alternative fuels in the automotive market

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Brussels
October 1995

ABSTRACT

A review of the advantages and disadvantages of alternative fuels for road transport has been conducted. Based on numerous literature sources and in-house data, CONCAWE concludes that:

- Alternatives to conventional automotive transport fuels are unlikely to make a significant impact in the foreseeable future for either economic or environmental reasons.
- Gaseous fuels have some advantages and some growth can be expected. More specifically, compressed natural gas (CNG) and liquefied petroleum gas (LPG) may be employed as an alternative to diesel fuel in urban fleet applications.
- Bio-fuels remain marginal products and their use can only be justified if societal and/or agricultural policy outweigh market forces.
- Methanol has a number of disadvantages in terms of its acute toxicity and the emissions of “air toxics”, notably formaldehyde. In addition, recent estimates suggest that methanol will remain uneconomic when compared with conventional fuels.

KEYWORDS

Gasoline, diesel fuel, natural gas, liquefied petroleum gas, CNG, LNG, Methanol, LPG, bio-fuels, ethanol, rape seed methyl ester, RSME, carbon dioxide, CO_2, emissions.

ACKNOWLEDGEMENTS

This literature review is fully referenced (see **Section 12**). However, CONCAWE is grateful to the following for their permission to quote in detail from their publications:

- SAE Paper No. 932778 ©1993 - reprinted with permission from the Society of Automotive Engineers, Inc. (15)
- “Road vehicles - Efficiency and emissions” - Dr. Walter Ospelt, AVL LIST GmbH.

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SUMMARY

This report reviews, in a European context, the emissions, economic and CO_2 advantages (or disadvantages) of alternative road transport fuels when compared with conventional petroleum derived fuels. The report is structured around two broad classifications of the alternatives:

- Gaseous fuels (from non-renewable sources)

- “Bio-fuels” (derived from renewable agricultural produce)

Methanol, which does not fit comfortably in either classification, is treated in a separate section.

Gaseous fuels have been used on a limited scale for many years. Historically they have been employed for a mixture of economic, availability and environmental reasons. Being gaseous and of relatively narrower compositional range than conventional liquid fuels they have the potential to be low emissions engine fuels. However, they do require more expensive and technically complex on-board storage and distribution systems. In addition, larger volumes of gas are needed to move the same vehicle weight a given distance. The extra weight of on-board storage compounds this problem. Emissions are better in some respects when compared with gasoline or diesel fuel, but worse in others - particularly methane which is not considered in US emission limits. Substantial investments are required by both fuel supplier and vehicle owner to "get started" with CNG. LPG offers much lower investment entry costs. All gaseous fuels present hazards that are different from their conventional liquid counterparts which need to be assessed. In addition, "well to wheel" energy balances continue to favour liquid fuels.

Methanol, derived from natural gas, is purported to offer two air quality benefits over gasoline. These are: lower ozone forming potential plus minimal benzene and polycyclic aromatic hydrocarbon emissions (assuming the use of methanol as a neat fuel). Offset against these advantages are high formaldehyde and buta-1,3,-diene emissions. The most serious drawback of all is the toxicity of methanol, which poses major problems for storage, distribution, dispensing and accidental ingestion or exposure.

The use of oxygenate materials derived from agricultural produce as transportation fuels is also receiving considerable attention in Europe. Since they are produced from renewable resources, bio-fuels appear to offer no net CO_2 emissions and reduce the dependence on fossil fuels. However, the true situation is more complex. In the case of bio-ethanol, the energy consumed in producing the fuel can equal the energy content of the ethanol itself, so that there are no net CO_2 and virtually no energy gains. The use of methyl ester (RSME) produced from oil-seed rape (canola or colza) oil gives a positive energy balance, but even here half the energy content of the fuel is required in its manufacture. Oxygenated fuels can give lower emissions of HC and CO, but some emissions, notably NOx, can be increased, and effects on diesel particulates are variable. The true costs of bio-fuels are several times higher than those of conventional gasoline and diesel fuels, and alternative investments are likely to achieve greater environmental and energy gains.

1. INTRODUCTION

Recent years have seen many pressures on road vehicle and fuel performance to meet increasingly stringent emissions regulations and improve fuel consumption, while maintaining and improving the acceptability and performance of vehicles. Much has been achieved through the combined efforts of vehicle and engine manufacturers and fuel producers. Three way catalysts, which have been used for many years on gasoline vehicles in the USA and Japan, are now required in Europe in response to new and tighter emission limits. In Europe, modern diesel engines rival the gasoline engine in the passenger car market not only in terms of fuel economy, but in power, emissions performance and smoothness. The adoption of uniform European (CEN) fuel standards will help to minimize regional variations in fuel quality.

Gasoline and diesel fuels sold for road use in Europe are subject to substantial taxes. These vary between countries, but can range up to 300% of the untaxed product cost. Tax differentials are used in some countries to encourage the use of certain products. For example, the additional costs of unleaded gasoline have been more than offset by tax advantages in many countries so that it has a price advantage at the pump. Lower taxes have also been applied to diesel fuel to support the lower cost of transporting goods by road and have been indirectly responsible for the rapid growth of the diesel passenger car market in Europe.

After coal, natural gas is the most abundant fossil fuel. World-wide, the ratio of proven gas reserves to annual production is double that of petroleum. Large conventional gas reserves exist in the US, Canada and Mexico, Russia, Kazakhstan, Iran, and Indonesia. Large quantities of additional gas are available in unconventional resources. Many of these would become economically recoverable with some increase in well-head gas prices. Adding these unconventional resources to conventional reserves results in a resource base capable of supplying world consumption for many years to come.

Natural gas and liquefied petroleum gas (LPG) have been used on a limited scale as vehicle fuels for more than 50 years. They have been employed, for example, in Russia, Argentina, Italy, the Netherlands, Canada, New Zealand, and the US. Until recently, the major motivation for using these fuels was price, particularly where low (or no) fuel tax was applied to gaseous fuels. Under these circumstances the low cost of natural gas and LPG compared with gasoline or diesel made their use attractive in certain applications such as taxicabs. Here, the fuel savings were sufficient to offset the higher cost of on-board storage and compression/dispensing systems. In recent years, attention has focused increasingly on the environmental as well as the economic benefits of gaseous fuels. Advances in the technology for gaseous-fuel vehicles and engines, new technologies and international standardization for CNG storage cylinders, and the production of new, factory-manufactured gaseous-fuel vehicles in a number of countries have all combined to improve the market potential for these fuels. However, gaseous fuels, like many alternatives, suffer from the classic “chicken and egg” problem. Capital investment in refuelling sites will only materialise if there is market demand. Development of vehicles to create that demand will only occur if the fuel is readily available. In addition, the limited on-board storage capacity of gaseous fuels and public perception of safety issues mitigate against more than niche market acceptance.

Most major urban centres and many minor ones in industrial countries are served by a large network of high-pressure natural gas pipelines. These are connected through "city gate" valves to urban gas distribution networks operating at moderate to low pressures, which transport gas directly to the point of use. Other technologies for natural gas transportation and distribution include liquefaction and shipment in liquid form (LNG), and short-distance transport of compressed natural gas (CNG) in large banks of cylinders. Japan, Taiwan, Korea, and many countries of Western Europe now import significant quantities of natural gas in the form of LNG.

Liquefied petroleum gas (LPG) is a by-product arising in the extraction and refining of crude oil and natural gas processing. The quantity available for the petroleum energy sector currently amounts to approximately 5% of the amount of petroleum produced. LPG also arises in the extraction of natural gas (approximately 3 per cent of the quantity of natural gas). Its availability is thus closely linked to crude oil production and refining (in particular, gasoline production). Thus, supply constraints would severely limit its further use as a substitute for conventional fuels. Nevertheless, it is at present the most widespread of alternative fuels, currently powering an estimated 4 million vehicles in several countries (primarily the Netherlands, Japan, Italy, Australia, New Zealand, Canada and the USA).

LPG presents a useful combination of combustion and storage properties. Like methane, it is a gas at normal temperatures, and thus mixes readily with air in any proportion. Cold starting is therefore not a problem and cold-start enrichment is unnecessary. The octane rating of LPG, while somewhat lower than that of methane, is still higher than gasoline's, and permits the use of compression ratios around 10:1. The lean combustion limit of LPG-air mixtures is also considerably higher than that of gasoline, allowing the use of lean-burn calibrations which increase efficiency and reduce emissions. These mixtures are also more resistant to knocking, permitting the use of still higher compression ratios.

On an energy basis, LPG has a lower carbon content than gasoline or diesel fuel, produces less non-CO_2 greenhouse gases during combustion, and requires less energy to produce than either fuel. LPG, when used in spark-ignition engines, is expected to produce virtually zero emissions of particulates, very little carbon monoxide and moderate hydrocarbon emissions. NOx emissions are a function of the air-fuel ratio. Under very lean conditions, LPG does not burn as well as natural gas, so the NOx levels achievable through lean-burn technology are expected to be somewhat higher. LPG and CNG vehicles produce significantly lower emissions than either gasoline or diesel vehicles. CNG provides a slightly better reduction in non-methane hydrocarbon (NMHC) emissions than LPG and it can be argued that the latter fuel provides less air quality benefits than CNG, primarily because the hydrocarbon emissions are more photochemically reactive, but also because they may emit more carbon monoxide. However, the higher methane emissions of natural gas fuelled vehicles needs to be addressed in a global context.

LPG is heavier than air and tends to "pool", therefore being more susceptible to explosion and fire than other gaseous fuels. This characteristic should be put in its proper perspective - all fuels burn and liquid fuels also “pool”. LPG fuel systems have proven integrity and thus LPG is inherently as safe as any other automotive fuel.

Because the supply of LPG is limited, any large-scale conversion of heavy-duty vehicles to LPG use is likely to absorb the existing glut, causing prices to rise. For this reason, LPG probably makes the most sense as a special fuel for use in "small" vehicles such as car fleets, urban buses and delivery trucks operating in areas that are especially pollution-sensitive.

Methanol can be produced from a variety of feedstocks, including natural gas, coal, biomass and cellulose. Currently the most economical source is natural gas and this is likely to pertain well into the next century.

Oxygenates already have a limited role in fuel production in Europe, principally through the use of Methyl Tertiary Butyl Ether (MTBE) as a high octane blending component in gasoline. Elsewhere, ethanol has found use in blends with gasoline (gasohol) in the USA, while Brazil has pioneered the use of pure ethanol as a transport fuel. More recently, the potential to use surplus agricultural production as a source of fuel energy has been studied both in North America and Europe. While some schemes have looked at direct use of agricultural produce as heating fuels, more prominence has been given to the production of liquid fuels suitable for vehicle use. The perceived incentives are diverse, and range from fossil fuel substitution, CO_2 reduction and self-sufficiency, to effects on air quality through reductions in both regulated and unregulated emissions.

Agricultural production is heavily regulated in Europe, and over-production of certain food crops has been addressed by a policy of 'setting aside' a proportion of land each year. The search for alternative outlets for farm products has been one driving force behind the interest in bio-fuels, which is a generic name for any fuel produced from agricultural produce. The second force is a desire to reduce global CO_2. The coincidence of these pressures resulted in a proposal by the European Commission for a 90% reduction in excise duty on road fuels produced from renewable sources. This proposal is currently on hold, although local tax exemptions are available in some countries for trial purposes. The questions surrounding bio-fuels are therefore complex, involving agricultural policy as well as energy and environmental issues. This report collates available information to assess the economic, energy and environmental impact of bio-fuels, with the aim of clarifying a complex issue, but does not attempt to address questions related to agricultural policy.

2. GASEOUS FUEL COMPOSITION AND PROPERTIES

The properties of the main hydrocarbon constituents of natural gas and LPG are summarized in **Table 1**.

Table 1 Properties of the main hydrocarbon fuel gases

	Methane	**Ethane**	**Propane**	**Propene**	**n-Butane**	**Iso-Butane**	**Butenes**
Energy Content (LVH) (MJ/kg)	50.01	47.48	46.35	45.78	45.74	45.59	45.32
Liquid Density(kg/l)	0.466	0.572	0.501	0.519	0.601	0.549	0.607
Liquid Energy Density (MJ/l)	23.30	27.16	23.22	23.76	27.49	25.03	27.51
Gas Energy Density (MJ/m$^{3)}$	32.6	58.4	84.4	79.4	111.4	110.4	113.0
Gas Specific Gravity (@25°C)	0.55	1.05	1.55	1.47	2.07	2.06	1.93
Boiling Point °C	-164	-89	-42	-47	-0.5	-12	-6.3 to 3.7
Research Octane No.	>127	-	109	-	-	-	-
Motor Octane No.	122	101	96	84	89	97	77
Wobbe Index (MJ/m^3)	50.66	65.11	74.54	71.97	85.46	84.71	81.27

Natural gas contains varying amounts of non-methane hydrocarbons, H_2S, CO_2, water vapour, nitrogen, helium, argon, and other trace gases. In most cases, it is necessary to upgrade the gas to pipeline specifications in a gas processing plant before injecting it into the transportation and distribution network. Water and H_2S must be removed to prevent corrosion damage to the pipeline network, and excess amounts of higher hydrocarbons must be removed to prevent them from condensing under the high pressures in the gas transmission lines. There is also an economic benefit to recovering these hydrocarbons, since "natural gas liquids" are more valuable as gasoline feedstock, petrochemicals, or LPG than as components of natural gas. Helium, where found at significant concentrations, is also a valuable by-product. Excess amounts of inert gases such as CO_2, Argon, and Nitrogen are also removed in processing .

Pipeline-quality natural gas is a mixture of several different gases. The primary constituent is methane (CH_4), which typically makes up 80 to 99% of the total. The remainder is primarily ethane and inert gases such as N_2 and CO_2, with smaller amounts of propane, butanes, and higher hydrocarbons. The mix of minor constituents varies considerably from place to place and from time to time, depending on the source and processing of the gas. In order to ensure consistent combustion behaviour, major natural gas pipelines generally impose specifications on the composition of the gas they will accept for transport. These specifications typically limit the percentage of propane, butane, and higher hydrocarbons, the volumetric heating value, and the Wobbe Index (see page 6).

Although pipeline gas generally exhibits a limited range of composition and properties, natural gas found in distribution systems may exhibit greater variability. In some cases, distribution systems in gas-producing areas receive gas directly from the well, with minimal processing. The resulting gas may be rich in non-methane hydrocarbons, inert gases, or both. Another factor affecting gas composition in distribution systems is the occasional supplementing of natural gas supplies with propane-air mixtures to meet peak winter demand. The high propane levels resulting from such use may pose problems for CNG fuel systems, since the propane can liquefy at pressures typical of CNG storage.

The term "liquefied petroleum gas," or LPG, refers to mixtures of three and four-carbon hydrocarbons such as propane (C_3H_8), propene (C_3H_6), n-butane (C_4H_{10}), isobutane and various butenes (C_4H_8). Small amounts of ethane (C_2H_6) may also be included. The major sources of commercial LPG are natural gas processing and petroleum refining. Natural gas often contains excess propane and butanes which must be removed to prevent their condensing in high-pressure pipelines, and to control variation in gas properties. LPG from refineries includes light hydrocarbons originally dissolved in the crude oil and separated during the distillation process, as well as those produced during catalytic reforming of naphtha for gasoline production and in the process of cracking heavy hydrocarbons to lighter products. Refinery LPG, unless further processed, often contains significant quantities of olefinic compounds (propenes and butenes) produced in the cracking process.

Uses for LPG, in addition to automotive fuel, include petrochemical production, home cooking and heating fuel, and fuel for industry. Presently, LPG supply exceeds the demand in most gas-producing and petroleum-refining countries, so the price is lower than that of other hydrocarbons. Depending on the locale, however, the additional costs of storing and transporting LPG may more than offset this advantage. Because the supply of LPG is limited, and small in relation to other hydrocarbon fuels, large-scale conversion of vehicles to LPG would probably absorb any existing surplus, causing prices to rise.

The composition of commercial LPG varies greatly from one country to another. In Europe, countries having relatively cold climates tend to use a high percentage of propane and propene in order to provide adequate vapour pressure in winter, while warmer countries, such as Italy, use mostly butane and butenes. LPG composition may also vary between summer and winter, with a higher percentage of propane and propenes in the winter months. **Table 2** summarizes the proportion of C_3 hydrocarbons in commercial LPG for a number of countries:

Table 2 Range of LPG composition for Different Countries

Country	**Propane and Propene (%)**
Belgium	40-60
Finland	100
France	20-50
Germany	100
Netherlands	30-70
United Kingdom	50-100
United States	98-100

Wobbe Index

The Wobbe index, also referred to as the Wobbe number, is an important parameter for gaseous fuels. The Wobbe index of a gaseous fuel is determined by its composition. The value of the Wobbe index, W, is calculated as:

$$W = \frac{H}{\sqrt{p}}$$

Where H is the volumetric heating value of the gas, and p is the specific gravity. Wobbe indices can be calculated from gas composition data or heating value and density measurements. Their influence on fuel metering is further discussed in **Section 6.1.**

Natural gas - Because changes in air-fuel ratio affect combustion and efficiency in many gas-burning appliances natural gas suppliers maintain close control of the Wobbe index of the gas they deliver. Pure methane has a Wobbe index of 1361 Btu/scf (50.66 MJ/m^3). Increasing concentrations of higher hydrocarbons such as ethane and propane increase the Wobbe index, while increasing concentrations of inert gases lower it. In practice, these two effects are used to cancel each other out, so as to maintain the Wobbe index of natural gas in the pipeline close to the nominal specification.

LPG - The three-carbon and four-carbon species in LPG differ in volumetric energy content, so that a change in LPG composition can affect the air-fuel ratio in engines and other combustion devices operating on LPG. Although seldom used in reference to LPG, the Wobbe index is equally applicable to assessing the effect of varying fuel composition on air-fuel ratio.

3. ORIGIN AND PRODUCTION OF BIO-FUELS

Bio-fuels are produced in two principal ways:

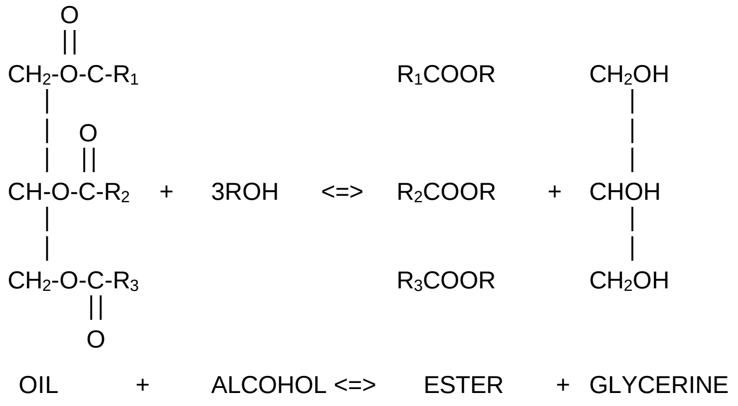
- production of alcohols through fermentation processes from grain, fruit or other sugar bearing materials, with or without further processing.
- use of vegetable oils, either following simple processing (e.g. alkali washing), or more usually after esterification to improve their suitability for use as fuels.

In Europe, there are large surpluses of grain and wine which provide a potential source of ethanol, while sugar beet provides a potential alternative. Ethanol has a high octane number, and correspondingly low cetane number, so is more suitable for use in spark ignition engines than as a diesel fuel. It currently has limited use in Europe but has recently been used in France to produce Ethyl Tertiary Butyl Ether (ETBE) for use in gasoline. The conversion process consists of:

$$\underset{\text{iso-butene}}{(CH_3)_2C = CH_2} + \underset{\text{ethanol}}{C_2H_5OH} ==> \underset{\text{ETBE}}{(CH_3)_3COC_2H_5}$$

The main focus of attention in Europe has, however, been on the use of Rape Seed Methyl Ester (RSME) as a fuel for diesel engines, either alone or in mixtures of up to 20% with conventional diesel fuel. Rape seed (also known as Canola or Colza) is an annual plant, similar to mustard producing oil bearing seeds. It is widely grown to produce cooking oil, but is currently in surplus in Europe. Many other plants produce oils, for example palm oil is under consideration in Malaysia, but for temperate crops, rape seed is currently the most likely candidate.

