Environmental Concerns of Natural Gas Vehicles: Do We Know Enough?

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ABSTRACT

Vehicles powered by natural gas are currently used in the United States and other parts of the world. Although the number of such vehicles in the United States is small, there is a potential for substantial growth. An overview of natural gas vehicle technology, markets, and environmental concerns is provided. The environmental concerns discussed are natural gas supply, emissions, and safety. It is concluded that more research is required in the areas of exhaust emissions and safety; no comprehensive data base exists in either area. The availability of natural gas does not presently appear to be a crucial issue.

Vehicles powered by compressed or liquefied natural gas (NG) are currently in use in the United States and other parts of the world. The number of vehicles in the United States is small; estimates range from 20,000 to 30,000, all in fleets (1,2). However, the Gas Research Institute (GRI) has projected that by the year 2000 from 1 to 4 million natural gas fleet vehicles might be operating in the United States (3). The personal-use market is expected to develop after major fleet use begins (1,2,4). Because of the potential for such growth and because natural gas-fueled vehicles have different performance-, emissions-, and safety-related characteristics than those of gasoline- or diesel-fueled vehicles, the U.S. Department of Energy (DOE) sponsored a study to document what is known about environmental concerns related to natural gas vehicles (5). This paper draws from the results of that study to provide an overview of natural gas vehicle technology, markets, and, in particular, environmental concerns.

VEHICLE TECHNOLOGY, FUELING, AND OPERATION

Natural Gas Vehicle Technology

Most current natural gas vehicles are powered by spark-ignition (SI) engines and have been converted to operate on both gasoline and natural gas. The natural gas is stored on board in compressed form at high pressure (approximately 2,400 psig) in steel cylinders; these vehicles are therefore called compressed natural gas (CNG) vehicles. The pressure is reduced to near atmospheric as the natural gas flows through pressure regulators and is delivered to a gas-air mixer that meters the natural gas into the engine. Figure 1 illustrates a typical system. No changes are required in the SI engine, except perhaps for the alteration of spark timing to improve engine power in natural gas operation. A gasoline shutoff valve is activated when the vehicle is operating on CNG; a similar valve shuts off the CNG when the vehicle is operating on gasoline. Some CNG vehicles have been designed to operate exclusively on natural gas; engine parameters (e.g., compression ratio) can then be optimized for natural gas. Ford Motor Company, in particular, has built several such "dedicated" CNG demonstration vehicles and is currently providing 27 of them to gas utilities for a 2-year test program (7).

The CNG cylinders are the dominant items in the natural gas vehicle system, accounting for much of the added weight, volume, cost, and operational constraints (1). Current CNG cylinders typically weigh 100 lb or more and have a capacity of 325 standard ft^3 (scf), or the equivalent of approximately 2.6 gal of gasoline. A two-cylinder system, which adds approximately 250 to 300 lb to a converted dual-fuel vehicle (and occupies a significant portion of the car's trunk volume), can thus provide a driving range of only 60 to 120 mi.

Design of lightweight cylinders for automobiles is under way and might include high-strength steel, aluminum alloy, or composite structures. For example, according to G. Peitsch, Ford Motor Company, Ford's dedicated CNG vehicles use aluminum composite cylinders. An alternative gas storage concept being explored involves adsorption of methane on molecular sieves or activated carbon particles at pressures of 350 to 400 psig (8). Roughly twice the gas could be stored in this manner as in the high-pressure tanks currently in use.

Vehicles with SI engines have also been converted to run on liquefied NG (LNG). Figure 2 is a schematic of an LNG system that has been used for a number of years in dual-fuel automobiles and trucks. It features a low-pressure (5 to 60 psig), cryogenic (<-259°F) tank mounted in the trunk. A combination pressure regulator/heat exchanger reduces pressure and vaporizes the LNG, if necessary, before delivery to the gas-air mixer. As in CNG systems, no changes are required to SI engines. Single-fuel LNG vehicle conversions have been displayed, but vehicle kits for such conversions are not commercially available.

The LNG tank permits a much greater travel range (200 to 400 mi) than CNG cylinders. An 18-gal tank that typically weighs 75 to 100 lb contains roughly the equivalent of 12 gal of gasoline. Like the CNG cylinder, it occupies more space than a gasoline tank. The LNG tank is made of steel and features double-wall construction, with the inner shell thermally isolated from the outer shell as much as possible. In the future, LNG tanks may be made lighter and more compact through the use of more efficient tank shapes, better material combinations (e.g., use of aluminum alloys), and more effective insulation.

Conversion kits designed to allow vehicles powered by compression-ignition (CI) engines (i.e., diesel) to operate on natural gas have only recently become

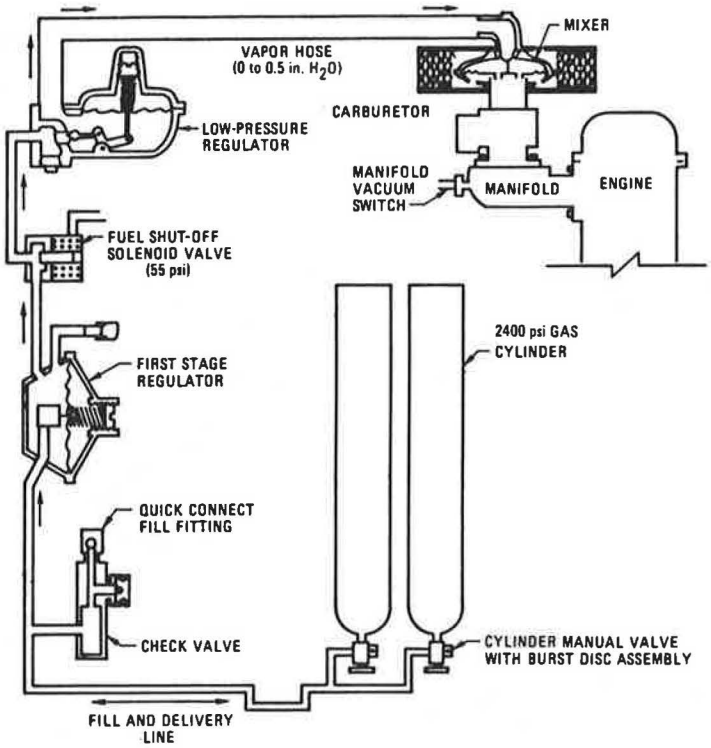

FIGURE 1 Vehicular CNG system for spark-ignition engines *(1,6)*.

