



INTERNATIONAL ENERGY AGENCY

AUTOMOTIVE FUELS FOR THE FUTURE

The Search for Alternatives

IEA AFIS



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FOREWORD

A world-wide search is underway for fuel alternatives to diesel and gasoline, which together provide 99 % of all road transport fuels. Do the available options offer clear advantages without disadvantages ? What fuels can and should we use in the future ?

The multitude of information sources and the vast range of unanswered questions about fuel production and use make this search extremely complex. The large number of criteria for measuring the performance of fuels further complicates the assessment process. Local emissions, greenhouse gas emissions, safety, the availability of raw materials as feedstock and, of course, cost need to be taken into account. Engine and fuel processing technology is evolving. Decisions taken today have to be viable tomorrow. In practice, no optimal fuel exists; the value of each choice has to be established on a case-by-case basis.

Drawing on its earlier series *Automotive Fuel Surveys*, the Automotive Fuels Information Service (AFIS) of the IEA Implementing Agreement on Advanced Motor Fuels has produced this study. It is published by the International Energy Agency. Distilling accumulated data from the extensive literature, *Automotive Fuels for the Future* offers a state-of-the-art assessment of the most important alternatives, liquid petroleum gas (LPG), natural gas, methanol, ethanol, hydrogen and dimethyl-ether (DME)) as compared to gasoline and diesel. It measures the fuel characteristics against distinct criteria for gauging environmental effects and their potential for reducing oil dependency and cost.

Designed for specialist and layman alike, *Automotive Fuels for the Future* is a balanced compendium of concise technical information. It offers decision-makers in industry and governments access to the key findings of the IEA/AFIS yearlong investigation.

Robert Priddle
Executive Director



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Hans Jørgen Koch
Director, Office of Energy Efficiency Technology and R&D

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TOWARDS THE FUELS OF THE FUTURE

WHY THIS BOOK?

Our societies devote much money and human energy to the ongoing search for ways to reduce energy consumption and road-traffic emissions. Although the topic is not quite in the forefront of parlour conversation, public awareness of the key forces driving the work — the negative effects of road traffic on our environment and concerns about energy security — reaches deeply into our cultures. Urban dwellers, for example, know about noxious vehicle emissions, and in many cities daily air-quality reports come along with the evening television news. The media regularly report developments in the great debate over climate change caused by greenhouse gas emissions. Prospective car buyers go to the showrooms with at least some inklings, that fuel economy and potential vehicle-generated pollution should have a place in the auto-purchase calculus. Governments actively use tax and other policies to steer fuel-choice decisions. Thus, efforts to develop technology and research on new fuel options respond to a lively social interest.

Around 600 million vehicles roamed the world's streets and highways in 1995, almost 80% of them passenger cars, the rest trucks and buses. The number probably will reach one billion before 2010. Vehicle use rises even faster than the vehicle stock; during the 1980s, road traffic in OECD countries increased by 40%, 3.5% a year, this was 3.5 times as fast as the vehicle fleet expanded. More than 99% of today's energy supply for road transport in OECD-countries stems from crude oil (69% gasoline and 30% diesel), while the most important alternative fuels, LPG (0.9%) and natural gas (0.05%) hold minuscule shares.

Thus, road traffic depends almost entirely on vehicles powered by fossil fuels. The pollution that comes with this fossil energy consumption is recognised around the world. Local air quality and its influence on public health, acidification and the greenhouse effect have become permanent areas of attention for decision makers.

This report, a summary¹ of a much larger study (1,2,3)², is intended to fill a gap. It concentrates on the available options for automotive fuel choices, their possibilities

1 The report draws on the first three volumes of the *Automotive Fuels Survey* (1,2,3), written by IEA/AFIS (Automotive Fuels Information Service), a series published on behalf of participants in IEA's Advanced Motor Fuels Implementing Agreement. Readers looking for more detailed information are advised to consult this series. More information is available under <http://www.iea-amf.vtt.fi/>. The *Automotive Fuels Survey* is based on an extensive survey of public literature. Because the information of the *Survey* is condensed in this report, distinctions which appear in the *Survey's* different sources — for example, differences in transportation distances for feedstocks — have become invisible. This is one reason why, as the reader will see later, data on the different fuels are presented in ranges rather than as point estimates. Choices had to be made on what to include, and simplifications have been unavoidable.

2 All references in the bibliography at the end of the book are numbered, and all source citations in the volume refer to these numbered entries.

and their constraints. It describes the most important characteristics of the different fuels and outlines a methodology for analysing them. It aims for a condensed but still balanced overview of the fuels currently under discussion — a “handbook” rather than an encyclopaedic study, and a guide to a continuously developing fund of information. The authors have borne in mind not only interested general readers but also decision makers in the automotive industry, the oil industry, government, consultancies and raw-material suppliers to the fuel industry, as well as other professionals.

HOW TO USE THE BOOK

The report has two quite different parts. Part A (Chapters 2-4), largely descriptive, presents information and data on the automotive fuels themselves and on important aspects of the different stages through which they move, from raw material (which could be crude oil, a vegetable or plain water!) through production and handling, and finally to consumption in a vehicle’s engine. Part B (Chapters 5-6) uses the information developed in Part A as a basis to compare the fuels on the grounds of local emissions, greenhouse emissions, the ability to reduce oil dependency and cost. It develops policy criteria (target levels for local emissions, for example) against which the fuels are measured. In a final section, it combines the results and defines the “ultimate” fuel or fuels that meet all the criteria simultaneously. The criteria, of course, are illustrative and arbitrary, although they make sense; they also serve to elaborate the methodology, which has robustness and adaptability to the needs of specific environments or objectives.

Readers with limited time may turn directly to Part B using Part A only for background, with perhaps a glance back at this chapter. The volume is not indexed, but a detailed table of contents will facilitate its use as a handbook. The authors apologise for an unavoidable plethora of technical terms, acronyms and abbreviations, all of which, if not clear from the text, receive full explanation in the Glossary at the back of the book.

SOME GENERAL POINTS

The Well-to-Wheel Concept

In a common misconception, people tend to focus on a fuel’s energy use or emissions only when it is burned or otherwise consumed in vehicle engines. The same misconception applies to considerations of fuel safety and fuel cost. Too little attention is devoted to the technology or the infrastructure that helped create the fuel and got it to the vehicle’s tank. A fair comparison of automotive fuels, by contrast, must take into account the fuel’s whole history, from raw material to energy output. For example, fuels that show very low pollutant emissions from the vehicle may emit mightily during their production phases. Fuels very suitable for use in combustion engines may be difficult and costly to transport and store.

A fuel's history resides in the complete “well-to-wheel” fuel chain³. The chain has five stages: feedstock production, feedstock transportation, fuel production, fuel distribution and, finally, vehicle use. This study looks consistently at the entire chain to examine all the aspects of fuel production and use, including feedstocks, energy consumption, emissions, safety, technology, costs and infrastructure.

The Fuels of Interest

This report compares the conventional and alternative fuels currently in use or under consideration and active research, with due recognition that some fuels need evaluation for different feedstocks. The list includes:

- Gasoline and reformulated gasoline from crude oil;
- Diesel oil and reformulated diesel oil from crude oil;
- Liquefied Petroleum Gas (LPG) from refineries and associated gas;
- Natural gas;
- Methanol from natural gas or cellulosic material;
- Ethanol from starch-rich or sugar-rich crops or from cellulosic material;
- Biodiesel (esterified oil from crops containing vegetable oil);
- Hydrogen by electrolysis of water; and
- Dimethyl ether (DME) from natural gas.