The oil produced after pressing the seeds can be used directly in a diesel engine, and early studies followed this approach. While performance of the engine was initially good, the high viscosity and gummy nature of the oil resulted in heavy engine deposits and crankcase oil dilution, so that engine life was dramatically reduced. To overcome these problems, the oil can be esterified by reacting it with methanol in the presence of a catalyst:



$$\begin{array}{ccccccc}
\begin{array}{l} CH_2\text{-}O\text{-}\overset{\overset{O}{||}}{C}\text{-}R_1 \\ | \\ CH\text{-}O\text{-}\overset{\overset{O}{||}}{C}\text{-}R_2 \\ | \\ CH_2\text{-}O\text{-}\underset{\underset{O}{||}}{C}\text{-}R_3 \end{array} & + & 3ROH & <=> & \begin{array}{c} R_1COOR \\ \\ R_2COOR \\ \\ R_3COOR \end{array} & + & \begin{array}{c} CH_2OH \\ | \\ CHOH \\ | \\ CH_2OH \end{array} \\
\text{OIL} & + & \text{ALCOHOL} & <=> & \text{ESTER} & + & \text{GLYCERINE}
\end{array}$$

4. STORAGE, DISTRIBUTION AND VEHICLE CONSIDERATIONS

4.1. GASEOUS FUELS DISPENSING AND STORAGE

Natural gas may be stored on-board a vehicle either as a compressed gas in high-pressure cylinders or as a cryogenic liquid. From the engine's standpoint, CNG and LNG are essentially interchangeable - it is only the on-board storage medium that is different. LPG is stored and dispensed at ambient temperatures, as a liquid under pressure.

4.1.1. Compressed Natural Gas (CNG)

Handling of CNG is similar to that of any high-pressure gas. Piping and connections must be strong and gas-tight. Refuelling is accomplished by connecting a manifold on the vehicle to a high-pressure gas line using a positive-lock connection, and then admitting the gas to the vehicle tanks.

Compressed natural gas refuelling systems can be divided into slow-fill and fast-fill designs. The main components of a typical "fast fill" station are a compressor to boost the gas pressure in the distribution line to about 33 MPa; a bank of storage vessels (often called a "cascade") to store the high-pressure gas; and a dispenser, which often resembles a gasoline pump from the outside but is very different internally. The compressor is driven by an electric motor or natural gas engine, and requires considerable power. The capital and running costs of the compressor and motor constitute a large part of the overall costs of a CNG refuelling system. These costs are typically much higher than those of refuelling systems for conventional liquid fuels. The complete package also includes controls and safety devices, and filters to eliminate oil and particulate matter from the compressed gas. Generally, the compressor, motor, controls, and auxiliaries are packaged and sold as a single unit. The package may also include the cascade storage and the dispenser, or these may be sold separately.

"Fast fill" CNG systems are designed to refuel one or two vehicles simultaneously, but to refuel each vehicle in a relatively short time. Nevertheless, such systems cannot currently approach gasoline refuelling rates - a medium size passenger car will typically take at least five minutes to fill. This is achieved by using the compressor to pump high-pressure gas into the cascade storage, which serves as a "buffer." The cascade storage vessels are divided into several groups which can be connected independently to the refuelling connector. To refill a vehicle, the cascade storage units are connected in sequence to the vehicle's fuel intake, and allowed to equalize pressure. The group having the lowest pressure is connected first, then the next lowest, and so forth, until the storage pressure on-board the vehicle reaches the desired level. This arrangement makes it possible to use a smaller compressor than would be required to achieve the same refuelling time by pumping directly from the compressor to the vehicle. New, ultra-fast dispensing systems are under development, for which bus refuelling times of 2.5 minutes have been claimed. The costs of such equipment are not known.

Because fast-fill systems dispense at a fairly swift rate, the gas in the cylinders has no time to lose heat to the environment. At the end of the fill, the gas in the vehicle cylinders will be considerably warmer than the ambient temperature. This makes it difficult to obtain complete refuelling by "fast fill". Although the tank pressure may be at the nominal "full" level after refuelling, the pressure will drop as the gas in the cylinders cools to ambient temperature.

A "slow fill" CNG fuelling system is designed to refuel vehicles such as buses that can be parked overnight. All of the vehicles are connected in parallel to the compressor, eliminating the need for cascade storage, but requiring a large number of high-pressure hoses and connectors. This arrangement makes it possible to achieve good compressor utilization since the compressor can run continuously all night. For even more effective compressor utilization, it is also possible to design a "hybrid" system that can be used for fast fill during the day and slow fill at night.

The current standard working pressure for compressed natural gas cylinders is 20 MPa. It has been suggested that working pressures should be raised to 25 MPa to provide better range, but this would be a disadvantage to those consumers who have already installed lower pressure systems.

The size and weight of CNG cylinders are often cited as major drawbacks of natural gas use in vehicles. However, recent developments in high-strength composite materials have made it possible to reduce the weight of CNG cylinders substantially. About 32 scf of natural gas, weighing less than 1 kg, are equivalent to the energy content (lower heating value) of one litre of gasoline. With conventional steel cylinders, the weight of the cylinder required to contain this quantity of gas is about 4.7 kg, giving a total fuel and storage weight of 5.4 kg per litre gasoline equivalent. For comparison, the weight of the fuel and tank for gasoline would be about 0.94 kg/l; for diesel fuel it would be about 1.0 kg/l.

With current fibre-wrapped steel cylinders, weight reductions of about 30% are feasible. Fibre-wrapped aluminium cylinders weigh about 2.9 kg/l of gasoline equivalent. All-composite cylinders weigh even less, approximating to 2.1 kg/l of gasoline equivalent. Despite these advances, CNG storage remains significantly heavier than that for conventional liquid fuels. Furthermore, the size and weight of the cylinders present “packaging” problems and the required strength of tank supports can add to the weight penalty. The additional weight introduces a further penalty in terms of loss of fuel economy, which is equivalent to 0.5 litres/100 km. for a modern passenger car fitted with steel cylinders. These disadvantages, coupled to the low energy density of the gas, place severe limitations on vehicle range between refuelling stops.

4.1.2. Liquefied Natural Gas (LNG) dispensing and storage

LNG is stored in double-wall, vacuum-insulated cryogenic (-260°F, -160°C or less) containers and is then vaporised, usually by engine heat. A sophisticated fuel tank storage/delivery system is required to allow pumping of LNG to and from the fuel system, while maintaining cryogenic temperatures over long periods of time. Current design LNG tanks are of double-walled construction: an inner vessel made of stainless steel, surrounded by an insulating material and an outer casing made of high-strength carbon steel. The space between the inner and outer shells is vacuum evacuated to 0.13×10^{-6} bar. For applications requiring multiple LNG tanks, vacuum jacketed piping (double walled pipe with vacuum separation) is used to interconnect the tanks.

The quality of LNG can vary greatly, and the quality needed by the user may also vary. The liquefaction process generally removes all of the minor natural gas constituents except ethane and nitrogen. Typical LNG is about 87-92% methane, with most of the remainder being liquid ethane. With additional processing, the ethane and nitrogen components can be removed as well, yielding a product that is 99+% pure methane. Since methane has substantially better antiknock properties than ethane, the use of pure liquid methane may be desirable for certain high-performance engines.

An important concern with the use of liquid methane/ethane mixtures is the possibility of changes in fuel composition during handling and processing. This is known as "ageing," "weathering," or “enrichment". The liquid ethane has a higher boiling point than methane. Therefore, at every stage in processing where evaporation can take place--central storage, distribution, transfer, refuelling station storage, and final fuelling--methane boils off, leaving the ethane behind. At the end of the chain, a higher concentration of ethane exists than did at the beginning. The Wobbe index of the fuel thus becomes progressively higher, while the knock-resistance becomes lower. This may be a significant problem for high-compression engines or those with very high BMEP levels, due to the increased potential for knock.

A number of LNG refuelling system designs exist. They can be divided into two categories: those with and those without vapour return. It appears that the industry is leaning toward single hose, no-vapour return refuelling systems. Tank de-pressurizing is automatic, with integrated hoses and nozzles. Both fuelling hoses and dispensing units must be designed according to the following needs: accurate flow measurement, accurate pressure regulation, sufficient hose support (hoses are heavier than gasoline or diesel hoses), leak detection, fire detection, frost and ice avoidance (especially in high-humidity areas), and protection of refuelling personnel. The lack of a standard LNG nozzle/dispenser design is presently a significant barrier to the commercialisation of LNG technology.

The newest design LNG tanks are filled from the top, providing a vapour-only interface at the nozzle connection. This practice is one of design convenience and safety. LNG entering the tank at the vapour interface cools the vapour present in the tank, condensing some of it back into liquid form. This eliminates the need for a vapour return line.

If the fuel is pumped into the liquid interface at the bottom of the tank, it will not cool the overhead vapour, but rather will compress it and increase the internal tank pressure. Older LNG tank designs using bottom fill require a vapour return system to maintain proper internal tank pressure during refuelling.

Nearly all LNG engines use the fuel in gaseous form. To accomplish this, a "vaporiser" employs engine heat (usually through heat exchange with the engine coolant) to help expand the cold liquid into its gaseous form. In some applications, the LNG is vaporised to a gas at close to ambient conditions and then pumped to the required pressure with a compressor. In other applications, the fuel is pumped as a liquid to high pressure and then vaporized. The latter requires less pumping power because liquids are much less compressible than gases. On some designs, a "CNG buffer," or expansion tank, gives additional space for sudden expansion of cold LNG when the fuel demand from the engine is suddenly reduced or interrupted. This buffer is also used to store natural gas for start-up of the engine. When the engine is restarted, there is enough gas in the buffer system to start the engine running and get the LNG vaporiser system working and producing gas for normal operation.

4.1.3. Liquefied Petroleum Gas (LPG) dispensing and storage

LPG is stored on the vehicle as a liquid under pressure. LPG cylinders must be designed to sustain an internal pressure of up to 3.0 MPa. They are generally cylindrical, with rounded ends, and are much stronger than tanks used for storing gasoline or diesel fuel, albeit marginally less robust than those used for CNG. LPG can be pumped from one tank to another like any liquid, but the need to maintain pressure requires a gas-tight seal. Except for the need for a standardised, gas-tight connection, LPG used as vehicle fuel can be dispensed in a similar fashion to that employed for gasoline or diesel fuel. To ensure that some vapour space is always available for expansion, LPG cylinders used in automotive applications must never be filled to more than 80% of their capacity. Automatic fill limiters are incorporated in the cylinders to ensure that this does not occur.

4.2. GASEOUS FUELS - VEHICLE CONSIDERATIONS

Technology for natural gas and LPG engines resembles that for conventional gasoline spark-ignition engines in many respects. This is especially the case for light-duty vehicles. Modern light-duty natural gas and LPG vehicles and conversion kits commonly employ three-way catalytic converters and stoichiometric air-fuel ratio control systems with feedback control via an oxygen sensor. Except for differences in the fuel metering hardware and the absence of cold starting aids, these systems closely resemble those used in modern light-duty gasoline vehicles.

Heavy-duty engines for gaseous fuels may resemble heavy-duty gasoline engines, with spark ignition and rich or stoichiometric air-fuel ratio operation. More commonly, however, these engines are based on heavy-duty diesel engine designs, and use either a high-compression, lean-burn, spark-ignition combustion system or, more commonly, stoichiometric combustion in conjunction with a 3-way catalyst. Natural gas and LPG can also be burned in dual-fuel diesel engines, in which the gaseous-fuel charge is ignited by injecting a small amount of diesel fuel.

4.2.1. Gaseous fuel metering systems

Gaseous fuels occupy considerably more volume than the amount of gasoline having the same energy. As a result, the volumetric energy content of a stoichiometric gas/air mixture is less than that of gasoline-air mixture. In addition, gaseous fuels do not benefit from the practice of "power enrichment" - the best power output from gas engines occurs at essentially the stoichiometric air-fuel ratio. When a gasoline engine is converted, the combination of these two effects typically results in a loss in maximum BMEP and power output of approximately 10%. For LPG, these effects are smaller than for natural gas, and the power loss is typically only a few percent. In dedicated engines, the reduction in power output with gaseous fuels can be compensated by increasing the compression ratio, thus increasing the amount of useful work extracted from a given amount of fuel input. Further increases in BMEP and power output can be achieved by turbocharging. Turbocharging is extremely common for lean-burn, heavy-duty natural gas engines, which can attain BMEP levels exceeding 1.4 MPa.

Gaseous-fuel vehicles require precise control of the air-fuel ratio to minimize emissions while maintaining good performance and fuel economy. Until about 1990, nearly all gaseous-fuel metering systems relied on mechanical principles, analogous to the mechanical carburettors used in gasoline engines, until the early

'80s. Although these mechanical systems can be designed to give good engine performance and efficiency, they are susceptible to fuel metering errors due to wear, drift, changes in elastomer properties, changes in fuel and air temperature, changes in fuel properties, etc. These mechanical systems are thus unable to meet the requirement of modern three-way catalytic converter systems for very precise control of the air-fuel ratio.

Over the last decade, air-fuel ratio control systems for light-duty gasoline vehicles have evolved from mechanical systems to digital electronic fuel injection. Gaseous fuel metering systems have recently undergone a similar evolution. The fuel metering and engine control systems installed on new LPG and natural gas vehicles[1] are essentially identical to the multi point sequential fuel injection systems installed on production gasoline vehicles, except for details of the fuel rail and injectors. Several manufacturers of gaseous-fuel retrofit kits now also offer systems using electronically controlled fuel injection.

4.2.1.1. Spark-Ignition Engines

Most of the natural gas and LPG vehicles now in operation have stoichiometric engines which have been converted from engines originally designed for gasoline. Such engines may be either dual fuel (able to operate on either gaseous fuel or gasoline) or dedicated to the gaseous fuel. In the latter case, the engine can be optimized to take advantage of the knock-resistance of the gaseous fuel. This is not usually done in retrofit situations because of the cost. Nearly all present light duty natural gas and LPG vehicles use stoichiometric engines, with or without three-way catalysts, as do a minority of heavy-duty natural gas vehicles and most heavy-duty LPG vehicles.

Developments in the field of modern LPG fuel systems have been rapid, with the Netherlands taking the lead in Europe. In countries where stringent emission standards are not required, conventional mechanical LPG systems are still employed - so-called first generation LPG equipment. This is briefly described below.

Vehicles are fitted with an LPG storage cylinder (tank). In passenger cars this is generally installed in the boot. In delivery vans it is usually in the freight compartment. The LPG tank incorporates a gas proof housing, covering the accessories. The housing typically contains

- Filling valve with 80% shut-off
- Level indicator
- Pressure relief valve
- Service valve with excess flow valve.

Filling an LPG tank takes place at an LPG filling-station, where the LPG is pumped into the tank in liquid form. As the expansion coefficient of LPG is quite high, the LPG tank may not be filled to more than 80% of its nominal capacity. To this end automatic shut-off valves have been compulsory for some years. Should the pressure in the LPG tank increase too much due to a rise in temperature, then the tank could burst. To prevent this a safety relief valve is fitted which ensures that the gas can escape via a blow-off line leading to the outside of the vehicle. In the open position the service valve makes it possible for the liquid LPG to flow through a pipe to the engine. The service valve also incorporates a excess flow valve. This almost completely shuts off the flow from the tank in the event of, for example, the feed-line bursting. Furthermore, an electro-magnetic shut-off valve is situated in the feed-line, close to the service valve, and this will only open when the engine is running. In the engine compartment the LPG pipe is connected to an evaporator-pressure regulator which converts the liquid LPG into gas. It also reduces the pressure to a value below or slightly above atmospheric pressure, depending on the system in use. The LPG shut-off is installed just in front of the evaporator-pressure regulator. This LPG shut-off comes into operation when the engine is switched over to LPG use.

In general this happens in such a way that gas is only supplied when the engine is running. An electro-magnetic shut-off is also situated in the gasoline line which comes into operation when the engine is switched to gasoline use. The pressure regulator is heated by connecting it to the engine's water cooling system to prevent freezing resulting from the expansion of the LPG. The gas is then mixed with the intake air in a gas air mixing unit situated below or above the gasoline carburettor from where it is transported to the engine as a dry gas/air mixture. Gas metering is determined by the pressure regulator and the mixing unit. Such a mixing unit is also installed in fuel injected engines in the air intake system. A switch for gasoline/LPG use and an LPG contents gauge are located on the dashboard. Further adaptation involves optimising the ignition advance curve and may also incorporate measures to minimise any degradation of gasoline performance

Modern electronics can help overcome some of the shortcomings of conventional LPG systems. This has led to the development of systems in which the basic metering of the gas flow is complemented by electronically governed precision control. In these systems the main metering of the gas flow still takes place in the combination evaporator-pressure regulator and mixing unit. Such systems use analogue or digital electronic control and a microprocessor is used in the latter case.

So-called second generation LPG equipment employs this approach. It is microprocessor controlled and works in combination with a standard LPG pressure regulator and mixing unit. It is suitable for use in fuel injected vehicles employing closed loop controlled 3-way catalysts. The input signals of the microprocessor are derived from engine speed, manifold pressure and the lambda sensor. In most second generation systems, the microprocessor controls the digital linear actuator (DLA) in either open or closed loop configurations. This actuator adjusts a variable jet mounted in the dry gas hose situated between the pressure regulator and mixing unit. Alternatively, the variable jet feeds air via an extra intake situated between the air-filter and mixing unit. The system is adjusted so that a rich mixture is supplied over the complete engine map. This rich mixture is leaned off by adding air which is controlled by the digital linear actuator in either open or closed loop.

Third generation systems are microprocessor controlled, incorporate adaptive learning and require no manual adjustments. Such systems can be either carburetted or fuel injected. The most recent developments utilize LPG injection, in either liquid or gaseous form. Various approaches have been conceived:

Single-Point Injection -

- continuous
- timed

Multi-Point Injection -

- continuous
- timed simultaneous
- timed sequential
- high pressure direct injection into the cylinders

Early single-point injection systems have now been superseded by multi-point configurations, which avoid backfiring problems.

In a typical vapour injection system, the LPG from the tank is controlled at the correct over-pressure by a two-stage regulator and a gas metering unit supplies the same amount of fuel to each cylinder. LPG is injected just upstream of the inlet valves via an injection valve. The system is microprocessor controlled, incorporates adaptive learning and cannot be adjusted. Signals representing performance, emissions and fuel consumption are measured by the microprocessor and converted to a system control input. The microprocessor acts primarily on engine speed signals and absolute manifold pressure, although other parameters can also be handled. As the configuration contains its own engine management system, it can also be employed for dedicated medium or heavy-duty LPG engines.

Liquid injection systems are also available. The main development objective was to achieve control strategies and performance comparable to those of gasoline injection systems. Information from the existing engine management system is used when running on LPG. This is possible, because both fuels are injected in liquid phase. The liquid injection system comprises a fuel pump located in the tank which pressurises the fuel and circulates it to prevent the fuel from vaporising in the vicinity of the bottom feed injectors. A pressure regulator is located downstream of the injectors in the fuel return line to maintain the fuel pressure at 5 bar above tank pressure. This excess pressure is necessary to prevent vapour build-up in the fuel system. LPG injectors are placed in the intake ports of the inlet manifold and the LPG is injected sequentially in front of each inlet valve. Fuel which is not used by the injectors is returned, via the pressure regulating unit, to the tank. The signal sent to the LPG injectors is derived mainly from the microprocessor signal controlling gasoline injection. This is possible since both injectors have comparable characteristics. The gasoline injection signal is used as an input for the LPG microprocessor. The most important additional input parameter is LPG pressure. The lambda sensor remains connected to the gasoline microprocessor so it still has control over the engine. It will not detect abnormalities provided the LPG system follows its commands. The existing gasoline microprocessor makes the basic calculations, including vehicle specific features such as lambda control strategy. Such a system can also be used for medium and heavy-duty applications, although in this case the system is equipped with a complete, stand-alone engine management system.