commercially available (according to L.C. Elder of Columbia Gas System and R.R. Tison of E.F. Technology, Inc.). For such vehicles to operate on natural gas, ignition aids are required; natural gas is a high-octane fuel that will not autoignite under pressure as diesel fuel will. Such ignition aids include chemical fuel additives, spark plugs, glow plugs or other heated surfaces, and pilot injection of diesel fuel (i.e., a small amount of diesel fuel is injected into the combustion chamber). In this last case, two fuel systems are required and operation on natural gas alone is not possible.

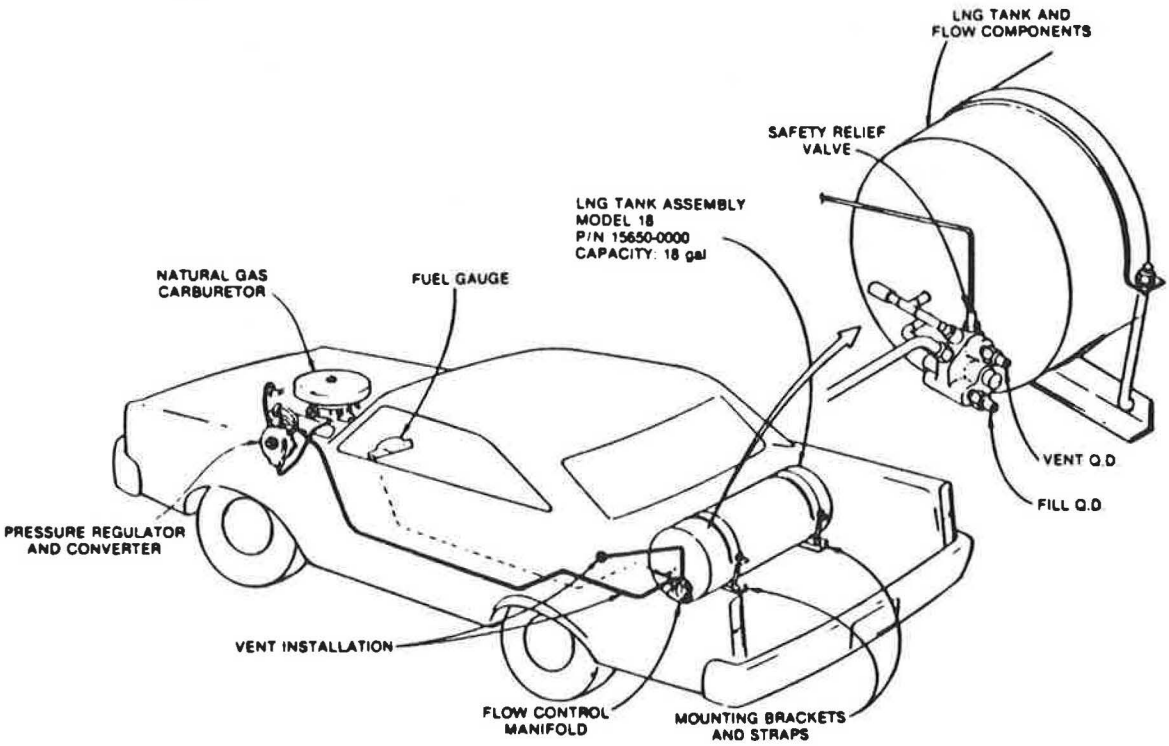

FIGURE 2 Typical LNG conversion kit installation in a passenger car *(1,9)*.

Fueling Methods

Two general approaches to the fueling of CNG vehicles are in current use. In slow filling, up to 80 vehicles can be simultaneously fueled with CNG delivered from a station compressor at approximately final-fill pressure. The time required for slow filling is a function of the number of compressors available, the size of piping and storage, and the number of vehicles being filled; up to 14 hr may be required. In fast filling, one or two vehicles at a time can be rapidly fueled from a cascade of high-pressure (3,600 psig) cylinders previously filled by a compressor, and fill time is only 2 to 5 min. A third approach, now under development, is the slow filling of vehicles from small compressors that may be located at private residences. In LNG vehicle fueling, the liquid fuel is fed from the station storage tank to a dispenser under low pressure. Several vehicles can be filled simultaneously, and fill time is approximately 10 min.

Vehicle Operation

In principle, natural gas (both CNG an LNG) lends itself well to use in SI engines (1). The primary advantage of natural gas as an SI engine fuel is its high research-octane number (estimated to be as high as 130) compared with that of current gasoline (91 to 95). This permits the use of engines with high compression ratios in vehicles designed specifically for natural gas, with accompanying fuel efficiency and performance benefits. In addition, broad flammability limits for natural gas allow engine operation at leaner air/fuel mixtures than with gasoline, which further improves thermal efficiency. Moreover, the gaseous nature of the fuel improves cylinder-to-cylinder fuel distribution and reduces engine pumping losses by replacing air.

On the other hand, natural gas has several disadvantages as an automotive fuel. Its gaseous state tends to result in reduced wide-open-throttle engine power at all vehicle speeds. The natural gas displaces intake air that would otherwise be inducted with partially liquid fuel and that would result in higher power output per piston stroke. Lean operation aggravates the power loss by limiting fuel input. The low flame speed of natural gas increases burning duration and thus decreases engine thermal efficiency. Some of these losses can be recovered through mixture enrichment at full load and advancement of spark timing. In a vehicle designed to use only natural gas, the power loss may also be eliminated by increasing the engine compression ratio and incorporating a turbocharger.