Alternative fuels may be blended with conventional fuels. Using blends enables a gradual increase of production capacity of the new fuel as well as the use of existing vehicle technology and distribution infrastructure. Methanol and ethanol may be blended with gasoline, and biodiesel with conventional diesel oil, in any mixing ratio. To distinguish clearly the characteristics of each fuel and to avoid blurring the picture, this report does not stress fuel blends or consider them in the same detail as the fuels themselves.

Local circumstances and issues determine fuel policies. Air pollution, for example, may take precedence over acid rain and require different fuel choices. Abundant gas reserves or the availability of large amounts of biomass in a given region may lead to

3 “Well-to-Wheel” is a slight misnomer, because the raw materials for biofuels do not come from wells; but the idea is clear.

fuel choices other than those in regions with abundant oil reserves. Many other factors may affect fuel policies in different regions or countries. This report cannot take all of these local effects into account, but its methodology has general applicability. Readers will find in it the keys to analysing their own situations.

Time

In assessing a fuel's usefulness in automotive applications, the outcome depends on time. Some fuels already have extensive use, while others remain as prototypes. Yet for long-term planning, fuels still not fully developed hold as much interest as those in or near current use. They, too, require evaluation because expectations for the future can influence current strategy.

This report deals with the effects of time by distinguishing two separate periods for the evaluation of automotive fuels. The "short term" extends to between one and five years from now; new fuels or technologies for introduction in the short term must already be fully developed. The "long term", by contrast, looks from 15 to 25 years ahead. In this perspective, new developments need not be ready for application but they must exist as prototypes; thus, known technical feasibility forms the main criterion for making assessments about the future.

Of course, knowledge about fuels and technology evolves with time. In this context, it should be kept in mind that the information collection that lead to the present assessment was closed in March 1998.

Technology

The main difference between today's fuels and those of the future lies in technological possibilities which may enable some fuels eventually to be applied on a large scale. Yet, it must be borne in mind, the technologies for using conventional fuels will develop as well. Increasingly stringent emissions legislation, for example, will result in reduced emissions from gasoline and diesel vehicles. Comparing alternative fuels against conventional fuels today becomes a comparison against a moving target, and alternatively fuelled vehicles will have to keep up.

Because the future is unpredictable, handling technological possibilities in a report like this becomes a delicate matter. One probably can say that technology on the market today may well develop further and current prototypes probably will gain maturity in the study's long term; but such generalisations can easily slip into excessive optimism. This report tries to avoid that stance. It remains rather conservative and cautious in its assumptions. Nevertheless, because technology for conventional fuels like gasoline and diesel has matured to a known extent while that for alternative fuels is still developing, a fuel comparison is never completely fair; some assumptions must enter about the future for the alternative fuels. Nor can one escape the constraining vision of the present. Technologies will change in currently unforeseeable ways; an exercise like this undertaken in ten years' time will look very different.

FUELS AND VEHICLES

Before embarking on the detailed descriptions of fuel characteristics in Part A, some introductory remarks will help set the stage and make the descriptions more quickly intelligible. These comments discuss engine types and rudimentary information about the fuels themselves.

Vehicle and Engine Technology

In *spark ignition* (SI) engines a spark ignites a compressed air-fuel mixture in the cylinder. Combustion starts at a single point, the spark plug. SI engines require electrical systems steered by their motor-management apparatus to obtain adequate spark timing. Modern SI engines have fuel-injection systems to control the air-fuel ratio accurately. SI engines have lower compression ratios (see below and Table 1) than *compression ignition* (CI) engines (diesel motors), which compress air in the cylinders until the temperature in the combustion chamber exceeds the auto-ignition temperature of the fuel, which then is injected in a very fine spray. Here, the motor-management system governs the timing and quantity of fuel injection. Ignition occurs after the fuel spray has formed a combustible mixture with the compressed air, with the ignition delay representing the time between fuel ignition and start of combustion. Combustion starts at a number of points simultaneously. The air-fuel mixture in diesel engines has a minimum auto-ignition temperature; a cold engine will not start if the compression stroke cannot achieve it, so a glow plug is used to raise the temperature before one engages the starter motor.

Table 1
Engine Types, Fuel Systems and Compression Ratios, by Fuel

| | <i>Engine Type</i> | <i>Fuel System</i> | <i>Compression Ratio Used</i> | <i>References</i> |
|--------------------|--------------------|--------------------|-------------------------------|-------------------|
| Gasoline | SI | mono | up to 11 | - |
| Diesel | CI | mono | 18 (DI) 22 (IDI) | [11] |
| LPG | SI | dual, mono | 11-13 | - |
| Natural gas | SI | dual, mono | 11-13 | [5] |
| Methanol | SI, CI, FC | FFV, mono | 9 (FFV) up to 19 (mono) | [13] |
| Ethanol | SI, CI | FFV, mono | 9 (FFV) up to 18 (mono) | [9] |
| Biodiesel | CI | mono (FFV) | similar to diesel | - |
| Hydrogen | SI, FC | dual, mono | 14-17 | [14] |
| DME | CI | mono | similar to diesel | - |

Sources: 1, 2. Other, fuel-specific references appear in the right column.

Notes: For engine and vehicle types, CI = Compression Ignition; SI = Spark Ignition; FC = Fuel Cell; mono = vehicles running on only one fuel; dual = vehicles with two fuel systems, able to switch between the two fuels; and FFV = Flexible-fuelled vehicle, able to run on two different fuels or a mixture of them.

Diesel engines have either of two types of fuel injection: direct injection (DI) and indirect injection (IDI). DI engines inject the fuel directly into the cylinder. IDI engines have a small combustion pre-chamber where combustion starts. IDI engines are less efficient but they allow operation at higher speed, produce less noise and use cheaper injection equipment.

The *compression ratio* of an SI or CI internal combustion engine is the ratio between the volumes of the combustion chamber at the beginning and at the end of the compression stroke. The higher the ratio, the higher an engine's efficiency, up to the point where increasing heat and friction losses start to counteract it. The maximum compression ratio for SI engines depends on the octane number of the fuel (see Glossary and Box 2, Chapter 2). The higher the octane number, the better the knock (uncontrolled combustion) resistance of the fuel and the higher the compression ratio possible.

In a *fuel cell*, a chemical reaction between hydrogen and oxygen (from air) generates electricity. Hydrogen fuel cells emit only water vapour and unused air. They produce no NO_x emissions because their operating temperature remains below that at which NO_x forms. Hydrogen may be either stored or produced on-board.

Dual-fuel vehicles run on one fuel at a time but can switch between two different fuels. Available fuel combinations for SI engines include gasoline-natural gas and gasoline-LPG. These vehicles have the advantage of not depending fully on the perhaps sparse distribution network of the “alternative” fuel, but they gain this advantage at the cost of carrying two on-board fuel systems. In CI engines, a diesel pilot injection system feeds a mixture of an alternative fuel and air into the cylinder, with a small quantity of diesel injected into the cylinder as the ignition source for combustion of the alternative-fuel and air mixture already present. Switching to 100% diesel oil remains possible. Diesel pilot injection can be used with LPG, natural gas, ethanol and methanol.

Flexible-fuelled vehicles (FFVs) can use two or even more fuels and mixtures of them — gasoline-methanol and gasoline-ethanol combinations, for example. Many diesel vehicles now on the market can operate on diesel-biodiesel mixtures without modifications to the vehicle; they are FFVs in all but name.

