FUTURE MARKETS AND TECHNOLOGIES FOR NATURAL GAS VEHICLES

FUTURS MARCHÉS ET TECHNOLOGIES POUR LES VÉHICULES AU GAZ NATUREL

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ABSTRACT

Lotus Engineering and BG Technology recently collaborated on the conversion of the Lotus Elise for operation on natural gas. This paper considers the world-wide opportunities for natural gas as an automotive fuel by comparison with other fuels. It looks at how technology can be used to exploit this potential, by examining the special features of the gas fuelled Elise, and how other technologies such as hybrid vehicles and fuel cells can be expected to respond to this challenge in future.

RESUME

Lotus Engineering et BG Technology ont récemment collaboré à la transformation d'une Lotus Elise en vue d'un fonctionnement au gaz naturel. Cet article considère les possibilités, à l'échelle mondiale, d'utiliser le gaz naturel comme carburant de voiture, en comparant cette solution avec les autres combustibles. L'article se base sur l'examen des caractéristiques particulières de l'Elise au gaz naturel pour exploiter ce potentiel, et étudie la façon dont d'autres technologies, telles que les véhicules hybrides et les piles à combustible, peuvent à l'avenir relever ce défi.

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1 INTRODUCTION

Today's global natural gas vehicle (NGV) fleet comprises over 1 million vehicles [1], representing just 0.16% of the total vehicle population. However, natural gas exists in abundant reserves, it has low production costs and environmentally beneficial characteristics. These features, combined with the notable substitution of oil and coal by gas as a global primary energy source [2] and the growing market for transportation, suggest that the demand for NGVs can be expected to grow significantly in future. The World Energy Council has reported that between now and 2020 gas will be the most technologically realistic and sufficiently abundant alternative fuel for ground transport [3]. It has already begun to be used on a relatively small scale in a number of countries, driven primarily by concern for air quality in the centres of large towns and cities. But gas has proven to be much more popular for vehicles in countries such as Argentina and Italy, where fuel supply issues are also significant. Egypt is another good example, where the Government has decided that all taxis that have access to natural gas must be converted to run on it.

Three key areas have constrained the extensive use of natural gas as an alternative fuel for vehicles in the past: the lack of widespread refuelling infrastructures; the relatively low vehicle range due to the low energy density of compressed gas; and the lack of a commitment by the original equipment manufacturers (OEM's) to producing purpose designed gas vehicles. These fundamental issues have shaped the development of NGV markets. The requirement to accommodate large gas cylinders in converted vehicles, typically with a significant loss of luggage or passenger space, has damaged customer perception of gas as an automotive fuel. The need to maintain a vehicle package, which is satisfactory to the customer, compromises vehicle range by forcing a reduction in onboard storage capacity. As a result, 'bi-fuel' vehicles, which are able to run on both gas and petrol, have been popular in the past, in order to ensure sufficient range between refuelling stations and overcome any inadequacy of infrastructure. Existing bi-fuel equipment represents an inevitable compromise in the technologies required to make use of the two quite different fuels.

As a natural gas infrastructure is put in place, the emphasis will move away from bi-fuel to mono-fuel engines which are currently most suited to 'return-to-depot' vehicle fleets such as those operated by postal services [4], airports [5] and taxi fleets. In these applications, daily mileage requirements are well understood and gas refuelling facilities can be maintained at the depot. But light duty NGVs have historically existed in the domain of the after market conversion. As a result, the integration of natural gas within the vehicle has been far from optimum and technology progression has been restricted. More recently, however, OEM commitment to gas fuelling has been growing. Most major manufacturers now offer NGVs within their product range and they are developing more integrated, better optimised vehicles. Technology demonstrators such as the Lotus bi-fuel 'Elise NGV', currently under development trials, illustrate the benefits that such an integrated approach can bring, particularly with regard to vehicle packaging and engine control.

On the Elise, a single engine control unit (ECU) is used to control both petrol and gas operation. This brings great advantages by allowing a more flexible control strategy and it does away with the requirement to bypass, or communicate with, the OEM's petrol ECU. This way, the same degree of control can be applied for both fuels and, significantly, this also maintains the onboard diagnostic capability. A flexible control strategy combined with automatic switching between fuels is key, as it allows the fuelling to be tailored to specific driving conditions. For example, reductions in peak power associated with gas fuelling can be overcome by switching to petrol under high load conditions. As the amount of time the vehicle spends at high load is small, the overall effect on emissions would be minimal.