Conclusive data are not yet available on the potential fuel economy and performance of natural gas vehicles, particularly those that are optimized single-fuel vehicles. In one study, data on fuel economy and performance were collected from 13 CNG and LNG fleets and seven tests of experimental vehicles (1). Most of the data were based on dual-fuel vehicles that were not fully optimized for natural gas operation. In all instances in which data were reported, power decreased with natural gas operation, whereas acceleration time increased (from 20 to 55 percent where quantified). Many fleet operators reported substantial increases in fuel economy (up to 30 percent), whereas some indicated substantial decreases (again 30 percent). The more controlled tests of experimental vehicles showed approximately equal energy-equivalent fuel economy for natural gas and gasoline vehicles. Variance in the fleet operator data is attributed to a number of factors, including questionable energy-equivalency factors, differences in driving cycles, and variations in degree of engine optimization. The fuel economy and performance results of the experimental vehicles are shown in Table 1.

In lieu of data on optimized natural gas vehicles, the Aerospace Corporation conducted a simulation of optimized natural gas vehicles and determined that energy efficiency gains of more than 20 percent could be achieved by light-duty, single-fuel LNG vehicles compared with gasoline vehicles with similar power (1). Optimized light-duty, single-fuel CNG vehicles, however, achieved at most a 3 percent fuel economy gain, but acceleration was slower. When acceleration (and range) was comparable with that of a gasoline vehicle, CNG vehicle fuel economy declined 10 percent.

Applicable compression-ignition (CI) vehicle data are minimal, and there are no data on fleet use. However, several sources indicate that the power and thermal efficiency of the natural gas-fueled CI engine are lower than those for normal diesel fuel operation at roughly half load, depending on system design parameters and engine speed, whereas power and efficiency are often increased at high load (10). Thus, the operating cycle of a diesel CI vehicle fueled by natural gas would greatly affect its efficiency and power.

MARKETS

Current Worldwide Use

Compressed natural gas has been used as a fuel for SI engine vehicles in Italy since the late 1930s;

TABLE 1 Fuel Economy and Performance Data for Experimental Natural Gas Vehicles *(1)*

	Vehicle		Percentage Change, NG Versus Gasoline		
Fleet Operator	Model Year	Use	Power	Acceleration Time	Fuel Economy
CNG					
DOE/BETC[a]	1978	Light duty	–[b]	–	1
DOE/Bureau of Mines	1968-1970	Light duty	Decrease[c]	Increase[c]	Decrease[c]
DOE/EPA	1969-1980	Light duty	-27	55	1
Dual Fuel Systems, Inc.	1977-1981	Light duty/ medium duty	–	–	-1
General Motors Corporation	1967	Light duty	-15	–	–
LNG					
Beech Aircraft Corporation	1980	Light duty	–	–	–
Shell Research, Ltd.	1970	Light duty	-24	–	13

[a]BETC = Bartlesville Energy Technology Center.
[b]Dash = no data reported.
[c]No specific value reported.

approximately 275,000 private and fleet vehicles there currently use it. This is by far the largest number in any country (1). New Zealand now has 65,000 fleet and private vehicles operating on natural gas (11). The Canadian government provides incentives to encourage the use of vehicles fueled by natural gas and other alternative fuels. In the United States, CNG is only used in fleet vehicles, of which there are currently 20,000 to 30,000 (1,2). Very few LNG vehicles are in operation here, primarily due to the limited availability of this fuel. Several thousand CNG vehicles are estimated to be in use in other countries.

Potential U.S. Markets

The driving force behind the current and potential use of natural gas as a transportation fuel in the United States is fuel cost savings. Gaseous fuels for vehicles currently cost less, on an energy basis, than do liquid fuels. In 1982, the American Gas Association (AGA) estimated the delivered price of CNG to be 45 cents less per gallon equivalent than the cost of gasoline (2). Some of these savings, however, may be eroded in the future because the price of natural gas is projected to rise more rapidly than the cost of gasoline (10,12).

Whether it will be economical for specific fleets (and eventually personal vehicles) to convert to natural gas will depend primarily on whether the fuel savings can offset the capital costs associated with conversion to natural gas. The current cost of converting fleets to CNG is estimated at $2,300 to $3,600 per vehicle (13,14). This includes the cost of the conversion itself ($1,100 to $1,500) and the construction of the refueling station (13,15). The cost of an LNG conversion (vehicle only) is approximately $2,200, whereas the station costs per vehicle should be lower than those for CNG (16,17). The cost premium of a high-production volume, dedicated natural gas vehicle has been estimated to be one-third to one-half the cost of an after-market conversion (15).

The fleet market is the focus of most discussions of potential markets for natural gas vehicles (1-4, 10,17). Fleet vehicles are particularly appropriate for fueling with natural gas because (a) many fleet vehicles are fueled at a common point, which justifies the costs of a compressor and station, and (b) fleet vehicles are more readily accessible for maintenance by specially trained mechanics (18). Many types of fleets may use CNG. In a recent study conducted for New York State, the fleet types identified as being particularly appropriate for CNG conversion in that state included school buses and newspaper, postal, and parcel delivery fleets (17). The GRI has estimated in its baseline projection of U.S. energy demand that by the year 2000, 1 to 4 million automobiles and trucks in fleets will be converted to natural gas (3).

