International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

Compressed Natural Gas (CNG): Potential Applications for Advanced Transportation Tanks and Vehicle Systems

Altenpohl, D. and Rogner, H.-H.

IIASA Working Paper

WP-88-047

June 1988

Altenpohl, D. and Rogner, H.-H. (1988) Compressed Natural Gas (CNG): Potential Applications for Advanced Transportation Tanks and Vehicle Systems. IIASA Working Paper. WP-88-047 Copyright © 1988 by the author(s). http://pure.iiasa.ac.at/3158/

COMPRESSED NATURAL GAS (CNG): POTENTIAL APPLICATIONS FOR ADVANCED TRANSPORTATION TANKS AND VEHICLE SYSTEMS

D. Altenpohl
H-H. Rogner

June 1988
WP-88-047

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

Preface

The adequate supply of transport fuel has been a continuous concern ever since the automobile and individual modes of travel began the so far impetuous penetration into the transport sector. Over the years it should have become obvious that the running-out of oil phenomena is largely the result of a misperception regarding the dynamic role of technical change on the economics of hydrocarbon exploration and production, in short on liquid fuel supply. Thus, oil availability appears not to threaten our mobility even in the medium-to-long-term future. The question of using natural gas as a transport fuel, therefore, is not a response to diminishing oil resources but the result of environmental considerations. This is particularly the case for diesel trucks and busses operating in densely populated metropolitan areas. In the past the use of compressed natural gas (CNG) as a clean and efficient vehicle fuel hinged on the heavy weight storage cylinders impacting adversely the available pay-load. Advanced light-weight reinforced aluminum storage cylinders have partially removed this obstacle. This paper reviews the state-of-the-art of CNG technology and offers indications of early application niches for CNG based vehicle systems.

Compressed Natural Gas (CNG)
Potential Applications for Advanced Transportation Tanks and Vehicle Systems

D. Altenpohl[*] *and H-H. Rogner*[**]

[*]Senior Industry Advisor to IIASA's Office for Sponsored Research
[**]Project Leader, Methane Technologies Project of IIASA

1. INTRODUCTION

The transport and storage of natural gas or methane has been one of the impediments to natural gas utilization. Pipeline transport is associated with large up-front capital requirements, long pay-back periods and inflexibility once constructed. Similarly, the transport (and storage) of methane as a liquid in form of cryogenically liquefied natural gas (LNG) is capital (and energy) intensive but potentially offers a certain degree of flexibility to sellers and buyers. Another option for natural gas transport/storage is compressed natural gas (CNG). Typically, CNG is filled via a compressor into pressurized steel gas cylinders and, in analogy to other commercially traded gases, transported to the site of the consumer by truck in bundles of up to 25 cylinders. At a pressure of 200 bar CNG reaches approximately 35 percent of the energy to volume ratio of LNG. There is significant disadvantage associated with this type of transport/storage system--the low pay load-to-weight ratio of less than 5 percent. In turn, CNG transport of methane offers a flexibility similar to that of oil products.

Typically a truck load of gas cylinders (pressure tubes) at an operating pressure of 200 bar amounts to the equivalent of 4000 to 7500 cubic meters of methane at ambient pressure. However, the weight of the steel tubes usually constitutes a severely limiting factor to the maximum carrying capacity of trucks/trailers way before the full carrying volume has been reached.

Latest achievements in the field of pressurized fiberglass reinforced aluminum gas cylinders point to the principal possibility of higher operating pressures. But more important is the fact that the significant weight reduction to one third of that of steel cylinders may result in a three fold increase in the pay load carrying capability (currently a doubling has been proven practical).

The improved performance characteristics of CNG transport technology offer a number of applications where other forms of methane transport and storage are beyond economic feasibility. The collection of associated gas of small dispersed oil fields or even small gas wells are good examples for the application of CNG cylinders. In the first case the gas price could be easily zero given the alternative of flaring. After separation of gas and cleansing, mobile compressors would fill the cylinders which then would be periodically exchanged. The so collected gas could either be transported by tube trailer or ship to a central station and fed into the grid or directly be sold to industrial, commercial and residential customers.

But the potential use of light weight methane transport and storage cylinders goes beyond the prospects of near range gas transport. The lighter the tank the easier could be the entry of methane into the motor fuel market. So far automobile manufacturers have not really thought about a CNG tailored car design because of lacking market interests.

But given the growing number of countries endowed with indigenous gas resources (most of which belong to the category of developing countries), CNG as a transportation fuel might be the most economic approach for oil import substitution.

Environmental considerations (pollutant-emissions and noise) may also pave the way for CNG in industrialized countries. Dual fuel methane/diesel trucks and buses or pure methane fueled vehicles offer an economic response to the most stringent environmental regulations.

Independent of the geographic location and the state of industrial development, any market introduction of CNG in the transportation sector requires three inevitable prerequisites:

- The CNG conversion of major municipality fleets where the vehicles periodically return to their home base (initial development of a CNG supply infrastructure);
- The build-up of a recharge system similar to present petrol stations; and
- CNG tailored vehicle design.

The long distance transport of methane is another potential option for CNG tubes, especially as an alternative to LNG. At pressures of 300 bar, the net methane contents per unit of storage volume of CNG amounts to approximately 50 percent of the LNG methane-to-volume ratio. The flexibility and cost advantage of CNG cylinders and compressors, compared to the high capital costs of liquefaction/regasification facilities and LNG tankers, might compensate for the less favorable net-to-gross shipping volume of CNG tube bundles.