Exhaust Catalysts : Catalyst systems reduce pollutants in the exhaust gases. The two types currently in use are the two-way (oxidation) catalyst and the three-way catalyst. The two-way catalyst reduces vehicular CO and HC emissions. The three-way catalyst abates CO, HC and NO_x emissions. With a three-way catalyst, the engine's air/fuel ratio λ (lambda) cannot be chosen freely. It must be kept within a small range around $\lambda = 1$, at which CO and HC can be oxidised and NO_x reduced simultaneously. A λ sensor in the exhaust sends a signal to the fuel-management system which steers the air/fuel ratio. A two-way catalyst, however, can operate within a broad range of air/fuel ratios and therefore may be combined with “lean-burn” technology. Three-way catalysts work only with SI engines, but two-way catalysts may operate with both SI and diesel engines. A third type of catalyst, now under development and getting increased

attention, is the de-NO_x (or “denox”) catalyst to reduce NO_x emissions of diesel engines.

Some Fuel-Specific Comments

Gasoline is always used in SI engines, with a current maximum compression ratio of eleven. At higher ratios, the mixture in the combustion chamber ignites spontaneously, causing engine knock, which may lead to severe engine damage. Very recently, gasoline has come into consideration as a hydrogen carrier for fuel-cell vehicles. *Diesel* (diesel oil) burns in CI engines.

Pure *LPG* can function only in SI engines — a gasoline engine retrofitted for dual-fuel use, a dedicated gas engine or a heavy-duty diesel engine retrofitted with a spark-ignition system. For dual-fuel systems, a gasoline vehicle is fitted with a gas conversion kit and the spark-plug voltage of the engine increased. Presently available fuel-injection systems enable the use of three-way catalysts with LPG engines. Gas injection reduces the risk of backfire, a problem in older gas systems. Dedicated engines optimise LPG use with, most importantly, a higher compression ratio than their gasoline counterparts. Retrofitting diesel engines for LPG presents more difficulty because spark plugs must be mounted and the compression ratio reduced.

Natural gas has properties similar to LPG’s. Both are gaseous, have high octane ratings, and use similar engine technologies. Exhaust-catalyst durability remains a concern for natural gas vehicles, however, because the very stable methane molecules (the main component) in natural gas are difficult to oxidise in a catalyst.

Of the alcohols, *Methanol* finds applications in SI engines, CI engines and fuel cells. *Ethanol* resembles methanol in both SI and CI engines, but its higher carbon/hydrogen ratio makes it less useful in fuel cells. Methanol SI-engine vehicles are mostly FFVs able to run on any mixture with gasoline but optimised for a methanol-gasoline blend with 85% methanol (M85). Larger fuel flows, lower air/fuel ratios and the corrosivity of alcohols make some adjustments necessary to use alcohol fuels in conventional vehicles. High octane numbers allow higher compression ratios in alcohol engines than in gasoline engines. Poor cold-start behaviour is alleviated by using additives like gasoline or by heating the alcohol to enhance its evaporation.

The high octane number of alcohols also makes them very suitable for the high compression ratios used in diesel (CI) engines. Their low cetane number (see Glossary and Box 2, Chapter 2), however, means poor ignitability, which can be resolved by fuel additives, diesel pilot injection, spark plugs or glow plugs. In fuel-cell vehicles, methanol is re-formed on-board to produce hydrogen to generate electric power.

Biodiesel goes only into CI engines. That includes existing diesel engines, which do require some attention to dilution of engine oil and incompatibility with certain coatings and elastomers. More frequent lubrication-oil changes and the use of biodiesel-

resistant materials solve these relatively minor problems. In principle, vegetable oils as well as their esters (biodiesel) can blend in any ratio with diesel fuel. Blends of more than one vegetable oil or ester are also possible. The problems associated with blends are about the same as with pure vegetable oil (clogging of fuel injectors, for example) and pure biodiesel.

Hydrogen can be used in SI engines and fuel cells. It has a very high octane rating and ignites in air/fuel mixtures varying from lean to rich. These characteristics lead to very high engine efficiencies, because hydrogen needs no fuel enrichment and works in lean-burn engines with higher compression ratios than gasoline engines. For equal engine power, however, the volumetric flow of the air/fuel mixture is larger, a disadvantage which fuel injection, especially direct injection into the combustion chamber, can reduce. Until recently, hydrogen caused ignition problems: backfiring, premature ignition, engine knock and excessive in-cylinder pressure peaks due to the fuel's high combustion speed. Lean combustion and/or hydrogen injection solve these problems. Hydrogen can be injected as a high-pressure gas or as a liquid. The pressure makes the first of these problematic, and liquid injection puts high demands on the fuel pump, because it has to operate with the fuel at a very low temperature (-253°C).

Hydrogen-powered fuel-cell vehicles require completely different systems. The four most important components are the hydrogen storage tank, the fuel cell, the electric motor and the batteries. The fuel cell converts the hydrogen and produces electrical energy for the motor. Because the fuel cell may not be able to meet the motor's dynamic load changes, the batteries store excess electrical energy for use during peaks of demand.

Because of its high cetane number, Dimethyl ether (*DME*) suits diesel engines very well, with the same high compression ratio as diesel oil. Due to DME's lower calorific value and its lower density, however, the fuel system must be adapted to supply a higher fuel volume to maintain equal engine performance. Fuel-injection pressure in DME engines can be considerably lower than in diesel engines. Because DME is not compatible with rubber and elastomers, fuel system sealings need attention. DME's poorer lubrication properties may increase wear on moving parts like the fuel pump, but fuel additives can help reduce this problem.

PART A

A DETAILED LOOK AT AUTOMOTIVE FUELS

FUELS AND THEIR CHARACTERISTICS

FUELS FROM CRUDE OIL

Gasoline, diesel and liquefied petroleum gas (LPG) all originate from crude oil (see Box 1). In its unrefined form crude oil has little or no use; it realises its value only when refining separates, breaks down or combines its many different hydrocarbon components with other chemicals. After its extraction on land and off shore, gas and salt water are removed before the crude oil goes to a refinery, which distils it into a number of fractions and cracks the heavier automotive fuel fractions with large hydrocarbon molecules into smaller molecules in the gasoline and diesel boiling range to increase their yield. Re-forming light distillate, the fraction used for gasoline, produces a higher octane number. Diesel oil comes from the middle-distillate range. LPG is a mixture of different petroleum gases (propane and butane are the most important) released during crude-oil and natural-gas extraction (field LPG) and as a by-product of crude-oil refining (refinery LPG).

Gasoline

Gasoline holds by far the largest consumption share among road-transport fuels — 69% in the OECD area (10). In use for over a century, it has a world-wide production and distribution infrastructure; its large-scale use enables low prices and the development of dedicated equipment like refineries, vehicle engines, exhaust catalysts and a servicing infrastructure. Its relatively high energy density makes it very suitable for SI engines; but it has a lower octane number than other fuels used in such engines, which limits the compression ratios and thus the energy efficiency of gasoline motors relative to those which can burn higher-octane fuels.

Compared with other fuels, gasoline has average well-to-wheel energy consumption in light-duty vehicles (LDVs). Gasoline cars have relatively low well-to-wheel NO_x emissions and relatively high CO emissions. Reducing exhaust and evaporative emissions provides an important stimulus to reformulating gasoline, which simultaneously changes several parameters of conventional gasoline to obtain better fuel characteristics. Reformulation generally includes at least adding oxygenates like MTBE or ETBE (see the sections below on methanol and ethanol); reducing aromatics, benzene and olefins content; and reducing evaporation temperatures.

