicle became difficult to start on gasoline. When the vehicle was serviced it was discovered that an intake backfire (presumably occurring during CNG operation) had damaged the air filter housing and the intake duct system. After replacing the damaged parts, the fuel system was readjusted to help prevent a reoccurrence.

The CNG Jeeps and Ford pickup trucks operated by NYSDEC experienced several fuel system related problems during the first months of operation. Repairs were performed under warranty to correct starting difficulties, lack of power, and fuel change-over related problems. The Jeeps were difficult to start on CNG especially during cold weather. Replacing the cold-start valves helped solve this problem. The support modules on the Fords caused hesitation and missing and needed to be replaced several times until units that performed satisfactorily were found. Both the Fords and the Jeeps had automatic fuel change-over valves. These valves are designed to operate the vehicles on CNG and to automatically switch over to gasoline when CNG runs low. The valves were originally prone to switching back and forth due to CNG pressure variations. In addition the switch-over itself was harsh. Adjustments to the valves operation eliminated the multiple switching. There was still a hesitation during switch-over but it was less pronounced.

After these initial problems were corrected the vehicles were relatively trouble free until a fuel leak developed in one of the Jeeps. The leak was at a fitting on one of the fuel cylinders. The installation included a polyethylene bag designed to vent fuel released from tank fittings outside the vehicle. Unfortunately the bag on the Jeep had been torn, which allowed released fuel into the passenger compartment. After this incident NYSDEC decided to discontinue CNG operation of the Jeeps. The CNG fuel system on the Fords is located outside of the passenger compartment and NYSDEC continues to operate these vehicles.

In Monroe County two of the three CNG vehicles operated by the county developed fuel cylinder leaks. These leaks were through the cylinder walls and developed after over a year in service. A new tank was installed in each of the leaking vehicles (the leaks occurred approximately three months apart). The leaks seemed to be intermittent and to date the manufacturer has been unable to find a cause.

The Chevrolet Caprice station wagons converted to CNG for the NYS Public Service Commission (NYSPSC) experienced several small fuel leaks that were corrected by the installers. One of the vehicles required a new compuvalve (combination microprocessor controller, pressure regulator, fuel injection unit) installed under warranty to correct stalling problem. After operating for two years, one of the Caprices was involved in a traffic accident. The front end was damaged causing a leak to develop in the fill port check valve. The driver was able to close the quarter turn valve and halt the flow of fuel. Due to concerns raised by the accident-related leak the NYSPSC decided to discontinue the use of CNG in these vehicles.

One of the passenger vans operated by South Beach Psychiatric Center experienced what seemed like CNG-related hesitation problems. After numerous attempts at repair, it was found that the problem was not CNG-related and was being caused by a faulty OEM engine control computer. Changing the OEM computer solved the problem.

Another important issue related to vehicle maintenance is overall equipment durability. Gasoline and diesel fuel tend to have higher levels of sulfur and other undesirable trace constituents, as compared with CNG, and have greater potential for negative interaction with an engine's lubricating oil. Proponents of CNG point out that this fuel, as compared with gasoline, tends to leave engines free of deposits and to greatly slow the rate at which lubricating oil degrades. For these reasons, one might expect that an engine would have a longer life and require fewer repairs and oil changes if it used CNG instead of gasoline. On the other hand, vehicle manufacturers incorporate hardened valve seats and other upgraded components in their dedicated OEM engines to counteract the higher exhaust temperatures and lower lubricity associated with using CNG, suggesting bifuel vehicles with gasoline engine origins may not be as durable as OEM CNG vehicles if CNG is used all the time.

Sufficient data are not available to determine conclusively the durability characteristics of light-duty CNG vehicles (bifuel or dedicated), relative to gasoline counterparts, except to say that bifuel vehicles equipped with standard gasoline engines accumulated a large amount of mileage operating on CNG in the AFV-FDP and no detrimental effects were noted. The Town of Tonawanda, one of the fleet operators participating in the AFV-FDP, accumulated extensive data documenting their success at reducing the number of oil changes on their dedicated CNG conversion vehicles without any apparent adverse effects on engine life.

Acceleration. Acceleration tests were performed on a portion of the fleet vehicles (at local airport runways or dragstrips to ensure safety and consistency). A radar gun with data collection system was used for all the tests and generated curves of speed versus time. Multiple tests were performed on each vehicle to minimize wind effects. The bifuel vehicles were slower when operating on CNG compared to the same vehicle operating on

gasoline. Likewise the dedicated CNG (with the exception of the OEM Dodge) vehicles were slower than gasoline control vehicles. Some of the performance deficit is due to increased weight from the CNG fuel systems and some is due to non-optimal fuel systems. Table 2.8 shows averaged results from some of the light-duty CNG vehicle performance testing.