2. METHANE AND TRANSPORT - STATUS-QUO AND OUTLOOK

2.1. Origin of Gas

For the rest of the century most of the methane in question is conventional natural gas, to a small amount biogas, the latter being of potential importance for developing countries but also in Scandinavia and North or Latin America.

The developments we are describing now therefore refer mostly to the utilization of conventional natural gas, i.e., associated oil production and dry gas from sedimentary geological formations.

Methane from deeper reservoirs trapped in tight formations might play an increasing role in long-term gas supplies after the turn of the century and thus is beyond the temporal scope of this paper.

2.2. Technology for Provision, Distribution and Use of Methane for Natural Gas Vehicles (NGVs)

The equipment in question consists mainly of the following components and systems:

1. A rather conventional compressor delivering up to 300 bar pressure;
2. Gas cylinders for a operational pressure of typically 200-250 bars made either from steel, fiber enforced aluminum alloy, or eventually from plastic with or without fiber enforcement.

   Such a container can either be made of large size tubes (length up to 12 m, diameter above 40 cm), which are put together in a tube bundle of up to 50 tubes with a total volume of up to 8000 cubic meters of gas at normal pressure.

   Or else, smaller tubes, typically 1 m up to 5 m long with diameters between 20 and 40 cm, can be used in cars or trucks to substitute conventional fuel partly or even completely.
3. For the transport of gas the before-mentioned tube bundles can be put on a rig or container and be moved either on roads ("tube-trailer") or else on ship or by rail.
4. For the filling of medium or small bottles in cars and trucks a new distribution system is required where either a slow fill can be achieved with compressors utilizing gas from an existing gas distribution network or else for rapid fill specially designed high-pressure steel containers and compressors of larger diameters. Alternatively, a system that integrates the before mentioned tube bundles could be used for filling purposes.

5. In car or truck applications specific equipment is needed for reducing the pressure of the gas before it enters the combustion cylinder and specific mixing valves and regulators are required especially for the dual-fuel systems. Dual fuel could mean either the alternative use of CNG or conventional liquid fuel or else a mixture for instance of diesel oil with CNG for better running performance of the diesel engine.

Today there is well proven equipment available partly pioneered by Italian companies. A word of caution is appropriate at this point and we would like to quote Lloyd G. Brown, technical director, Welgas Holdings Ltd., Wellington, New Zealand from his speech on the Second Metanauto Congress, Bologna, 1984: "We must all be prepared to spend effort, time and money in ensuring that adequate retraining programs are in place. *The best* equipment in the world can enjoy *the worst* reputation in the world if it is put in the hands of inexperienced tradesmen, labor or what have you, to carry out the installation and operation of *this best* equipment. We have had some experience in my country in this regard. Manufacturers have as much responsibility as the purchaser to see that their equipment is designed for local conditions and also backed up with service that will ensure the success of the installations. In a small country, such as New Zealand, this is relatively easier to accomplish and it was possible to plan before the program got underway, training programs for the engineers, technicians and mechanics in the motor trades to ensure they understood the retuning that was necessary when a vehicle was converted from gasoline to natural gas. It is equally important that correct maintenance manuals and instructions are given with regard to the compressors and all the other ancillary equipment that goes toward making a success of any new technology."

We will now go into some detail for two specific technologies important for the success of NGVs.

2.3. Specific Technologies

Performance and Structure of CNG Containers. The dominant material today is steel which has an excellent safety record except for cases where gases contain sulfur components as a result of insufficient cleansing of natural gas or as an internal component of biogas.

Farmers in various parts of the world have been filling their biogas into steel cylinders to drive tractors and trucks but the reaction between steel and aggressive components of the gas, namely H_2S, may lead to hydrogen embrittlement and eventually this cylinder could have a catastrophic failure.

Since well over a decade aluminum cylinders have been introduced for various pressurized gases mainly for oxygen supply to divers and firemen.

The alloy corresponds to the European DIN standard AlMgSi 1. These cylinders have been since several years reinforced on the outside by application of a wrapping of high strength fiberglass like Epoxy resin in a suitable matrix structure. The wrapping can be all around especially for short cylinders or could be preferably only in the cylindrical part of the bottle to compensate the radial stresses in the wall of the cylinder. It is known a long time that in a gas cylinder with internal pressure the stresses in radial direction of the wall are twice as high as in longitudinal direction. To compensate these "hoopes stresses" outside reinforcement of the cylindrical part of the container is therefore logical. Already Napoleon's engineers knew this and were wrapping high strength steel wires around canons to increase the explosive load without destroying the gun barrel.

For CNG aluminum bottles the structural design is similar to prestressed concrete: the high strength fiber puts the bottle in empty stage under a considerable compression stress to achieve that the filled bottle with, for instance, 200 bar pressure in its metallic wall exposed to only a rather modest elastic dilatation. Therefore fatigue cracking by frequent filling and emptying of such bottles is highly unlikely because the elastic stresses are far below the yield strength.

The described composite bottle has very high safety features: the metallic bottle without reinforcement withstands a pressure which is at least 10 or 20% above the maximum pressure in the bottle. For instance, the burst pressure of the nonreinforced aluminum bottle is around 300 bars.