Both gasoline and diesel can be considered as safe fuels — not without risk, but over the years people have learned to handle them safely. They carry one considerable disadvantage: both are hardly biodegradable; spilled fuel may penetrate the ground and pollute soil and water.

Box 1

The Origins and Characteristics of Automotive Fuels
(See Box 2 for Concepts and Definitions)

A. Production Methods and Burning Qualities

| <i>Fuel/ Feedstock</i> | <i>Conversion Method</i> | <i>Energy Content (MJ/l)</i> | <i>Octane Number (RON)</i> | <i>Cetane Number</i> |
|--|--|--|--|--------------------------|
| Gasoline | refined from crude oil | 31.2 | 90-95 ³ 97-99 ⁴ | n.a. |
| Diesel | refined from crude oil | 35.7 | n.a. | 48-50 |
| LPG | | 24.2 ¹ 23.4 ² | 107.5 ¹ 112 ² | n.a. |
| Field | purification (separation of natural gas liquids), fractionation to LPG | | | |
| Refinery | by-product of crude oil refining, fractionation to LPG | | | |
| Natural Gas | no conversion; dried and purified as necessary | 23.3 ⁵ | 120 | n.a. |
| Methanol | | 15.6 | 110 | 5 |
| Natural Gas | steam re-forming of natural gas, conversion of synthesis gas to methanol | | | |
| Cellulose | gasification of raw material, conversion of synthesis gas to methanol | | | |
| Ethanol | hydrolysis of biomass to glucose, fermentation | 21.2 | 109 | 8 |
| Biodiesel | vegetable oil extraction, esterification | 32.8 | n.a. | 51-58 |
| Hydrogen | electrolysis of water | 8.9 | 106 | n.a. |
| DME | production of synthesis gas from natural gas, then oxygenation | 18.2-19.3 | n.a. | 55-60 |
| <p>Sources: 1, 2, 11, 12.</p> <p>Notes: 1. LPG 70/30 consisting of 70% propane and 30% butane. 2. Propane. 3. Regular. 4. Super. 5. Liquefied natural gas. n.a. = not applicable</p> | | | | |

| <i>Box 1 (continued)</i> | | | | | | | | |
|---|------------------|------------------|------------------------------|------------------------|----------------|-----------------|-------------------------------|----------------------|
| B. On-Board Storage and Safety Characteristics | | | | | | | | |
| <i>On-Board Storage</i> ¹ | | | <i>Safety</i> ² | | | | | |
| | <i>Mass</i> | <i>Volume</i> | <i>Combustion of Vapour:</i> | | | <i>Toxicity</i> | <i>Ground Water Pollution</i> | <i>Air Pollution</i> |
| | | | <i>in Open Air</i> | <i>in Closed Areas</i> | <i>in Tank</i> | | | |
| Gasoline | 46 kg | 68 l | * | -- | -- | ** | ** | *** |
| Diesel | 100 | 88 | -- | -- | -- | * | ** | *** |
| LPG | 180 | 154 | ** | ** | -- | * | * | * |
| Nat. Gas (CNG) | 240-490 | 360 | -- | ** | -- | -- | -- | * |
| Nat. Gas (LNG) | 140 | 180 | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| Methanol | 191 | 176 | -- | * | ** | *** | *** | ** |
| Ethanol | 165 | 151 | -- | * | ** | * | * | ** |
| Biodiesel | 117 | 100 | -- | -- | -- | * | -- | -- |
| Hydrogen (liquid) | 154-269 | 376-515 | *** | *** | *** | -- | -- | -- |
| DME | 147 ³ | 166 ³ | ** | ** | -- | * | * | * |
| <p>Sources: 1, 2, 12.</p> <p>Notes: 1. These columns compare the vehicle storage systems needed to carry the energy equivalent of 55 litres of gasoline, including the vehicle tank. The entries for gasoline show the weight (in kg.) and the volume (in litres) for this reference case. The entries for all other fuels are expressed as percentages of the gasoline reference figure.</p> <p>2. These columns indicate the relative safety and health risks of conventional and alternative vehicle fuels. Asterisks (*) show the risks: the more asterisks, the higher the risk. A double-dash (--) indicates that no risk exists in the situation.</p> <p>3. For DME, the vehicle tank (volume and weight) is not included. If it were, mass and volume would increase because DME requires a bulky and heavy tank.</p> | | | | | | | | |

Passenger cars can use plastic or metal gasoline tanks, but the material choice must be compatible with the fuel. Gasoline will dissolve or corrode some plastics and metals, especially when it contains added alcohol.

Diesel

Ranking second in usage, diesel oil commands 30% of the OECD road-transport fuel market (10), mainly in heavy-duty vehicles (HDVs) because the extra weight of a diesel (CI) engine compared to an SI engine, for a given power output, has less relative disadvantage in heavier vehicles. A diesel tank can be slightly smaller than a gasoline tank because of the higher energy content per litre and the more efficient diesel engine. Comparatively cheap and safe, diesel oil enjoys the same advantages of large-scale use as gasoline, with an even higher energy density. Yet its cetane number falls below those of other fuels suitable for CI engines.

Diesel oil has the lowest well-to-wheel energy consumption of all fuels and relatively low CO and HC emissions, but high well-to-wheel NO_x and particulate matter (Pm) emissions. The emission disadvantages have potential for improvement. A reduction of sulphur content, for example, reduces not only SO₂ emissions but also vehicular Pm emissions. As with gasoline, emission control provides an incentive for diesel oil reformulation, to reduce both sulphur content and fuel density.

LPG

LPG, the most common alternative fuel for SI engines, plays only a minor role in aggregate road-traffic energy consumption — 0.9% in the OECD area — but it commands a significantly higher share in some countries. In the Netherlands, for instance, it accounts for 12% of the energy used to propel passenger cars (4). Its price generally remains low because supply still exceeds demand. Its high octane number (especially that of propane) allows engines running on LPG to have higher compression ratios than gasoline engines and thus higher energy efficiencies. But LPG LDVs, mostly retrofitted gasoline cars, do not exploit this advantage and have sub-optimal engine efficiencies. Heavy-duty LPG engines have lower compression ratios than heavy-duty diesel engines.

LPG's well-to-wheel energy consumption falls below that of gasoline but above that of diesel. In LDVs, its well-to-wheel NO_x emissions approximate those of gasoline, but other emissions are lower. In HDVs its low particulate emissions stand out.

Gaseous at ambient temperature and pressure, LPG is stored as a liquid under moderate pressure (6-8 bar). On-board the vehicle, its pressure tank takes almost twice the space and over 1.5 times the weight of the tank needed for an equivalent amount of energy in gasoline. A pressure relief valve vents LPG when the pressure rises above 20 bar. The tank itself will burst only at a pressure over 100 bar. The LPG tank in a vehicle

must never be filled to more than 80% to 85% of its capacity, to leave sufficient space for expansion of the fuel.

Generally considered a safe fuel, LPG is heavier than air. With spilling or leakage, the vapour will therefore tend to stay at ground level where it may come in contact with ignition sources. Parking in underground facilities can be prohibited for this reason. LPG in air ignites more easily than gasoline and diesel but, because LPG tanks are designed as pressure vessels, fuel spills in accidents become less likely than from gasoline or diesel tanks.