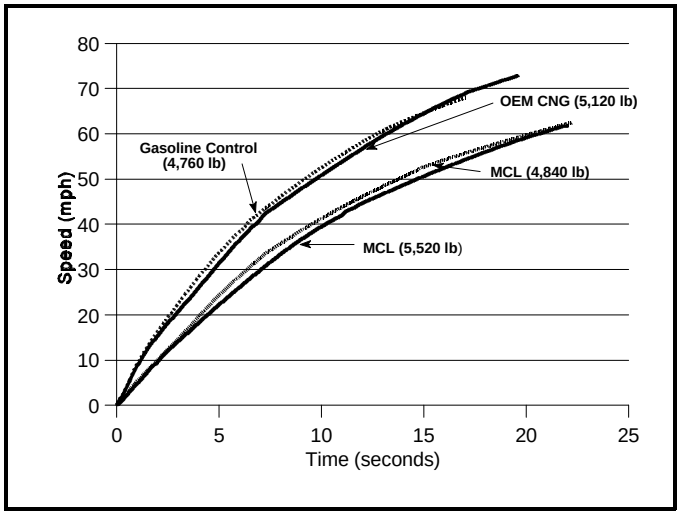
Table 2.8 Average Acceleration of CNG Test and Gasoline Control Vehicles

Vehicle Type	Fuel	Fuel System	Engine Size, liters	Test Weight, lb	Acceleration[1] (sec)
Ford Taurus	Gasoline	OEM	3.0	3,300	11.8
Ford Taurus	CNG	MCL	3.0	3,300	14.4
Ford F150	Gasoline	OEM	4.9	4,730	15.7
Ford F150	CNG	MCL	4.9	4,730	18.6
Dodge Van	Gasoline	OEM	5.2	4,760	12.5
Dodge Van	CNG	EMPCL (OEM)	5.2	5,120	12.9
Dodge Van	CNG	MCL	5.2	4,840	19.9
Dodge Van	CNG	MCL	5.9	5,520	20.4

[1] Time to reach 60 mph from a standing start.

As shown, the MOL and MCL systems significantly increased acceleration time compared to the same vehicle operating on gasoline. The EMPCL equipped van showed essentially no difference when tested against an older, gasoline model. The results for the four Dodge Vans are shown in Figure 2.22.

Figure 2.22 Acceleration Performance of Four Dodge Vans



Emissions. A mix of light-duty AFV-FDP CNG vehicles were dynamometer-emissions tested. Tests were performed at either the New York City Department of Environmental Protection (NYCDEP) laboratory or the NYS Department of Environmental Conservation (NYSDEC) laboratory in Albany. The results from testing over the FTP city cycle are shown here to compare how different fuel systems (MOL, MCL, ESPCL, EMPCL, and gasoline control) performed. Table 2.9 lists the type of vehicles using each type of fuel system and the number of FTP tests performed on each vehicle type.

Table 2.9 Characteristics of Light-Duty CNG Vehicles Tested for Emissions

Vehicle	Engine Size	Fuel System	Fuel	Number of FTPs
Chevrolet S10	4.3L-V6	OEM	Gasoline	11*
Chevrolet S10	4.3L-V6	MCL	CNG	4
Dodge B350	5.2L-V8	OEM	Gasoline	3
Dodge B350	5.2L-V8	OEM (EMPCL)	CNG	13
Dodge B350	5.2L-V8	MCL	CNG	1
Dodge B350	5.9L-V8	MCL	CNG	4
Ford F150	4.9L-I6	OEM	Gasoline	28*
Ford F150	4.9L-I6	MCL	CNG	9
Ford Taurus	3.0L-V6	OEM	Gasoline	14*
Ford Taurus	3.0L-V6	MCL	CNG	6
Ford Taurus	3.0L-V6	ESPCL	CNG	7
Ford Taurus	3.8L-V6	OEM	Gasoline	1
Jeep Cherokee	4.0L-I6	OEM	Gasoline	26*
Jeep Cherokee	4.0L-I6	MCL	CNG	10
Grumman Postal Van	2.5L-I4	OEM	Gasoline	29*
Grumman Postal Van	2.5L-I4	MOL	CNG	12
Grumman Postal Van	2.5L-I4	ESPCL	CNG	14

* Includes dedicated gasoline control vehicles, bifuel (gasoline/CNG) vehicles tested on gasoline and preconversion gasoline tests.

The results are presented graphically by fuel system type for all of the light-duty vehicles in the AFV-FDP allowing comparisons of the different fuel systems. Each measured emission component

(hydrocarbons/non-methane organic gases, CO, and NO_x) is presented separately. Figure 2.23 shows hydrocarbon/non-methane organic emissions. Figure 2.24 shows the CO results and Figure 2.25 shows the NO_x results.

During emission testing of the gasoline vehicles total hydrocarbons were measured. The main hydrocarbon constituent found in CNG vehicles is methane. Since methane has low reactivity and does not significantly contribute to the formation of ground level ozone, CNG vehicle total hydrocarbon emissions are usually not reported, rather non-methane organics gases (NMOG) are measured. NMOG includes all hydrocarbons, other than methane, and any organic compounds (usually unburnt oxygenates, and aldehydes). Figure 2.23 shows the HC/NMOG emissions for each of the fuel systems. As expected NMOG emissions for vehicles operating on CNG were lower than the HC emissions from the gasoline vehicles regardless of CNG fuel system used. The EMPCL and ESPCL systems gave the lowest NMOG emissions with the exception of an ESPCL outlier.