Modern vehicles equipped with On Board Diagnostics (OBD) can only be converted to LPG use when microprocessor controlled LPG injection systems are used in combination with the original engine management information database. For these applications close cooperation with the vehicle manufacturer is a necessity.

4.2.1.2. Compression Ignition/Commercial Transport Engines

LPG and CNG can be used as automotive fuels in diesel engines, despite the fact that their high octane numbers would tend to support their role as gasoline replacements. There are two options:

- Dual fuel (pilot injection)
- Conversion to spark ignition

Dual-Fuel Conversion

The dual-fuel approach, often referred to as pilot injection (or mixed diesel-gas) has some superficial advantages, not least because the engine requires minimal adaptation, and the diesel combustion principle is quasi-maintained. A second fuel system for LPG or CNG is mounted on the engine. The amount of injected diesel fuel is reduced to a level sufficient to initiate diesel combustion and the original power level is restored by mixing the correct amount of gaseous fuel in the intake air. In effect, such “dual-fuel” diesel engines are a special type of lean-burn engine in which the air-gas mixture in the cylinder is ignited by injection of a small amount of diesel fuel which combusts under conventional compression ignition conditions. The flexibility of this approach has been popular for retrofit applications.

Because of its greater tendency to knock, the use of LPG in dual-fuel applications is subject to severe limitations, and is much less common than natural gas. Where LPG is used, it is generally limited to substituting for 30-40% of the diesel fuel, as compared with 70-90% substitution with natural gas. In terms of energy input this represents about 35% LPG, rising to a maximum of 40% at full load. Over a complete cycle (in, for example, city bus use) the average replacement is approximately 25%. The city of Vienna has extensive experience with Diesel-LPG systems. Several hundred buses were built and a few are still in use. The system was developed in such a way that switching to 100% diesel remained possible.

The emissions performance of current dual-fuel engine systems is mixed and generally represents a poor solution for emissions reduction. These engines can be designed to have very low NOx emissions, but tend to have high HC and CO emissions and poor efficiency at light load. This is because they operate unthrottled, so that the air fuel mixture becomes leaner as the load is reduced. As the mixture becomes leaner, combustion eventually degrades, leaving large amounts of partial reaction products in the exhaust. Possible solutions to this problem include throttling the intake air at light loads or the use of electronically controlled turbochargers.

Spark-Ignition Conversion

Another possibility is that the diesel power unit is converted to a spark ignition engine. This approach is more radical and diesel use is no longer possible. It can be argued that engine manufacturers are more inclined to co-operate in this type of venture. Unlike mass-produced passenger cars, service vehicles are constructed in smaller series and are frequently built to individual customer specifications.

The Otto gas engine differs in several ways from the diesel engine. The diesel fuel injection system is discarded and the cylinder head is adapted to accommodate spark plugs. The in-piston combustion chamber is modified and the compression ratio is lowered. A gas carburation or injection system is fitted, and the speed-governor is modified. Instead of controlling the amount of diesel fuel injected, a throttle-valve in the inlet duct is driven by a mechanical or electronic speed governor. A modern gas engine for use in buses incorporates a microprocessor-driven lambda control and three-way catalyst to control emissions. Most systems are also equipped with a control for both air/fuel ratio and engine idle speed, additionally, gas supply is shut off during deceleration. In engines with a turbocharger the wastegate is driven by an electronic control module and in certain instances the ignition advance is also controlled by the electronic module. It is possible to reach very low exhaust emissions with such a control system, while still attaining acceptable fuel consumption.

Lean-burn engines use an air-fuel mixture with much more air than is required to burn all of the fuel. The extra air dilutes the mixture and reduces the flame temperature, thus reducing engine-out NOx emissions, as well as exhaust temperatures. Because of reduced heat losses and various thermodynamic advantages, lean-burn engines are generally 10-20% more efficient than stoichiometric engines. Without turbocharging, however, the power output of a lean-burn engine is less than that of a stoichiometric power unit.

With turbocharging, the situation is reversed. Because lean mixtures knock less readily, lean-burn engines can be designed for higher levels of turbocharger boost than stoichiometric engines, and can thus achieve higher BMEP and power output. The lower temperatures experienced in these engines also contribute to engine life and reliability. For these reasons, the great majority of heavy-duty natural gas engines are of the lean-burn design.

Large, heavy-duty natural gas engines have been used for many years in stationary applications. More recently, a number of heavy-duty, lean-burn natural gas engines have been developed and marketed specifically for automotive use. Some lean-burn LPG engines have also been developed. These engines are able to achieve NOx emissions of less than half those of present diesel engines. Because of the legislative interest in reducing mobile-source NOx and particulate emissions, some observers expect to see wider use of heavy-duty, lean-burn natural gas engines during the next decade.

In summary, the availability of gaseous fuels equipment for passenger cars and heavy-duty vehicles still retains a “cottage industry” image, despite the strenuous efforts of its protagonists. The advances made have been substantial, but as later economic analysis demonstrates, the utilization of gaseous fuels is highly dependent upon government support.

4.3. BIO-FUELS DISPENSING AND STORAGE

4.3.1. Ethanol

Gasoline distribution systems reach an equilibrium position where varnish, gums and small amounts of sludge and water are deposited throughout the system. Thereafter, normal good housekeeping practices avoid the pick-up of such materials by gasoline in transit. The addition of ethanol to such a system will disturb this equilibrium and can lead to severe handling and performance problems.

For these reasons it is essential that:

- distribution systems are cleaned and dried before the introduction of ethanol/gasoline blends. In the event that conventional gasoline is subsequently passed through the system, this process may have to be repeated;
- all contact between ethanol/gasoline blends and water is avoided;
- gasoline is not mixed with ethanol/gasoline blends in distribution systems;

The above considerations indicate that a dedicated distribution system must be established for neat ethanol and is preferable for ethanol/gasoline blends.

4.3.1.1. Rape Seed Methyl Ester (RSME)

No data are currently available on the storage and handling of RSME, either in blends with conventional diesel fuel, or as the neat product. However, limited experience in field trials with vegetable oils suggests that further investigation of potential problems is required. For example, diesel fuel distribution systems tend to be wetter than their gasoline counterparts and contamination by yeasts and fungi at the fuel/water interface are not uncommon. Vegetable oils, or their derivatives, are likely to provide an even “richer” source of nutrients for this form of airborne contamination.

4.4. BIO-FUEL VEHICLE CONSIDERATIONS

The existing vehicle population, and vehicle models likely to be marketed in Europe in the foreseeable future, are designed to use conventional transport fuels. If fuels containing significant concentrations of oxygenates (or neat RSME) are to be introduced to this market they must meet criteria which ensure that vehicle performance is indistinguishable from that obtained when using conventional fuels without any need to modify the vehicle.

The main aspects to be taken into account are:

- compatibility - this presupposes that the existing vehicle population can employ the fuels without modification to the fuel system (elastomers, metallic components, etc.), engine and its basic tuning calibration or engine management system.
- the different characteristics of the oxygenate blends should not result in detectable differences in vehicle or emissions performance (e.g. cold-starting, hot-engine operating performance, fuel economy) compared with the use of conventional gasolines.

Consequently, the European Union issued Directive 85/536/EEC, dated 25 November 1985, which defined the maximum permissible concentrations of a wide range of oxygenates in gasoline to respect these principles and to ensure consumer protection. Within overall limits on the maximum permissible oxygen content of blends, an absolute limit of 5.0 vol% is applied for ethanol. Note that the current Directive does not include RSME and limit values need to be developed for the reasons outlined above.

Dedicated ethanol engines would need to be optimized to take advantage of both the octane quality of the fuel and its charge cooling potential.

5. GENERAL PERFORMANCE CONSIDERATIONS FOR ALTERNATIVE FUELS

5.1. GASEOUS FUELS - WOBBE INDEX AND FUEL METERING

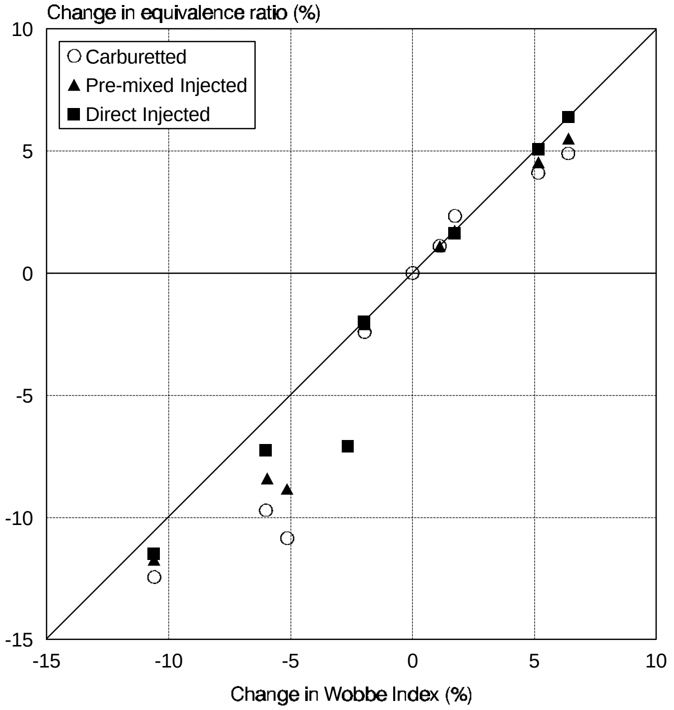
As discussed earlier, the Wobbe index is an important parameter for gaseous fuels and is determined by its composition. The value of the Wobbe index, W, is calculated as:

$$W = \frac{H}{\sqrt{p}}$$

Where H is the volumetric heating value of the gas, and p is the specific gravity

The Wobbe index of a gas is proportional to the heating value of the quantity of gas that will flow subsonically through an orifice in response to a given pressure drop. Since virtually all gaseous fuel metering systems are based on orifices, a change in Wobbe index of the fuel (other things being equal) will result in a nearly proportional change in the rate of energy flow, and thus in the air-fuel ratio. Departures from strict proportionality may occur in fuel systems using choked (sonic) flow, or because of changes in the H/C ratio of the fuel. Even in these cases, however, the Wobbe index provides a good indicator of the change in air-fuel ratio. **Figure 1** shows the effect of Wobbe index variations on equivalence ratio in a natural gas engine ^{2} using different types of fuel metering.

Figure 1 Effect of variation in Wobbe Index on equivalence ratio



The effect of variations in the Wobbe index for gaseous-fuel vehicles is similar to the effect of varying the fuel's volumetric energy content in gasoline vehicles. A lower Wobbe index results in a leaner air-fuel ratio, while a higher Wobbe index gives a richer mixture. Depending on the fuel metering technology, variations in the Wobbe index may affect engine performance and emissions. Modern, stoichiometric spark-ignition engines with closed-loop control of the air-fuel ratio are able to compensate for reasonable variations in the Wobbe index, just as they compensate for variations in gasoline energy content due to refining differences or use of oxygenate blends. For engine control systems without air-fuel ratio feedback, such as those used in heavy-duty lean-burn engines, variations in fuel composition can present a significant problem - possibly resulting either in poor engine performance (due to too lean a mixture) or engine damage due to overheating (with the mixture too rich).

5.2. THE PROPENSITY OF GASEOUS FUELS TO KNOCK - OCTANE AND METHANE NUMBERS

As is the case with liquid gasoline, the degree of resistance to engine knock is an important property of gaseous fuels. This tendency is measured in several different ways. Often, the knock resistance of gaseous fuels is reported in terms of the familiar research and motor octane numbers (RON and MON) used with gasoline. However, the present RON and MON methods are intended for liquid fuels and are not well adapted for measuring the knock resistance of natural gas. ASTM has defined a standard (D 2623) for measuring the MON of LPG mixtures, but no RON method has yet been adopted for gaseous fuels.

5.2.1. Natural gas

Natural gas generally has excellent antiknock properties; the knock resistance of most natural gas blends exceeds the maximum range of the ASTM octane scale (120.34). This is one reason that no standard octane testing methods exist for natural gas. In order to better measure the knock resistance of natural gas blends, a separate methane number scale has been created.[3] In this system, the reference fuels are mixtures of methane and hydrogen. Pure methane has a methane number of 100, and pure hydrogen has a methane number of 0. To define the relationship between MON and methane number, the Southwest Research Institute [4] extended the ASTM MON method for LPG to a number of typical natural gas blends, as well as samples of pure methane, ethane, and propane, and methane-propane blends. It was found that MON and methane number are closely correlated. The best-fit relationships were found to be:

$$\mathrm{MON} = 0.679 \times \mathrm{MN} + 72.32$$
$$\mathrm{MN} = 1.445 \times \mathrm{MON} - 103.42$$

with R^2 in each case greater than 0.95.

Because of the excellent knock resistance of natural gas, engines designed specifically for natural gas fuel can use higher compression ratios than gasoline engines, with a consequent improvement in efficiency and power output. Typical compression ratios for natural gas engines range from 10:1 (for large engines) to 13:1. The knock-resistance of natural gas also permits supercharging with much higher boost pressures than gasoline engines, enabling these engines to attain BMEP levels comparable to those of modern heavy-duty diesel engines. The antiknock performance of natural gas is best for pure methane or methane/inert gas mixtures, and declines somewhat with increasing concentrations of non-methane hydrocarbons. This effect is not usually significant for the typical range of pipeline gas composition, but may become important in high-compression engines burning unprocessed gas or propane-air mixtures.

5.2.2. LPG

Of the hydrocarbons commonly included in LPG, propane has good antiknock properties compared with gasoline. The antiknock performance of the other LPG constituents is inferior to that of propane, raising the possibility that an engine optimized for use on high-octane propane might suffer damage from knock if operated on LPG containing significant quantities of propylene, butanes, or butenes. This is the main reason that the US HD-5 standard (ASTM D 1835) for automotive LPG specifies nearly pure propane. This standard was developed in order to accommodate specialised, high compression propane engines used in heavy-duty applications such as tractors.

With the exception of special-purpose heavy-duty power units, nearly all LPG engines are converted from engines designed for gasoline, and they retain the relatively low compression ratios that gasoline use imposes. Thus, for most engines, the extra octane quality of pure propane far exceeds the octane level required, and provides no benefit. Since pure propane may not be the most economic fuel to supply, a more practical approach could be to specify a minimum octane requirement for LPG, based on considerations both of supply economics and of technical efficiency. At a minimum, this octane requirement should be set high enough to ensure trouble-free operation with gasoline engines. This is the approach that has been taken in Europe with the development of norms for automotive LPG by the European Committee for Standardization (EN 589).

European experience indicates that the critical value in establishing antiknock requirements for LPG is the motor octane number (MON). If the MON is satisfactory, this also guarantees that the research octane number (RON) will be high enough. From various studies, the CEN working group concluded that a minimum MON of 89 is required to ensure satisfactory operation on LPG of engines designed for European premium leaded gasoline having a MON of 87. It was also concluded that 87 MON LPG would suffice for engines designed for Europremium unleaded fuel.[5] The actual European standard specifies 89 MON, thus accommodating older engines designed for premium leaded gasoline.

Table 3 shows the blending MON values ascribed to the common constituents of LPG by the CEN working group. As this table shows, the MON values of propane and isobutane significantly exceed the required MON level. n-Butane just meets the requirement whilst the olefins (propene and especially butenes) are below the accepted MON level. Whilst the CEN standard was designed for gasoline conversions, it is clearly inappropriate for dedicated, high compression engines. There is therefore a need to develop inter-industry discussions on the use of LPG for both light- and heavy-duty dedicated engines.

Table 3 Blending MON of LPG components

Gas Component	Blending MON (% mole)
Propane	95.4
Propene	83.9
n-Butane	89.0
i-Butane	97.2
Butenes	75.8

5.3. GASEOUS FUEL SAFETY

5.3.1. Compressed Natural Gas

Overall, CNG vehicles are expected to be almost as safe as gasoline vehicles. Compressed natural gas storage cylinders are built to rigorous quality standards. As natural gas is lighter than air, the sudden release of CNG from a vehicle cylinder would not form a spreading pool or vapour cloud on the ground (such as in a gasoline spill). Instead, the gas cloud would rise and would rapidly disperse unless it contacted some nearby ignition source. Except for trace contaminants such as hydrogen sulphide (H_2S), natural gas is non-toxic and biologically inert. Due to the high ignition temperature of natural gas, simple exposure to a hot surface (such as an exhaust manifold) is unlikely to lead to a fire. Overall, the risk of fire as a result of uncontrolled release of CNG is much lower than that from gasoline, and comparable to that which might be expected with diesel fuel.

5.3.2. Liquefied Natural Gas

The safety record of LNG vehicles is not as well established as that of CNG, due to the much smaller number of LNG vehicles in use. As with compressed natural gas, vaporized LNG is non-toxic and biologically inert. Being a cryogenic liquid, LNG boils at any temperature above -160°C, and therefore tends to vaporise quickly when spilled. Experience has shown that the vapour cloud above a pool of spilled LNG is very difficult to ignite, due to the narrow range of flammability of natural gas vapour. Spillage onto water may lead to a rapid phase transformation, which can give rise to explosive over-pressure during the liquid/vapour transition.

One of the major concerns with the use of LNG in vehicles is the possibility that excess vapour pressure might be vented in an enclosed area such as a garage, possibly causing an explosion. Although LNG tanks are very well insulated, heat gradually leaks into the tank and raises its temperature and pressure. LNG tanks are equipped with pressure relief valves, so that if the internal pressure rises above a certain level (generally 10.3 bar in vehicle applications) the excess vapour will be vented. New technology fuel tanks regularly guarantee fuel storage for up to eight to ten days without pressure relief valves being activated. Even with these safety provisions, this could pose a safety problem for inactive vehicles left in enclosed spaces for long periods of time.

LNG storage in cryogenic vessels also introduces the risk of a Boiling Liquid Expanding Vapour Explosion (BLEVE). This could occur if the storage vessel were heated rapidly from the outside, causing an equally rapid temperature and pressure rise inside. The likelihood of BLEVE incidents is reduced by using materials for the inner vessel that fail predictably and non-catastrophically, so that the fuel is not ejected suddenly. Although LNG storage tanks are heavier than the thin sheet steel or plastic gasoline or diesel tanks they would replace, they are also much stronger due to their construction. This added strength means LNG tanks are more resistant to damage from an impact sustained in a vehicle collision.

Another danger associated with the use of LNG is the possibility of cryogenic burns due to contact with spilled LNG during refuelling or as the result of an accident. Because of the level of training required, it is unlikely that members of the general public would be allowed to dispense their own LNG. LNG nozzles, hoses, and dispensers are equipped with valves to prevent excessive release of LNG in the event of an accident. The fact that LNG tanks are tough and designed to fail predictably reduces the likelihood of contact with spilled fuel during an accident.

5.3.3. LPG

LPG poses a greater safety risk than CNG. Unlike natural gas, LPG vapours are heavier than air, so that leaks from the fuel system tend to "pool" at ground level, where they might contact ignition sources. To some extent, the same remarks apply to conventional liquid fuels, although their volatility is somewhat lower. The flammability limits of LPG vapour in air are also broader than those for natural gas. However, where appropriate ventilation systems and work practices are employed, LPG vehicles can be parked and maintained in enclosed premises without any problems. In addition, the risk of leaks from modern fuel systems is very small. Nevertheless, vehicles fitted with LPG systems may be subject to restrictions on parking in enclosed spaces and currently, for example, may be prohibited from using underground communal parking facilities.