After reinforcement the burst pressure can easily be maintained at 500 or 600 bars. Therefore, the extra strength in "hoopes" direction is just for the purpose of extra safety if ever by accident a bottle would be somewhat overfilled (safety valves could easily avoid that overfilling goes too far). The prestressing of the fiberglass can be achieved in two different ways according to literature:

- By "autofrettage": for this purpose mostly pressurized water is pumped into the wrapped bottle to achieve a plastic expansion in "hoopes" direction which creates just the right amount of prestressing in the fibers.
- Prestressing can also be achieved during the winding operation.

The described composite structure of reinforced aluminum alloy bottles is quite important for the transport of compressed gases like hydrogen or methane over distance because the aluminum composite bottle weighs half or less compared with the steel bottle of the same volume. Therefore, the net load of gas for a given transport weight doubles.

The light weight composite bottle may also be of increasing importance within vehicles driven as natural gas vehicles (NGV), for instance, buses, trucks, or eventually also passenger cars. For the time being, CNG cylinders for buses or trucks are located at the bottom of the vehicle somewhere between the axles. Weight considerations play only a minor role. The typical passenger car so far uses CNG cylinders in the trunk and the extra weight of steel cylinders is only acceptable for larger sedans. For smaller passenger vehicles the extra weight far behind the center of gravity deteriorates driving quality and could even create a certain hazard for the car safety.

Therefore the redesigned car, truck, or bus incorporating light weight or steel tubes in the right position in the vehicle's structure is a necessary prerequisite for expanded use of CNG for transportation purposes. Technically this would pose no problems, it seems merely a matter of design given sufficient market demand (or policy).

Last but not least we wish to mention all plastic containers which were first applied in the People's Republic of China, where on the roof of buses collapsible plastic containers were filled with methane (mostly biogas) to fuel diesel engines. However, the relatively light weight plastic containers withstand only limited pressure. Developments to reduce the pressure in plastic CNG-containers include the use of absorbents within the cylinders like Zeolite. Development took place since a decade mainly in the USA. Results so far are not encouraging.

In Sweden now a development takes place of a fiber enforced plastic tank which is claimed to be ready developed by the end of this year. It could provide gas for 300-500 km distance with no extra weight in the car if the diesel tank system is dismounted (gas as mono-fuel). In reality, however, the dual fuel system will be dominating especially for diesel engines. This brings us to our next point, a few specifics of retrofitting engines from conventional fuel to CNG.

Retrofit Configuration of CNG Containers in NGVs. Figure 1 shows the configuration of gas cylinders in a bus which was retrofitted to CNG. In passenger cars, the CNG bottles are often placed in the trunk, in Italy often on the roof of the car.

Now after light-weight bottles of larger diameter and greater length are available, the retrofit configuration would, for instance for buses or trucks, be already different, and preferably large cylinders will be placed underneath the car between the axles and parallel to the driving direction.

But even this is a retrofit concept, the ultimate solution will be a redesigned OEM-vehicle[1] where the CNG cylinder has its optimum location and where the dimension of the liquid fuel tank is in a logical relation to the CNG tank.

---

[1] OEM = Original Equipment Manufacturer (producer of cars, trucks, or buses).

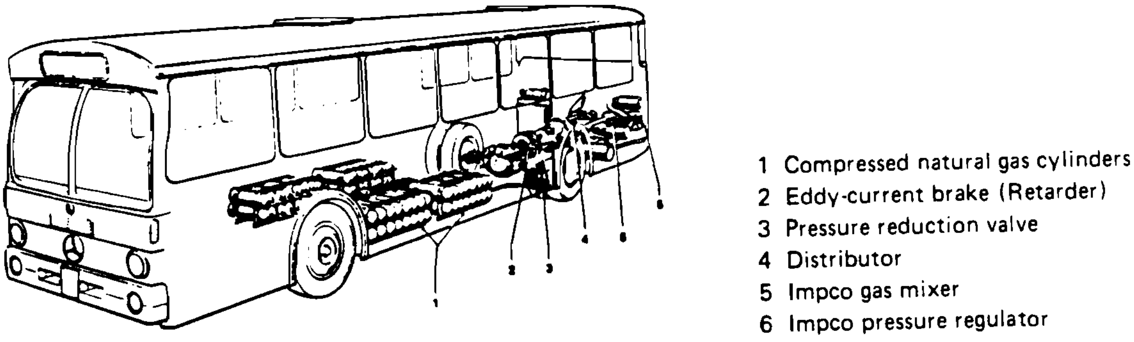


Figure 1. Test Bus Retrofitted to CNG. SOURCE: Christ (1986).

Specifics of Engine Technology. The ordinary passenger car with gasoline engine (Otto engine) today is almost exclusively retrofitted and not an option offered by automobile manufacturers. The advantage of retrofitting is that these cars can be operated as dual fuel systems by switching (at the dashboard) from CNG to gasoline if the opportunity to refill CNG does not exist.

For diesel engines (mainly for trucks), the situation is different. We quote from the Journal *High Technology*, August 1986: "Two types of dual-fuel systems are currently available for heavy trucks. One uses a fixed ratio of about 20% diesel and 80% methane; it can be manually switched to operate on diesel fuel only if methane is unavailable. The second dual-fuel method, promoted by Controlled Fuel Systems of Stuart, Fla., varies the ratio of natural gas to diesel depending on engine load. Under full-load conditions the engine complies with EPA emission standards under low engine loads. This method burns an average of 80% methane and 20% diesel, but it optimizes both diesel and methane by using a higher mix of the fuel that performs best under particular conditions.