This paper addresses the world-wide opportunities for natural gas in the transport market by comparison with other fuels; it looks at how technology can be used to exploit this potential, by examining the features of the gas fuelled Elise; and how other technologies, such as hybrid vehicles and fuel cells can be expected to respond to this challenge.

2 FUELS FOR VEHICLE MARKETS

The world demand for transport fuel currently stands at 1.9 million PJ/year and road transport is projected to continue to grow at 2.5% per year over the next 20 years. Road transport accounts for 21% of the world's demand for energy and is currently satisfied almost solely by petrol and diesel; clearly a huge potential market for natural gas if the barriers to its use can be overcome. However, there are a number of fuels being used as alternatives to petrol and diesel and in order to understand what the markets for natural gas might be as a vehicle fuel, it is important to understand its characteristics by comparison with all other fuels.

2.1 Traditional Liquid Fuels

Petrol and diesel are used in most spark and compression ignition engines throughout the world. It is believed that for many applications they are the ideal fuels. In particular, for heavy duty vehicles, diesel fuelled engines provide a high efficiency solution. It is likely, therefore, that liquid fuels will continue to be used for non-urban traffic until supplies become limited.

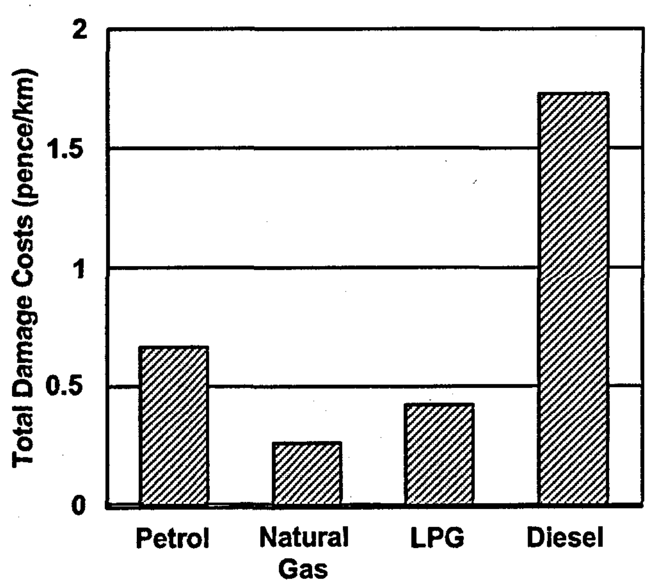


Figure 1. Comparison of the environmental damage cost of automotive fuels using ETSU [6] emissions data and Eyre [7] analysis methods.

However, there is a significant variation in the damage caused by the whole-fuel cycle emissions of different fuels (Figure 1). Petrol and diesel are the most damaging to health, whereas natural gas results in the lowest impact. Each of the vehicles used in these tests was fitted with 'equivalent' clean-up technology. Note also that the vehicles tested were bi-fuel, so the engine was not optimised for natural gas. A dedicated natural gas engine is about ten percent more efficient, which would further reduce damage effects.

It is expected that a combination of improvements in engine technology and fuel quality will allow traditional liquid fuels to meet future emissions legislation. Fuel can be improved by adding components that improve combustion, a relatively low cost option, or by increasing its quality and consistency. However, the cost of improving fuel quality can be high and this may make other fuels more attractive.

Oxygenated additives can be used to boost the octane rating of petrol. Four stroke engines are tolerant of oxygenated fuels, but they cannot be used in two stroke or rotary engines. Although these additives reduce harmful emissions they also tend to reduce fuel economy which increases emissions of CO_2. Methyl Tertiary Butyl Ether (MTBE) is an additive that has been used recently in the US. However, its use is likely to be limited in future in view of the health risks that have come to light since its introduction. MTBE has been detected in 35% of Californian active public water wells. At least twelve states have detected MTBE in drinking water, and at least twenty-three states have found it in groundwater. The cost of lawsuits that have arisen due to the contamination is likely to be greater than $1 billion.

2.2 Synthesised Diesel Replacements

Diesel fuel substitutes can be synthesised from a number of sources. One of the main methods being considered is making diesel from natural gas. A stable oil price of at least US$18-20 per barrel will be required before the synthesis of diesel from natural gas becomes economically viable, even if the gas were a free by-product of oil extraction. Even so, oil companies are already making some diesel from natural gas and using it to blend with conventional diesel to reduce its sulphur content.