Like natural gas, LPG is non-toxic. Also like natural gas, LPG is stored on the vehicle in sealed pressure vessels which are much stronger than typical gasoline fuel tanks. The probability of a tank rupturing and releasing fuel is thus less than for gasoline. The sealed pressure vessel does raise the possibility of a BLEVE explosion, but standard precautions such as pressure relief valves make this an unlikely occurrence.

5.4. BIO-FUELS

5.4.1. Ethanol - Octane quality

In laboratory tests ethanol demonstrates high values of Research Octane Number (RON). When ethanol is blended with gasoline a RON boost is achieved but the MON increase may be minimal or even zero. Ethanol/gasoline blends have produced road performance similar to or better than gasoline of the same RON and MON, under low speed and accelerating conditions. However, the high-speed high-load performance of such blends is inferior to that of gasoline. This fundamental performance difference of ethanol gasoline blends must be compensated by increasing the MON of the base gasoline by additional processing to ensure the same high speed antiknock performance in order to prevent the risk of engine damage.

5.4.2. Ethanol - Solubility in water

Whereas ethanol is completely miscible in gasoline, the presence of even small amounts of water will rapidly lead to phase separation i.e. ethanol will be absorbed by any water present in the system. This can result in poor vehicle performance and, possibly, engine damage. The actual phase separation conditions are a function of ethanol content, temperature, and properties of the gasoline phase, but the effect is particularly marked at the low ethanol concentrations defined in Directive 85/536/EEC. Therefore, only anhydrous ethanol should be considered for blending in gasoline.

5.4.3. Ethanol/gasoline blends - Volatility

Blends of ethanol and gasoline form azeotropes which cause a disproportionate increase in vapour pressure together with a reduction in front-end distillation temperature. This effect varies with ethanol concentration but is particularly significant at ethanol concentrations up to around 10%. Such an increase in vapour pressure would cause hot driveability problems in vehicles. As a consequence, the base gasoline must be tailored to accept the ethanol.

This tailoring of the base gasoline requires the omission from the gasoline pool of high-performance components such as butane. Such displaced products must be incorporated in alternative outlets where their properties may not be fully utilised, thus leading to less efficient use of a valuable energy resource. Mixing of ethanol/gasoline blends with gasoline which has not been tailored to accept the ethanol may also lead to hot driveability problems in some cases.

The higher latent heat and fuel/air mixture leaning effect, resulting from the oxygen content of ethanol will lead to cold driveability problems at high ethanol concentrations in a blend.

5.4.4. Ethanol/gasoline blends - Fuel economy

Although the volumetric energy content of ethanol is only approximately 65% of gasoline, the fuel economy of vehicles using ethanol/gasoline blends is mainly dependent on engine type and driving conditions. Tests on dynamometers and in road trials have produced results on non-catalyst cars varying from an increase in fuel consumption of 8% to a decrease of 10%. Motorists driving cars at this level of technology will not detect a change in fuel economy for ethanol contents up to 5% volume. However, for catalyst equipped cars fitted with closed loop air/fuel ratio control the lower volumetric energy content will lead to a noticeable reduction in fuel economy.

6. EMISSIONS PERFORMANCE OF ALTERNATIVE FUELS

6.1. EFFECT OF GASEOUS FUEL COMPOSITION ON EMISSIONS

As discussed overleaf, emissions from natural gas and LPG vehicles are generally lower than those from gasoline vehicles at the same level of engine technology. Nonetheless, variations in gaseous fuel composition can affect the level of pollutant emissions. The primary effect is due to variations in the Wobbe index. This can directly affect the air-fuel ratio, and thus pollutant emissions. Given appropriate engine control hardware and software, reasonable variations in Wobbe index have little effect on emissions from light-duty vehicles using modern engine technology with three-way catalysts and closed-loop feedback control by means of an λ sensor. This is because the feedback control makes it possible to compensate for variations in air-fuel ratio.

In addition to their effects on the Wobbe index, differences in the concentration of different hydrocarbons in the fuel can affect the species composition and reactivity of the HC emissions in the exhaust. The proportion of non-methane hydrocarbons in the fuel gas directly affects the level of NMHC emissions in the exhaust In order to limit the possible increase in pollutant emissions due to variation in natural gas properties, the California Air Resources Board has established specification limits for natural gas sold commercially as vehicle fuel. Both the Air Resources Board and the US EPA have also established limits for natural gas used in emissions certification testing. These limits are summarized in **Table 4**.

Table 4 Specifications of natural gas used for emissions certification and for general automotive use

Constituent (mole %)	CARB Certification Fuel	CARB In-Use Fuel	EPA Certification Fuel
Methane	90.1 ± 1.0	88.0 (min)	89.0 (min)
Ethane	4.0 ± 0.5	6.0 (max.)	4.5 (max.)
C_3 and higher	2.0 ± 0.3	3.0 (max.)	2.3 (max.)
C_6 and higher	0.2 (max.)	0.2 (max.)	0.2 (max.)
Hydrogen	0.1 (max.)	0.1 (max.)	-
Carbon Monoxide	0.1 (max.)	0.1 (max.)	-
Oxygen	0.5 ± 0.1	1.0 (max.)	0.6 (max.)
Inert Gases (CO_2 +N_2)	3.5 ± 0.5	1.5 - 4.5	4.0 (max.)

The effects of varying LPG composition on the exhaust hydrocarbon species and reactivity have not been documented. However, according to the Carter reactivity scale (used by the California Air Resources Board) olefins such as propene and butenes are much more reactive in contributing to ozone formation than paraffins such as propane and the butanes. Thus, it is reasonable to suspect that increasing the olefin content of LPG will result in increased ozone-forming potential in the exhaust. In order to reduce the possibility of emissions increases due to variation in LPG composition, the California Air Resources Board requires that LPG sold for automotive use in California comply with the HD-5 standard (**Table 5**). Due to concerns about supply availability, the maximum 5% propene content required by the HD-5 specification has been delayed until January l, 1997. In the intervening period, LPG containing up to 10% propene is permitted.

Table 5 Composition requirements for HD-5 propane for use as motor vehicle fuel

Property	**Spec.**
Propane (vol%)	85 min
Propene (vol%)	5 max.
Butane and heavier (vol%)	2.5 max.
Vapour pressure at 100°F	208 psig
Sulphur (ppm mass)	120 max.

6.2. EMISSIONS PERFORMANCE OF GASEOUS FUELLED VEHICLES

6.2.1. Light-duty vehicles

Data from a number of NGVs using modern electronic emission control systems have demonstrated the ability to meet California ULEV emissions standards. Two such vehicles, the Chrysler B350 natural gas van and the Chrysler natural gas mini-van, have been certified to meet the California LEV and ULEV emission standards, respectively (**Table 6a)**. It should be stressed - and this point is emphasized throughout the report - that the CNG vehicle emissions data refers to non-methane hydrocarbon, (or non-methane organic gases), emissions. Methane is a greenhouse gas and due consideration must be given to these emissions.

Table 6a Emissions certification data for US light and medium-duty natural gas vehicles

		Emissions (g/mile)			
	Mileage	**NMOG***	**CO**	**NO_x**	**HCHO****
LEV Std	50,000 120,000	0.195 0.280	5.0 7.3	1.1 1.5	0.022 0.032
ULEV Std	50,000 100,000	0.050 0.070	2.2 2.8	0.4 0.5	0.009 0.013
Chrysler B350 Ramvan (5751-8500 lb.)					
Gasoline	50,000	0.19	3.4	0.51	NA[3]
CNG	50,000	0.031	2.3	0.05	0.002
(LEV)	120,000	0.040	3.1	0.05	0.003
Chrysler Minivan (3751-5750 lb.)					
Gasoline	50,000	0.20	1.2	0.19	NA[3]
CNG	50,000	0.021	0.4	0.04	0.0002
(ULEV)	120,000	0.035	0.4	0.05	0.0002

* NMOG = Non-methane organic gases
** HCHO = Formaldehyde

Notes :

[1] LEV standard for medium-duty vehicles: 5751-8500 lb. GVW
[2] ULEV standard for light-duty trucks: 3751-5750 lb.
[3] Not Available

The reasons for the emissions performance of NGVs are claimed to be as follows.[6]

- Inherently low emissions of non-methane hydrocarbons, since the fuel is 85-99% methane.
- Low ozone-forming reactivity of the residual NMHC, which are primarily ethane.
- Low emissions of “air toxics”, such as benzene and 1,3 butadiene.
- Low "off-cycle" emissions. Unlike gasoline vehicles, NGVs are not calibrated for enrichment at high loads, so their HC and CO emissions do not increase significantly under these conditions.

- Low cold-start emissions. NGVs do not require mixture enrichment for cold starting, so that HC and CO emissions from NGVs are unaffected by low temperatures. However, the introduction of early light-off catalysts for gasoline vehicles will largely negate this advantage.

- Potentially improved emissions durability, due to the reduced complexity of NGV emission control systems and the reduced chance of catalyst damage from overheating due to mixture enrichment.

- Zero evaporative and running losses, due to the sealed fuel system, and negligible refuelling emissions. Against this must be offset the need for regular inspection of system integrity.

- Low "fuel cycle" emissions from fuel processing, distribution, and marketing, due to pipeline transport. This, however, presupposes no leaks from the distribution system.

- Reduced emissions of greenhouse gases, especially CO and CO_2. Against these advantages, the potential increase of methane escapes to the atmosphere should be calculated.

With the exception of inherently low NMHC emissions and methane escapes, the same comments are applicable to LPG vehicles. Here, however, research is still continuing to achieve ULEV standards, although modern European dual fuelled vehicles have achieved impressive results,[46] see **Table 6b**, below:

Table 6b Comparison of five modern European passenger cars operating on gasoline and LPG

Emissions & Fuel Consumption	Gasoline	LPG
CO (g/km)	0.87	0.72
HC (g/km)	0.14	0.12
NOx (g/km)	0.12	0.16
Fuel Consumption (l/100km)	8.7	11.3
Energy Consumption (MJ/km)	2.8	2.7

Average emissions and fuel consumption for five vehicles fitted with closed-loop, three-way catalysts and third generation LPG equipment. Tests conducted over the ECE+EUDC cycle (91/441/EEC).

6.2.2. Heavy-duty vehicles

Emissions from heavy-duty natural gas engines can be lower than those of heavy-duty diesel or gasoline vehicles. Over the last few years, a number of heavy-duty engine manufacturers have developed diesel-derived lean-burn natural gas engines for use in applications such as urban transit buses and delivery trucks. These engines incorporate low-NOx technology used in stationary natural gas engines, and often include an oxidation catalyst. They are capable of achieving very low levels of NOx, particulate, and other emissions (less than 2.0 g/bhp-hr NOx and 0.03 g/bhp-hr particulate) with high efficiency and high power output. Four such engines, the Cummins L10, Detroit Diesel Series 50, and Hercules GTA 5.6 and 3.7 engines have been certified in the US, and are in production. The Cummins and Detroit Diesel engines are employed in transit buses and other urban fleet applications such as refuse collection, whilst the smaller Hercules engines are used in small buses and delivery trucks. **Table 7a** summarizes emissions certification data for these engines. Similar emission levels have been reported for heavy-duty LPG engines.

Table 7a Emissions certification data for US heavy-duty natural gas engines

Emissions (g/bhp-hr)					
Manufacturer and Model	bhp	NMHC	CO	NO_x	Pm
Cummins					
L10	240	0.2	0.2	1.4	0.02
L10	260	0.2	0.4	1.7	0.02
Detroit Diesel Series 50G	275	0.9	2.8	2.6	0.06
Hercules					
GTA 3.7	130	0.6	2.7	3.1	0.08
GTA 5.6	190	0.9	2.8	2.0	0.10

It is also possible to meet stringent heavy-duty emission standards with modern LPG fuel systems. As illustrated in **Table 7b,**[47] gas engines in conjunction with a 3-way catalyst have no trouble in meeting the most stringent emission standards. Lean burn gas engines in combination with an oxidation catalyst can also achieve very low emission results. Over the last few years considerable advances have been made in attaining low emission levels from diesel engines. Major improvements come from relatively simple techniques such as higher injection pressures, improved combustion matching and better lubricant control. The current situation is that there are several diesel engine manufacturers (European and US) who have Euro 2 (or equivalent US) level engines on the market, and it is expected that the others will follow shortly. These engines are much cleaner and quieter than their smoky predecessors.

Nevertheless, the ultra low emission levels attainable with gaseous fuels and lambda controlled stoichiometric combustion remain several steps ahead of even the most advanced diesel engine. The "too low to be measured" levels of particulate with both stoichiometric and lean- burn engines will continue to be their strongest points, particularly as this is attainable with low NOx emissions.

Table 7b Typical exhaust emission levels for various types of gas engine (13-Mode Test Cycle)

Fuel	Engine Type	Emissions (g/kWh)			
		HC	CO	NOx	Pm
CNG or LPG	Otto stoich + 3-way cat.	0.4	0.8	0.4	<0.05
CNG	Otto lean burn, no cat	2.5	2.0	2.5	<0.05
CNG or LPG	Otto lean burn + cat	1.0	0.2	2.5	<0.05
Diesel CNG	Diesel pilot injection	16.0	12.6	6.0	0.15
Diesel CNG	Diesel dual fuel	5.6	7.8	8.6	0.20
Euro 1 Limit value (1993)		1.1	4.5	8.0	0.36
Euro 2 Limit value (1996)		1.1	4.0	7.0	0.15
Euro 3 Limit value (1999)*		0.6	2.0	4.5	0.12

(*Projected levels)

A further argument in favour of LPG is that fuels of simple molecular structure burn “cleaner”, resulting in lower emissions of unregulated emissions such as aldehydes and PAH, or reactive hydrocarbons. Although bio-ethanol or methanol are also of simple molecular structure, they cannot compete against the gaseous fuels in terms of unregulated emissions. If these alternatives are used in a diesel cycle engine partial combustion products result in higher aldehyde emissions (formaldehyde and acetaldehyde respectively).

As far as CO_2 emissions and energy consumption are concerned, the energy consumption of heavy-duty vehicles with LPG is typically 20-30% higher than with diesel fuel. However, because LPG has a higher energy content per kg than diesel and a lower carbon mass fraction, the CO_2 emissions of LPG in heavy-duty use are roughly comparable to diesel. LPG also has an advantage over CNG in that it is stored at relatively low pressure. Steel CNG fuel tanks will add significantly to the weight of a vehicle, so that the energy penalty of CNG compared with LPG can be high. This is illustrated in **Table 7c**:[46]

Table 7c Comparison of city buses using diesel fuel, LPG and CNG

Characteristic	Diesel (1995)	LPG		CNG	
		Stoich	Lean burn	Stoich	Lean burn
Weight increase (kg)	-	200	200	975*	975*
Range (km)	450	450	450	430	430
Energy consumption (%)	100	130	120	130	120
Power (%)	100	100	100	100	100
Noise emissions (%)	100	60	60	60	60
HC emissions (%)	100	100	250	100	250
CO emissions (%)	100	100	25	100	25
NOx emissions (%)	100	5	30	5	30
Pm emissions (%)	100	20	20	20	20
Cost increase (%)	-	10	10	15	15

* Steel cylinders

6.2.3. Spills, water pollution, and hazardous waste

Spills and leaks of gasoline and diesel fuel from underground tanks, pipelines, trucks, and ships are potential sources of water and soil pollution. Contamination of various materials with gasoline or diesel fuel is also a potential source of hazardous waste. Safe disposal of these wastes is a topic of increasing concern in most industrial and industrialising countries. Because of their non-toxic chemical composition and gaseous form, natural gas and LPG are less likely to contribute to hazardous waste generation, water pollution, or soil contamination.

6.3. EMISSIONS PERFORMANCE OF BIO-FUELLED VEHICLES

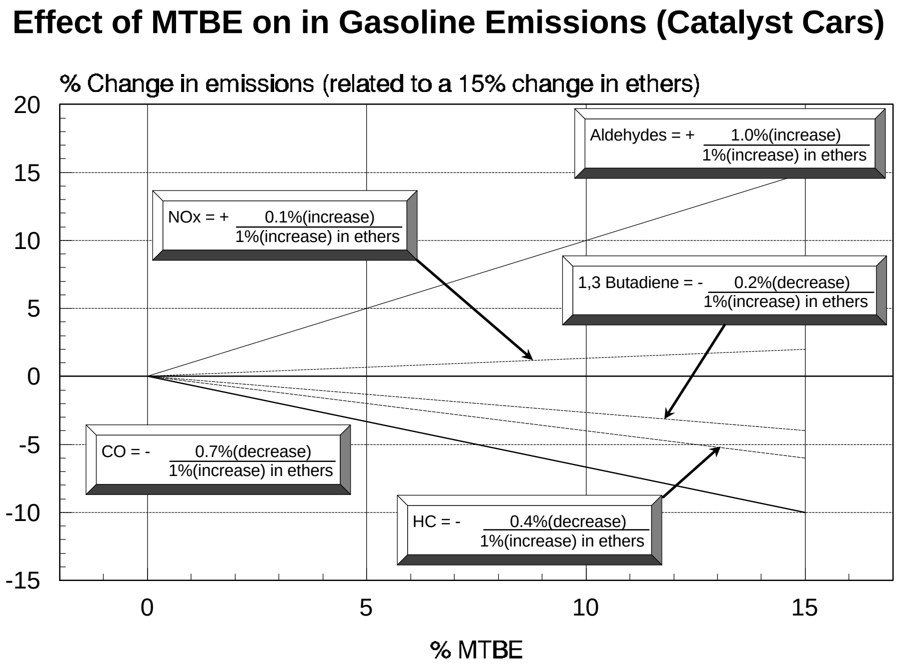
Oxygenates influence emissions primarily by their effect on the balance of fuel and air in the engine. If a car, tuned to run on gasoline, is run on fuel containing an oxygenate without readjustment, the effective air-fuel ratio will be increased as a result of the oxygen contained in the fuel, at least for older model cars. Modern adaptive learning vehicles will compensate to some extent, so the effects of a change in fuel may not be so large. The leaner air-fuel ratio will tend to reduce CO and HC emissions, but in some cases at the expense of an increase in NOx.

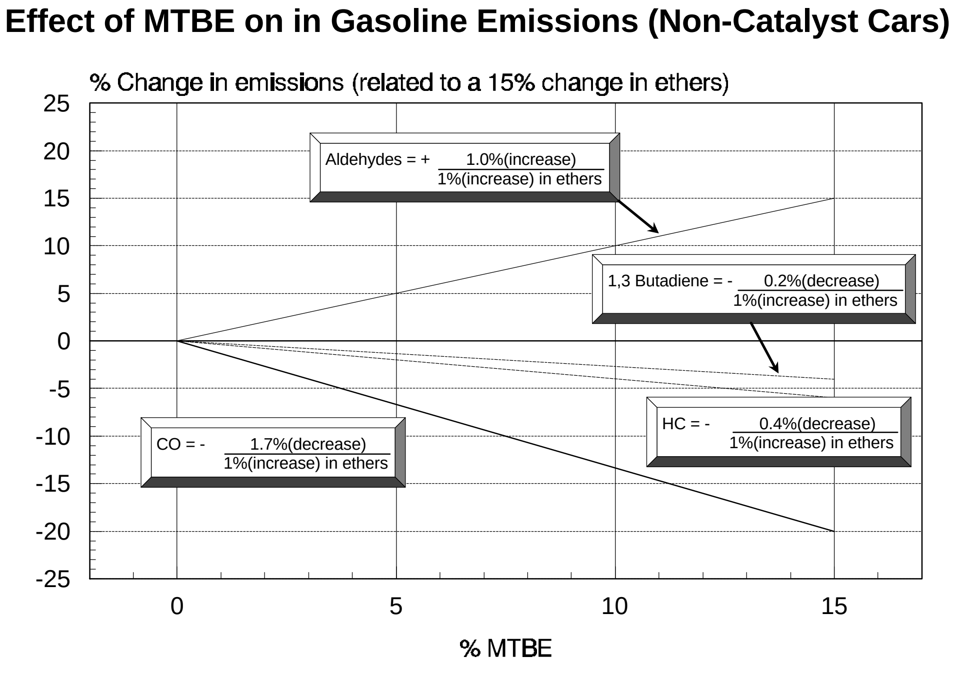
The introduction of oxygenated gasolines to an existing population of vehicles can therefore give immediate reductions in HC and CO emissions, but will increase aldehydes. Fuel consumption, NOx and evaporative emissions also need to be considered. The emissions impact of oxygenates will depend to some extent on how vehicles are maintained and run in service, and the results of technical tests must be interpreted with this in mind. In a similar way, if a diesel engine is run on a fuel containing RSME, the full load smoke, which is very sensitive to air-fuel ratio, can be expected to be reduced. Again, engine tuning and maintenance play a part, especially if engines are retuned to recover the power loss associated with the use of oxygenates.