NATURAL GAS

Natural gas (predominantly methane, chemical formula CH_4), the only fuel that needs almost no processing for automotive use, occurs by nature in the earth's crust. It requires only drying and removal of hydrogen sulphide (H_2S) from "sour" gas. Natural gas converted to synthesis gas ("syngas") becomes a feedstock for producing methanol and DME as well as for hydrogen recovery. Italy, Argentina, New Zealand, the Russian federation and the United States have significant natural-gas vehicle fleets, but otherwise it is not an important automotive fuel. It supplies only 0.05% of the energy used for road transport in the OECD area. Countries that already have natural-gas distribution grids can introduce it as a vehicle fuel relatively easily, but nations without such infrastructures will find them very costly to establish.

Like LPG, natural gas has a high octane number, which allows higher compression ratios and can raise the thermal efficiency of a dedicated engine by about 10% compared to a gasoline engine. Natural-gas engine efficiency is 15% to 20% lower than that of heavy-duty diesel engines, however (11). Well-to-wheel energy consumption compares with that of LPG (lower than for gasoline and diesel). Natural gas also has low well-to-wheel emissions, except for hydrocarbons that escape through natural-gas leaks throughout the fuel chain. Lighter than air, with a high ignition temperature, it has better safety characteristics than LPG, although a risk of explosion exists in closed spaces. Safety precautions are comparable to those for LPG tanks but stricter because of the much higher tank pressure.

Natural gas has a very low energy content under ambient conditions, but in liquid form it compares well with LPG. Its on-board storage usually takes place under high pressure, as compressed natural gas (CNG), and sometimes also at low temperatures, as liquid natural gas (LNG). Yet compression of the gas is energy-intensive and storage requires relatively heavy high-pressure vessels, which take up a lot of vehicle space.

CNG generally goes into heavy steel tanks at a pressure of 200-240 bar. These tanks need about five times the weight and four times the volume to reach the same driving ranges as gasoline vehicles. Composite or aluminium tanks for cars weigh roughly half as much as steel pressure tanks but are relatively expensive. LNG is stored on-board

Box 2

Concepts and Definitions

What is energy content? What are octane and cetane numbers?

Energy content: The lower calorific value (or heating value, thermal value, heat content or heat of combustion) measures the energy that becomes available when a fuel is burned; it provides the basis for calculating the thermal efficiency of an engine using that fuel. Energy content can be expressed in Megajoules per kilogram (MJ/kg) or per litre (MJ/l).

Octane number: An important property of fuels used in spark-ignition engines, the octane number indicates a fuel's knock resistance. Knocking is the spontaneous and uncontrolled ignition of the air-fuel mixture, with resulting pressure waves that can cause severe engine damage. Using a fuel with an octane number too low, an engine will knock at high loads. The maximum allowable compression ratio of an engine (and hence its efficiency) depends on the knock resistance of the fuel: The higher the octane number, the more knock-resistance and the higher the efficiency of the engine. Octane numbers are cited as either RON (research octane number) or MON (motor octane number).

Cetane number: In compression-ignition engines, by contrast, an important fuel characteristic lies in the *readiness* of the fuel to ignite spontaneously under the temperature and pressure conditions in the combustion chamber of the engine. Fuel injected into the cylinder just before maximum compression occurs must ignite within a few milliseconds — at any engine load and at every engine and fuel temperature. The cetane number expresses this propensity to ignite. A higher cetane number gives better starting properties and a shorter ignition delay (the interval between injection and ignition), which produces smoother combustion and a quieter engine.

What are the key storage and safety issues?

Storage: On-board storage design must deal with volume, weight and safety. The prospective driving range and the characteristics of the fuel determine volume and weight. The ratios between fuels shown in Box 1 depend considerably on how much energy one wants to store, because the *relative* mass of the tank drops with increasing tank volume. The more efficient the engine, the smaller the fuel tank needed for a given driving range — a significant effect, especially for hydrogen fuel-cell vehicles. Dual-fuel vehicles have two fuel systems, which increase vehicle weight considerably.

Liquid fuels can use steel or plastic tanks. Plastic's advantages over steel include larger fuel capacity because the tank can be shaped to fit exactly in the available space, no corrosion and 30% less weight. Gaseous fuels need steel, composite or aluminium tanks; the last two are lighter but more expensive.

Safety considerations include risk of explosion, fire hazard, toxicity to human beings and ecotoxicity. To minimise risks most countries have regulations for handling fuels, especially fuel transfers like vehicle refuelling, when human mistakes and therefore dangerous situations become most likely.

at a pressure of 2 to 6 bar and a temperature of -161°C . The insulated tank can hold the liquid for at least a week without any boil-off losses. An LNG tank with the same energy content as a diesel tank requires twice the space but has only 40% more weight.

A third storage alternative, adsorbed natural gas (ANG), remains in the research phase. With ANG the methane molecules are adsorbed to carbon molecules in a porous carbon structure — which takes 12% of the available volume — mounted inside the fuel tank. Amoco used a pressure of 35 bar for their experiments. At this low pressure, the mass of fuel and tank lies midway between those of CNG and conventional gasoline/diesel fuels. An ANG tank is relatively cheap and safe, and very suitable for home-refuelling applications because of the low pressure. Some problems remain: refuelling takes too long and produces a lot of heat; and the carbon surface deteriorates from repeated bondings with methane, in a way that reduces its bonding properties.

METHANOL

Methanol (CH_3OH) is an alcohol usually made from natural gas. The first step in the production process uses steam re-forming to convert the natural gas to synthesis gas and shift this “syngas” to the required CO/H_2 ratio ($\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ and $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$). In a second step, and after removal of impurities, carbon oxides and hydrogen are catalytically reacted to methanol ($\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}$ and $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$).

Methanol production from biomass (*i.e.* cellulosic material, mostly wood) is technically but not yet commercially feasible. It converts the feedstock into syngas and then into methanol. The raw material must first be prepared by milling, grinding and drying. The syngas comes from gasification — essentially combustion with a balanced supply of oxygen to yield carbon monoxide and hydrogen rather than the normal combustion end products, carbon dioxide and water. The syngas is formed partly by oxidation of the biomass and partly by steam re-forming (pyrolysis). The raw syngas then receives treatment similar to the production of methanol from natural gas.

Methanol costs more than gasoline and has a lower energy density but a quite high octane number. A liquid fuel, it finds uses mostly in mixtures with gasoline for flexible-fuelled vehicles (FFVs) with SI engines. CI engines in HDVs can use almost-pure methanol, but its cetane number is low, which requires adaptations (ignition assistance or additives). With its lower energy density, methanol, which is stored like gasoline, requires a fuel tank 75% larger than and roughly twice as heavy as a gasoline tank for a given driving range. Fuel systems need adaptation with materials resistant to the wear, corrosion and chemical effects of alcohols. The cold-start properties of alcohol fuels are relatively poor; during evaporation, methanol uses about three times as much energy as gasoline.

Methanol also is the most common fuel for fuel-cell vehicles although, in principle, any hydrogen-containing feedstock (including gasoline and diesel oil) could serve.

Because fuel cells consume hydrogen, an on-board re-former produces hydrogen from methanol, with CO and CO₂ as by-products. In still another role, methanol is reacted with iso-butylene to form MTBE (methyl tertiary butyl ether), an anti-knock component in gasoline (up to 20%) which replaces lead-containing additives.

Methanol's well-to-wheel energy consumption is relatively high, especially when it originates from biomass. Well-to-wheel hydrocarbon emissions also are high, particularly for methanol from natural gas. Well-to-wheel CO₂ emissions for methanol from biomass, however, can be very low. Paradoxically, its slow evaporation provides one advantage: alcohols have lower evaporative emissions than gasoline.