Figure 2.23 CNG Vehicle NMOG and Gasoline Vehicle HC Emissions

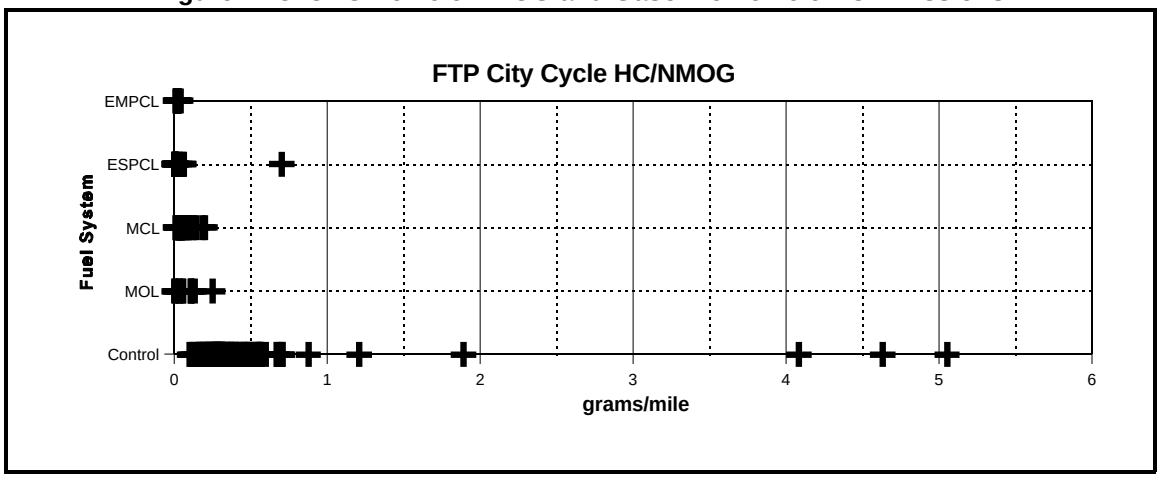
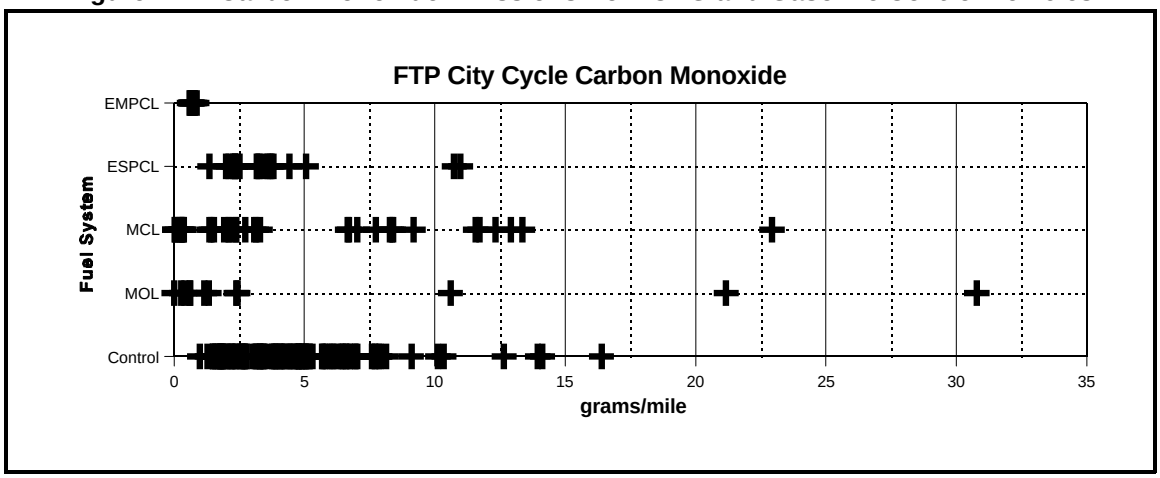


Figure 2.24 presents the CO emissions from AFV-FDP CNG vehicles. While all the CNG fuel system types were capable of lower CO emissions than gasoline, both the MCL and the MOL systems showed highly variable results. The MCL and the MOL systems each had several tests where CO emissions were higher than the highest emitting gasoline control vehicles. Some of the mechanical systems also had emissions lower than all but the EMPCL systems. The mechanical system performance will depend on the accuracy of the initial setting and how much these settings drift over time. The ESPCL systems had CO emission levels quite similar to the gasoline control vehicles. Since these systems do not depend entirely on installers making fuel mixture adjustments, they provide more consistent results. The Dodge Van using the EMPCL system had consistently

Figure 2.24 Carbon Monoxide Emissions from CNG and Gasoline Control Vehicles



lower CO emissions than either the MCL or the gasoline control vehicles. This system is capable of faster adjustments (because the fuel injectors are located closer to the combustion chamber) to changing operating conditions, allowing tighter control of the air-fuel ratio during transient operation.