It is also possible to power an engine on pure methane if spark plugs are used for ignition. This makes pure methane a natural alternative fuel for spark-ignited gasoline engines common in passenger cars and light trucks. But diesels - which do not need spark plugs since diesel fuel ignites spontaneously when engine compression raises its temperature to 536° F - are used in industrial applications because of their durability and inherent efficiency; diesels transform about 35% of their fuel's latent energy into power, compared with about 28% in high-efficiency gasoline engines. Compression ignition of methane occurs at 1292° - unattainable by engine compression. Thus, in dual-fuel engines the diesel fuel is necessary to start combustion. Spark-ignition systems can be added to diesels, permitting them to burn pure methane. But the cost of this modification - about $5000 - limits it to engines intended for urban areas, where emissions are most critical. Mexico City officials, for example, are considering changing 5000 city buses to spark-ignited natural gas. In Hamilton, Ontario, the provincial and Canadian governments are observing six test buses that were modified for spark-ignited methane last year.

Either spark-ignited or compression-ignition methane engines could be produced as original equipment for trucks. The engine makers - including major truck makers plus Caterpillar Tractor (Peoria, Ill.) and Cummins Engine (Columbus, Ind.) - have so far shown minimal interest in supplying methane engines since there is no market demand to justify their development costs. But they are major targets for the natural-gas industry's lobbying efforts. Whereas in the 1970s the industry pushed the economics of abundant methane availability compared to oil-based fuels, it is now selling natural gas as a way of meeting emission standards. The Gas Research Institute (Chicago) recently began doing its own research on methane-fueled diesels, and it is planning to sponsor educational conferences for engine companies. Meanwhile, some gas utilities are operating duel-fuel fleets to demonstrate the concept: Columbia Gas in Columbus, Ohio, for instance, runs 19 methane/diesel dump trucks.

Until engine manufacturers lend their backing to the concept, dual-fuel engines will continue to come from after-market conversion kits that cost about \$1500-\$2000, plus another \$2000-\$3000 for the heavy-duty cylinders that carry the methane. Leading suppliers are Controlled Fuel Systems, East Coast Conversions (Martinsburg, W.V.), and the Italian company B&B Engineering of Bologna. In Canada, where an alternate fuel policy encourages methane use, prominent engine converters are Fiba-Canning (Agincourt, Ont.) and the Vancouver companies Cryogas, Mogas, and Pro-Staff Fuels.

Regardless of its advantages, an alternate fuel must overcome considerable market inertia: Conventional diesel power has been embraced by truckers for decades. But advocates such as Bryan Memmott, president of East Coast Conversions, point out that the dependability of methane engines has already been proven in nonvehicle applications. "Large, 1000- to 3000-horsepower stationary diesel engines using dual fuel have operated reliably for years," he says. The trick to turning them into a mobile, automotive technology is now a matter of successful marketing."

Adjustments of Diesel Engines. Modifications to achieve dual-fuel operation in a conventional car engine are rather modest. However, to achieve from a large diesel engine optimum performance, a number of specific adjustments are necessary. We quote once more Lloyd G. Brown from his speech at the Second Metanauto Congress, 1984: "The Accolade II, an ore carrier, is designed to operate on 93% natural gas and 7% diesel and powered by two 1600 shaft horsepower engines, which has given completely successful operation out of the Port of Adelaide. This vessel carries limestone for the production of cement from a quarry located some 100 sea miles from the Port of Adelaide. As the vessel is being unloaded, it is being refueled with natural gas and carries sufficient natural gas for two complete round voyages. The vessel was very carefully surveyed, and the performance has been monitored by Lloyds of London, who are now prepared to accept this application of natural gas. Their agents in New Zealand and Australia endorse this fuel and consider it a very important development. In North America, three U.S. companies, Northern States Power Company which distributes natural gas and electricity in the upper midwest region, Inter North, Inc. the parent company of Northern Natural Gas are both major gas pipeline companies, and the Burlington Northern Railroad, one of America's largest railway system, have embarked on a test program to show that natural gas can provide a low cost alternative to diesel fuel in railroad locomotives. A series of static load tests have already been concluded at Burlington's Minneapolis facility and road tests are now being conducted. Burlington Northern's No. 1961, a standard diesel fueled locomotive, has been converted to dual fuel operation at the West Burlington shops. CNG fuel will be carried in conventional highway tube trailers, which are mounted on a railway flat coupled immediately behind the locomotive. These tests are designed to demonstrate that compressed natural gas is safe and economically feasible for railway operations and can reduce operation and maintenance costs. The locomotive selected for these trials is a General Motors 567-C locomotive. The modification of cylinder heads, pistons, and camshafts has been carried out and a dual fuel system installed. The camshaft angle was reduced from 100 to 60 and the compression ratio was reduced from 16.1 to 13.5 to one. A new governor linkage suitable for railroad operation was also fitted.

In Detroit, the Ford Motor Company has recently delivered a fleet of dedicated natural gas fueled Ranger trucks, which will be tested in the United States and Canada by a number of gas utilities. The vehicles were taken from the assembly line and modified to run solely on natural gas, to take advantage of the higher octane rating. The gasoline carburator, fuel system and tank were removed. High dome pistons were installed to increase the compression ratio of the 2.3 liter engine from the standard 9.1 ratio for gasoline to 12.5 to 1. Special piston rings were used to assure that the rings will wear in quickly. Exhaust valves with hardened seat inserts were installed to avoid valve seat recession. The ignition system was recalibrated for optimum firing with natural gas, and a three-stage Renzo Landi pressure regulator was installed. These vehicles have an operating range of approximately 225 miles. Ford has projected improved acceleration with the converted engines and also lower fuel costs, longer engine life, reduced maintenance costs, and smoother engine performance."