All of the processes producing synthesised diesel replacements have an associated energy requirement. It is as a result of this that the economics of the process are rarely better than for conventional liquid fuels and also, whole-fuel cycle emissions benefits could also be marginal.

2.3 "Clean" Diesel

Low sulphur diesel has a reduced sulphur content compared to conventional diesel. Reducing the sulphur content can reduce the production of particulates by 50%. However, the fuel is less energy-dense so fuel consumption rises and the additional processing to remove the sulphur from the fuel requires an energy input that increases the whole-fuel-cycle emissions.

Ultra low sulphur diesel (<50ppm) allows the particulates to be removed from the exhaust using a continuously regenerating trap (CRT). CRT's cannot be used with higher sulphur fuels as the sulphur damages them. Using a CRT, together with ultra low sulphur diesel reduces particulate emissions to levels similar to those obtained from heavy duty natural gas powered vehicles.

	Total HC	CO	NOx	PM 10	CO_2
Early Generation natural gas	3.01	0.66	9.92	0.05	1,344
EURO 2 Diesel	0.7	1.3	5.7	0.32	800
EURO 2 with low sulphur diesel	0.61	1.29	14.27	0.18	1,323
EURO 2 with low sulphur diesel & CRT	0.14	0.2	11.9	0.02	1,281
Latest generation LPG	0.36	0.91	3.53	0.09	?
2^{nd} Generation natural gas	0.13	0.06	0.7	0.02	850

Table 1. Emissions from Buses [8] (g/km measure over an urban drive cycle)

Fitting a CRT to a diesel vehicle costs as much as converting that vehicle to natural gas (DM12,000 for a truck CRT quoted by Mercedes-Benz) and the NOx emissions are still higher from a diesel vehicle with a CRT than from a modern natural gas vehicle (Table 1). The table also shows, however, that it is possible to reduce emissions from diesels considerably by fitting suitable clean-up equipment; the key issue will be the cost of doing it. Many local authorities see clean diesel as the easiest option for improving their fleet's emission performance.

De-NOx technologies for diesels exist in prototype form at present but these can be expected to add still more to the cost of a vehicle. It is anticipated that de-NOx technologies will also require very low sulphur levels in the diesel, which will be reflected in the fuel price and whole-fuel-cycle emissions due to the increased energy required for processing.

2.4 Liquefied Petroleum Gas (LPG)

LPG is a by-product of oil and natural gas production. As a result, the supply of LPG is limited by the rate of extraction of other fuels. It is possible to produce LPG by cracking oil, but there are costs involved, the process is inefficient and the whole-fuel cycle emissions may be higher than for conventional petrol and diesel.

Fiscal measures introduced to encourage the use of alternative fuels, usually promote both natural gas and LPG (unless the fuel duty is related to CO_2 emissions; CO_2 emissions are lower for natural gas). As a result, both fuels are in use in most European countries. The lower cost of LPG refuelling infrastructure and vehicle conversions gives LPG a short-term economic advantage for light duty vehicles. For heavy duty vehicles using the higher efficiency dedicated natural gas engines, there is little economic advantage for LPG. Fuel costs and possible supply limitations give a longer-term advantage to natural gas. A recent report by MarketLine [9] predicts that the supply limitations will cause the take up of LPG to be limited to those countries where there is an existing surplus of the fuel. Because of plentiful supply of natural gas, some governments have legislated specifically to encourage its use. This is the reason for the large take up of natural gas in Argentina and it is expected that other countries with plentiful natural gas supplies will follow this example in future. This is likely to have an important and positive impact on the use of gas as an automotive fuel in future.

In the event of a fuel spill, LPG will form a dense ground-hugging cloud that could present a significant hazard, particularly in a tunnel or underground area where ventilation ducts are usually in the roof. Conversely, natural gas is lighter than air and will disperse away from the vehicle if there is a release. Roof level ventilation will clear natural gas from a tunnel or other enclosed environments. Natural gas is also harder to ignite than LPG due to its higher and narrower flammability range in air and its higher ignition energy.