Penetration in the personal-use automobile and truck market is expected to develop only after major fleet use begins (1,2,4). Public fueling stations will be expensive, and market prospects for personal-use CNG vehicles will have to be more certain before such stations are developed. Drawbacks (such as high costs) associated with home compressors appear to make their use in the near term even more uncertain. Projections of the potential for personal use of these vehicles are sparse. One report indicated that in 1995 approximately 12 percent of urban passenger vehicle miles of travel (VMT) could be in natural gas-fueled vehicles (19). However, the authors of this report caution that these figures actually indicate that there is a substantial market for any alternative-fueled vehicle with performance similar to that of gasoline-powered vehicles and with lower operating costs.

ENVIRONMENTAL CONCERNS RELATED TO NATURAL GAS VEHICLES

The Argonne National Laboratory (ANL) state-of-knowledge report comprehensively documents the environmental issues associated with natural gas vehicles and the regulations affecting them (5). In the following sections major areas of concern are discussed: natural gas supply, exhaust emissions, and safety.

Natural Gas Supply

A key concern about the use of natural gas as an automotive fuel has been whether adequate supplies of natural gas will be available during the next 20 years. The United States has the world's third-largest proven reserves of conventional natural gas (198×10^{12} scf in January 1981) (20). However, at a domestic consumption rate of about 18×10^{12} scf per year, this supply will not last long. In addition to these reserves, however, there may be a much larger, although uncertain, quantity of potential natural gas from conventional and unconventional sources. Gas industry projections of supply indicate that the development of nonconventional sources of gas and Alaskan gas, as well as the increase of imported gas, can meet the nation's needs well into the 21st century (10).

Although natural gas availability does not appear to be a constraint on the use of natural gas as a vehicle fuel, if a large number of vehicles were converted to natural gas, the impact on the domestic natural gas consumption rate could be significant. However, the level of demand projected by GRI in its baseline estimates (0.3 quad by the year 2000) is clearly insignificant (3). Only if a great number of fleets were converted and the personal-use market opened up would there be a significant incremental demand for natural gas.

Exhaust Emissions

Emissions of natural gas-fueled vehicles with SI engines will depend on the degree to which engine calibration and hardware configuration are optimized to take advantage of this fuel (1). For example, engine operation at the lean air/fuel ratios allowed by natural gas reduces carbon monoxide (CO) and nitrogen oxide (NO_x) emissions. Furthermore, because gaseous fuels do not require fuel enrichment for satisfactory vehicle operation during cold-start operation (as do gasoline vehicles), vehicle operation on natural gas results in lower emissions of CO and hydrocarbons (HC) during cold starts. Because natural gas reduces engine power at all speeds, an additional spark advance is often used to recover some of this loss. This, however, causes HC and NO_x emissions to increase. Alternatively, if the engine is designed for natural gas only, the compression ratio can be increased to improve fuel efficiency. This, however, causes increased HC emissions. Experimental data are reviewed in the following paragraphs to illustrate more precisely the emissions impacts from the use of natural gas in vehicles. Available fleet data are limited and based on older model vehicles (1960s and mid-1970s) that used relatively rich air/fuel ratios in the gasoline model and therefore had high levels of emissions; these data are therefore not reviewed here [see Aerospace

TABLE 2 Summary of Emissions Data for Experimental Natural Gas Vehicles *(1)*

Fleet Operator	Vehicle Model Year	Vehicle Use	Optimization Parameter	Percentage Change, NG Versus Gasoline HC	CO	NO_x
CNG						
DOE/BETC[a]	1978	Light duty	Performance	150	-12	26
DOE/Bureau of Mines	1968-1970	Light duty	Emissions	-47	-87	-22
DOE/EPA	1979-1980	Light duty	Emissions	150	-99	-20
Dual Fuel Systems, Inc.	1977-1981	Light duty/ medium duty	Emissions	340	-96	-46
General Motors Corporation	1967	Light duty	Emissions	0	-81	-50
LNG						
Beech Aircraft Corporation	1980	Light duty	Economy	Similar to gasoline		
Shell Research, Ltd.	1970	Light duty	Economy	-65	-80	47

[a]BETC = Bartlesville Engergy Technology Center.

Corporation report (1) and ANL report (5) for further discussion of the fleet data].

Table 2 presents available data on experimental natural gas-fueled vehicles. The tested vehicles were dual-fuel vehicles and were not fully optimized for natural gas. Some of these vehicles were also older models. However, in general (and particularly when results of the more recent model years are examined), the table shows lower CO and NO_x emissions but higher HC emissions with natural gas.

Of particular interest in Table 2 are the results of DOE's vehicle test program conducted at the Environmental Protection Agency (EPA) Ann Arbor Motor Vehicle Emissions Laboratory (shown as "DOE/EPA" in Table 2). Two dual-fuel vehicles (a 1979 Impala and a 1980 Diplomat) were tested with both gasoline and CNG. Spark timing was not changed and the air/fuel ratio was adjusted for minimum emissions at idle and light load. Emissions were measured over the EPA city and highway driving cycles in accordance with federal test procedures. As Table 2 shows, CO and NO_x were lower with CNG than with gasoline, and HC was higher.

The increase of HC was significant, and the 1980 Diplomat exceeded the applicable federal HC standard of 0.41 g/mi; this increase was due to higher methane emissions. Levels of reactive nonmethane hydrocarbons (NMHC) were lower by 35 to 55 percent per mile. The NMHC fraction was reported to be 12 to 18 percent for CNG compared with 56 to 87 percent for gasoline. Current automotive exhaust catalysts are relatively ineffective in eliminating methane, which is the most stable of exhaust HC and is thus difficult to oxidize in these catalysts. Although methane HC emissions increase with natural gas operation, they are considered environmentally benign (1). Because methane HC emissions are nonreactive, they do not actively participate in processes that form photochemical oxidants or adversely affect the atmosphere's ozone layer (18). In California (the only state known to have an emissions approval program for conversions to natural gas), approval is granted on the basis of NMHC emissions rather than total HC emissions.