2.4. Country Survey

Italy. Their are at least a quarter of a million NGVs in Italy in circulation and the development goes back well over 20 years. Italian technology is leading worldwide (except for provision of advanced CNG cylinders).

New Zealand. In 1973 the government established an Energy Research and Development Committee and 1980 it was decided to convert by the end of this decade 10% of all vehicles to NGV; 1984 over 65,000 vehicles had been converted.

USSR. Over 50,00 trucks operate on NGV. Partly, a mixture of diesel and methane is used during startup of diesel engines.

USA. 1986 only about 30,000 natural gas vehicles accounting for less than 1% of the nation's total vehicle fleet were NGVs.

Canada. The Canadian government has decided to reduce as rapidly as possible dependence on imported oil and further the pollution levels in large cities.

In consequence, NGV is now in a very rapid development and the government wants most modern technologies to be applied inclusive the CNG containers.

Pakistan. The government decided to convert 21,000 trucks to NGV.

Scandinavia. The Scandinavian countries, especially Sweden, have long been known for their demand for high air quality. Despite serious environmental incentives the introduction of LPG as an automotive fuel was not a success, except for Denmark. As natural gas becomes more available in Scandinavia, the possibility of using methane as an automotive fuel has increased, despite the LPG experiences.

The Swedish approach is concentrating on heavy vehicles, starting with city buses. On average there is one citybus to every 1000 inhabitants, which gives a comparatively large fleet.

From economic, financial, technical and environmental points of view the approach will be on 100% CNG. In depth investigations are now being made on finding a concept where all three parameters meet with a good performance and drivability for a converted diesel engine.

West European Countries Besides Italy and Scandinavia. Practically all European countries are candidates for application of NGV for various good reasons (see Section 2.6). The main incentive would be reduction of air pollution and/or reducing dependence on imported oil.

Asia and the Pacific. We quote from the International Association for Natural Gas Vehicles News Letter of January 1987: "There is considerable interest in natural gas vehicles in developing Asian countries. Delegates from Pakistan, Bangladesh, Burma, Malaysia, China, Thailand, Indonesia, Vietnam and Korea attended a United Nations ESCAP (Economic and Social Commission for Asia and the Pacific) workshop on natural gas utilization. The main topic of the workshop was in fact use of natural gas for transport.

Position papers on NGV were presented by Pakistan, Bangladesh, Malaysia, Indonesia, Thailand, Burma, Vietnam and China".

Latin America. Argentina with high surplus of natural gas shows now great interest to develop NGV use, also in neighboring countries like Brasil. A cost-benefit-risk-analysis of CNG versus ethanol as large scale fuel is obviously overdue in Brasil. Many Latin countries are short on indigenous liquid fuel for transport. Biogas may have some potential too.

Rest of the World. Meanwhile, there are well over one hundred countries who have considerable resources of natural gas but have either no oil or insufficient oil resources to meet today's or tomorrow's demand for transport fuels (Tempest, 1986). For all these countries NGV could be an interesting alternative to conventional transport fuels. Even the oil producing countries might use NGV technology to eke out oil exports.

2.5. Driving Forces

There are several driving forces to convert existing or new vehicles of all kinds (road, rail, ship) from conventional fuel to NGV. It depends from country to country what driving force is the strongest. Further it depends whether the application is in metropolitan areas or remote.

Pollution Control. We quote from the *Natural Gas Vehicle Reporter*, January/February 1987: "Natural Gas Vehicles: Pollution Solution for Urban America. Metropolitan areas are under pressure from the environmental Protection Agency (EPA) to clean up the air. Denver, New York City, Phoenix, and Tucson, to name just a few, all face a loss of millions of dollars in federal highway funding if a solution to pollution isn't found by the end of 1987. Time is short and the stakes are high.

The major contributors to environmental pollution in urban America are cars, trucks, and buses, most of which are fueled by either gasoline or diesel. Engine pollution – nitrogen oxide (NO_x), hydrocarbons, carbon monoxide (CO), and sulfur oxides (SO_x) – all contribute to making the air less breathable. As for the sooty diesel, increasingly stringent EPA emission standards are likely to put additional pressure on both the commercial and government sectors to use vehicles that do not significantly pollute the atmosphere.

City-level and state government decision makers are starting to scurry for solutions to their dirty air problems, particularly as the November 1987 deadline for meeting EPA emission levels approaches. What choice do cities have?

At one level, cities can work to change driving habits. Schemes such as allowing drivers into the city and prohibiting others by odd/even license plates has been considered, for example, in New York City. Banning cars in downtown metropolitan areas also is a consideration, leaving the streets available only for taxis, buses, and delivery trucks. Incentives to ride public transportation – where available – is another possible solution. Car and van pooling, supported widely during the 1970s to conserve gasoline, would also be beneficial.