2.5 Alcohols

Methanol is viewed by some groups as the fuel of the future as it can be produced from renewable sources (although there is evidence that the energy input required for growing and processing the crops results in very little net energy gain from this process) and can be distributed and handled in a similar way to traditional liquid fuels. Methanol can also be synthesised from natural gas, or by cracking oil products. In fact, making the fuel in this way is more cost effective than using renewables at present. Although methanol is a liquid, it cannot actually make use of the existing refuelling infrastructure and vehicles without major modifications; the fuel is particularly corrosive.

There are also significant health and safety issues associated with the use of the fuel. Alcohol powered vehicles emit significant quantities of aldehydes, which are damaging to health. Emissions control technology would have to be developed to cope with this. Methanol fuelled spark ignition vehicles are available from several OEM's in parts of the USA where emissions are a particular concern, although the market is believed to be very small. One of the major benefits of methanol is that it is seen as a potential hydrogen source for fuel cell powered vehicles. Modification of the current refuelling infrastructure for spark ignition vehicles would allow the introduction of fuel cell vehicles to be less costly in future.

Ethanol has similar advantages and disadvantages to methanol. It is easier to use in conventional vehicles, and it is used as an additive to petrol in some parts of the US and in Brazil. However, it is unlikely to be used as a source of hydrogen and it contains more carbon than methanol, so it is not considered to be a viable alternative.

2.6 Hydrogen

Although hydrogen is seen as a future fuel for the fuel cell, it has also been used in conventional spark ignition engines. Both BMW and Toyota have demonstrated hydrogen fuelled cars. Also, Shell have set up a 'hydrogen team' to evaluate the impact of the introduction of a hydrogen economy. Hydrogen benefits from almost no carbon emissions, of course, although there are some from the lubricating oil. There are also NOx emissions to be dealt with. The US Government does not fund any work on hydrogen fuelled conventional engines as they believe fuel cells will be available before hydrogen is likely to be used this way.

2.7 Future Market Developments

As regards emissions, natural gas is in most respects the cleanest automotive fuel on the market. Modern exhaust clean-up technologies applied to vehicles using conventional fuels can also produce very good results; but at a cost. Ultra low sulphur diesel with particulate trap (CRT) and de-NOx technology may well be ultimately more expensive than natural gas. Clearly, however, the existing fuels will be very difficult to displace as they have a distribution infrastructure and vehicles in place. Unless there is an overriding fuel supply issue, it is likely that alternative fuels will find most use in niche markets such as urban transport. In these circumstances, the bi-fuel option that would allow vehicles to use cleaner fuels in town centres may well become even more attractive in future. Rather than being a necessity occasioned by a lack of refuelling infrastructure, the bi-fuel vehicle could, in future, be viewed as a form of hybrid concept that allows vehicles to switch to cleaner fuels in town. This approach would have the additional advantage of being able to use smaller gas tanks as bi-fuel vehicles do not have a problem with range. As the market becomes more established, we can expect vehicle manufacturers to produce a greater range of purpose designed gas vehicles; both bi-fuel and dedicated.

It is clear that LPG is the most serious 'alternative fuel' competitor to natural gas. In countries where it is available, LPG can be expected to take a significant share of the alternative fuel market, particularly for light duty vehicles. Natural gas, however, is the better fuel for heavier duty vehicles and buses. Natural gas would fare much better if the cost of refuelling installations were lower. On the world market, natural gas is also much more plentiful than LPG and there will therefore be more countries like Argentina in future that have specific reasons for encouraging its use. When governments see advantages in using indigenous natural gas supplies for transportation, rather than their own or other country's expensive petroleum products, then they can mandate the use of gas in specific markets to kick-start the business. This is seen as the most likely route for growth of natural gas as an automotive fuel on world markets in future. Under such circumstances, again, the bi-fuel vehicle will have an important role to play by allowing existing vehicles to be converted to run on gas, thereby maximising the market growth rate.

3 NATURAL GAS VEHICLE TECHNOLOGY TODAY

In order to maintain its emission advantages and overcome barriers to wider uptake, NGV technology must be advanced with the active participation of vehicle manufacturers, engine developers and component suppliers. In the following section the work by Lotus Engineering to convert a Lotus Elise to bi-fuel compressed natural gas (CNG) and petrol operation is described and technology developed on other vehicles world-wide is discussed.