The DOE/EPA test program also found that when these dual-fuel vehicles were operated on gasoline, emissions of HC, CO, and NO_x were 5 to 30 percent higher than those from the baseline gasoline vehicle. In some instances the applicable emission standard was exceeded. For example, although the baseline 1979 Impala met the NO_x standard, the converted vehicle operating on gasoline did not, although operation with CNG was in compliance. Other studies have reported similar increases (21).

Also of interest in Table 2 is that NO_x emissions were occasionally reported to be higher with natural gas operation. In particular, for two vehicles in which optimization was for performance or fuel economy rather than for emissions, NO_x emissions were higher with CNG than with gasoline. Use of increased spark advance, plus the particular air/fuel ratio chosen, led to the NO_x increase in the LNG vehicle. It is unclear what adjustments were made that contributed to the increased NO_x in the DOE/BETC vehicle.

Although exhaust emissions data for natural gas SI vehicles are limited and exhaust emissions will vary depending on the degree of optimization for natural gas, some general conclusions can be drawn. In general, relative to gasoline-fueled vehicles, CO emissions from natural gas-fueled vehicles are significantly reduced, total HC emissions are higher, nonmethane (reactive) HC emissions are lower, NO_x emissions can be higher or lower, and dual-fuel vehicles operating on gasoline may produce higher emissions. In contrast, available data are inconclusive with respect to emissions impacts of natural gas-fueled CI vehicles. Few emissions data are available to analyze because, to date, the use of natural gas in CI engines has essentially been restricted to stationary and marine engines. However, the results of two studies indicate the potential for increased CO and NO_x emissions (at least at full load) as well as HC (22,23).

Safety

Safety concerns related to natural gas vehicles focus on fuel-system hazards in normal operation and in accidents. These hazards are based in part on the properties of natural gas. The hazards include fuel leakage in normal operation due to malfunctioning of the fuel system, necessary venting of LNG vapor to relieve pressure buildups, corrosive failure of CNG cylinders, fuel release in an accident because of tank puncture or crushing or from damage to other parts of the fuel system, intrusion of fuel system components into the passenger compartment, and fuel release during vehicle refueling. It is impossible to review each potential hazard in this paper. Such a review can be found in reports by the Aerospace Corporation and Argonne National Laboratory (1,5). Instead, (a) the safety-related properties of natural gas, (b) the safety history of these vehicles, (c) vehicle tests, (d) accident scenario analyses, and (e) applicable safety regulations and standards are briefly summarized in the following paragraphs to provide a perspective on the safety concerns associated with these vehicles.

TABLE 3 Selected Properties of Vehicle Fuels

Property	Natural Gas[a] CNG	Natural Gas[a] LNG	LPG[b]	Gasoline	Diesel Fuel 2
Flammability limits (vol. % in air)	5.3-15.0	–	2.1-9.5	1.0-7.6	0.5-4.1
Detonability limits (vol. % in air)	6.3-13.5	–	3.1-7.0	1.1-3.3	–
Minimum ignition energy in air (mJ)	0.29	–	0.27	0.24	0.3 (est.)
Autoignition temperature (°F)	1,004	–	855	442-880	500
Flash point (°F)	Gas	Gas[c]	Gas[c]	-45	Minimum 125
Energy content (lower heating value)					
Btu per gallon	19,760 at 2,400 psi and 70°F	76,300 at NBP[d] and 1 atm	82,450	116,400[e]	129,400[e]
Btu per pound	21,300	21,300	19,770	18,900[e]	18,310[e]
Diffusion coefficient in air[e] (cm/sec)	0.16	–	0.10	0.05	–
Buoyant velocity in air[f] (m/sec)	0.8-6	–	Nonbuoyant	Nonbuoyant	Nonbuoyant
Density of liquid (g/cm^3)	–	0.4226 at NBP	0.585 at NBP	0.70-0.78	0.82-0.86
Density of gas relative to air (air = 1.00)	0.555	–	1.56	3.4	>4.0 (est.)
Vapor pressure or equivalent (atm)[g]	1	1	1	0.60-0.8 at 311 (100)	0.0005 at 311 (100) (calculated)
Normal boiling point (°F)	–	-259	-44	100-400	405-620
Storage conditions	Compressed gas at 2,400-3,000 psig	Liquid at 25-60 psig	Liquid at 105-140 psig	Liquid at ambient temperature and pressure	Liquid at ambient temperature and pressure

[a]Properties are primarily those of methane. Because natural gas sources vary in composition, values will deviate to a small extent from those of pure methane.
[b]Properties are primarily those of propane. For vehicle applications, only the special grade HD-5 is suitable.
[c]LNG and LPG will flash at all temperatures above their normal boiling points.
[d]NBP = normal boiling point.
[e]Average value.
[f]At normal temperature and pressure.
[g]For gaseous fuels, refers to "equivalent vapor pressure" when released from high-pressure storage container or maximum possible in ambient environment. For liquid fuels, taken as the value of the vapor pressure at maximum ambient temperature.

Safety-Related Fuel Properties

The physicochemical properties of natural gas relative to those of gasoline, diesel fuel, or both result in different safety hazard levels. For example, density affects safety; natural gas released at an ambient temperature from CNG tanks is considerably less dense than air and will rise, diffuse, and disperse in unconfined spaces (1,24). Thus in comparison with gasoline vapor, which is heavier than air, methane vapor at ambient conditions tends to be safer in unconfined areas (1,24). In confined areas, however, the more rapid dissipation of natural gas is a disadvantage because flammable air/fuel mixtures could accumulate more rapidly (1). However, because the flammability limit of natural gas is 5 percent, considerably more fuel must mix with the air to render the mixture combustible than is the case with gasoline and its 1 percent limit (25). Furthermore, the fire hazard would persist longer with gasoline (26).