Figure 2.25 Oxides of Nitrogen Emissions from CNG and Gasoline Control Vehicles

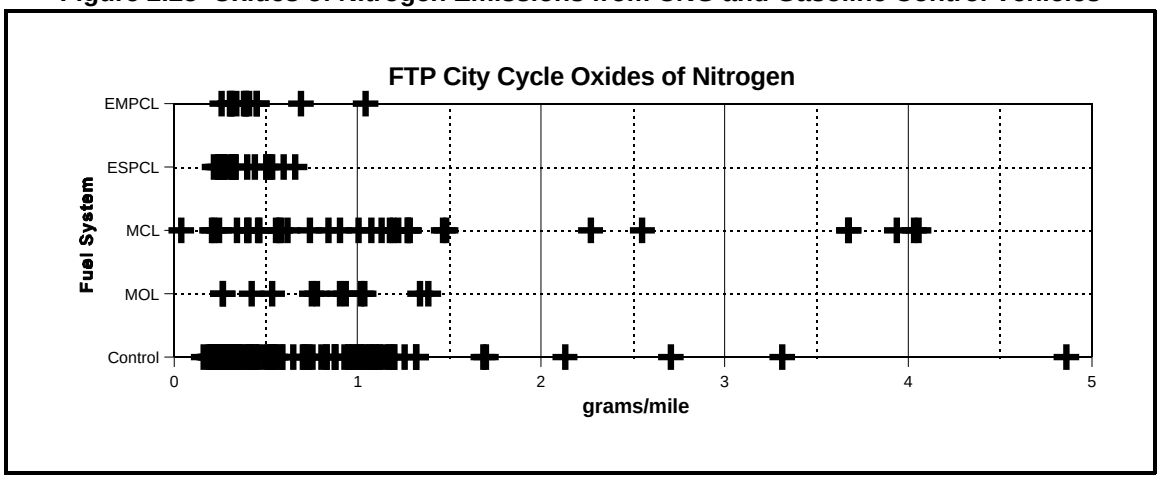


Figure 2.25 presents the NO_x emissions by fuel system type. These data show that the CNG fuel systems had generally lower NO_x emissions when using CNG than when using gasoline. The high NO_x emissions from the MCL systems are unexpected given that these systems have feedback control. It is possible that some of these systems had drifted just lean of stoichiometric, causing high NO_x emissions. The basic MOL systems without feedback control demonstrated less variability than the MCL systems. The ESPCL and EMPCL systems had low NO_x emissions as expected given their sophistication relative to the MOL and MCL systems. The ESPCL systems had essentially the same NO_x emissions as similar vehicles (Ford Tauruses and Postal vehicles)

operating on gasoline. The EMPCL system had lower NO_x emissions being approximately one-quarter the NO_x emissions of the control (Dodge B350) vehicles.

The ozone-forming potential of exhaust emissions from CNG vehicles is only about half that of gasoline vehicles. Moreover, evaporative, running loss, and refueling emissions of late model gasoline vehicles are estimated to be nearly 50% higher than their exhaust hydrocarbon emissions.[11] Dedicated CNG vehicles thus should have overall ozone-forming potential that is between 15 and 20% that of gasoline vehicles. Bifuel vehicles operating on CNG should have from one-half to three-quarters the ozone-forming potential of gasoline vehicles since they have evaporative, running loss, and refueling emissions from the gasoline they use.

Both CO and NO_x emissions from aftermarket CNG conversions are dependent on proper adjustment of the fuel system, and the experience of the AFV-FDP suggests such adjustments need to be performed periodically to counteract drift. Fully electronic conversions (e.g., ESPCL systems) performed somewhat better than either the MOL or the MCL. The OEM vehicle with EMPCL had consistently lower CO and NO_x emissions than either the control vehicle or similar vehicles using MCL systems.

Fuel Costs. In most cases, the cost of CNG is less than that of an equivalent amount of gasoline, resulting in lower fuel operating costs. The cost of CNG in New York State varies according to utility service area. Prices—including road-use, excise, and sales taxes—are typically in a range between the price of regular grade gasoline and as much as 25 cents per gallon less.[12] Table 2.10 lists the miles a vehicle would have to travel to achieve a three-year simple payback of a typical CNG fuel system costing $4,500 (or a CNG vehicle having an incremental cost of $4,500) for various vehicle fuel economies and fuel price differentials. For example, a vehicle having a fuel economy of 15 miles per gallon (mpg) would have to travel 90,000 miles per year to achieve three-year simple payback, if CNG were priced 25 cents per gallon lower than gasoline. The figures in Table 2.10 indicate that only a vehicle that uses large quantities of fuel, either because the vehicle achieves low mpg, high annual mileage, or both, is a good candidate for CNG if the vehicle owner is trying to accomplish a three-year simple payback. As the price of CNG fuel systems change, the numbers in Table 2.10 would change correspondingly; e.g., if CNG fuel system prices were cut in half, it would take half the miles to achieve three-

[11] Evaporative emissions, running losses, and refueling losses for late model gasoline vehicles were estimated using the EPA MOBILE5a model.