3.1 The Lotus CNG Elise

Following the increasing interest and environmental importance of using alternative fuels, an Elise was converted to bi-fuel (gasoline and CNG) operation. Supported by BG Technology, a second multi-point, port injection fuel system was installed on the vehicle, with minimal loss of passenger or luggage space. The Lotus Engine Control Unit (ECU), as used on the Lotus Esprit V8, was installed to allow complete control of both fuel systems.

3.2 Vehicle and engine installation

In conjunction with BG Technology, an additional fuel system was installed on the Elise consisting of a 40 litre gas cylinder, gas fuel lines and refuelling point. Lotus sourced a single stage pressure regulator, an existing production fuel rail and special natural gas fuel injectors. Fig. 1 shows the position of the gas cylinder and the relocated smaller gasoline tank (reduced from 40 to 25 litres). This illustrates the possibility of installing the gas cylinder within the confines of the chassis without loss of luggage or passenger space. The gas is stored in the cylinder at a maximum of 200 bar and this is reduced to 7.5 bar at the injectors by the water heated pressure regulator. The regulator feeds a single fuel rail which holds four gas port injectors. The original plastic inlet manifold was replaced with an aluminium one to allow easier installation of the second set of injectors. The original distributor was also replaced with an ignition coil pack as used on the Lotus Esprit V8 to give compatibility between the Lotus software and the spark control. Other than these, no other changes were carried out to the engine.

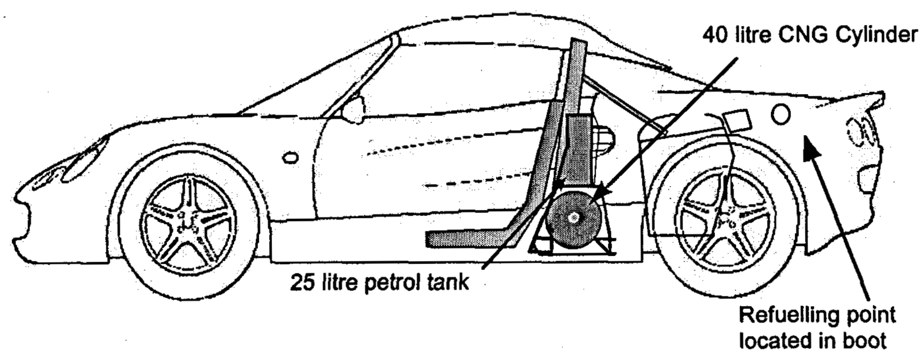


Figure 1. Fuel Tank Positions

The vehicle has an overall range of approximately 310miles with a range of 90miles on CNG and 220miles on gasoline. A standard gasoline Elise has a range of approximately 350miles.

3.3 Engine Management System

The engine was fitted with a single Lotus ECU, as used on the Lotus Esprit V8, which allows full control of both the gas and gasoline fuel systems. Fig. 2 shows the Lotus ECU and a list of the engine specifications.

Initial tests showed a power loss of 10% when running on natural gas. This is a known characteristic of natural gas as it occupies more volume than gasoline and displaces approximately 10% of the air available for combustion.

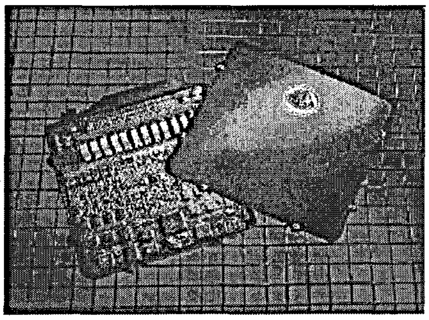


Fig. 2 - Lotus ECU

Engine specification:

Capacity	1796cc, 4 cylinder, 16 valve
Comp. ratio	10.5:1
Air & fuel	naturally aspirated, Multi-point fuel injection
Emissions	3 way catalyst
Fuel	95 RON @ 3bar delivery
	CNG @ 7.5bar delivery
Max. power	88kW @ 5500rpm
Max. torque	165Nm @ 3000rpm

3.4 Switching Strategies

Further calibration work was carried out to develop switching strategies, as the use of the Lotus ECU allows automatic switching between the two fuels.