Selected physicochemical properties of natural gas, gasoline, diesel fuel, and liquefied petroleum gas (LPG) are listed in Table 3. In a study conducted for DOE, Los Alamos National Laboratory developed preliminary relative safety rankings based on specific physicochemical properties in isolation and in combination (24). These rankings are presented in Tables 4 and 5. On the basis of these rankings alone,

TABLE 4 Preliminary Relative Safety Rankings of Fuels Based on Selected Properties *(24)*

Property	Ranking Order of Hazard[a]
Lower flammability limit	D > G > LPG > NG
Diffusion coefficient	NG > G[b] or G > NG[c]
Autoignition temperature	G and D > LPG > NG
Energy content by volume	D > G > LNG > LPG > CNG
Energy content by mass	Approximately equivalent
Ignition energy	Approximately equivalent
Heat release rate	D > G > LPG > NG

[a]NG = natural gas (methane); LNG = liquefied natural gas; LPG = liquefied petroleum gas (propane); G = gasoline; D = diesel fuel.
[b]Confined.
[c]Unconfined.

TABLE 5 Preliminary Relative Safety Rankings of Fuels Based on Selected Secondary Hazards *(24)*

Fuel	Leakage Flow	Thermal Radiation	Dispersion Unconfined	Flammability
CNG	D	A	A	C
LNG	D	A	A-B	C
LPG	C	B	B-C	C
Gasoline	B	C	C	B-C
Diesel fuel	A	D	D	A

Note: The assignment of letters to rank fuels is done qualitatively, with the progression from A through D suggesting greater hazard levels. No mathematical relationship between the letters exists.

Los Alamos concluded that it is difficult to designate any one fuel as significantly safer than another.

In addition, health risks from each fuel can be evaluated on the basis of the toxicity of the fuel when inhaled, ingested, or in contact with the skin. Methane in sufficient quantities acts as a simple asphyxiant by displacing air, but is otherwise nontoxic. A potential LNG health hazard is skin tissue damage from contact with the cryogenic fluid or with cold fueling equipment.

Safety History of Natural Gas Vehicles

The safety history of natural gas vehicles to date has been reported to be good and even excellent (1, 24,27). However, the data to support this statement are acknowledged to be quite limited (1,24,27). Accident data from Italy, for example, are generally not available (24). Reports indicate that explosions associated with accidents have not occurred in Italy in 30 years of operation, although there have been several fires (24). Cylinder failures occurred during the early years of operation, but with better control over gas quality, these have decreased significantly. Even if data from Italy were available, however, they would not be directly applicable to the use of natural gas vehicles in the United States

because of the significantly different cylinder design and safety devices employed in the two countries.

In the United States only one study of natural gas vehicle fleet data is known. The AGA prepared a preliminary safety analysis of natural gas vehicles in 1979 with fleet data collected from 1970 to 1979 by three gas utilities and one taxicab company (28). The 2,700 vehicles included approximately 500 sedans, 2,000 light-duty trucks, and 200 medium- and heavy-duty trucks. The total mileage of the vehicles was about 175 million mi; that of the dual-fuel vehicles in the fleets was estimated to be 133 million mi. Of the estimated 1,360 collisions in which CNG vehicles were involved, there were no reported collision-related failures or fires involving the natural gas systems. Several other incidents, however, were reported in which the natural gas system was identified as the fire source. These fires were attributed to faulty installation of the gasoline bypass pipeline and to deficiencies in venting systems (28). No deaths, and only one injury, occurred in accidents where natural gas was a contributing factor.

Vehicle Tests

Tests of natural gas vehicles and their fuel system components appear to be quite limited and in some cases outdated. For example, the only test of the likelihood and severity of fires due to vehicular natural gas leaks reported in the literature was conducted in 1970 by the California Highway Department (29). This test indicated the need for improved venting of the trunk, isolation or venting of the passenger compartment, or both.

Vehicle impact testing was conducted by the U.S. Department of Transportation (DOT) in 1971; no further U.S. government testing has been conducted since then (24,30). Furthermore, the vehicles, fuel systems, and test conditions in these tests were not representative of current lightweight designs. A more recent vehicle impact testing program using 1981 vehicles was conducted in Canada (31). These tests included 50-mph rear-end collisions. No fuel release, fire, or explosion occurred with the CNG vehicles, nor was there any passenger compartment intrusion, although the tanks and supply lines were slightly dislocated. Neither program tested complete LNG vehicles.

Fire tests of CNG vehicles were also conducted in the Canadian test program. Although no explosions occurred, pretest tank pressure was 1,100 psig, far lower than normal.

Current CNG cylinders are quite rugged. However, lightweight tanks now being developed have not been thoroughly tested for their integrity in accidents. Rear-impact tests using these lightweight tanks have been conducted by a cylinder manufacturer and they have been found quite promising to date.

Finally, tank corrosion is a safety concern in CNG vehicles. In the past, corrosive natural gas constituents such as hydrogen sulfide (H_2S) have caused catastrophic failure of a number of steel cylinders used to transport and store natural gas. To date, the maximum allowable safe concentrations of H_2S and other contaminants in natural gas have not been determined, and the long-term effects of H_2S exposure on CNG steel cylinders are unclear. A major research program was recently recommended to examine the effects of differing gas qualities on CNG storage cylinders under stress conditions (32). Testing is also required to determine the corrosive effects of natural gas on aluminum because aluminum cylinders or composite cylinders with aluminum inner shells may replace steel cylinders in CNG vehicles. Few applicable data exist (10).

Accident Scenario Analyses

In the Los Alamos study, several accident scenarios were evaluated in order to rank gaseous and liquid fuels (CNG, LNG, gasoline, and diesel fuel) according to relative safety. (LPG was also evaluated, but the results are not reported here.) The analyses indicated that diesel fuel is relatively and significantly safer than the other fuels and that in some cases CNG and LNG had increased risks relative to gasoline whereas in other cases they were as safe as, if not safer than, gasoline (24). In other words, the relative safety rankings of CNG, LNG, and gasoline depended on the specific scenario being evaluated.