ETHANOL

Although very similar to methanol in its properties, ethanol usually comes from biomass — crops rich in sugar, starch or cellulosic material — rather than from natural gas. Its manufacture involves the fermentation of sugar, using yeast. Because sugar (glucose) occurs as such in only very few plants, larger carbohydrate molecules have to be cracked by hydrolysis to fermentable sugar, after the raw material has been size-controlled by splintering and milling. Varied hydrolysis techniques reflect the most important differences in production methods required by different feedstocks. Most of the glucose can be extracted directly from sugar-rich plants, which demands no or only a very mild hydrolysis; the starch-rich crops yield to available technology for enzymatic hydrolysis; and cellulosic materials require acid hydrolysis.

Ethanol costs three to five times as much to produce as gasoline, depending largely on feedstock costs. Both SI and CI engines use it and, like methanol, it mostly enters into mixtures with gasoline—both as a fuel and, after conversion into ETBE (ethyl tertiary butyl ether), as an anti-knock additive; its renewable origins in biomass provide the main reason for its use in place of MTBE. On-board storage resembles methanol's; it requires a tank 50% larger and 65% heavier to deliver a gasoline-equivalent amount of energy. Ethanol's energy density is higher than methanol's but still low compared to gasoline and diesel. Its slightly lower octane number explains in part why it offers less energy-efficiency enhancement than does methanol (11). Ethanol, especially when made from cellulosic material, shows very high well-to-wheel energy consumption, but because it comes from biomass it yields lower well-to-wheel CO₂ emissions than gasoline and diesel. It produces low CO and HC emissions compared with gasoline LDVs but high ones compared with diesel HDVs.

As regards safety, both methanol and ethanol have a larger range of ignitable air-fuel mixtures than gasoline or diesel. At ambient temperatures, alcohols can easily form an explosive vapour above the fuel in the tanks. In accidents, however, alcohols present less danger than gasoline because their low evaporation speed keeps alcohol concentration in the air low and not explosive. Methanol is toxic when consumed or inhaled, but ethanol (consumption alcohol) is not harmful when taken moderately. Both methanol and ethanol are biodegradable.

BIODIESEL

“Biodiesel” designates a group of esterified vegetable oils produced from different oil-containing crops, most importantly rapeseed, soybean, sunflower and palm. In common parlance, abbreviations like “RME” — for rapeseed methyl ester, the variant for which the most data exist — are used to describe these esterified oils. Esterification offers a low-cost way to transform vegetable oil molecules into molecules similar to the diesel hydrocarbons, although costs of such biodiesels exceed those of fossil diesel. With properties very similar to those of fossil diesel, biodiesel can go almost directly into existing diesel vehicles and it mixes with fossil diesel in any ratio; its energy content is a little (about 8%) lower, but it has higher fuel density and better ignition qualities with its higher cetane number.

Biodiesel production begins with pressing the crop, which yields a liquid oil fraction to be converted and a first by-product, oil cake, used as cattle feed. After filtering, esterification provides a low-cost way to transform the large-branched molecule structure of the extracted oils into smaller, straight-chained molecules similar to the hydrocarbons in the diesel boiling range. During esterification, the addition of a monovalent alcohol, usually methanol, replaces the trivalent alcohol glycerine, which gives methyl ester and releases glycerine, a second by-product used in the pharmaceutical and cosmetics industries.

Well-to-wheel energy consumption of biodiesel is higher than for fossil diesel but generally lower than for gasoline. Well to wheel emissions are very similar to diesel emissions: high for NO_x and particulates but relatively low for CO and hydrocarbons; CO₂ emissions remain low because biodiesel comes from biomass.

Biodiesel can be handled and used safely. Experience in handling stems from the oils used in the food sector and the esters employed as feedstocks in the detergent, cosmetics and soap industries. Biodiesel causes less health risk to humans or animals than fossil diesel and present less danger to the environment because of its biodegradability.

Stored like diesel fuel, biodiesel needs approximately 15% more fuel weight than diesel fuel for equivalent vehicle ranges, but tank volume has to increase by only 9%. Deposits generated by biodiesel require more frequent filter replacements and shorter tank-cleaning intervals, and elastomers must be biodiesel-resistant. If the biodiesel is RME, protection of the vehicle’s exterior from spill damage during refuelling calls for RME-resistant coatings.

HYDROGEN

Hydrogen, a gaseous fuel, can come from almost any hydrogen-containing feedstock. The two main ways to produce it involve electrolysis of water and steam re-forming or gasification of a hydrogen-containing raw material. Hydrogen by-products in the chemical industry provide a third resource. Natural gas provides the most important

feedstock for hydrogen production by steam re-forming, which converts natural gas to syngas, from which carbon dioxide and carbon monoxide are removed. Other feedstocks for steam re-forming include LPG and naphtha. Heavy oils, coal and potentially biomass may be converted into hydrogen through gasification.

Electrolysis splits water into its constituents by passing an electric current through an electrolyte, which is why electricity production plays an important role with respect to costs, environmental aspects and energy consumption. Using electricity generated with renewable energy like hydropower or wind for the electrolysis of water results in very low emissions, but electricity from a coal-fired power station results in relatively high emissions. The analysis of this Report on hydrogen as a fuel focuses exclusively on hydrogen produced by electrolysis. It has the highest well-to-wheel energy consumption of all fuels, especially in the production stage. Well-to-wheel emissions depend heavily on the production method, and vehicle emissions can be neglected, except for NO_x emissions from combustion engines.

Because hydrogen's energy content on a *volume* basis is relatively low, on-board storage needs big tanks. Hydrogen does have a high energy content per unit of *mass*, however, almost three times that of gasoline, and a high octane number; a hydrogen engine could have better thermal efficiency than its gasoline counterpart. SI engines and fuel cells (which convert it into electric energy) can use hydrogen, but both fuel and vehicles are more expensive than conventional ones.

Two different methods for on-board storage now receive active consideration: hydrogen storage in hydrides and liquid hydrogen. A third option, high-pressure, gaseous on-board storage, has practical implications fatal for vehicle use because the tank (200 bar) would have twenty times the volume of a gasoline tank.

In a hydride, hydrogen is chemically bound to a metallic material. Although the system has an acceptable storage volume, the mass (weight) remains at about 20 times that of a gasoline storage system. Moreover, extracting hydrogen from the hydride requires energy, and hydride storage capacity shows great sensitivity to certain pollutants like water, oxygen, nitrogen and sulphur compounds.

Liquid storage of hydrogen weighs approximately 1.5 times as much as gasoline storage and has a volume about four times as great. The storage temperature, -253°C , requires an isolated vehicle tank. With super isolation and a tank pressure of five bar, it is possible to avoid venting for three or four days, after which evaporative losses remain at less than 1% per day. Most cars will get sufficiently frequent use to avoid these losses.

Hydrogen requires very low ignition energy and has very wide flammability limits. Safety thus presents an issue in closed spaces and for on-board storage, but adequate measures can prevent accidents. Safety parameters resemble those of conventional fuels in open environments because hydrogen rises when it is released into the open air, but in closed spaces hydrogen is more dangerous. It can burn in air mixtures ranging from very lean — with excess air — to very rich, and its very high flame-propagation

speed gives the combustion an explosive character. A spark from a light switch, for example, can start the combustion process.