Either gasoline or gas can be selected manually by a button on the dashboard. If gasoline is selected, there is no automatic switching to gas. However, it was deemed necessary to allow automatic switching to gasoline when gas is selected. The following switching strategies were employed when running on gas:

1. At present the default initial start up at all coolant temperatures is on gasoline, gas can then be manually selected as soon as it is required. At higher coolant temperatures, if the engine is restarted a short time after it has been switched off then the vehicle can automatically be started on gas.
2. Gasoline is selected if full load (triggered at 60% throttle angle opening) is detected, to allow maximum power for overtaking manoeuvres, for example.
3. When the gas in the tank reaches a low level (the actual level can be selectively entered in the calibration (e.g. 3%)) gasoline is automatically selected and the gas selector switch flashes to warn of low gas level.

It should, however, be noted that because of the flexibility of the ECU, any switching strategy that may be required on a specific engine set-up can be applied as desired.

3.5 Emissions Results

The CNG Elise is presently undergoing an emissions programme to show the benefits of CNG over gasoline in producing cleaner emissions. Initial European Stage II emissions tests already showed a great improvement with reductions of up to 50% over gasoline. Along with further development of the Elise and also more detailed work on CNG combustion these results will be improved still further.

3.6 Alternative Fuel Strategies

Most major automotive companies world-wide are involved with the production or conversion of their vehicles to run on alternative fuels. Fleet owners are being encouraged to convert their vehicles to alternative fuels by conversion programmes which are supported by government schemes providing tax incentives and funding. The most popular programmes presently involve CNG and liquid petroleum gas (LPG), bi-fuel or dedicated engines. Many alternative fuel vehicles are after market conversions but a few manufacturers are producing natural gas vehicles on the production line. Discussed below is the general strategy as regards alternative fuel vehicles and also details of some examples of other alternative fuel vehicles presently on the market.

Bi-fuel or dedicated - The ultimate goal is to produce a dedicated CNG vehicle. If the engine and vehicle is designed and developed from the outset as a production mono-fuel (or bi-fuel) unit, then the main issues such as tank storage and power loss can be confronted from the start. The small reduction in power often associated with gas vehicles is no great disadvantage for most passenger car drivers and can be improved with additional engine technologies (e.g.: variable valve timing). However, with onboard storage problems and present lack of refuelling infrastructure, many people see the role of CNG (as well as LNG, LPG etc.) as an additional fuel rather than a full alternative to gasoline or diesel and some also believe that alternative fuels will never be able to fully replace gasoline or diesel [10].

System Integration - The Lotus Elise had shown the possibilities of integrating the fuel system within the safety cell of the vehicle, which has no adverse effects on handling and also avoids any loss of passenger or luggage space. The addition of the CNG fuel system required no changes to the internal geometry of the original engine. The use of a single ECU allows completely integrated control of both fuel systems which reduces part counts and cost. The automatic switching employed means there need be no loss of performance when it is required.

The future - At present and in the next few years the use of multi-point sequential injection with natural gas will be the major technology. However as direct injection becomes more popular with gasoline so it will with natural gas to achieve increasingly demanding emissions and fuel economy targets. As world resources of oil become more critical, CNG will move towards dedicated rather than bi-fuel applications. Therefore, analysis of the fundamentals of gas flow in the intake manifold and into the combustion chamber as well as gas combustion itself is essential to enable the design and development of purpose built engines for dedicated natural gas use. The addition of technologies such as variable valve control, cylinder and valve deactivation have been applied to gasoline engines to help improve performance, emissions and fuel economy. These same technologies can also be applied to CNG fuelled engines to achieve the same benefits. It should also be recognised that the development of hybrid engines, for example (as discussed in the next section), where a combination of an IC engine and an electric motor are used to power the vehicle, CNG is a viable, clean fuel to power the IC engine, with gasoline not being the only option.

3.7 World-Wide Examples of CNG Vehicles

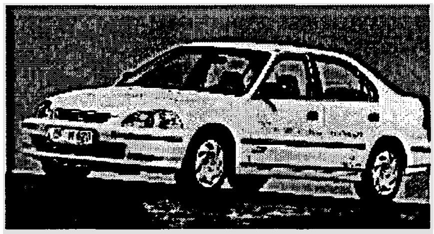
Vauxhall have produced after-market conversions of some of their present models. The Combo van (based on the Corsa) has an additional 60litre CNG tank installed behind the front seats which does not take up too much of its carrying capacity. The engine has a single point distribution system for the gas and does not have automatic switching between the fuels apart from a switch from gas to petrol when the gas level is low. When manually switching it was reported to be virtually impossible to detect the difference between the performance of the two fuels [11].