For example, if a fuel leak was assumed in the presence of an ignition source, CNG and LNG were found to have a significant explosion hazard relative to gasoline in a residential enclosed garage. Fundamentally, a confined system exists in a residential garage despite some minimal degree of ventilation. In an underground public garage, where air change is more frequent, no difference was found among CNG, LNG, and gasoline.

In all three collision scenarios (urban, rural, and tunnel) examined, the rapidly dispersing natural gas was found to be relatively safer than gasoline. The likelihood for fire alone was found to be the same as gasoline or slightly higher for CNG and LNG. The likelihood for fire plus personal injury (i.e., burns), however, was greater with gasoline in all three cases. Furthermore, the likelihood of an explosion, although small for all fuels, was determined to be significantly greater for gasoline than for CNG and LNG.

In the fueling line rupture scenarios (rupture during fuel transfer to a personal-use vehicle, and rupture during refill of the station's storage tank), natural gas exhibited a higher relative level of fire hazard. Personal injury was also more likely with CNG and LNG because of injuries from flailing hoses and cryogenic burns, particularly in the station storage tank refueling scenario. However, the explosion hazard with CNG or LNG was lower because of their relatively rapid dispersion.

In another study, conducted by A.D. Little in 1972, what might be termed "worst-case" scenarios were also addressed (33). The operation of vehicles powered by gaseous fuels in Boston harbor tunnels and on connecting toll roads was the setting for the study. One of the scenarios analyzed the consequences of a CNG cylinder failure resulting in a fire in one of the tunnels, assuming that the tunnel was without ventilation. The hot combustion products from 300 scf of natural gas were estimated to fill a 60-ft section of the harbor tunnel. The likelihood of serious damage to an oncoming vehicle or injury to its occupants was deemed slight on the basis of the short residence time in the combustion zone. Hazards to occupants of the CNG vehicle, however, were not considered. Another scenario examined the distance up to which personal injury could occur and the extent of tunnel damage assuming that a CNG or LNG tank burst because of failure of the pressure relief device. Personal injury occurred at greater distances with CNG than LNG. Additional analyses of such worst-case scenarios appear desirable.

Federal Safety Regulations

With the exception of design and inspection criteria for compressed gas cylinders, there are no federal regulations that specifically address natural gas as a motor vehicle fuel. A review of the Code of Federal Regulations (CFR) was conducted for DOE for potentially applicable federal regulations, including

regulations for fueling operations (18). This review revealed considerable uncertainty in regulatory agencies regarding which federal regulations actually apply to motor vehicles fueled by natural gas (18).

The Materials Transportation Bureau (MTB) of DOT, which sets regulations for transport of hazardous materials, has established regulations for the design and testing of compressed gas cylinders (49 CFR, Part 173: DOT-3A[CNG] and DOT-4.L[LNG]). The regulations apply to vehicles that transport bulk industrial gas, including methane, but not natural gas. Exemptions are available for the transport of bulk natural gas, but levels of corrosive materials are restricted (1,32). The allowable levels of H_2S and water are more stringent than those for pipeline-quality gas from gas distribution systems used to fuel natural gas vehicles. However, steel cylinders designed to meet MTB specifications are widely used in natural gas vehicles (1). DOT has also issued specifications for the manufacture of one type of aluminum tank for use in methane service (10). No standard exists for composite cylinders, although a series of exemptions does exist that allows their use in specific applications before publication of a standard (L.C. Elder, Columbia Gas System; 10).

DOT's Bureau of Motor Carrier Safety (BMCS) regulations on the safety of interstate trucking cover fuel system integrity in vehicles operated by regulated private, common, or contract carriers, but these regulations do not mention CNG or LNG vehicles specifically (49 CFR, Part 393) (18). BMCS regulations do exist for LPG systems, but disagreement exists within the BMCS as to whether these LPG requirements apply to vehicles powered by LNG (18).

DOT's National Highway Traffic Safety Administration (NHTSA) has promulgated a series of Federal Motor Vehicle Safety Standards (FMVSS) that set forth design and test criteria for various aspects of vehicle design (49 CFR, Part 571) (18). The FMVSS apply to new motor vehicles and, in some instances, vehicles already delivered to the "ultimate consumer." In practice, the only FMVSS likely to be applicable to converted natural gas vehicles is FMVSS 301-75, a vehicle standard that specifies the amount of liquid fuel permitted to escape from a fuel system after a controlled test impact. The standard, however, applies only to vehicles that use a fuel with a boiling point above 32°F. Thus, it only applies to a vehicle converted from gasoline to a dual-fuel natural gas/gasoline system. It does not apply to vehicles converted to operate on natural gas alone.

The federal Occupational Safety and Health Administration (OSHA) is charged with promulgating and enforcing standards in areas not regulated by another agency. No OSHA standards are directly applicable to natural gas as a motor fuel. However, under 29 CFR, Part 1910.101 ("Compressed Gases"), OSHA required that inspections of compressed gas cylinders be conducted as prescribed by the MTB (18). Finally, no federal specifications exist for natural gas transmitted by pipeline or distributed to consumers.

State and Local Safety Regulations

State and local regulation of natural gas vehicles and equipment was reviewed in a study by Jack Faucett Associates (JFA) (18). California was found to have a comprehensive set of regulations applicable to natural gas vehicles and refueling operations. The California Highway Patrol (CHP) has issued design and installation regulations for CNG and LNG vehicles that require construction and inspection of cylinders in accordance with DOT regulations (18). The CHP code has further requirements with respect to the crashworthiness of LNG-fueled vehicles. Other California regulations address LNG and CNG tanks that may be used for storage and refueling (18). New York State recently promulgated vehicle specifications for converting school and transit buses to CNG.