6.3.1. Oxygenates in gasoline

In terms of impact on exhaust emissions, the AQIRP study [7] has shown that MTBE and ETBE have similar performance at the same fuel oxygen content, and that use of oxygenated components in gasoline can reduce CO and total HC emissions from vehicles (**Figure 2**).

Figure 2 Influence of MTBE on exhaust emissions





The benefits in CO and HC reduction must be balanced against some drawbacks:

- NOx emissions can be increased, particularly in older cars.
- Aldehyde emissions are increased. While total hydrocarbon emissions are reduced, the AQIRP study reported that there was no significant reduction in overall ozone formation potential due to changes in the nature of species emitted. Fuel consumption is increased, as described earlier.

From the above it is clear that use of oxygenates in gasoline would produce some reduction in CO and HC emissions, but with some disadvantages. Higher evaporative emissions are another disadvantage with ethanol blends. Since ethanol significantly increases fuel RVP, there is an increase in evaporative emissions unless this is compensated in the blend, again making fuel production more expensive.

Alternative approaches to reducing emissions from vehicles already in service may be more cost-effective. For example, Stedman [8] has shown that 50% of exhaust emissions arise from only 10% of vehicles. Targeting these vehicles for remedial action could have a major impact on emissions.

6.3.2. Oxygenates in diesel

For European operations, attention has centred on RSME, and the data presented here concentrate exclusively on this material. A considerable number of studies now exist on the effects of RSME on emissions, either in pure form, or blended at up to 20% with diesel. In considering any emissions data, it is important to include:

- a representative range of engine types
- test procedures appropriate to the application
- whether the engine is to be tested 'as received', or modified.

6.3.2.1. Regulated Emissions

For road diesel engines, emissions of HC, CO, NOx and particulates are controlled through legislated test procedures:

∗ For light-duty vehicles: ECE+EUDC in Europe, FTP in the US
∗ For heavy-duty vehicles: 13-mode (R49) in Europe, EPA transient test in the US

The available data on the legislated tests are summarized in **Table 8**.

Table 8 Emissions performance of RSME compared with diesel
(Data are for 100% RSME except where stated)

		% change					
	Test	**HC**	**CO**	**NO_x**	**Pm**	**Ref. No**	**Notes**
DI-NO CATALYST							
Same 3 cyl	R49	-43	-18	+4		15	
Rugg 2 cyl	R49	-43	-51	-3		15	
3.1L, 42kW	13 mode	-22	-3	+17		16	
2.3L	13 mode	-5	-21	+33	-5	14	(1)
2.3LT/C, EGR	cold FTP	-18	-12	+19	-16	17	
" "	hot FTP				-21	17	
DD 6V92TA	hot transient	-80	-46	+16	-28	12	
2.3L	cold ECE15	-23	-3	+15	+64	14	
DI-WITH CATALYST							
MB OM 447	R49				-90	15	
3.1L, 42kW	13 mode	-20	+7	+15		16	
IDI-No Catalyst							
VTM TC 3cyl	R49	-30	-9	0	-61	15	
Volvo 900	FTP	0	0	+15	-10	4	
P309	cold ECE	15	+2	+1	+3	20	(2)
	EUDC	-4	-1	+2	-6	20	(2)
	ECE/EUDC	-1	0	+1	-4	20	(2)
R21/EGR	cold ECE	-38	-11	-18	+52	13	(2)
	hot ECE	-39	-18	+3	-6	13	(2)
	hot EUDC	-51	-27		-24	13	(2)

Notes : (1) engine power was adjusted to give the same output on the two fuels
(2) tests on 20% RSME/80% diesel

A number of trends can be seen:

- HC and CO are lower when running on RSME compared with diesel
- NOx is consistently increased.
- Particulates generally show a small decrease, but some tests show a dramatic increase.
- HC and CO emissions from diesel engines are generally low, NOx and particulates being more difficult to control.

The increased NOx emissions may result from increased combustion temperatures, due to the better availability of oxygen within the combustion zone. This same phenomenon may also influence the formation of soot, and an insight into the mechanism can be gained through an analysis of particulate composition (**Table 9**). Data are available from studies on a 2.3L T/C Dl engine [9].

Table 9 Comparison of particulate composition - Diesel vs. RSME

Test	Fuel	Total Pm g/mile	Insolubles g/mile	Fuel solubles g/mile	Lube solubles g/mile	Soluble inorganic fraction %
Cold FTP	Diesel	0.311	0.259	0.021	0.031	17
	RSME	0.258	0.118	0.104	0.036	54
Difference %		-17	-54	+495	+16	+318
Hot FTP	Diesel	0.239	0.206	0.012	0.021	14
	RSME	0.190	0.101	0.068	0.021	47
Difference %		-21	-51	+567	0	+335

When the engine is operated on RSME, soot emissions (insolubles) are dramatically reduced, but the proportion of the emissions composed of fuel derived hydrocarbons (fuel solubles), condensed on the soot, is much higher. This implies that the RSME may not burn to completion as readily as diesel fuel. It should, however, be noted that gaseous HC emissions were reduced with RSME in these tests. Since concern over particulates arises partly from the potential harmful effects of the soluble fraction, it might be suspected that emissions from RSME would be more harmful, however data from reference 10 show no tendency for the mutagenicity of exhaust gas to increase for a vehicle running on 20% RSME/80% diesel.

The dominance of the soluble fraction is a likely explanation for the different effects shown in different test procedures for the data in **Table 9**. The data show reductions in particulates for tests run on the R49 (13 mode), FTP or EPA transient procedures. These procedures, although different in their nature, all incorporate some moderately high load and high speed conditions. By contrast, the tests run to the cold ECE15 procedure - a low speed, light load test - show an increase in particulates with RSME, and in two cases the increase is large. No particulate analyses are available for these studies, but higher levels of unburned fuel would be expected at these conditions. This observation is made in spite of the lower recorded HC figures, which capture only hydrocarbons in the vapour phase at 180°C. An investigation of this effect would be valuable, since it raises the question of how emissions are affected under cold starting conditions, when smoke and hydrocarbon emissions are most noticeable .

6.3.2.2. Unregulated Emissions

Some data are available on the impact of RSME on unregulated emissions. Woergetter,[11] reported aldehydes 14% lower, while PAH emissions were dramatically lower for an engine running on pure RSME. Courtois et al [10] reported reductions of aldehydes of 15-29% using a 20% RSME blend in an IDI passenger car. PAH emissions were also lower in hot start tests using the ECE and EUDC cycles, but a small increase was seen in a cold ECE test. Tritthart,[9] testing a 2.3 litre DI engine vehicle on the cold FTP cycle, reported aldehydes up 34% using 100% RSME. PAH emissions showed only a small change.

As illustrated in the following sections, the energy and economic cases for bio-fuels are not strong. Considering the overall environmental aspects (CO_2, emissions, plus impacts of bio-fuel production) it is also difficult to make a strong environmental case for their use, as has also been pointed out by Taschner.[12]

7. IMPACT ON CONVENTIONAL FUEL QUALITY

7.1. INTRODUCTION

This section of the report concentrates on bio-fuels as these are likely to impact on existing storage and distribution systems for gasoline and diesel fuel, either as 100% replacements, or as blends. Gaseous fuels and methanol would only affect fuel quality if there was a major demand switch away from conventional automotive fuels. This is viewed as highly unlikely and is beyond the scope of the current report.

7.2. GASOLINE

Although pure ethanol can be used as a fuel for spark ignition engines, its characteristics differ from conventional gasoline sufficiently that substantial changes to the engine are needed.

For use in the existing vehicle fleet, maximum ethanol content in gasoline must be limited to around 10% (the current European limit is 5%). For gasoline/ethanol blends the main impacts on fuel quality were described in **Section 6** and are summarized below:

- increased vapour pressure
- water tolerance/loss to water bottoms
- effect on distillation curve
- driveability
- materials compatibility (at high ethanol concentrations)

These effects can be substantial, and explain why MTBE, which has far fewer side effects, has become the most widely used oxygenate in gasoline. If the use of ethanol in Europe is to be pursued, its conversion to ETBE would reduce the adverse effects. The effects of oxygenates on key gasoline quality parameters are shown in **Table 10** using data from reference 13. Further comparison of properties of ETBE with MTBE is given in reference 14.

Table 10 Oxygenate effect on gasoline quality

	Ethanol	MTBE	ETBE
% blend for 2.7% Oxygen	7.8	14.9	17.2
Octane (R+M)/2	115	110	111
Blending RVP (bar)	1.6	0.6	0.3
H_2O Solubility (%vol)	100	1.4	0.6

7.3. DIESEL FUEL

Initial studies on the use of plant oils in diesel engines concentrated on the use of pure oils. Although many diesel engines will operate on these products, they lead to a rapid build-up of gums. These cause plugging of injectors and combustion chamber deposits, and do not meet the high standards of cleanliness expected of today's diesel fuel. Trans-esterification of the oil to produce methyl esters overcomes these problems, provided that the process includes a thorough removal of the glycerine residues produced as a by-product. Various national specifications have been issued for RSME in Europe (see **Appendix 1**). RSME meeting these specifications can operate in most road diesel engines without major problems, although there are some performance areas where a deterioration compared with conventional diesel may be expected.

RSME has been compared with a typical European diesel fuel in a range of standard analysis tests, as shown in **Table 11**.

Table 11 Properties of RSME and diesel fuel

Property	**Units**	**Method**	**Diesel**	**RSME**
Flash Point	°C	D93	73	157
Carbon Residue	%m/m	D524	0.08	-
Ash	%m/m	D482	nil	nil
Water	mg/kg	AM-S 86.004	50	500
Particulate matter	mg/kg	DIN 51419	3.31	3.37
Cu corrosion		D130	1A	1A
Oxidation stability	mg/100ml	D2274	0.11	0.06
Sulphur	%m/m	XRF	0.17	<0.01
Pour point	°C	D97	-27	-12
Cloud point	°C	D2500	-6	-1
CFPP	°C		-18	-14
Density 15°C	kg/l		.8472	.8838
Viscosity 40°C	mm^2/s	D445	3.115	2.381
Cetane number		D613	49.5	51.5
Distillation		D86		
T10	°C		227	334
T50	°C		283	336
T95	°C		348	345

The flash point of RSME is higher than that of conventional diesel, and cetane is comparable with that currently found in the European market. Results for ash, copper corrosion, particulate matter and oxidation stability are all satisfactory and require no comment. For the remaining characteristics the following observations can be made:

- Density and distillation characteristics are somewhat different from current diesel fuels, RSME being a much heavier product. This evidently presents no problem in starting and running vehicles in relatively high ambient temperature conditions, but could lead to some problems at low temperatures, because of the fuel's low volatility.

- Water content of RSME may be high (500 ppm has been reported[15]), compared with a normal diesel level of around 100-150 ppm maximum, and may exceed the CEN specification for diesel fuel. Oxygenates in general have an affinity for water, and will need care in storage.

- Cold flow properties of RSME are generally poorer than those of European diesel fuels, and this could lead to filter plugging problems. The cloud point of RSME is inadequate for winter fuels in all but the warmest areas of southern Europe. Blending of RSME with diesel fuel raises the cloud point, pour point and CFPP (Cold Filter Plugging Point), although the fuel appears to be able to accept some RSME addition without a large change in CFPP and cloud point. The use of RSME would therefore involve an economic penalty to meet winter cloud point targets in most European countries, through the need for kerosene addition. Cold flow additives can be used to improve the CFPP. However these additives tend to be fuel specific, and there is some evidence [15] that RSME will require unique additive formulations to effectively lower CFPP. The consequence of this is that to operate effectively in cold climates, RSME and RSME blend fuels would need to be correctly formulated; simply blending RSME into an existing fuel could lead to problems.

- Materials compatibility could cause difficulties, since RSME may interact with some paint and polymer materials. For new vehicles, compatible materials can be chosen, but care is needed with existing equipment.

- Bio-degradability is an advantage of RSME. It is reported [16] that 98% of spilled material is broken down within three weeks and the remainder within five weeks. RSME may therefore find application in those niche markets where sensitivity to pollution can justify its substantial additional cost.

8. ENERGY/CO_2 BALANCE

8.1. INTRODUCTION

Currently, the reciprocating internal combustion (ic) engine is, to all intents and purposes, the only practical power source for automotive applications. Interest is growing in electric vehicles in view of the Californian “Zero Emissions Vehicle” (ZEV) initiative. However, the dominance of the ic engine is expected to continue in the future because of its high efficiency and ready availability. When comparing power source concepts, global effects (greenhouse gas emissions and local effects - ozone and smog formation) have to be considered. This includes fuel production and delivery as well as CO_2, NOx and hydrocarbon emissions ("from well to wheels").

Current exhaust emissions legislation for vehicles does not include CO_2 which is an important greenhouse gas. In addition, most legislation to date has excluded considerations with respect to the optimum use of energy from production to end use. The “Rational Use of Fuels in Transport” (RUFIT) study was, perhaps, the first attempt at developing such an approach. CO_2 emissions from ic engines are proportional to their fuel consumption. NOx and hydrocarbon emissions (HC) are primarily affected by engine, combustion and after-treatment technology, and there is also a trade-off between efficiency and NOx emissions, which are influenced by a variety of parameters.

In order to select the optimum engine technology and fuel for a given application (type of vehicle, transportation objective, transportation area), the “well to wheels” approach is generally agreed to provide the most comprehensive comparison. **Table 12** shows the characteristics of the most important gaseous and liquid fuels for internal combustion engines. Hydrogen has been included for comparative purposes only. As long as it is produced from electricity (thermal power-plants), its low life cycle efficiency prohibits its use. For all other fuels methane has the lowest CO_2 production relative to its lower heating value.

Table 12 Characteristics of fuels for internal combustion engines

Fuel	H/C ratio	Density		Lower heating value MJ/kg	Stoichiometric air consumption	CO_2 emissions	
		760 Torr, 0C kg/m^3	15°C kg/l			kg/kg fuel	g/MJ
Hydrogen		0.09		119.6	34.2	0	0
Methane	4.0	0.716		47.7	17.2	2.74	57.5
Ethane	3.0	1.343		47.9	16.05	2.93	62.2
Propane	2.7	1.969		47.4	15.64	2.99	63.2
Butane	2.5	2.596		47.6	25.42	3.03	63.4
Diesel	1.9		0.849	42.8	14.59	3.16	75.3
Euro premium gasoline	1.88		0.748	42.0	13.96	3.08	73.3
Ethanol	3.0		0.795	26.7	8.98	1.91	71.0
Methanol	4.0		0.796	19.6	6.46	1.37	70.0

The available data regarding required energy input and emissions output during exploitation, transportation, refining and distribution differ in magnitude according to the information source. This is not only due to the differing geographical and technological exploitation conditions, but also because various methods of data generation, analysis and presentation have been employed by various workers in this field. [7 to 24] **Table 13** is divided into two sections:

- the upper part shows CO_2 emissions
- the lower section indicates the total CO_2 equivalent, which also contains the global warming potential of the other gaseous emissions produced during the various steps of production and transportation.

The data are presented as minimum/maximum figures. The greatest uncertainty is ascribed to natural gas, simply because there is inadequate information with respect to gas leaks and venting from oil and gas wells. In addition, the figures were produced before the societal changes took place in eastern Europe, i.e. although their data are included, its reliability is uncertain. It is suggested that the contribution of vented methane in these countries to total methane emission is greater than that indicated.

Table 13 CO_2 emissions during fuel production

CO_2 Emission g/MJ Fuel		**CNG**	**Gasoline**	**Reformulated Gasoline**	**Diesel**
Exploitation	min/max.	1.8 / 8.9	1.29 / 3.45	< -	0.47 /1.8
Transport	min/max.	-	0.47 /4.64	< -	0.22 / 2.6
Refining	min/max.	1.2 / 6.02	6.6 / 9.16	12.0	3.74 / 6.45
Distribution	min/max.	1.44 / 7.05	1.76 / 3.02	< -	1.76 / 2.98
Compression		8.38			
Total g/MJ Fuel	min/max.	12.8 / 26.4	12.16 / 18.0	15.4	6.18 / 14.9
Total g/g Fuel	min/max.	0.61 / 1.44	0.511 / 0.76	0.649	0.26 /0.62

Total CO_2 Equivalent g/MJ Fuel		**CNG**	**Gasoline**	**Reformulated Gasoline**	**Diesel**
Exploitation	min/max.	3.0 / 5.64	2.5 / 4.25	4.25	2.5 / 4.75
Transport	min/max.	-	1.0 / 2.67	2.63	1.0 / 2.99
Refining	min/max.	1.59 / 2.5	13.0 / 17.17	17.13	6.92 / > 7.5
Distribution	min/max.	1.8 / 4.78	1.49 / 1.5	< -	1.0 / 1.58
Compression		13.5			
Total g/MJ Fuel	min/max.	19.9 / 26.4	18.0 / 25.5	25.51	12.0 / 16.15
Total g/g Fuel	min/max.	0.95 / 1.26	0.76 / 1.07	1.07	0.5 / 0.68

The upper part of **Table 14** focuses on passenger cars and compares on the left side a typical gasoline engine (SI) powered vehicle with a vehicle employing an IDI (indirect diesel injection, swirl chamber or prechamber) diesel engine. The fuel consumption expressed as the so called “One third mix” (1/3 in ECE 15 test, 1/3 at 90 km/h, 1/3 at 120 km/h) is converted into tail pipe CO_2 and CO_2 equivalent, considering additionally the other gaseous emissions from the engine. Total CO_2 equivalents in this figure thus include all other emissions generated during fuel production and are synonymous to the "well to wheel" greenhouse contribution.

A comparison between IDI diesel and DI (direct injection) diesel over the ECE+EUDC European test cycle is shown on the right side of the table. According to these data, an IDI engine is roughly 12% better than a gasoline engine and a DI diesel engine is 10% better than an IDI diesel engine.

8.2. GASEOUS FUELS

As far as heavy-duty engines are concerned, the lower section of **Table 14** shows the results for a spark ignited compressed natural gas engine compared with a DI diesel engine. Both engines are representative of technology targeted to meet stringent emission regulations (US 1998 or Euro 3).