The two car conversions (Vectra and Omega) run on gasoline and LPG. This allows a smaller, neater tank to be packaged but in the case of the Vectra the spare wheel well is used for the tank and in the Omega the boot loses some space to a 68litre tank. Vauxhall's policy appears to be to use CNG for commercial vehicles where more space is available and LPG in passenger cars to keep the loss of space to a minimum.

Fiat and Honda are two of the first companies to produce production alternative fuel vehicles. The new Fiat Multipla [12] has been specially developed to accommodate under-floor gas cylinders for both bi-fuel and dedicated versions. Like the Elise the fuel system consists of an additional set of gas fuel injectors to provide multi-point port fuel injection. The under-floor space allows room for up to 4 gas cylinders (or 3 cylinders and a gasoline tank) with a total capacity of 216litres, providing a considerable range of 435miles on gas. Although the dedicated engine has modifications (ignition timing and increased

compression ratio) both engines still suffer from power loss when running on gas. The additional weight of the gas cylinders (190kg on the dedicated vehicle) has some effect on the handling although some suspension adjustments have been carried out.

The Honda Civic GX [13] is a production, dedicated CNG vehicle. The engine includes several modifications to optimise it for CNG use. These include changes to the compression ratio, valve seat and piston materials and the use of variable valve control (VTEC system). Once again there is a performance loss but the use of VTEC keeps this to a minimum. The combination of clean fuel and engine technology gives claimed emissions levels of only one tenth of the Californian ULEV limits. Although the engine has been modified, no changes to the vehicle have been carried out. The gas cylinder once again takes up space in the boot and its weight and position effects the performance and driveability



4 OTHER TECHNOLOGIES AND THE CHALLENGE FROM CNG

The increasing world population has resulted in a greater demand for personal transport. This demand must be satisfied with consideration to the environmental impact and the choice of power plant and fuel will have a major influence of the performance and efficiency. Three major choices for the future power plant are the IC engine, electric vehicles and the fuel cell [14]. The following section discusses the various power plants that presently exist and/or are under major development in the automotive industry. The advantages and disadvantages of these are discussed and also compared to those power plants that use natural gas as a fuel. It can be seen that although there are many alternative options for power plants the use of natural gas offers an additional or alternative benefit in several areas.

4.1 IC Engines

From a fuel demand-supply perspective, the internal combustion engine is most likely to remain the predominant power plant for personal transport for the next few decades. Technical developments such as cylinder deactivation (CDA) and gasoline direct injection (GDI) are being implemented to improve efficiency, emissions and fuel economy. However, these technologies are not only applicable to gasoline. By using natural gas in addition, even further improvements can be obtained. The flexibility of the IC engine to accept various technologies and alternative fuels means that extensive development of the IC engine together with the use of natural gas will provide strong competition in the near future for any alternative power plants.

4.2 Electric vehicles

Battery storage is applicable in specific markets but generally suffers from power storage density problems which, even at their most efficient, are some three orders of magnitude below that of rival liquid fuels. This handicap greatly limits the range of vehicles and, therefore, hinders market acceptance of battery technology. Owing to the fact that batteries must be charged up from an external power supply (usually a fossil-fuel burning power station), battery powered vehicles are somewhat less environmentally friendly compared with existing internal combustion engines when total environmental impact is considered. Although the range of CNG fuelled vehicles is a major problem it is less so than with battery powered vehicles. The storage density of gas is higher than with batteries and the overall 'well to wheel' emissions of a CNG fuelled car are considerably lower.

4.3 Hybrids

Hybrid vehicles attempt to harness the best features of two, or more, powertrain technologies in order to optimise the characteristics of the vehicle drive systems across the vehicle operating range. The most common hybrid systems, e.g. as found in the Toyota Prius, comprise of a gasoline IC engine and an electric motor with battery power storage. The use of the two power units allows the engine to operate either on gasoline or battery, or a combination, so that the engine can operate at peak efficiency. Together with regenerative braking, energy can be 'reclaimed' so requiring no external charging of the battery. Of course, it is possible to use natural gas as the fuel in the IC engine. In combination with the motor and battery this would increase the range compared with a dedicated CNG vehicle and also decrease the emissions levels even more than when using a gasoline engine.