Alternatively--with few exceptions--other state and local regulations applicable to natural gas used as a vehicle fuel are set forth in fire codes and enforced by local fire prevention officials (18). The JFA study concluded that a series of complex and sometimes inappropriate regulations has been developed by local governments because there has been no guidance from federal standards, the National Fire Protection Association (NFPA), or other national standard-setting bodies (18). These regulations are not comprehensively reviewed here, but include tunnel and bridge restrictions, expressway restrictions, restrictions on use in school buses, zoning regulations on refueling stations, and restrictions on parking in garages. One example of the wide variation in these regulations is that the state of Maryland prohibits the use of natural gas fuel for school buses, whereas some school districts in New York State are in the process of purchasing CNG-fueled school buses (18). Finally, state regulations for pipeline gas are usually restricted to odorant content.

NFPA Standard

Recognizing the lack of a national standard for natural gas vehicles and the proliferation of locally developed and widely differing regulations for natural gas vehicles and refueling stations, the NFPA formed a committee in 1982 to develop and review a standard for CNG vehicles and associated fueling systems. In 1984 that standard was adopted.

The NFPA standard is intended for use by manufacturers of natural gas system components and by installers and operators (18). It relies heavily on established compressed gas technology and standards recommended by the DOT, the Compressed Gas Association (which are incorporated by reference in the MTB standards), and others. The standard applies to the design and installation of CNG engine fuel systems in vehicles of all types and to their associated fueling systems. A gas quality standard is included. The NFPA standard will serve as an interim standard until specifications based on a statistically valid data base can be developed. The NFPA standard generally parallels the California regulations, except that the latter are somewhat more specification oriented than those of the NFPA (18). However, standards for LNG vehicles are not included as they are in the California regulations. Furthermore, although the standards for fueling station dispensing are included, standards for home compressors are not.

Although adoption of the NFPA standard is an important step, the standard itself is not a regulation. It will be reviewed by state and local agencies for inclusion in fire codes and can be adopted as written by government entities or its provisions can be amended as deemed appropriate. The standard is expected to be accepted by local fire marshals (18).

CONCLUSIONS: DO WE KNOW ENOUGH?

Of the three areas of concern discussed earlier, it is clear that further evaluation of the safety of the vehicles and fuel systems and of the exhaust emissions associated with their operation is required. The availability of natural gas does not appear to be an issue, although if a large number of vehicles were converted to natural gas, the impact on the domestic natural gas consumption rate could be significant.

With respect to exhaust emissions, it appears that

more study is required in a number of areas. Whether an NMHC standard should be developed and what it would be needs further evaluation. If original-equipment-manufactured natural gas vehicles are to be marketed in significant numbers, emission standards must be developed for them. Furthermore, very few data exist on the use of natural gas in CI engines. Now that conversion kits for automotive vehicles have become commercially available, additional testing of emissions is necessary. Even with converted SI vehicles, the effectiveness of conventional emissions control technologies [spark timing, exhaust gas recirculation (EGR), etc.] must be better quantified. Available data are limited, particularly for late-model-year vehicles with electronic feedback systems.

The safety of CNG and LNG vehicle systems remains an important issue that has not yet been completely resolved. A number of studies have concluded that engineering technology and safety regulations can be used to address the risks that exist and that no data have so far been presented that would disqualify natural gas vehicles from public use (1,24,34). However, a documented, comprehensive data set on which the crashworthiness and system integrity of natural gas can be thoroughly evaluated has not been developed (33). Some of the reported data are old and not comprehensive. Two types of studies are required in particular: (a) crash testing of CNG vehicles using both steel and aluminum composite cylinders and LNG vehicles (the last crash tests in the United States were conducted in 1971), and (b) research into the effects of different fuel qualities on steel CNG cylinders and on alternative materials that might be used in the design of lightweight CNG cylinders. In addition, controlled safety-related data collection from test fleets and worst-case accident scenario analyses would be useful.

Finally, some may question the value of conducting extensive safety and emissions tests on vehicles whose total vehicle market share may not be very substantial in the near- and mid-term future. However, 1 to 4 million fleet vehicles by the year 2000 is not an insignificant share of the total fleet market. Furthermore, such testing is essential before the personal-use market can be effectively opened to this alternative fuel.

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Structural Ceramics in Transportation: Fuel Implications and Economic Effects

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ABSTRACT

A description based on a study at Argonne National Laboratory funded by the U.S. Department of Energy is given of the potential application of structural ceramics in motor vehicle engines. With their high-temperature strength and their resistance to wear and corrosion, these high-technology ceramics are excellent candidates for the harsh environment of the advanced engines being considered for automobiles and trucks. The critical role of ceramics in the adiabatic diesel, gas turbine, and Stirling engines is discussed, along with an indication of the fuel efficiency potential and multifuel capability of each engine. A market penetration analysis of the advanced engines uses two alternative commercialization scenarios for ceramic component engines--one with the United States dominating the market and the other with Japan dominating. Changes in major national economic indicators are noted after simulations of the economy with a macroeconomic model. Effects on the use of strategic materials are also noted.

Research in energy conservation technologies was stimulated by the energy crises of the 1970s. The crisis situation no longer exists, but the interest in improving energy efficiency remains. The transportation sector has historically been vulnerable to energy disruptions and price shocks and remains susceptible to them in the long-term future despite the current petroleum glut. Indeed, as the residential, commercial, and industrial sectors have increased their use of nonpetroleum fuels, the transportation sector has consequently begun to account for a significantly larger share of petroleum use. From the 1950s through the 1970s--even after the first oil crisis--transportation's share of oil use consistently remained between 53 and 55 percent. This share has steadily increased since 1979, and transportation is now responsible for more than 61 percent of the petroleum used in the United States (1).

In the mid-1980s, highway transport continues to dominate transportation energy use, with automobiles and trucks consuming nearly three-fourths of the sector's total energy use (2). As a result, con-