If methane emissions from leaks could be reduced, the CNG engine would have a CO_2 advantage over the DI diesel engine. The great advantage of the CNG diesel engine is its low NOx emissions, which makes it attractive for urban transport applications (buses, delivery trucks, and possibly passenger car fleets, e.g. taxis). The low NOx emissions are ascribed to a particularly sophisticated lean combustion system. [25]

Table 14 Emissions and efficiency of different vehicles/engines/fuels

Passenger car/engine type **Fuel** **Test sequence**		**SI** **Gasoline** **1/3 mix**	**IDI** **Diesel** **1/3 mix**	**IDI** **Diesel** **91/441/EEC**	**DI** **Diesel** **91/441/EEC**
Fuel consumption	l/100km	7.8	6.05	8.1	7.1
CO_2 engine combustion	g/km	182	159	215	189
CO_2 equiv. eng. combustion	g/km min/max.	207/	186 / 202	215 / 218	189 / 197
Total CO_2 equivalent	g/km min/max.	252 / 270	212 /237	253 /265	227 / 237

Bus and truck/engine type **Fuel**		**SI** **CNG**	**DI** **Diesel**
BSFC @ rated power	g/kWh min/max.	210 / 236	220 / 226
Engine efficiency	% min/max.	36 / 32	39 / 38
CO_2 emission eng. combustion	g/kWh	576 / 647	696 / 715
CO_2 equiv. eng. combustion	g/kWh min/max.	587 / 658	738 / 757
Total CO_2 equivalent	g/kWh min/max.	707 / 1080	849 / 910
NO_x emission (R49 test)	g/kWh	1.1	4.8
THC emission (R49 test)	g/kWh	0.22	0.3

8.3. BIO-FUELS

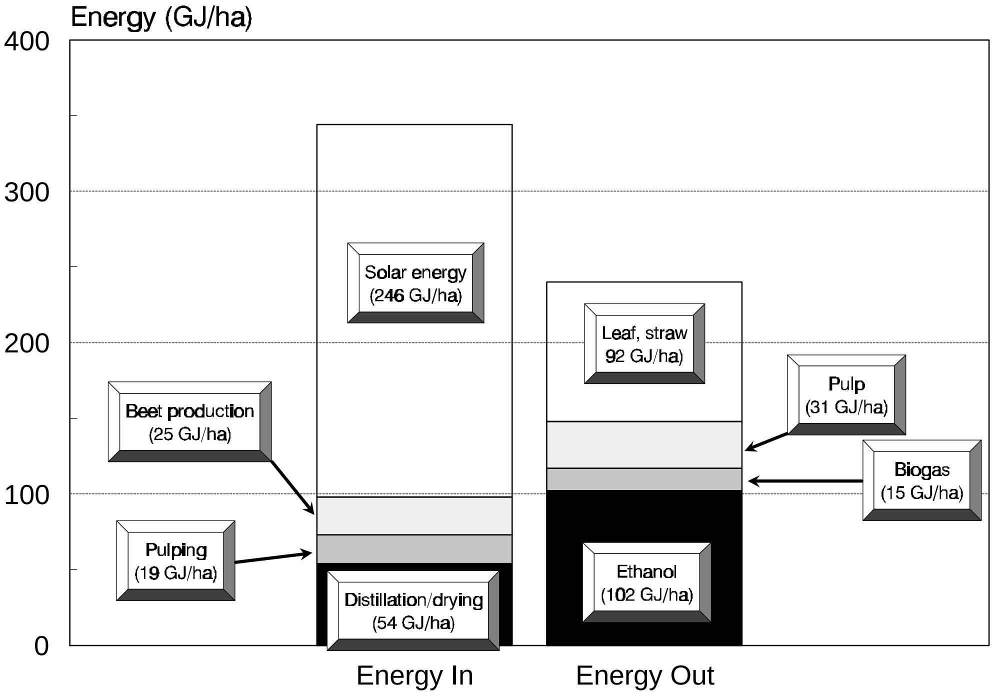
One of the motivations for the use of bio-fuels is that they are perceived firstly to be renewable energy sources, and secondly, because of their biological origin, to make a zero contribution to CO_2 emissions. Both of these assumptions can be challenged on closer inspection, and a detailed analysis of the whole production process is needed to obtain the true picture. A number of comprehensive studies have been carried out, [16, 26 to 35] and form the basis of the review that follows.

8.3.1. Energy balance

A schematic view of the energy balance for ethanol production from sugar beet is shown in **Figure 3**. The major part of the input comes from 'free' solar energy. Nevertheless, substantial inputs, which have a large impact on the overall energy balance, are required:

⇒ to produce the crop (fertiliser, fuel for farm equipment)
⇒ to pulp the sugar bearing roots
⇒ to separate and dry the alcohol after fermentation

Figure 3 Energy flow for ethanol production



The figures quoted come from reference 34, and are subject to some variation, depending on the efficiency of the various processes. The results of a number of studies are shown in **Table 15**, expressed as the energy required to produce the fuel as a percentage of the energy released when the fuel is burned. A figure of zero % would represent a completely renewable fuel, while a figure of 100% means that the production of the fuel consumes as much energy as is produced.

Table 15 Energy balance for bio-ethanol production

Input energy as % of fuel energy	**crop source**	**reference no.**
90	grain	27
211	-	28
114	grain	29
92	grain	29
84	beet	34
109	beet	29
90	beet	29

The situation for RSME is very similar. An outline of the energy flow is shown in **Figure 3**, with a summary of available data in **Table 16**. This shows a mean figure of 58%, indicating a positive energy balance for the production of “bio-diesel”.

Figure 4 Energy flow for RSME production

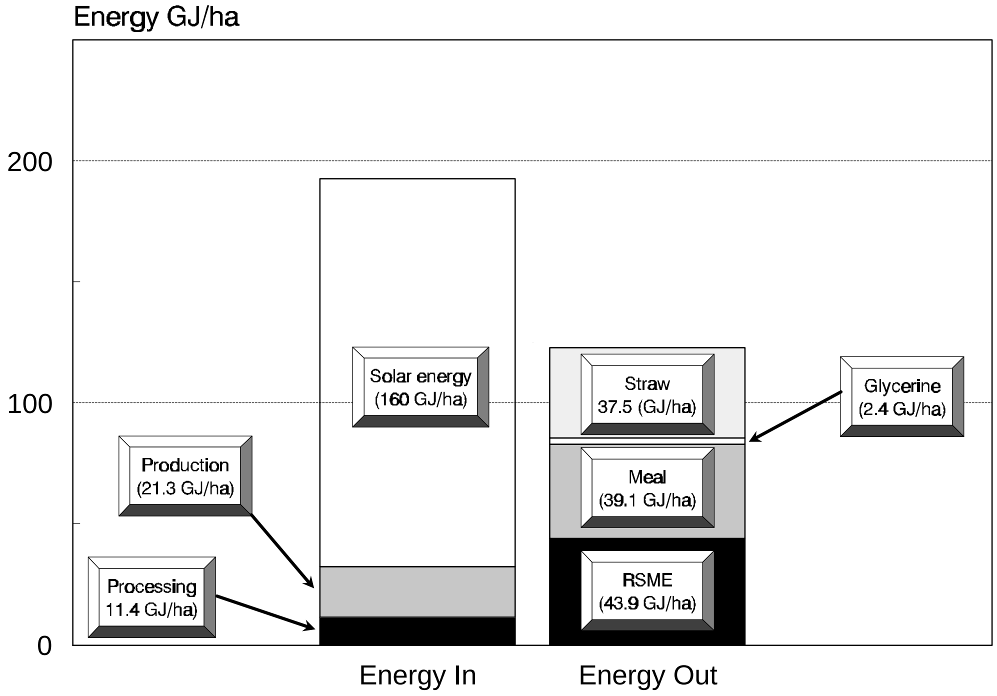


Table 16 Energy balance for RSME production

Input energy as % of fuel energy		**reference no**
without animal feed credit	with animal feed credit	
53		27
74	39	16
46	29	34
142		28
67	55	29
49		33

8.3.2. CO_2 emissions

The impact of bio-fuels on carbon dioxide emissions is closely allied to the energy balance presented above. The position of ethanol is not encouraging, as shown in **Table 17**, where the figures represent the percentage savings relative to gasoline:

Table 17 CO_2 saving (%) for bio-ethanol

	Reference
-16	29
0 to 10	29
-5	28

Negative numbers indicate that the use of ethanol produces more CO_2 than gasoline, when the overall production process is taken into consideration.

For RSME the balance is more favourable when compared with diesel:

Table 18 CO_2 saving (%) for RSME

	Reference
55	16
60	29
46	28

9. ECONOMICS OF ALTERNATIVE FUELS

9.1. GASEOUS FUELS

Owing to the difficulty of transportation, the cost of natural gas varies greatly from country to country, and even within countries. Where gas is available by pipeline from the field, its price is normally set by competition with residual fuel oil or coal as a burner fuel. The market-clearing price of gas to industrial customers under these conditions (which pertain in North America and much of Europe) has typically been about $2.00 to $4.00 per million Btu (higher heating value) in the 1990s. This is equivalent to a tax free gasoline price of approximately $0.066 to $0.132 per litre. For typical gas composition, one million Btu is equivalent to 930 standard cubic feet (scf), or 26.4 standard cubic metres.

To be used in vehicles, natural gas must be compressed or liquefied for on-board storage. Capital and operating costs of the compression system can add another $0.50 to $2.00 per million Btu ($0.016 to $0.066 per gasoline-equivalent litre) to the cost of CNG for automotive use, depending on the size of the facility and the natural gas supply pressure. Other costs to be taken into account include road taxes, if applicable, and the dealer's margin. The cost of LNG varies considerably, depending on specific contract terms (there is no effective "spot" market for LNG). The cost of small-scale liquefaction of natural gas is about $2.00 per million Btu, making it uneconomic in comparison to CNG in most cases. Where low-cost remote gas is available, however, LNG production can be quite economic. Typical 1993 costs for LNG delivered to Japan were about $3.50 to $4.00 per million Btu.

Non-attainment of certain US national ambient air quality standards led to numerous alternative vehicle and fuel proposals during the debate on the Clean Air Act Amendments. Compressed natural gas (CNG) was considered to be one of the fuels that could potentially help meet air quality objectives. As a consequence the American Petroleum Institute (API) conducted an analysis evaluating the likely economics of CNG vehicles as an emission reduction strategy.[38] The following summarizes their conclusions.

With compressed natural gas taxed at the same rate as gasoline, the average private cost of CNG vehicles was estimated to be somewhat higher than comparable future gasoline or diesel vehicles. From a broader social perspective, including avoided emission reduction costs and possible energy security benefits, the status of CNG vehicles was improved. Under these circumstances their cost varied from somewhat less to somewhat more than comparable future conventional vehicles. CNG vehicles could be cost effective from a private as well as a social perspective if more favourable technical or economic assumptions were made. These assumptions included:

- improved CNG vehicle efficiency
- lower relative CNG prices
- lower CNG taxes

Oil import reductions and energy security benefits were considered to be modest. CNG vehicles programmes would require increased natural gas production or imports. In addition, the delivery infrastructure would need to be expanded. Overall, it was concluded that areas with expensive emission control programmes and low to moderate natural gas prices might find that CNG vehicles had a role in cost effective emission control strategies.

From the vehicle owner's perspective, the incremental or net user costs of CNG vehicles includes all increased costs of vehicle ownership and operation compared with a conventional vehicle. This would involve purchased fuel as well as the cost of the vehicle, maintenance, and the additional time required for refuelling. Incremental fuel costs, if any, would depend on the price of natural gas to the refuelling station, the cost of compression, storage, and dispensing equipment, plus station operation. Because of the relatively high capital requirement for refuelling equipment, the private costs of CNG vehicles can be reasonably estimated only when appropriate refuelling facilities are included in a specific programme.

For this reason, incremental CNG costs were estimated for three different CNG vehicle scenarios involving private vehicles, fleet vehicles, and transit buses. Case 1 reviewed a private CNG vehicle programme with public refuelling stations, comparable to the administration's original nine city alternative vehicle proposal. This included a 280,000 per year vehicle purchase requirement for Los Angeles. Case 2 studied a CNG vehicle requirement for centrally fuelled fleets in the nine cities. Both Case 1 and Case 2 were based on city specific information. Case 3 looked at a CNG transit bus operation in metropolitan areas, with populations greater than one million.

The analysis focused on the incremental cost of the CNG programmes for the vehicles under consideration. It also converted these results to an incremental cost on a gasoline or diesel litre equivalent basis. A litre equivalent is the quantity of CNG required to drive an equal distance to that achieved with a litre of gasoline or diesel fuel in a comparable vehicle. To evaluate the potentially high costs during the initial stage of CNG vehicle introduction, evaluations were conducted on an annual basis from the assumed date of implementation (1991 or 1996) until 2005. All costs were in 1990 US cents. Taxes on CNG were assumed to be the same as a litre equivalent basis of gasoline. Gasoline taxes in the nine cities included in the private and fleet vehicle programmes were estimated at 7.7 cents per litre. No taxes were assumed on diesel fuel or CNG used for transit buses.

In addition to the private costs of vehicle ownership and operation, social benefits for each of the three CNG vehicle cases were evaluated. The main social benefits of CNG vehicles would be emission reductions and the potential energy security benefits of reduced oil imports. Probable emissions of non-methane hydrocarbons, carbon monoxide, nitrogen oxides, and particulates from CNG and future conventional vehicles were evaluated. Note that these estimates did not review total hydrocarbon emissions, which might be important, given the greenhouse potential of methane. The potential emission reductions from CNG vehicles were valued at “avoided cost”, that is the cost-effectiveness of other ways of achieving the same emission reductions as CNG vehicles. Cost effectiveness estimates varied substantially by region. For example, emission control costs for non-methane hydrocarbons were reported to range from $5,000 to $20,000 per metric ton in Los Angeles and from $2,000 to $6,000 per metric ton in other areas. The potential benefits from increased energy security depend on the reduction in gasoline consumption and the per barrel benefits of reduced imports. CNG use might also provide other benefits, such as reduction in air toxics or greenhouse gases, but these could not be evaluated with the available information.

The nine city net user cost for privately owned CNG vehicles was estimated to average about 5.3 to 6.3 cents per litre equivalent This approximated to 0.5 cents per kilometre, which was higher than for future conventional vehicles over most of the 1996 to 2005 period. Note that these estimates assumed the same taxes as gasoline. However, because of technological and economic uncertainties, as well as varying regional natural gas prices, net user costs could be substantially below or above this estimate. Net social costs also varied by region because of different net user and different "avoided emission control" costs. The ranges summarized in **Table 19** reflect these regional differences as well as economic and technical uncertainties.

Table 19 Estimated CNG Vehicle Net User and Net Social Costs in 2005 (1990 US cents per litre equivalent)

	Case 1 Private Vehicles [a]	**Case 2 Fleet Vehicles** [a]	**Case 3 Transit Buses** [a]
Los Angeles			
Net user cost	+0.3 to +9.5 [b]	+0.3 to +9.5 [b]	-
Net social cost	-14.5 to +0.3 [b]	-14.0 to +0.3 [b]	-
Eight other cities [c]			
Net user cost	+0.3 to +14.8	+0.3 to +12.7	-
Net social cost	-6.3 to +9.8	-6.9 to +7.7	-
Areas over 1 million population			
Net user cost	-	-	+1.1 to +13.2
Net social cost	-	-	-9.2 to +7.1

Notes:

a) Cases 1 and 2 are in gasoline litre equivalents and include equal taxes for CNG and gasoline. Case 3 is in diesel litre equivalents and includes no taxes for CNG or diesel fuel.
b) Based on a comparison with conventional vehicles meeting future federal emissions standards.
c) Consists of two groups: Greater Connecticut, New York, Baltimore and San Diego, which were ozone and carbon monoxide non-attainment areas at the time of the study (1990); and Philadelphia, Milwaukee, Chicago and Houston, which were ozone non-attainment areas.

Compared with conventional vehicles meeting assumed future federal emission standards, the net user costs for privately owned CNG vehicles in Los Angeles in 2005 were estimated to range between plus 0.3 and plus 9.5 cents per litre equivalent. Overall incremental social costs are estimated to range between minus 14.5 and plus 0.3 cents per litre equivalent. These estimates indicated that from an overall social perspective, private CNG vehicles could constitute a component in a cost effective emission reduction programme in Los Angeles. A similar comparison of CNG vehicles and California LEVs could not be made as there were no accepted cost estimates for LEVs or their fuel,

CNG vehicles, tuned to LEV emissions levels, would obviously provide little or no reduction in emissions compared with other vehicles just meeting LEV standards, so there would be little or no emissions benefit of CNG vehicles compared with other LEVs. For the eight other cities analyzed, four cities were out of attainment for carbon monoxide and ozone, the remainder only failed to meet the ozone standard. For all eight cities, the likely net user costs in 2005 were estimated to range between plus 0.3 and plus 14.8 cents per litre equivalent. Contributing to the somewhat higher cost range are the higher natural gas prices in the east coast cities. The overall social cost of private CNG vehicles in the eight cities was estimated to range between minus 6.3 and plus 9.8 cents per litre equivalent.

Results for the assumed CNG fleet vehicle requirement were similar to the private vehicle programme. When taxed the same as gasoline, the net user cost of CNG fleet vehicles was probably higher than that of future conventional vehicles. The average net user cost for future CNG fleet vehicles was estimated at about 5 to 5.5 cents per litre equivalent, or roughly 0.45 cents per kilometre. These costs were higher than those for conventional vehicles over most of the 1996 to 2005 period. Costs would also be somewhat higher in earlier years because of the small number of vehicles. As with the private vehicles, uncertainty and regional natural gas differences yield a broad range of possible net user costs. In Los Angeles, for example, CNG net user costs compared with conventional vehicles meeting future federal emission standards would probably range between plus 0.3 and 9.5 cents per litre equivalent.

When measurable social costs and benefits are included, overall social costs of CNG fleet vehicles were estimated at between minus 14 and plus 0.3 cents per litre gasoline equivalent in Los Angeles. As with private vehicles, no conclusions could be reached comparing fleet CNG vehicles with fleet LEVs in California. In the other eight cities, fleet vehicle net user cost was estimated to range between plus 0.3 and plus 12.7 cents per litre equivalent. The net social cost of CNG fleet vehicles in these cities is estimated to range from minus 6.9 to plus 7.7 cents per litre equivalent.

The net user cost of CNG transit buses was estimated to range between 0.5 and 8.5 cents per diesel litre equivalent - more than that for diesel fuel buses in the 1990s. These figures rise to a range of about 1.0 to 13.2 cents per diesel litre equivalent in 2005, because of changing relative fuel prices. Contributing to the higher incremental cost of CNG compared with diesel is the relatively high efficiency of diesel engines. However, even in 2005 overall incremental social costs of CNG transit buses, including net user costs, were estimated to range from minus 9.2 to plus 7.1 cents per diesel litre equivalent. This indicates the potential for CNG vehicles to contribute to a cost effective emission control programme, despite their higher net user cost.

The sensitivity of the estimates to important assumptions was also evaluated. Three factors were particularly relevant. First, a 10 percent decrease in the assumed price of natural gas lowered the net user cost and the incremental social cost in each case by 1.8 to 2.6 cents per litre equivalent. This indicated that CNG vehicle cost was sensitive to relative fuel prices, and that CNG vehicles would probably be more cost effective in regions with relatively low natural gas prices. Second, a 10 percent increase in relative CNG vehicle efficiency lowered net user and incremental social cost in each case by 2.6 to 2.9 cents per litre equivalent. As a result, CNG vehicles became increasingly competitive with modest technical improvements.

Third, taxes have a significant impact on the private costs of CNG vehicle use. The analysis assumed that CNG would be charged the same taxes as gasoline on a litre equivalent basis. With no taxes, CNG vehicles could be cheaper than gasoline vehicles from a user perspective. While this improves the apparent cost-effectiveness of CNG vehicles, it does so with an offsetting loss in tax revenue. The loss in tax revenue would increase each year as the number of CNG vehicles increased. Looking only at federal and state fuel taxes of 6.3 cents per litre, the large private CNG vehicle programme would lower fuel tax revenues by $810 million in 2005, and the smaller fleet programme would lower revenues by $142 million, in 1990 dollars. Fuel taxes are generally viewed as user fees for roads, bridges, and maintenance provided by government. Exempting CNG vehicles from fuel taxes would not change the overall social cost of CNG vehicles, it would merely shift it from vehicle owner to the government.