[12] Natural gas has an octane value higher than that of any premium gasoline, which could allow engine designs more efficient than gasoline engines. However, to date auto manufacturers have taken only very limited steps to optimize their dedicated natural gas engines to achieve significant efficiency advantages relative to gasoline engines. If natural gas engines are developed that are optimized for maximum efficiency, the price of CNG should most appropriately be compared with the price of premium gasoline.

year simple payback. Also, if the price of CNG drops with increased infrastructure growth, the CNG price differential could increase beyond the range shown in Table 2.10, leading to improved CNG economics.

Table 2.10 Annual Miles Traveled to Achieve Three-Year Simple Payback of a CNG Fuel System[1] at Various Fuel Economies and Equivalent Gallon CNG Price Differentials

CNG Price Differential, $/Gallon	Vehicle Fuel Economy, Miles per Gallon			
	5	10	15	20
$0.35	21,429	42,857	64,286	85,714
$0.30	25,000	50,000	75,000	100,000
$0.25	30,000	60,000	90,000	120,000
$0.20	37,500	75,000	112,500	150,000
$0.15	50,000	100,000	150,000	200,000

[1] $4,500 installed fuel system price or vehicle incremental cost

Safety. Because of the high pressures in CNG systems, concern is often expressed about the potential for leaks, fires, or catastrophic failure of storage tanks. Isolated instances of CNG fires and tank failures have been reported outside the AFV-FDP, and have usually been attributed to external abuse of the tanks or other human error, similar to circumstances surrounding fuel-system fires and other problems in gasoline vehicles. Participants in the AFV-FDP were provided training to ensure safe operation and handling of vehicles and refueling equipment. Safety incidents with light-duty CNG vehicles in the AFV-FDP were limited to a few leaks that did not cause any injury, fires, or property damage.

One occurrence involved a slow leak from a valve on a CNG cylinder mounted behind the rear seat of a NYSDEC sport-utility vehicle. The leak was caused by a loose fitting of a type that has been superseded by improved designs. Although the leak was fixed quickly, NYSDEC elected to discontinue using CNG vehicles in which any part of the fuel system was inside the vehicle body. On two other occasions, the composite tanks used in two of Monroe County's bifuel passenger cars appear to have developed slow leaks. The manufacturer is working to diagnose the problem and reports that only one other similar leak has occurred with this type of cylinder, which is sold nationwide. Lastly, one of the NYSPSC's CNG vehicles leaked as a result of a fitting loosened by the impact of a traffic accident. The driver turned off the fuel shut-off valve, stopping the leak, as he was trained to do. This incident led to improvements in recommended practice for fuel component mounting.

NYSERDA, along with Brooklyn Union and Consolidated Edison, funded a study of the safety of bifuel vehicles.[13] The analysis assessed the relative hazard of vehicles containing both CNG and gasoline, compared to the hazard of a dedicated CNG vehicle. The study concluded that a bifuel vehicle poses a slightly greater risk than a dedicated CNG vehicle; however, this marginal increase in risk is small and is within the bounds of risk posed by gasoline-powered vehicles.

Facility Modifications

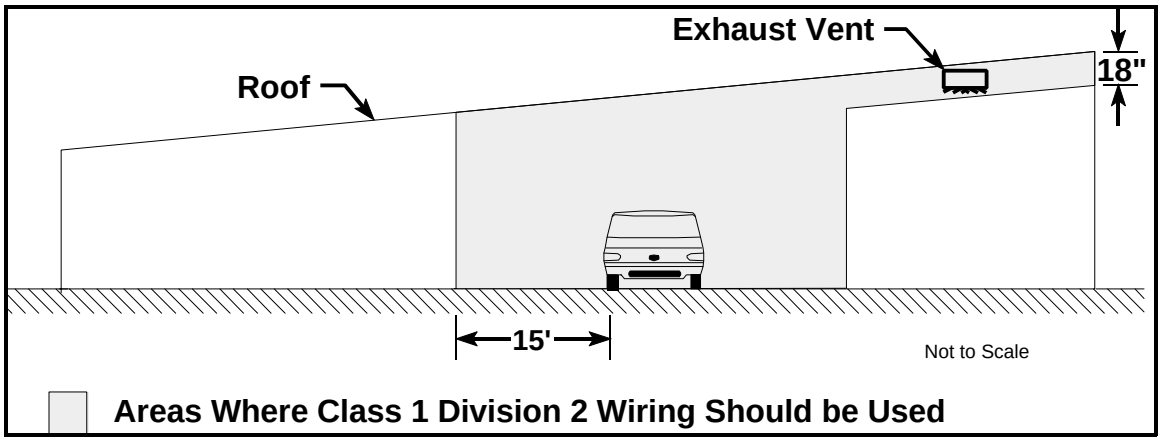
The current national mechanical and electrical codes are designed to prevent accumulation and/or ignition of vapors generated from unplanned releases of conventional fuels. National Fire Protection Association (NFPA) codes and standards and the National Electric Code (NEC) provide ventilation and electrical requirements for garages where gasoline and diesel vehicles are repaired. These standards are designed to prevent the accumulation of vapors inside the garage and limit sources of ignition in locations where released fuel vapors are likely to be found. Although the current codes describe ventilation requirements for facilities servicing conventional liquid fuel vehicles, they can be used as a basis to determine the needs of facilities servicing CNG vehicles.