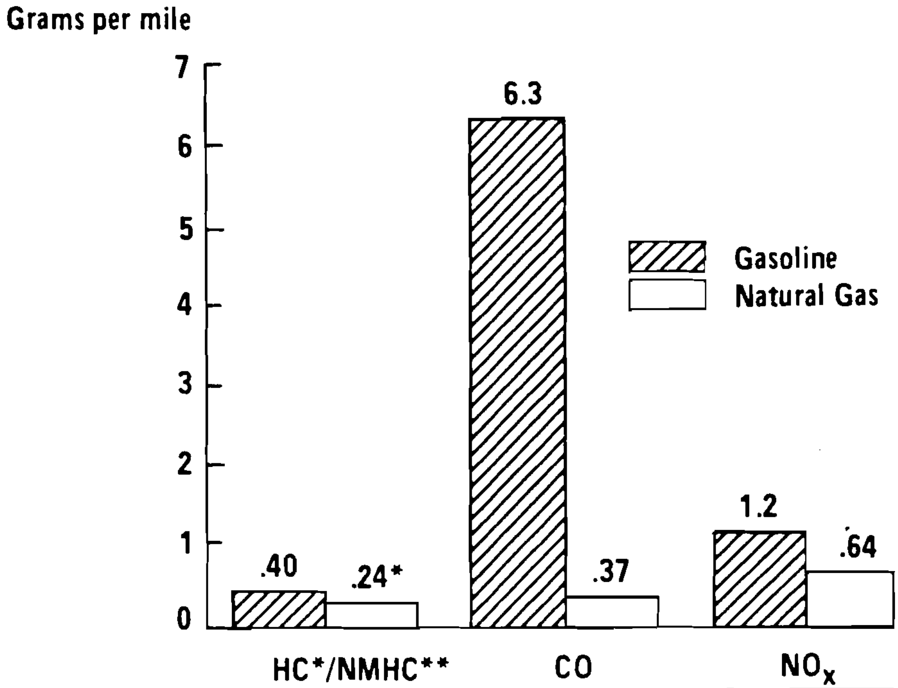
Fuel alternatives is the adjunct route to take. Essentially there are three choices: natural gas, propane, and methanol. Electric vehicles, especially the trolley or bus, would be a good alternative but modern, cost effective electric vehicle technology is well suited to only a limited type of short range, lightweight vehicle.

Propane has been a popular fuel substitute and is used today in some one and a half to two million vehicles nationwide (USA). But current costs of propane are as high or higher than gasoline in many parts of the country, so conversions to propane today have declined.

Methanol, a liquid derivative of natural gas, is receiving much attention. As a high octane (110), low emission liquid fuel it is being viewed favorably by EPA and several auto and bus manufacturers. There are a number of methanol demonstrations currently underway in Sacramento, Calif.; Seattle, Wash.; Los Angeles, Calif.; and Florida.

But there are some yet-to-be resolved issues associated with using methanol to fuel cars and trucks. It is highly corrosive and toxic and requires very special handling. Methanol emits formaldehydes and aldehydes when burned in a vehicle, so a device like a catalytic converter needs to be developed, as well as inexpensive emission testers to monitor aldehyde and formaldehyde exposure. Though the supporters of methanol are confident that the shortcomings can be overcome, there is still concern among oil companies and some government offices that not enough is known about the negative effects on health and the environment caused by widespread use of methanol in vehicles. Also, it is estimated that methanol will be economical only when gasoline sells for $1.30 per gallon, or more.

Natural gas is generally recognized as a potential for a quick solution – and very possibly in the longer term – to air pollution problems in cities. The fuel sells across the country today for between 41 to 75 cents for an equivalent gallon. While the economic benefits of converting vehicles to natural gas have been diminished due to the price drop in gasoline, some cities will recognize the benefits of the avoided costs of converting to natural gas vehicles if it prevents the loss of million of dollars in federal highway funds."



		HC*/NMHC**	CO	NO_x
EPA Emissions (grams per mile) Passenger Car	1980	.41	7.0	2.0
	1987	.41	3.4	1.0

*Hydrocarbons
**Non-Methane Hydrocarbons

Figure 2. Emission from 13 Gasoline Vehicles Converted to Natural Gas. SOURCE: U.S. Department of Energy (1982).

Table 1. Emission Reductions Resulting from Conversion of One Million Gasoline Vehicles to Natural Gas.

	Annual Tons Emitted		Difference	
Pollutant	Gasoline	Natural Gas	Annual Tons	Percent
Carbon monoxide	225,000	30,000	-195,000	-87
Nitrogen oxides	42,000	22,200	-19,800	-47
Reactive hydrocarbon	12,600	8,600	-4,000	32

SOURCE: *NGV* (1987).

Pollution Control for Diesel Engines. "Stricter pollution limits may boost the appeal of methane power. Natural gas is emerging as an alternative fuel that enables diesel-powered trucks to meet tightening U.S. pollutant-emission standards.

So far, engine makers have complied with Environmental Protection Agency (EPA) emission standards by sweetening conventional diesels with improvements like turbochargers. They are developing computer-controlled fuel injection for more precise fuel management, and ceramic engine parts to reduce emissions by improving efficiency. And they are experimenting with exhaust system particulate traps, even though the devices could add $5000 to $6000 to the price of heavy trucks and their long-term durability is questionable.

But marginal improvements may be inadequate for meeting the new regulations. In 1988 the EPA will limit heavy-truck particulate emissions to 0.6 gram per horsepower-hour (g/hp-hr), dropping to 0.1 g/hp-hr by 1994. Nitrogen oxide emissions, currently restricted to 10.7 g/hp-hr, drop to 6 g/hp-hr in 1988 and 5 g/hp-hr in 1991. At the same time, heavy-truck engine noise levels will drop to 80 decibels in 1988 from the current 83-dB.