Based on current information, the report concluded that compressed natural gas vehicles are probably somewhat more expensive to own and operate than conventional vehicles when taxed at the same level. However, there could be circumstances when incremental social benefits would more than offset the higher net user costs. In particular, CNG may currently be a cost effective emission control strategy in regions with low to moderate natural gas prices and moderate to high emission control costs. Additionally, improvements in CNG vehicle efficiency could significantly lower the net costs of CNG vehicle use. If CNG carried no tax, there would be circumstances where CNG would be advantageous, albeit strictly from a net user cost perspective.

Similar conclusions can be made for LPG. In western Europe, (particularly the Netherlands, Italy and Austria), there is extensive successful experience with LPG as an alternative fuel for both passenger cars and bus fleets.

For example, the city of Vienna has been using LPG in its bus fleet for more than three decades. The Vienna Transport Board began to look at LPG as early as 1963 and is currently employing it in a 500 vehicle bus fleet. It was believed that the utilization of liquefied petroleum gas would only make sense if overall operating costs were cut - despite the additional cost for engine re-design, changes to maintenance and inspection, new fuel dispensing facilities and more stringent bus depot facilities.

A detailed investment appraisal suggested that an attractive LPG purchase price would reduce operating costs. More specifically:

- Because of its environmental advantages, LPG was exempted from mineral oil tax when employed in public transport fleets. As a consequence, a price-per-litre comparison favoured LPG as a “cost effective” fuel.
- Despite the higher fuel consumption of LPG engines, fuel cost savings are approximately 50% per kilometre.

However, operating cost is not the only factor to incorporate in an investment appraisal of this kind. Account should also be made of the higher cost of vehicle purchase, approximately 10% higher for a LPG bus than a comparable diesel vehicle. Nevertheless, despite this additional cost, plus increased fuel consumption, slightly higher maintenance costs, and the exchange of catalytic converters every two years, a reasonable pay-back period is achieved over an average service distance of 50,000 km. per annum.

In the Netherlands a number of buses have been operating on LPG since 1994 in Amsterdam, Gronigen, Eindhoven and Breda. To evaluate the potential of LPG as an alternative fuel, the vehicle costs per kilometre over the total vehicle lifetime were viewed as important. These costs included:

- total fuel costs (consumption, pricing)
- maintenance costs (equipment, workshop, man-hours)
- fiscal consequences
- investment in vehicles

A number of calculations were made[46] which confirmed that, in economic terms, liquefied petroleum gas could contribute to useful diversification of fuel usage in a variety of countries or regions.

9.2. BIO-FUELS

A number of studies have calculated the cost of production and use for different bio-fuel options. [10, 31 to 36] Inevitably, the calculations are influenced to some extent by both the assumptions made and by regional differences. These latter differences affect both the economics of crop production and the ease with which they can be processed and incorporated into the fuel distribution system. The economic calculation is twofold:

I. What is the cost of the bio-fuel compared with the value of the gasoline or diesel which it displaces?
II. What is the effect on vehicle fuel consumption?

In the analysis that follows, the costs are presented free of any agricultural or industrial subsidy or tax concessions. This is the true cost of production, regardless of whether the cost is recovered directly from the consumer or indirectly through subsidy.

The report of R H Levy,[27] prepared for the French Government, addressed the first of these questions and has the advantage that it covers both ethanol/ETBE and RSME, using similar assumptions and conditions. It therefore provides a uniform comparison which should also be generally applicable to the rest of Europe and has been used in the discussion that follows.

9.2.1. Bio-ethanol and ETBE

The potential application considered is the substitution of small amounts (i.e. up to 5% ethanol or up to 15% ETBE) in gasoline. At these levels, the fuel can be used in existing vehicles without modification. The Levy Report presents data on ethanol production from sugar beet and from wheat. The figures quoted (**Tables 20 and 21**) have been converted to US$ per litre of fuel. These figures are based on the most favourable conditions, using spare capacity in existing distillation plant. Production from beet can be seen to be the lowest cost option. Figures for new plant exceed this level by between 5 and 25%, even taking into account possible economies of scale. Levy notes, however, that costs in the USA are around 25% lower than those calculated for France.

To the cost of production must be included the costs associated with incorporating the ethanol into the gasoline.

Table 20 Production costs for bioethanol ($/l)

	From Beet	**From Wheat**
Agricultural costs (1)	0.213	0.255
Harvesting storage	0.058	0.058
Fermentation, distillation and drying of ethanol (2)	0.191 (4)	0.276 (3)
Total Production Cost	0.462	0.589

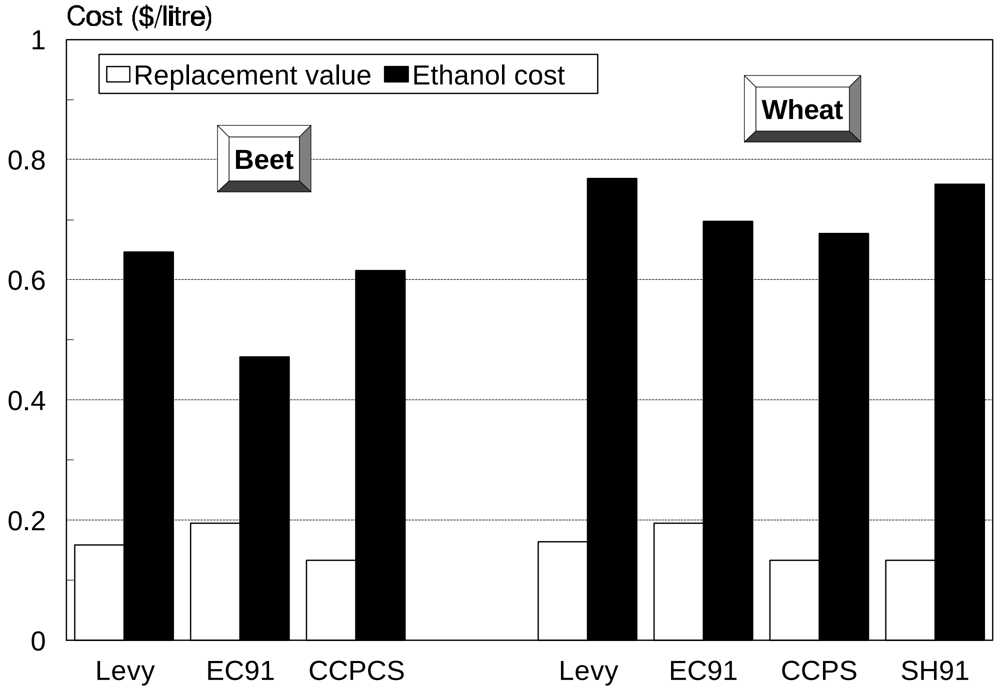
Notes : (1) cost for best agricultural regions, with no profit margin, without subsidy
(2) including credit for by-products
(3) future cost reductions in distillation likely to be offset by fall in by-product prices, so figure unlikely to fall
(4) lowest possible figure - range quoted up to 0.280

Table 21 Cost/Benefit of 5% bioethanol in leaded gasoline ($/l)

Source crop	beet	wheat
Production cost from **Table 20**	0.462	0.589
Capital costs	0.096	0.096
Downgrading of butane	0.078	0.078
Transport costs	0.011	0.011
Total costs	0.647	0.774
Replacement value of gasoline, based on Rotterdam values	0.160	0.160

These figures are compared with data from other studies in **Figure 5**. As expected, there is some variation in the estimates, but the studies all agree that production from sugar beet is a less costly approach than the use of wheat as a source crop. For beet, the estimates range from 2.5 to 4.6 times the replacement value, with the more recent study [27] giving a figure of 4.0.

Figure 5 Comparison of bioethanol costs from various studies



Ethanol has some disadvantages as a gasoline component, since it increases vapour pressure and can present water handling problems. For this reason, the use of ethanol to replace methanol in ether production has been pursued, particularly in France. Using essentially the same process as for MTBE, Ethyl Tertiary Butyl Ether (ETBE) is produced from reaction of ethanol with iso-butylene. ETBE has properties very similar to MTBE and can be used in the same way as a high octane blending component, without the drawbacks associated with ethanol itself.

Economically, ethanol faces the same disadvantages whether used as a stand-alone fuel, gasoline blending component or ether feedstock - it is competing with a much cheaper fossil derived fuel. To be competitive with methanol, bio-ethanol would need to be delivered to the processing plant at $0.105/l, or one sixth of its production cost.[27]

The true costs of bio-ethanol are very high and it could only be seriously considered attractive to the consumer if substantial tax incentives are applied. Such proposals have been under consideration within the EU - a tax on bio-fuels at only 10% of the level applied to conventional transportation fuels has been debated. Since fuel taxes in Europe are high, this would have a significant impact on the apparent cost of bio-fuels, and such a proposal could cover the necessary subsidies shown in **Table 22**, although at a very high price to the taxpayer.

Table 22 Suggested subsidies for bioethanol ($/l)

Proposed use	Ethanol in gasoline	To produce ETBE
Cost of bio-ethanol	0.647	0.507
Replacement value	0.160	0.105
Subsidy needed	0.487	0.402

9.2.2. Rape Seed Methyl Ester (RSME)

Plant oils themselves present serious difficulties when employed as diesel fuels due to the rapid formation of engine deposits. Esterification produces a material which has far fewer problems. RSME can be used as a fuel itself, provided that the engine has been designed to avoid material incompatibilities, particularly with respect to seals and drive belts. An alternative approach is to mix RSME with diesel in proportions from 5 to 50%. Both approaches have been considered in Europe.

Production costs for RSME, based on information from Reference 33, are shown in **Tables 23** and 24.

Table 23 Production costs for RSME

(Source: Ref. 33)	$/tonne Oil	$/litre RSME
Agricultural cost (1)	463.3	0.388
Collection and storage (2)	77.8	0.065
Transport	20.7	0.017
Milling costs (3)	79.6	0.067
Credit value of seed cake	(194.0)	(0.163)
Production cost (4)	447.4	0.374 (5)

Notes : (1) Based on use of best agricultural regions, no margin. Includes set-aside subsidy. Sunflower oil cost is similar.

(2) Variable cost only, fixed costs estimates at 44$/tonne.

(3) Currents costs using existing facilities. New installations could be supplied at similar cost because of economies of scale.

(4) The cost as calculated above is similar to the world price, which was taken by Levy as $427/tonne. It uses the relationship:
1.05 tonne ➔ 1.0 tonne RSME + 0.1 tonne glycerine.

(5) The conversion to US$/litre has been performed using an RSME density of 0.88kg/l.

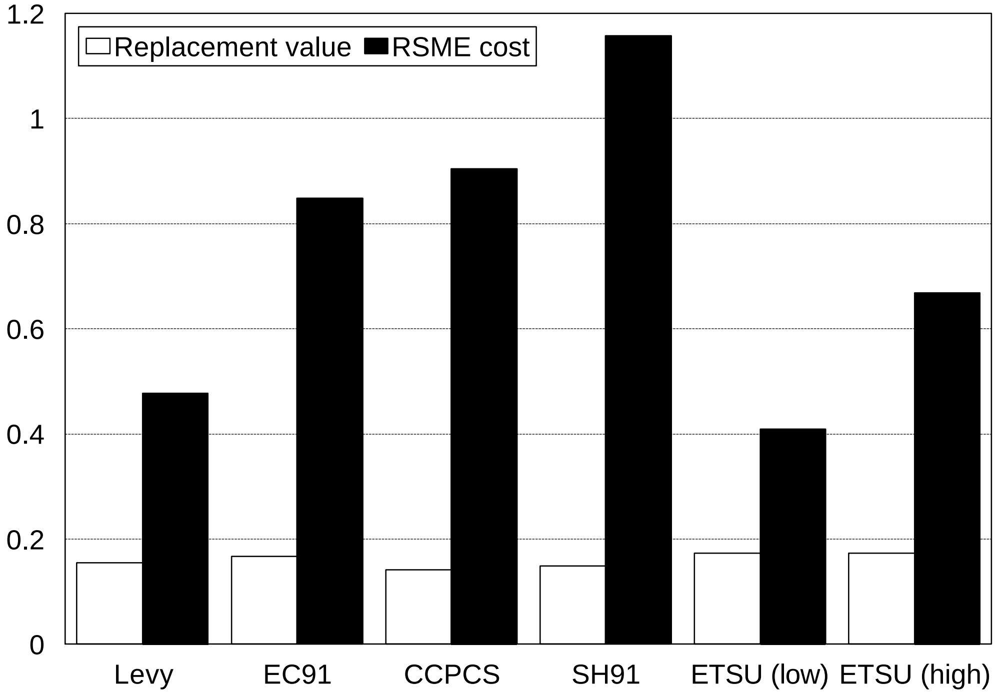
Table 24 Total costs for rape seed oil

Units	$/tonne Oil	$/litre RSME
Production cost (1)	447.4	0.374
Processing costs (2)	115.2	0.097
Distribution costs (3)	8.2	0.007
Total cost	570.8	0.478
Replacement value, based on Rotterdam spot market	-	0.156

Notes :
(1) From **Table 23**
(2) Estimate from Ref. 27, based on the most cost-effective proposals available.
(3) Typical figure for refinery blending; blending at depots would be more costly (up to 53.6$/tonne)

Data from other studies are compared in **Figure 6**.

Figure 6 Comparison of RSME costs from various studies



The estimates show more variability than those for ethanol. One factor which has a large effect on the estimates is the assumptions made about the value of by-products, namely glycerine and feed cake. The two sets of figures shown for the ETSU study [16] illustrate the effect. The 'low' cost includes full credit for both products, while the 'high' estimate gives no credits. If more emphasis is placed on the most recent studies, both the Levy Report and the mean of the ETSU estimates give a figure close to three times the replacement value of the fuel.

9.2.3. Fuel consumption effects

Oxygenates, simply because they contain oxygen, have a lower energy content than hydrocarbon fuels of similar boiling range. Each litre of fuel will therefore contain less energy when oxygenates are used, and fuel consumption can be expected to increase. This is illustrated by the relative heating values in **Table 25**.

Table 25 Energy content of oxygenated fuels

	Gasoline	Ethanol	ETBE	MTBE	Diesel (1)	RSME (2)
Lower heating value (MJ/kg)	41.9 - 44.2 100%	26.7 62%	36.0 84%	35.1 82%	42.8 100%	36.8 86%
Lower heating value (MJ/l)	30.4 - 33.2 100%	21.2 67%	26.8 84%	26.1 82%	36.0 100%	32.4 92%

Notes : (1) CEC Reference fuel RF-03-A-84 (typical figure)
(2) Reference 15

Tritthart [9], in tests on a 2.3l DI engine vehicle using RSME fuel found that on the FTP test cycle the volumetric fuel consumption was reduced by 9%, in proportion to the volumetric heating values of the fuels. This implies that the thermal efficiency of the engine calculated volumetrically remained unchanged, and the effects observed can be explained purely by the amount of energy delivered to the engine by the two fuels.

Prankl [37] tested a European IDI passenger car engine on a test bed and found that specific fuel consumption was increased (**Table 26**). The amount of increase observed was less than would be expected from the energy content of the two fuels, implying some increase in thermal efficiency when operating on RSME

Table 26 RSME fuel consumption - IDI bench engine tests

(Source: Ref. 16)	1400 rpm		2400 rpm	
	Diesel	RSME	Diesel	RSME
Specific fuel consumption (g/kWh)	270 100%	300 110%	278 100%	304 109%
Specific fuel consumption (l/kWh)	0.322 100%	0.342 106%	0.332 100%	0.344 104%

Such thermal efficiency increases measured on a volume basis in fuel consumption tests can be explained by considering the engine fuel/air ratio settings which are a compromise between power output and responsiveness on the one hand, and fuel economy and emissions performance requiring even leaner operation on the other hand. Thus, on average over a test cycle, an engine which has been overall performance optimized on straight "regular LHV" fuel will tend to move towards the fuel economy side of its operating range when run on lower LHV oxygenated fuel.

Thermodynamics theory says that the mass of fuel consumed to provide a constant amount of transportation should increase (very nearly) directly in proportion to any reduction in fuel LHV measured on a mass basis. This may be considered to be the most appropriate relationship to use when considering fuel efficiency in certain long-term planning studies.

Another consideration is that a reduction in density due to oxygenate addition, in the absence of any change to retail price and taxation structure (which is based on volume), would transfer additional cash from the motorist to the retailer and government revenues in direct proportion to the density difference.

In summary, compared with conventional gasoline and diesel fuels, oxygenates produced from agricultural sources are very costly. To this cost disadvantage must be added the poorer fuel consumption resulting from the lower energy content of oxygenated fuels.

10. METHANOL

10.1. INTRODUCTION

Methanol (CH_3OH) is a simple, single compound. It contains no sulphur or complex organic species. Ideally, it provides four air quality benefits over conventional fuels:

- Lower ozone forming potential
- Minimal emissions of benzene and polycyclic aromatic hydrocarbons
- Negligible sulphur compound emissions
- Low evaporative emissions of a relatively unreactive compound

Conversely, three areas of concern have been identified:

- High formaldehyde and buta-1,3,-diene emissions; this latter point is still open to conjecture.
- Acute toxicity.
- Real costs - given the need for world-scale plant investment, revised or new vehicle technology and the need for a dedicated distribution network.

Although methanol is probably not the “cleanest” of the gasoline alternatives, and is unlikely to be the cheapest, it has received more attention (in the US, at least) than other fuels as a means of controlling ozone. In part, this is because the technology for vehicles that can run on M85 (a blend of 85% methanol with 15% gasoline) is currently available, and because the EPA and others have found it to promise significant ozone improvements at “low” cost. Conversely, other studies indicate that methanol is a costly fuel, delivering too few environmental benefits.

10.2. ORIGIN AND PRODUCTION OF METHANOL

Methanol can be produced from a variety of feedstocks, including natural gas, coal, biomass and cellulose. Currently the most economical source is natural gas and this is likely to pertain well into the next century. Methanol is utilised as a chemical in its own right and increasingly as a feedstock for MTBE. If a substantial demand for fuel methanol was established, new production facilities would be much larger than many of the units currently installed, leading to some economy of scale benefits. In addition, the technology of methanol production is evolving, so that manufacturing costs may further reduce. However, compared with natural gas or conventional automotive fuels, methanol is not in great supply. The principal advantage that methanol has over natural gas is that it is a liquid. This means that it can provide some of the benefits provided by natural gas vehicles without the high capital cost of a pressurised or cryogenic distribution system. From a consumers viewpoint, methanol represents just another liquid fuel.

Methanol production has a disadvantage against gasoline and diesel fuel that refining process have become progressively more efficient. In simple terms, the thermal efficiency of methanol manufacture is approximately 60-75% whereas modern refineries operate at around 93% efficiency. A ‘world-scale’ methanol plant is generally assumed to have a capacity of 600,000 tons per year, costing between $200 and $350 million, depending on location. By comparison a world-scale oil refinery is larger. The average refinery processes over 4 million tons of crude a year of which about 30% will be gasoline. Even this is much smaller than new refineries in, for example, the Middle East and Asia.

World-wide, existing refinery capacity amounts to over 70 million barrels a day, capable of producing as much as a billion tons of gasoline per annum. World-wide methanol capacity, by contrast, is now approaching 25 million tons. Furthermore, refineries are highly flexible whereas a methanol plant manufactures a single product. This probably accounts for the varying profitability record of existing methanol manufacturers and suggests that the investment risk is greater than that associated with oil refining.

The energy content of methanol is less than half that of gasoline or diesel fuel (20.2 MJ/kg compared with, typically, 41.9 - 44.2 for gasoline and 42.8 for diesel). This fundamental disadvantage is partially offset by its more advantageous stoichiometric air-fuel ratio, charge cooling capability and high octane number. It is now generally assumed that 1.5 litres of methanol will give roughly the same mileage as one litre of gasoline. To place this in perspective, the current world-wide supply of methanol would equate to about 16 million tonnes of gasoline, or just over half the annual consumption of unleaded gasoline in Germany.