The hazards posed by flammable vehicle fuels are controlled by attempting to keep vapor concentrations low (outside flammability limits) and removing ignition sources from areas where flammable vapors might be found. CNG vehicles present similar hazards, and similar methods are needed to control the hazards. The main difference between conventional fuels and CNG is that fuel released from CNG vehicles is buoyant. The existing codes require that areas below grade used for vehicle repair have forced ventilation. This ventilation requirement helps prevent accumulation of heavier-than-air fuel vapors, which could accumulate in below-grade areas. Potential ignition sources must be removed from areas where fuels may accumulate. For example, suspended unit heaters must be located at least 8 feet above the floor and heaters with glowing elements must be at least 18 inches above the floor. Electric equipment installed less than 18 inches above the ground must be designed to limit the probability of ignition.

Current code requirements, allowing ignition sources above vehicles, place potential ignition sources in areas where released CNG may travel. Storing or repairing CNG vehicles in facilities not designed for them can thus present problems. In the AFV-FDP, vehicle storage and maintenance facilities were inspected to identify potential hazards from AFVs. Reports highlighting problem areas were written and presented to the facility managers. These inspections involved walking through the facility, noting potential ignition sources (both electrical and heating related), looking for areas where released fuel could become trapped, and observing how

[13] Grant, Dr. T.J., et. al. (EBASCO Services Inc.), "Safety of Natural Gas Dual-Fueled Vehicles," Addendum to NYSERDA Report 90-2, January 1991.

Figure 2.26 General Electrical Requirements for CNG Repair Areas Based on Modification of National Codes



the facility is used. Recommendations on changes in ventilation, heating, electric equipment, and work processes were then made. The recommendations strive to remove potential ignition sources from areas where released CNG would travel or accumulate. Figure 2.26 shows a representative vehicle repair area. The shaded areas represent areas where ignition sources could present unacceptable hazards. These generalized areas were chosen based on existing codes for heavier than air fuels, the properties of CNG, and existing codes for industrial handling of lighter than air flammable gases.

Table 2.11 lists the facilities for which reports detailing recommended changes were written. Most of the facilities were able to operate with minor facility modifications combined with changes in operating procedures. South Beach Psychiatric Center is an example of a fleet that took an active role in implementing the recommended changes. The site improvements included a methane detection system, increased ventilation above the repair area, and signage designating a single repair bay for CNG vehicle repairs. These modifications cost $35,000. While this cost is high if the fleet does not increase its CNG fleet beyond the current four vehicles, the changes should allow SBPC to operate a larger percent of its fleet on CNG.

For new facilities being constructed, the added cost would be small. Heating and electrical equipment could be located or configured to limit problems caused by both CNG and conventional fuels. Likewise ventilation could be designed to help prevent fuel from accumulating both above and below vehicles.

Table 2.11 Garage Safety Assessments Performed as Part of the AFV-FDP

Location	Planned Alternative Fuel	Vehicle Type	Date Issued
CENTRO	CNG	Transit Buses	7/92
NFTA	CNG	Transit Buses	7/92
Broome County Transit	CNG	Transit Buses	8/92
RGR	CNG	Transit Buses	8/92
NYCDOT Harper Street	CNG	Light-Duty Vehicles	1/93
NYCDGS Front Street	CNG	Light-Duty Vehicles	1/93
NYCDEP Madison Street	CNG	Light-Duty Vehicles	1/93
Erie County West Seneca	CNG	Light-Duty Vehicles	2/93
Erie County Tonawanda	CNG	Light-Duty Vehicles	2/93
Erie County Hamburg	CNG	Light-Duty Vehicles	2/93
City of Buffalo Municipal	CNG	Light-Duty Vehicles	3/93
Kenmore-Town of Tonawanda U.F.S.D.	CNG	School Buses	4/93
Village of Hamburg	CNG	Light-Duty Vehicles	4/93
Town of Tonawanda Water and Sewer	CNG	Mixed Truck Fleet	5/93
South Beach Psychiatric Center	CNG	Light-Duty Vehicles	5/93
NYSDEC Delmar	CNG	Light-Duty Vehicles	5/93
James Baird State Park	LPG	Light-Duty Vehicles	11/93
Monroe County	CNG	Light-Duty Vehicles	4/94
NYSDOT Hamburg	CNG	Mixed Truck Fleet	3/95
NYSTA Albany	CNG	Light-Duty Vehicles	3/95
SUNY Buffalo North Campus	CNG	Light-Duty Vehicles	2/96
SUNY Buffalo South Campus	CNG	Light-Duty Vehicles	2/96
Town of Amherst Highway Department	CNG	Light-Duty Vehicles	2/96
Town of Amherst Municipal	CNG	Light-Duty Vehicles	2/96
West Seneca Development Center	CNG	Light-Duty Vehicles	2/96

Other Demonstrations

At the same time the AFV-FDP was being conducted other fleets were also in the process of evaluating alternative fuel vehicles. Many of these have published the results of their operating experiences.