"It may not be practical to adapt some high-emission diesels to meet the 1988 particulate limit," says Karl Springer, director of emissions research in the engine and vehicle division at Southwest Research Institute (San Antonio, Tex.). "Some models may even be taken off the market."

Thus, proponents of methane-fueled vehicles - including the natural-gas industry and some engine equipment makers - see the new truck emission requirements as another opportunity to promote their NGV-diesel concept."[2]

Volume and Weight Comparison Between CNG and Competing Fuels. Figure 3 describes various fuels used or proposed for operation of vehicles regarding weight and volume per unit of energy content.

A few comments to this data:

- The cleanest fuels, hydrogen and electricity, are by far the most demanding regarding space and weight per unit of energy (both fuels do not emit CO_2).
- CNG in light weight bottles achieves about half of the energy density of LNG.
- A CNG tank has almost three times the volume of a tank for conventional liquid fuel.

Economy. Their is no clear-cut division between ecology and economy because more and more external costs by pollution to the society are turned back to the emitter (internalization of external costs). Already the above quoted example of heavy financial penalties to metropolitan areas not complying to the new EPA standards is a good example.

---

[2] Quoted from *High Technology*, August 1986.

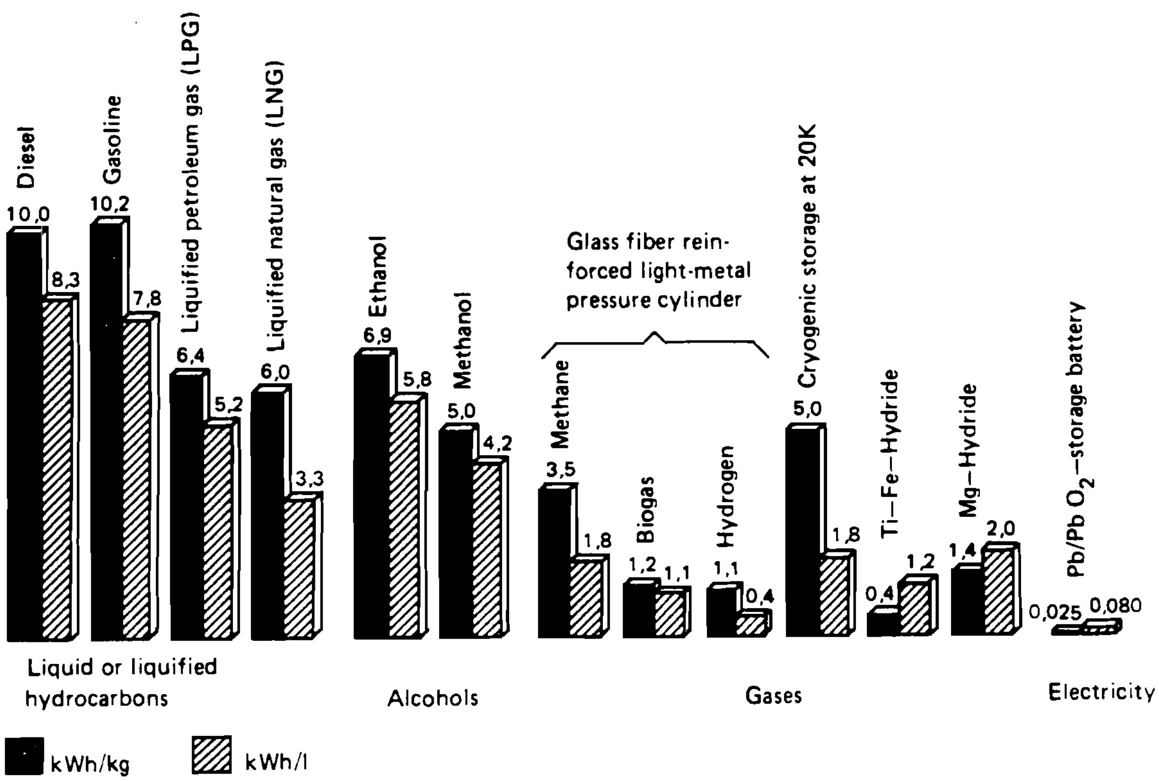


Figure 3. Weight and Volume per Unit of Energy Content of Fuels Used or Proposed for Operation of Vehicles. SOURCE: Christ (1986).

And natural gas gives in case of diesel engines a clearly superior engine performance like smoother driving and lower noise level.

Besides comparisons in dollars per unit of fuel, other parameters enter an economic evaluation. Lloyd G. Brown in his Bologna speech states 1984 the following: "Major American refineries are announcing high octane fuels, none of which can compare to the octane value of natural gas. From a safety point of view, natural gas is the safest fuel available to mankind. When an engine is converted to the best compression ratio for natural gas, it is also the most efficient usage of any fuel. We are operating diesel vehicles in New Zealand with reduced compression ratios and spark ignition as mono fuel natural gas vehicles, giving smoother and quieter operation, longer engine life – exhaust emissions meeting the most stringent codes and excellent torque performance at half the cost of diesel fuel."

Enthusiasm for a New and Superior Technology. When reading the *Natural Gas Vehicle Reporter NGV* one encounters page-by-page such enthusiasm. We once more quote from the January/February 1987 issue: "When it comes to fueling vehicles, natural gas knows no bounds. A natural gas powered dragster that can go from 0-135.6 miles per hour in 9.923 seconds has been raising eyebrows around the auto drag racing circuit. Designed by Joe Mezquita in Ohio, the natural gaser dragster will be in competition for the 1987 racing season at drag strips in Northeast and Central Ohio and Indianapolis.