4.4 Fuel Cells

Fuel cell systems are still heavily under development and in their present state very expensive. They require very pure fuel (e.g. hydrogen or methanol) and at present the infrastructure of these fuels needs to be extensively increased in order to make the fuel available to the market. Hydrogen presents significant disadvantages in terms of fuel storage and handling on-vehicle with fuel needing to be cryogenically stored at around -250°C. The relative complexity and expense of the fuel cell is likely to preclude its immediate use from all but a few (niche) areas in the future. There is a possibility that the hydrogen fuel can be produced by reforming an intermediate fuel such as natural gas. This will offer easier onboard storage if this is carried out on the vehicle. It is also possible that the hydrogen can be produced externally at refuelling stations, also by reforming natural gas, and then stored onboard the vehicle offering an interim solution to the infrastructure and provision of hydrogen to the market.

5 CONCLUSIONS

Because of its ready availability and clean burning characteristics, natural gas has a promising future as an alternative fuel for vehicles. It is likely that it will find readier markets in those countries where fuel supply issues support its use, but it will also be used in countries where there is concern about local air quality, particularly for transportation in urban areas. LPG is likely to be natural gas's main competitor in the alternative fuel market, but only in those countries where it is available in the sufficient quantities, and even here, natural gas will compete effectively for larger vehicles.

The developing markets for alternative fuels will require a wide range of vehicles, both bi-fuel and dedicated, that can use natural gas. The gas fuelled Lotus Elise has demonstrated the potential for integrating the gas fuel system within the safety cell of the vehicle, such that there is no adverse effects on handling and no loss of passenger or luggage space. Also, the use of a single engine control unit has shown it is possible to completely integrate the control of both fuel systems; reducing part counts and cost. The automatic fuel switching employed allows the control system to take full advantage of the qualities of both fuels and ensures there is no loss of performance when it is required.

The internal combustion engine is most likely to remain the predominant power plant for personal transport for the next few decades. The technical developments that are being implemented to improve efficiency, emissions and fuel economy are likely to be as beneficial for operation on natural gas as they are on liquid fuels. It is expected that extensive development of the internal combustion engine together with the use of natural gas will provide strong competition in the near future for any alternative power plants. In the longer term, both hybrid and fuel cell powered vehicles may begin to penetrate the market, but in either case, natural gas will be a good fuel for these technologies.

6 REFERENCES

1 - Stephenson, J. (1997). Position Paper on Natural Gas Vehicles, *International Association for Natural Gas Vehicles.*
2 - Allen, J. (1997). The Long Term Future of Aerospace.
3 - World Energy Council (1995). Global Transport Sector Energy Demand Towards 2020. *London Modifications IANGV Position Paper,* 8 & 223.
4 - Han Dinh, P. E. (1998). The United States Postal Service Alternative Fuels Utilisation Program - A 1998 Overview, *NGV '98,* 172.
5 - Rajeana, G. and King, T. (1998). Natural Gas Vehicles in Major US Airports, *NGV '98,* 165.
6 - Gover, M. P. (1996). Alternative Road Transport Fuels: A Preliminary Life-Cycle Study for the UK, *The Stationary Office ISBN 011-515410-9 & 011-515411-6,* Vols. 1&2.
7 - Eyre, N. J. (1997). Fuel and Location Effects on the Damage Costs of Transport Emissions, *Journal of Trans. Economics and Policy.*
8 - Parker, F. (1998). Review of Progress - Natural Gas Vehicles, *Natural Gas Association.*
9 - MarketLine International, (1997). World-wide Demand and Growth in LPG.
10 - Burnicle, D. (1998). Gas Attack, *Engine Technology International,* Issue 5, Vol. 1.
11 - Johnson, G. (1999). Pumping Gas, *Engine Technology International,* Issue 1, Vol. 2.
12 - Crosse, J. (1999). The Coffee Pot Special, *Automotive Engineer,* Vol. 24: No. 2.
13 - Brachmann, T. and Yatabe, F. (1998). The Natural Gas Honda Civic GX, an Unique Clean Vehicle for Today and the 21sr Century, *NGV Conference '98,* Cologne, Germany.
14 - Allen, J., Evans, T., Law, D., Martin, J., Robinson, D., Taitt, D. (1998). Future Engine Design - What are the Possibilities, *Institute of Petroleum Conference,* London, UK.