10.3. STORAGE, DISTRIBUTION AND VEHICLE CONSIDERATIONS

General comments on the use of alcohols will be found in **Section 5.3.1**. To this must be added some additional points relating to either neat methanol or methanol/gasoline blends:

Leakage: Methanol is toxic

Safety: Different fire-fighting foams are preferred and special precautions are required to store methanol or blends of 85% methanol with gasoline (M85). This is because the vapour space over neat methanol has a flammability range of 7 to 43°C. By contrast, the flammable range of the vapour space over gasoline is generally below ambient temperatures. Neat methanol also presents a special safety hazard as it burns without a visible flame, and even alcohol-water wastes may be flammable.

Storage & Distribution:

Methanol is completely soluble in water and will therefore leach out into water bottoms, presenting difficulties of disposal and loss of methanol from blends with gasoline.

The acute toxicity of methanol presents a serious drawback to its acceptability as an automotive fuel, given the general consumer perception that gasoline and diesel are intrinsically ‘safe’. Methanol can cause blindness or death on ingestion of between 25 and 100 ml. This has to represent a serious cause for concern, given that siphoning gasoline from vehicle tanks for use in lawn-mowers or degreasing hands and components are common practices. This latter point is of particular significance, as methanol can be adsorbed into the blood stream through accidental or deliberate spillage on the skin. A study by the US National Capital Poison Centre suggested that: “A comparison of methanol and gasoline fatality rates reveals a 25 fold greater fatality rate for methanol. From a public health vantage, the acute hazard posed by conversion to methanol based fuels is unacceptable unless appropriate measures are undertaken to prevent the predicted increases in fatalities, blindness and permanent neurological disability”. As stated above, methanol, unlike gasoline or diesel, mixes readily with water and is completely soluble.

As far as vehicles are concerned, two approaches are mooted. The first, applicable to many of the alternatives, is to employ the intrinsic properties of the ‘new’ fuel to its greatest effect. The second option, viewed by many as a more pragmatic approach, is to use methanol in a mix with varying, but small, quantities of gasoline - the so-called flexible fuel vehicle (FFV) approach. The second option represents a reversal of earlier European experiments, which focused on the incorporation of small (3%) quantities of methanol in gasoline. It should be added that this latter technique has little impact on emissions performance.

The primary advantages of methanol, purely in terms of engine combustion characteristics, are:

- High octane quality
- High heat of evaporation - providing for charge cooling

To this can be added its low vapour pressure, which clearly assists the control of evaporative losses.

As **Section 10.4** will show, the potential emissions benefits of neat methanol (M100) are still a matter of some conjecture. There is, however, general agreement that M85 offers some advantages. First, the presence of 15% gasoline renders flames visible, an important safety consideration. It also reduces the already debatable attractiveness of the flavour of methanol. Additionally it will increase vehicle range and improves cold starting compared with M100. Like M100 however, the solubility of methanol in water presents significant difficulties. Both fuels have to be handled carefully, but the real problem for M85 is that of phase separation in the presence of water.

Whilst M85 will still allow a dedicated vehicle to be optimized to take advantage of lean burn characteristics and increased compression ratio, some doubt must exist as to the benefits of the flexible fuel vehicle approach. It does have the advantage that it has an omnivorous “appetite” for either gasoline or methanol, but it cannot then utilise the octane quality available.

10.4. EMISSIONS PERFORMANCE

As **Table A**, [42 & 43] below, indicates, both M85 and M100 offer a number of emissions benefits in comparison with a range of other alternative and conventional fuels. The area of concern has to be the high emissions of formaldehyde (HCHO), a first oxidation product of methanol. Methanol can produce more than five times the amount of formaldehyde emitted from gasoline and can also emit larger amounts of other “air toxics”, such as buta-1,3,-diene - this latter point is open to some conjecture, as work by the EPA (1993) suggest that buta-1,3,-diene emissions from M100 would be virtually nil.[44] Formaldehyde, however, is toxic and probably a carcinogen and in confined spaces the emissions from methanol vehicles might increase its concentration to potentially harmful levels. M85, on the other hand, exhibits lower formaldehyde and buta-1,3,-diene emissions but acetaldehyde emissions approach the levels seen with ethanol blends.

Table A Emissions from various alternative and conventional fuels

Emission Species (mg/km) FTP Cycle	Gasoline	RFG[1]	M85[1]	M100[1]	E85[1]	CNG[1]	LPG[1]
THC	161.59	-	111.87	124.30	-	-	-
CO	733.37	-	683.65	870.11	-	-	-
NOx	490.99	-	379.12	285.89	-	-	-
Evaporative Emissions (mg/test) FTP Test	1720.00	-	680.00	880.00	-	-	-
Benzene	7.95	4.88	4.38	0.32	1.21	0.242	0.242
Toluene	33.66	3.45	8.66	2.11	0.75	0.695	0.695
m&p Xylenes	4.57	4.77	1.54	0.30	1.30	0.705	0.033
o-Xylenes	1.95	1.58	0.46	0.16	0.39	0.399	0.101
Buta-1,3,-diene	0.19-0.50	0.24	0.44	2.05[2]	0.12	0.093-0.404	-
Formaldehyde	4.78	0.60	13.87	21.76	3.15	2.712	4.870
Acetaldehyde	0.94	0.50	10.02	0.27	13.32	0.529	0.641
Acrolein	1.12	-	4.44	0.09	-	0.330	0.118

Notes:

1. RFG = reformulated gasoline; M85 = 85% methanol blend; M100 = pure methanol; E85 = 85% ethanol blend; CNG = compressed natural gas; LPG = liquefied petroleum gas
2. Other sources (e.g. EPA, 1993) suggest that emissions of buta-1,3,-diene from M100 could be virtually nil.

10.5. ECONOMICS OF METHANOL

As far as cost-effectiveness is concerned, a number of studies have been conducted. The estimates vary enormously, from positive - that is, methanol costs less than gasoline and provides emissions benefits, to about one million dollars per ton of volatile organic compounds reduction. It has even been argued that the cost-effectiveness is “infinitely negative”, based on a combination of high methanol costs and research that suggested that emissions from methanol vehicles had higher ozone forming potential than their gasoline counterparts.[40] None of the studies appear to have considered the full body of literature on emissions estimates and some of the studies applied questionable methods to obtain cost estimates.

One investigation [41] attempted to address these and other deficiencies and concluded that methanol would cost from $33,000 to nearly $60,000 per ton reduction of reactive hydrocarbons. This compared unfavourably with several other available options, which were estimated to cost under $10,000 per ton. The alternative strategies considered included:

- RVP reduction
- Installation of Stage II vapour recovery systems
- Introduction of reformulated gasoline
- Improved inspection and maintenance
- Remote sensing of “gross emitters”

More recently, the Economics Committee of the Auto/Oil Air Quality Improvement Research Program (AQIRP) retained Dr. Robert W. Hahn, of the American Enterprise Institute, to perform an independent study of the costs of using M85 in flexible/variable fuelled vehicles.[45] Dr. Hahn was asked to review existing research and literature as the basis for his assessment. His principal conclusions were:

- M85 is likely to be more costly relative to conventional gasoline, particularly in the short term and medium term.
- The transition cost for methanol in attaining a significant market penetration will be high. Transition issues are critical in evaluating the costs and cost-effectiveness of methanol-based fuels
- Flexible/variable fuelled vehicles (FFV/VFVs) are likely to cost more than gasoline vehicles.

The major findings were quantified as follows:

1. Cost Estimates

M85 as a motor fuel would cost from 19.5 to 21 cents more per equivalent energy litre (in 1988 dollars) than conventional gasoline in the near term. This is primarily because of the high production cost of methanol obtained from current-design "single-train" world-scale plants (2,500 metric tons per day of methanol), and because of the incremental costs of FFV/VFVs.

The incremental FFV/VFV cost was estimated to be $400 per car, which was calculated to be equal to 4.2 cents per equivalent litre. This figure was included in the cost estimate range mentioned above. However, the FFV/VFV cost was viewed as optimistic. It did not include issues related to maintenance, driving range, and boot space. As a result, it is likely that the costs to consumers of FFV/VFVs were understated. "A doubling of these costs would be within the realm of possibility."

On a longer-term basis (by 2005-2010), the costs associated with using M85 narrowed to between 7.4 and 9.2 cents per equivalent energy litre above the costs of using conventional gasoline. This range again included 4.2 cents for FFV/VFV costs. The decline in cost was predicted to occur because of the expected prevalence of more efficient, "four-train" plants (10,000 metric tons per day), and because of an assumed lower cost of capital with a maturing methanol industry.

2. Variations on Cost Assumptions

Given the uncertainties associated with the cost elements of any future motor vehicle fuel, sensitivity studies were conducted. The factors varied were the capital investment level for methanol plants (+/- 20%), the real after-tax cost of capital (+/- 3%), the price of the input raw material, natural gas (+/- 25%), and FFV/VFV cost (+/- 25%). The results were:

- The combination of all these factors at their most favourable extreme values (most favourable to a lower M85 cost) resulted in an M85 cost 13.2 cents per equivalent litre more than conventional gasoline in the near term. The cost difference declined to 2.6 cents per equivalent litre in the long term.

- The combination of all factors at their least favourable extremes resulted in costs of over 26.5 cents per litre more than conventional gasoline in the near term, declining to 14.5 cents per litre in the long term.

The report was favourably received by the AQIRP Economics Committee. However, a diversity of viewpoints by the committee membership emerged in response to the report's specific findings.

Several committee members expected that if there were to be a strong national consensus for the widespread use of methanol-based fuels, then the lower-cost, four-train plants could be built much sooner than assumed. The risks associated with methanol development might then be reduced, resulting in a lower cost of capital. Under this view, the lower long term cost estimate could be indicative of costs that might prevail earlier in the forecast period.

Conversely, several committee members expected that the near term cost estimate could understate the premium that investors would require to commit large amounts of capital to methanol projects in an uncertain regulatory environment. In addition, the more efficient, four-train plants assumed for the long term could carry a significant risk. According to this scenario, predictions for such mega-projects involving a new construction strategy have been historically optimistic. Thus, unanticipated factors could drive the costs of M85 above those projected for the long term.

11. CONCLUSIONS

11.1. GASEOUS FUELS

Natural gas and LPG offer some environmental advantages. However, comparison of hydrocarbon emissions should be based on total, not non-methane, hydrocarbons.

The complexities and cost of storage and handling LNG suggest that CNG provides a more practical alternative. LPG is an even more attractive proposition in this regard but its availability is limited.

The energy density of CNG and the weight of on-board storage cylinders place serious range limitations on dedicated vehicles. LPG performance is significantly better in this context.

Slow filling times and the complexity of CNG refuelling installations (plus the capital cost) are also likely to limit the popular appeal of the fuel. Filling rate performance is superior for LPG and less complex, lower cost refuelling systems are available.

Safety considerations, leading to refuelling site location restrictions, are likely to prevent the construction of facilities in many urban areas.

Dedicated engines are required to take full advantage of the properties of gaseous fuels.

For these reasons, CNG and LPG are likely to be considered as an alternative to diesel powered vehicle fleets operating in urban areas where dedicated vehicles and refuelling facilities can be closely controlled. The advantages of gaseous fuels as replacements for gasoline are more tenuous, particularly with regard to on-board storage limitations.

The issue of methane leakage and unburned methane emissions needs to be considered in any “cradle to grave” analysis of the greenhouse effect for CNG.

11.2. BIO-FUELS

Oxygenates can be attractive blending components in certain circumstances, as illustrated by the use of MTBE in gasoline. The benefits of oxygenates can be obtained without the need for costly production from biological sources .

Bio-fuels such as RSME may have application in niche markets where their special characteristics justify the high cost.

Production of bio-ethanol consumes about as much energy as is produced, and so makes no contribution to energy conservation. Figures for RSME are more favourable, but even here half the energy produced is consumed in the production process.

Bio-ethanol makes no net contribution to CO_2 reduction since the production process itself produces CO_2. For RSME, cradle-to-grave CO_2 emissions are roughly half those of diesel fuel, but the potential impact on total European CO_2 emissions is small, around 3%.

Bio-fuels can have favourable impacts on some emissions, notably HC, CO and diesel particulates, however these benefits vary greatly depending on engine design, adjustment, and test conditions. Increases are seen in emissions of some species, notably NOx and aldehydes

The cost of bio-fuels is 3-4 times that of gasoline or diesel. Considering the relatively small emissions and energy benefits, general use of bio-fuels does not appear to be an effective use of resources to provide real benefits for the environment or for energy self-sufficiency.

11.3. METHANOL

Methanol offers advantages in terms of reduced ozone potential. However, its cost, toxicity and formaldehyde emissions performance, coupled with the need for innovative engine technology, mitigate against widespread acceptance.

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APPENDIX 1

This **Appendix** [39] covers the European specification requirements for esterified vegetable oils and briefly reviews the legislative position of alternatives to conventional hydrocarbon fuels in the United States.

Europe

Vegetable Oil Methyl Esters (Biodiesel)

The European Commission has put forward a draft Council Directive for a specification for vegetable oil methyl esters (biodiesels). The proposal is presented in the framework of EU's ALTENER Programme for the promotion of alternative fuels. Within this programme the EU has the objective of securing a five per cent market share of total motor fuel consumption for biofuels, of which it is expected that biodiesel will form the major share. Some countries, notably Austria and Italy, have already produced their own specifications (see **Tables 25** to **27**).

Biodiesel production units are in operation or under construction in Austria, Belgium, Germany, France and Italy and others are planned.

Rapeseed methyl ester diesel fuels are already sold in Italy but can only be marketed outside retail outlets. A Government Decree fixes a maximum of 125,000 tons per year to be exempted from gas oil excise tax. When claiming tax exemption producers have to show that at least 80% of the raw vegetable oil used derives from "set-aside" crops.

Table 25 EU Draft Specification for Vegetable Oil Methylester Diesel Fuel (Biodiesel)

Properties		**Limit**	**Analytical Method**
A. Fuel Specific Properties	**Units**		
Density at 15 °C	g/cm^3	0.86-0.90	ISO 3675
Kinematic viscosity at 40 °C	mm^2/s	3.5-5.0	ISO 3104
Flash point	°C	min. 100	ISO 2719
Cold filter plugging point	°C	summer max. 0 winter max. < -15	DIN EN 116
Sulphur content	%wt	max. 0.01	ISO 8754/DIN EN 41
Distillation:			
5% vol. evaporated at	°C	to be indicated	ASTM-1160/ISO 3405
95% vol. evaporated at	°C	to be indicated	
Carbon residue Conradson (10% by vol. residue on distillation at reduced pressure)	%wt	max. 0.30	ISO 10370
Cetane number	-	min. 49	ISO 5165/DIN 51773
Ash content		max. 0.01	EN 26245
Water content (Karl Fischer)	mg/kg	max. 500	ISO 6296/ASTM D 1744
Particulate Matter	g/m^3	max. 20	DIN 51419
Copper corrosion (3h/50° C)		max. 1	ISO 2160
Oxidation stability	g/m^3	max. 25	ASTM D 2274
B. Methyl Ester Specific Properties	**Units**		
Acid value	mg/g	max. 0.5	ISO 660
Methanol content	%wt	max. 0.3	DIN 51413,1
Monoglycerides	%wt	max. 0.8	GLC
Diglycerides	%wt		GLC
Triglycerides	%wt		GLC
Bound glycerine	%wt	max. 0.2	calculate
Free glycerine	%wt	max. 0.03	GLC
Total glycerine	%wt	max. 0.25	calculate
Iodine number	-	max. 115	DIN 53241/IP 84/81
Phosphorous content	mg/kg	max. 10	DGF C-VI 4

Note : Many of the test methods have yet to be finalized.

Table 26 Italian Specification for Vegetable Oil Methylester Diesel Fuel

Property	Units	Limits	Test Method
Appearance	Visual	Clear & Bright	
Density	@ 15° C kg/m^3	0.86-0.90	ASTM D1298/ISO 3675
Flash point	PM ° C, min.	100	ASTM D93
Cloud point	° C max.	0	ASTM D97
Kinematic viscosity at 40° C	mm^2/s	3.5-5.0	ASTM D189/ISO 3104
Distillation	° C		ASTM D86
IBP min.		300	
95%v max		360	
Sulphur content	%m max.	0.01	ASTM D1552/ISO 8754
Carbon Residue Conradson (CCR)	%m max.	0.5	ASTM D189/ISO 10370
Water content	ppm	700	ASTM D1744
Saponification number	mg/KOH/g min.	170	NGD G33-1976
Total acidity	mg/KOH/g max.	0.05	ASTM D664
Methanol content	%m max.	0.2	GLC
Methyl ester	%m min.	98	GLC
Monoglycerides	%m max.	0.8	GLC
Diglycerides	%m max.	0.2	GLC
Triglycerides	%m max.	0.1	GLC
Free glycerine	%m max.	0.05	GLC
Phosphorus	ppm max.	10	DGF GIII 16A-89

Table 27 Austrian Specification for Rapeseed Oil Methylester Diesel Fuel (Önorm Vornorm C1190, revised 01.01.95)

Property	**Units**	**Limits**	**Test Method**
Density	@ 15°C kg/m^3	0.87-0.89	ISO 3675:1976; ASTM D4052:1991
Flash point	PM °C, min.	100	ÖNORM EN 22719: 1994
CFPP (01.04-30.09)	°C max.	0	ÖNORM EN 116
CFPP (01.10-31.03)	°C max.	-15	ÖNORM EN 116
Kinematic viscosity °C	mm^2/s	6.5-8.0	ISO 3104: 1976
Sulphur content	%m max.	0.02	ÖNORM EN 24260: 1994; ISO 8754: 1992
Carbon Residue Conradson (CCR)	%m max.	0.05	DIN 51 551
Sulphated Ash	%m max.	0.02	ÖNORM C 1134
Cetane number	min.	48	ISO 5165: 1992
Neutralisation value	mgKOH/g, max.	0.80	ONORM C 1146
Methanol content	%m max.	0.20	DIN 51413
Free glycerine	%m max.	0.02	GLC/enzymatic
Total glycerine	%m max.	0.24	GLC/enzymatic
Phosphorous Content	mg/kg max.	20	ASTM D 3231

United States

The Clean Air Act Amendments (CAAA) include legislation on fuel composition and emissions performance, as well as vehicle emission limits. President Bush’s original proposal called for a major shift to the use of “*clean alternative fuels*”, i.e. methanol, ethanol, CNG, LPG and hydrogen. However, as the debate progressed the emphasis shifted from alternatives to reformulated fuels, i.e. conventional gasoline whose composition has been modified to reduce exhaust emissions.

Contrary to President Bush's original proposals, the final version of the bill contains no mandate for the introduction of alternative fuels. Instead it describes performance criteria for "*Clean alternative fuels*" which may include:

- Methanol and ethanol (and mixtures thereof)
- Reformulated gasoline
- Natural gas and LPG
- Electricity and any other fuel which permits vehicles to attain legislated emission standards.

Since the emission standards set in the CAAA appear likely to be achievable by future conventional vehicles it is likely that "*conventional*" gasoline and diesel will qualify as clean fuels under certain specific circumstances.

The Act does make provision for a Clean Fuels programme which will apply from 1998 to fleets of 10 or more vehicles that are capable of being centrally refuelled (but NOT including vehicles that are garaged at personal residences under normal circumstances) which operate in areas which have problems achieving air quality standards. This programme mandates emission standards for these vehicles which are the same as those specified in California's Low Emission Vehicle (LEV) programme.

This part of the CAAA also specifies a pilot programme for the introduction of lower emitting vehicles in California, beginning in 1996. Under this programme 150,000 clean fuel vehicles must be produced for sale in California in 1996 and this figure will rise to 300,000 in 1999. These vehicles will initially be required to meet Transitional Low Emission Vehicle (TLEV) standards. These limits remain in force until 2000 when the LEV standards outlined above come into operation.