"On the Road With Natural Gas" will be held at the Adams Mark Hotel in Indianapolis on September 22-24, 1987 and will include a "Track Day" at the world famous Indianapolis Speedway. The conference will be a technical and marketing conference, appealing to a range of individuals including NGV marketers, fleet managers and operations staff, NGV researchers, government officials, and in particular, city and urban managers concerned with improving the local environment. Three full days of presentations, exhibits, and test driving will include:

- Diesel Day: to evaluate new technologies for converting diesel engines to run on natural gas - dual fuel and dedicated. Emphasis will be on urban vehicles - metropolitan buses, garbage and delivery trucks. R&D progress will be tracked to determine how natural gas/diesel engines can contribute to improving the urban environment.
- NGV Equipment Day: to focus on the broad range of NGV underhood, storage, and dispensing equipment, highlighting a number of NGV success stories with emphasis on urban-area successes.
- Track Day: ordinarily private individuals are prohibited from driving on the world famous 2 1/2 mile Indianapolis Speedway track. A.G.A. is renting the track for a day of test driving a wide variety of NGVs that will be displayed there, including diesel dump trucks, school buses, the dedicated Ford Ranger, a myriad of light duty vehicles and automobiles, and will highlight the first production line NGV truck ever built."

Proven and Safe Technology. As was outlined above, all the components for the retrofit into a NGV are on hand. But the dominant majority of all of today's NGVs are not (yet) up to standards of an integral and optimal design of OEM vehicles.

Market Pull. The progress in the introduction of NGV has not only driving forces but also certain inertia by lacking market pull. This is especially true if the costs for retrofit are high compared to the economic benefits.

Diesel engines will be the first target where the driving forces are already today widely accepted and understood. Of all factors, three are consistently quoted by drivers, mechanics, and supervisory personnel: the quieter ride, greater fuel savings in money, and clean air benefits.

Therefore, there is no doubt that a converted truck performs better and is quieter on natural gas.

2.6. Two Likely Scenarios

The *first scenario* is based on a slow evolution of further use of NGVs because of the small interest by OEM producers of vehicles and/or of the users.

The exception of metropolitan areas will not create such a great many number of NGVs, keeping in mind that LPG or propane or ethanol are other substitute clean fuels. In fact, in downtown Tokyo since many years all taxis and most of the commercial vehicles are driven by LPG or other clean fuels.

Still even for this first scenario there will be important exceptions, triggered off by government decisions like it is the case in New Zealand, Canada, Pakistan and foreseeable for many other countries.

The *second scenario* is the one of the eternal optimists, like Lloyd G. Brown, whom we have quoted several times. Also in North America and Scandinavia we can find a large group of believers in a scenario where NGVs within one decade will come on stream very strongly. Whether the triggering element is pollution control or more independence from imported oil or simple economics is difficult to predict. It could be a combination of all three in a number of countries.

2.7. Summary and Outlook

We will try to summarize in just a few sentences: There is a proven package of technology available which is safe and in many cases more economic than the conventional fuel systems. But more importantly the largest advantages are its environmental benignity, i.e., emission and noise reductions (see also Swedish National Board of Technical Development (1988)).

Because of the latter factors, a certain landslide effect within a decade is not unlikely, given strict pollution legislation as well as adequate energy policies at the level of municipalities. However, the period of rapidly increasing oil and fuel prices (1974-1981) created a wave of optimism for the rapid introduction of NGVs, mainly in the U.S. Today, the unexpected drop of oil and fuel prices has disillusioned many of previous enthusiasts for NGVs.

One of the authors of this article by looking into a crystal ball feels obliged to submit a vision that NGV will come strongly into use in at least one or two dozen countries within five years time. But this is just an opinion and time will tell us whether the visions of Lloyd G. Brown and others will hold true.

References

Brown, L.G. (1984), The future of methane in transport. In *Proceedings of the Second Metanauto Congress*, Bologna, Italy.

Christ, H. (1986), *Individueller Verkehr und Energieprobleme in der weiteren Zukunft*, Referat der 23. Sitzung der Studiengruppe Energieperspektiven, Baden, Schweiz.

International Association for Natural Gas Vehicles, Inc. (IANGV) Newsletter , no. 3, January 1987.

Metanauto Congress Bologna (Italy), 1982, 1984, 1986.

NGV - Natural Gas Vehicle Reporter 4(1) (1987).

Reznik, I. and M. Utz (1986), Glasfaserverstärkte Aluminiumzylinder für komprimierte Gase, *Alusuisse Intern*, November. Zurich: Alusuisse.

Seisler, J. (1986), Natural gas lets trucks run clean. *High Technology*, pp. 64-65, August issue.

Sweden and Scandinavia Goes into NGV? EKEN Newsletter 1-4, Handen, Sweden: HB Eken (1986/1987).

Swedish National Board of Technical Development (1988), *Natural Gas and Biogas Propelled Buses. Case Study for a Demonstration Project*. Stockholm, Sweden.

Tempest, P. (1986), Beyond the rainbow: gas in the twenty-first century. In *The World Gas Trade: A Resource for the Future*, Melvin A. Conant, ed. Boulder and London: Westview Press.

U.S. Department of Energy (1982), Assessment of methane-related fuels for automotive fleet vehicles. Washington, D.C.