The Federal Government's experience with AFVs has been summarized in several National Renewable Energy Laboratory (NREL) publications.[14,15,16] The State of Texas evaluated CNG fuel systems by operating 42 CNG vehicles (3 OEMs and 39 conversions) in the state fleet.[17]

The vehicles whose emission tests were included in the NREL reports were either aftermarket conversions (using ESPCL fuel systems) or OEM vehicles (using EMPCL fuel systems). Emission test results were similar to those for the AFV-FDP vehicles. Table 2.12 compares the emission test results for the vehicles in the NREL emissions test program to similar vehicles in the AFV-FDP. For the automobiles and the light trucks using EMPCL (OEM Dodge Vans) the results were similar. The results for the ESPCL vehicles were inconsistent. Differences between the vehicles in each fleet help explain these differences.

One method NREL used to check vehicle reliability was driver evaluation forms. Drivers were asked to fill out postcards at every refueling. They were asked to check boxes for various operating problems. The reports provide data for the first 10,000 miles of vehicle operation. The CNG vehicles averaged a little over six complaints/vehicle during the first 10,000 miles. The gasoline vehicles averaged approximately one-half a complaint/vehicle during the first 10,000 miles. The CNG vehicle complaints included poor idling (23% of the total complaints), hesitation (18%), hard to start (17%), stalling after starting (13%), and lack of power (11%). The OEM vans had significantly fewer complaints than the converted vehicles.

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[14] Motta, R.C., K.J. Kelly, and W.W. Warnock, "Compressed Natural Gas and Liquefied Petroleum Gas Conversions: The National Renewable Energy Laboratory's Experience," National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401-3393, April 1996.

[15] Whalen, P., et al., "Alternative Fuel Light Duty Vehicles — Summary of Results from the National Renewable Energy Laboratory's Vehicle Evaluation Data Collection Efforts," National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401-3393, May 1996.

[16] Kelly, K, et. al., "Round 1 Emissions Test Results from Compressed Natural Gas Vans and Gasoline Controls Operating in the U.S. Federal Fleet," SAE Paper No. 961091, SAE International, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001.

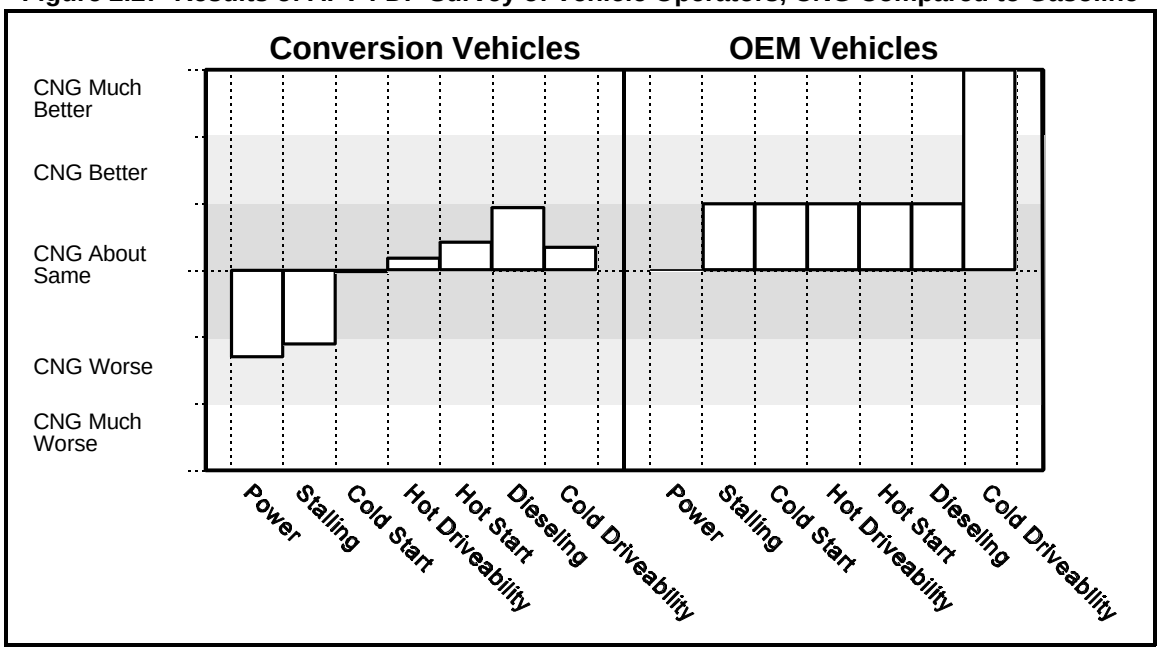
[17] Matthews, R.D., et al., "The Texas Project: Part 1-Emissions and Fuel Economy of Aftermarket CNG and LPG Conversions of Light-Duty Vehicles," SAE Paper No. 962098, SAE International, 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001.