Safety is also an important issue for on-board storage of liquid hydrogen. As noted above, when a vehicle is not used for a time some hydrogen evaporates because tank isolation cannot be perfect. The necessary venting requires measures to avoid ignitable mixtures of hydrogen in the air. Safety in accidents presents no problem. Adequate measures can reduce the risk of damaging the vehicle tank during collisions, and if tank damage does occur the hydrogen evaporates very quickly. With hydride storage, no hydrogen can escape in accidents.

DME

DME (dimethyl ether) has emerged only recently as an automotive fuel option. Its manufacture, very similar to methanol production, uses natural gas or biomass feedstocks to form syngas just as for methanol, then forms DME in a process called oxygenate synthesis. In handling and use it resembles LPG: it too is a gas at ambient conditions and it can be stored as a liquid under moderate pressure (six bar), with safety precautions about the same as those for LPG. With an energy density about half that of diesel oil, it needs big on-board storage tanks for equivalent driving ranges. Its high cetane number (higher than diesel) makes DME very suitable for CI engines, and its engine efficiency competes with that of diesel fuel. DME's volatility gives it an advantage over diesel oil in air/fuel-mixture preparation. DME is more expensive than gasoline and probably will remain so, but in the long term it may well become price-competitive with diesel.

Because DME has only recently come under consideration as an automotive fuel, data on its energy consumption and emissions are scarce. One can assume that its energy consumption in production approximates that of methanol. Its vehicular energy consumption in LDVs falls significantly below that of gasoline. Data on DME vehicle emissions range between very low on all components to equivalence with diesel for CO and HC and equivalence with gasoline for NO_x and Pm. DME has no toxicity for humans but it does irritate the eyes and the respiratory system.

On-board, DME can be stored like LPG. Experiments have used a tank pressure of 9 bar, with a pressure-relief valve necessary to avoid excessive tank pressures. For equivalent energy content, DME tank loads will have about 66% more volume than gasoline tanks and weigh about 47% more. The fuel supply pump has to increase fuel pressure to 12 to 30 bar in order to avoid vaporisation of DME in the fuel lines.

WELL-TO-WHEEL ENERGY CONSUMPTION AND EMISSIONS

Against the background of the preceding chapter, this one develops an analysis of the well-to-wheel chains of the fuels under review, in two key dimensions — their overall consumption of energy, on the one hand, and their propensities to produce both local and greenhouse-gas emissions, on the other. Juxtaposing these two aspects of fuel performance gives some sense for whether they present trade-offs. Would a fuel switch from conventional to one or more alternative fuels in a search for less energy intensity help, hinder or have little effect on improving emissions patterns? Alternatively, what consequences for energy use might develop from fuel choices oriented chiefly towards emissions reduction? In either case, what are the technical constraints? Chapter Four takes up the cost factors.

For both consumption and emissions, the analysis follows a building-block approach. It looks successively at the five stages of the well-to-wheel chain for each fuel — feedstock production, feedstock transport, fuel production, fuel distribution and vehicle use — to develop a fund of information with which to estimate overall well-to-wheel consumption and emissions. For ease of comparison with conventional fuels, it casts the results in their terms: gasoline represents the reference fuel for LDVs and diesel the reference for HDVs.

ENERGY CONSUMPTION, STAGE BY STAGE

For conventional fuels, vehicles themselves take by far the largest part of well-to-wheel energy use, and, as Table 2 shows, vehicular consumption is on the same order of magnitude for all the fuels. Differences in well-to-wheel consumption stem predominantly from other stages of the fuel chain. For some of the alternative fuels, either feedstock production or feedstock conversion holds the first place. Feedstock production for biomass-based fuels generally devours more energy than for fossil fuels. Feedstock conversion shows relatively high energy use for methanol from natural gas, fuels from biomass and hydrogen. Feedstock transport and fuel distribution play a minor role for all fuels.

No single figure can adequately describe the well-to-wheel consumption of each fuel. Different situations cause differences in fuel chains. Crude oil for European refineries, for example, may come from either the Middle East or the North Sea, whose proximity reduces energy consumption for feedstock transportation. Differences in crude oil composition and the final fuel quality required may generate differences in energy use at the refinery. Dispersion in energy-use patterns can be even larger for biomass production and conversion. Local climate, fertiliser use, transportation distance and

allocation of energy consumption to by-products represent just a few examples of factors that influence the well-to-wheel chains of biomass-based fuels.

The data used here (see Table 2) stem from a number of publicly accessible references, each with its own background. The presentation selects minimum and maximum values from the mass of available data, to offer a range estimate for the energy consumption of each step of the fuel chain. In individual, special cases, deviation from these figures remains possible, but these ranges reflect most of the actual well-to-wheel fuel chains as they appear around the world. Note also that energy consumption is not split between renewable and fossil energy; only totals appear. Moreover, because this report uses existing data, the energy consumption figures depict a conservative view based on current technology. Technological developments likely will reduce energy consumption in all steps of the fuel chain, but the analysis makes no speculations about such future events.

Feedstock Production

Energy consumption during production of crude oil, field LPG and natural gas occurs on the production platform. For crude oil, it includes the stabilisation of the crude by separation of LPG and other light gases, usually using wet gas and a small amount of diesel oil to supply the necessary energy. Natural gas flaring creates an important energy loss during crude oil and natural gas extraction. Exploration and drilling play only a small role, but low-pressure oil reservoirs do require energy to extract the crude.

For biomass-derived fuels, cellulosic material may come from natural forests, forest plantations or agriculture (residues from farming or purpose-grown crops). Energy consumption depends on the origin of the biomass. For wood, it consists of energy used by machinery and embodied in fertilisers, agrochemicals and young plantings. For agricultural crops, farm machinery plays some part, but fertilisers, agrochemicals and seeds take the largest share of energy input⁴.

Feedstock Transportation

Crude oil, the raw material for gasoline, diesel and refinery LPG, moves either by pipeline or by sea in large tankers, and the energy required for such transport depends strongly on the distance between the extraction site and the refinery. Crudes extracted near centres of consumption have a clear advantage over those from farther away. Field LPG goes to terminals in dedicated LPG tankers.

⁴ For hydrogen, this report limits itself to that produced by electrolysis of water, currently the most common source of industrially produced hydrogen (8). It therefore ignores energy consumption in producing other hydrogen-containing feedstocks such as natural gas or biomass.