Table 2.12 Comparison of CNG Vehicle Emissions to Gasoline Control Vehicle Emissions (AFV-FDP and NREL Vehicles)

Vehicle Type	Fuel System	NMHC/NMOG [a]		Carbon Monoxide		Oxides of Nitrogen	
		NREL	AFV-FDP	NREL	AFV-FDP	NREL	AFV-FDP
Automobile [b]	ESPCL	-21%	-89%	-25%	-31%	+191%	+65%
Light Trucks (under 6,000 lb GVW) [c]	ESPCL	-47%	-78%	+39%	-46%	+33%	+6%
Light Trucks (over 6,000 lb GVW) [d]	EMPCL	-83%, -77%	-95%	-68%, -3%	-88%	-31%, -31%	-71%

[a] NREL Results are reported as NMHC; AFV-FDP results are reported as NMOG
[b] NREL-Ford Taurus and Plymouth Acclaim; AFV-FDP-Ford Taurus.
[c] NREL-Dodge Caravan, GMC Safari and Chevrolet Astro; AFV-FDP-Postal LLV
[d] NREL-Dodge Van result reported separately for each test laboratory; AFV-FDP-Dodge Van

Figure 2.27 Results of AFV-FDP Survey of Vehicle Operators, CNG Compared to Gasoline



Drivers of the 1992 OEM vans had fewer than two complaints/vehicle and drivers of the 1994 vans had fewer than one-half a complaint/vehicle (same rate as gasoline controls). Many drivers also complained about lack of operating range for the CNG vehicles—a volunteered complaint since it was not included as a choice on the cards. A survey of drivers also was performed for the AFV-FDP. Although a different format was used, the results, shown graphically in Figure 2.27, were similar to those obtained by NREL. The OEM vehicle had a better rating than the conversions. The most negative aspects of the vehicles from the drivers' point of view were power, stalling, and cold starting.

Emission tests of CNG vehicles also have been reported for fleets operating in California.[18] Emission testing of CNG vehicles included EMPCL systems on Dodge and Ford vans and MCL systems on Chevrolet Vans. These results are shown in Table 2.13. The results for NMHC and CO were similar to those obtained in the AFV-FDP. The results for NO_x are variable with some increases over control vehicles and some decreases.

Table 2.13 Comparison of CNG Vehicle Emissions to Gasoline Control Vehicle Emissions (AFV-FDP and California Energy Commission vehicles)

Vehicle Type	Fleet Program	Fuel System	NMOG	Carbon Monoxide	Oxides of Nitrogen
Dodge Van	AFV-FDP	EMPCL	-95%	-88%	-71%
Dodge Van	CEC Clean Fleet	EMPCL	-90%	-74%	-18%
Ford Van	CEC Clean Fleet	EMPCL	-55%	-67%	+97%
Chevrolet Van	CEC Clean Fleet	MCL	-73%	-62%	-51%

Lessons Learned

Based on the data collected and analyzed during the AFV-FDP, several observations about light-duty CNG vehicles were made:

- Properly tuned, CNG conversion equipment can meet fleet needs and EPA emission standards.
- It is difficult to accurately set air-fuel ratio of mechanical CNG fuel systems in the field or at installation facilities, resulting in poor starting, hesitation, and higher emissions.
- Air-fuel ratios for conversion CNG fuel systems tend to drift and require periodic readjustment to maintain proper operation.
- OEM CNG fuel systems operate with fewer problems and require no periodic fuel system adjustments to maintain proper state of tune.

[18] Battelle Memorial Institute, "Clean Fleet Final Report-Volume 7 Vehicle Emissions," December 1995.

- While ESPCL conversion CNG fuel systems do not require field adjustment of air-fuel ratios, repair records indicate that vehicles with these systems require more repairs to maintain starting performance.

- Natural gas costs less than gasoline, but vehicles must use a large quantity of fuel each year to offset the high incremental price of CNG fuel systems.

- Except for the OEM CNG vehicle, all the vehicles converted to use CNG had lower fuel efficiency.

- Conversion CNG vehicles have significantly slower acceleration, but OEM CNG vehicles do not.

- OEM dedicated CNG vehicles can meet ULEV emission standards, and do not have refueling, evaporative, or running loss emissions.

- Reactive emissions from dedicated CNG vehicles can be 80 to 85% lower than similar gasoline vehicles.

- Existing garages may need modification to safely store and maintain CNG vehicles.

- Drivers consider OEM dedicated CNG vehicles to be better than bifuel conversion vehicles in terms of drivability and performance.