Table 2
Energy Consumption Along the Well-to-Wheel Chain

| <i>Fuel</i> | <i>Feedstock Production</i> | | <i>Feedstock Transport</i> | | <i>Fuel Production</i> | | <i>Fuel Distribution</i> | | <i>Vehicle</i> | | <i>Well-to-Wheel</i> | |
|--------------------------------|-----------------------------|-------------------------------------|----------------------------|-------------------------------------|--------------------------|-------------------------------------|--------------------------|-------------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| | <i>MJ/GJ¹</i> | <i>Rel. to Gasoline²</i> | <i>MJ/GJ¹</i> | <i>Rel. to Gasoline²</i> | <i>MJ/GJ¹</i> | <i>Rel. to Gasoline²</i> | <i>MJ/GJ¹</i> | <i>Rel. to Gasoline²</i> | <i>LDV¹⁰</i> | <i>HDV¹¹</i> | <i>LDV¹⁰</i> | <i>HDV¹¹</i> |
| Gasoline | 30-62.4 | 100 | 7-8.2 ⁴ | 100 | 93-135 | 100 | 2-15 | 100 | 100 | ND | 100 | ND |
| Diesel | 30-58.7 | 94-100 | 7-7.7 | 94-100 | 50-53 | 37-55 | 1.9-10 | 67-95 | 78-96 | 100 | 75 | 100 |
| LPG | | | | | | | | | 91-99 ⁹ | 109-114 ⁹ | | |
| Field | 50-52.9 ³ | 85-167 | 7.3 | 89 | 0 | 0 | 13.1-30 | 200-655 | | | 83-92 | 105-109 |
| Refinery | 30-81.4 | 100-130 | 7-10.6 ⁵ | 100-129 | 87-100 | 74-90 | 13.1-25 | 167-655 | | | 89-102 | 117 |
| Natural Gas | 30.9-50 | 50-167 | 0 ⁷ | 0 ⁷ | 0 | 0 | 30-90 | 600-1500 | 84-103 | 111-140 | 88-91 | 113-116 |
| Methanol | | | | | | | 10-22 ⁹ | 133-500 ⁹ | 87-96 ^{9, 12} | 97-113 ^{9, 12} | | |
| Natural Gas | 30 ³ | 100 | 0 ⁷ | 0 ⁷ | 400-531 | 296-459 | | | | | 110 | 132 |
| Cellulose | 44-130 | 71-433 | 27-30 ⁶ | 329-429 | 337-1000 | 291-741 | | | | | 110-165 | 135-199 |
| Ethanol | | | | | | | 8-10 ⁹ | 67-400 ⁹ | 85-103 ⁹ | 98-105 ⁹ | | |
| Cellulose | 54-180 | 180-600 | 15-30 ⁶ | 214-429 | 1060-1880 | 917-1393 | | | | | 176-269 | 224-283 |
| Sugar/Starch | 271-360 | 434-1200 | 15 ⁸ | 183-429 | 305-870 | 317-809 | | | | | 117-151 | 143-207 |
| Biodiesel (RME) | 300-415 | 665-1000 | 10-20 | 122-286 | 89-470 | 92-406 | 5-10 | 67-250 | 78-96 | 95-105 | 100-116 | 119-138 |
| Hydrogen (electrolysis) | 0 ⁷ | 0 ⁷ | 0 ⁷ | 0 ⁷ | 860-2730 | 637-2022 | 620-1080 | 4133-7200 | 83-85 | ND | 178-346 | ND |
| DME | ND | ND | 0 ⁷ | 0 ⁷ | ND | ND | 10 | 167-280 | 104 ¹³ | ND | ND | ND |

Sources: 1, 2, 6, 8. **General Notes:** The figures in this table, while approximately consistent, have been drawn from several different sources with different analytical starting points. Consequently, the correspondences among the entries are not exact and one cannot calculate directly from the absolute values to the percentages (index numbers), or obtain the numbers in the « Well-to-Wheel » columns directly from those to the left. ND = No data or insufficient data.

Numbered Notes: 1. Expressed in terms of MJ per GJ of each fuel. 2. Expressed as a percentage of the value for gasoline, *i.e.* an index number, where Gasoline = 100. 3. For extraction and processing. 4. Or 1% to 1.5% of the energy of crude oil transported from the Middle East to Europe. 5. North Sea to UK terminal. 6. Wood transport of 50 km. 7. No entry is included. For hydrogen, water for hydrolysis is assumed to have no feedstock or transport cost. Natural gas transport is included under fuel distribution. Methanol and DME production are assumed to occur at the natural gas recovery site. Elsewhere in the table, entries of « 0 » in fact signify values of zero. 8. Wheat transport of 260 km. 9. Where data do not permit breakdowns of the different origins of LPG, methanol and ethanol, the entries in the rows containing the main headings relate to those fuels from all their origin feedstocks. 10. The reference vehicle is a gasoline-equivalent LDV and the figures are expressed as percentages of fuel consumption therein. 11. The reference is a diesel-equivalent HDV and the figures are expressed as percentages of fuel consumption therein. 12. The figures relate to a mixture of methanol and gasoline with 85% methanol (M85) for LDVs, and to pure methanol (M100) for HDVs. 13. This figure relates to a single-vehicle test and the reference is a diesel LDV.

Natural gas usually gets processed (as far as necessary) at the gas production site, so no feedstock transport intervenes; subsequent passage to market falls under the rubric of fuel distribution. The same points apply to liquid fuels produced from remote natural gas. This report assumes that methanol and DME production occur at the natural gas recovery site, because it is more energy-efficient, as is transporting them as liquids rather than shipping the gas feedstock itself⁵.

Compared to liquid fossil fuels, cellulosic material (wood) is voluminous and often has a high moisture content, which give the feedstock relatively low energy density and relatively high energy consumption during transportation. Distance thus plays an important role here as well, and most cellulosic material gets converted to fuel near its production location. Road transport predominates, as it does for agricultural products (feedstock for ethanol and biodiesel), also usually over short distances.

Fuel Production

Refining crude oil into finished products requires energy — electricity, fuel and steam. The amount varies among refineries, depending on their complexity, but in general a refinery uses energy equal to about 8% of the energy content of product output. Diesel oil needs less processing than gasoline; its production consumes only 37% to 55% of that of gasoline. Refinery energy consumption has recently trended upward because reformulated gasoline and desulphurised diesel oil take more production energy than their conventional counterparts. Refinery LPG is a by-product or co-product, and part of the refinery's energy usage can be assigned to it. Estimates place that share at slightly less than gasoline's because not all refining processes are involved.

Energy consumption of producing natural gas is almost negligible. Its processing, if any, consists of drying and cleaning (removal of hydrogen sulphide). Field LPG also needs almost no processing. Energy use attributable to both these fuels is included in feedstock production in Table 2.

Converting natural gas to methanol uses three to five times as much energy as crude oil conversion to gasoline⁶. Making methanol from cellulose takes three to seven times as much. Production of ethanol also costs more than gasoline in energy inputs. Conversion of cellulosic material (wood) to ethanol consumes nine to 14 times the energy of crude oil conversion into gasoline, but for agricultural products whose hydrolysis requires less energy, the multiple is three to eight. In both cases, most of the energy

5 Natural gas produced at remote locations may move to the market as liquefied natural gas (LNG) in specially built seagoing vessels. Liquefaction is energy-intensive, and energy consumption of LNG transportation by sea reaches 19 MJ/GJ gas per 100 km (1). This report does not further address LNG transport because it accounts for only a limited share of worldwide natural gas transportation. The most prominent example involves LNG shipping of Malaysian off-shore gas to Japan.

6 The reader will note that DME is not mentioned in this subsection and others. The reason is that data on the conversion of natural gas to DME are not available; but a good working assumption puts its energy use in production — and its total well-to-wheel energy consumption — at about the same as for methanol from natural gas.

used in ethanol production involves milling, hydrolysis, by-product drying and distillation; fermentation requires no energy. The sugar/starch production process based on farm products yields a by-product (animal-feed) energy credit of 90-160 MJ per GJ ethanol (6, 8), because it represents energy use avoided in other animal feed production.

The energy needed to process biodiesel depends strongly on the energy source. Using straw instead of a fossil fuel calls for a much lower *net* energy input — less than for gasoline — because the energy content of straw is considered as internal to the system. (The same applies to producing alcohols from biomass.) Nevertheless, firing biodiesel production with straw on a large scale becomes an unrealistic option, and turning to a fossil fuel (natural gas) raises the energy input to about three times as much as for gasoline.

Electrolysis of water to hydrogen is very energy intensive and one must look to the power plant and its efficiency to measure how much so. What powers the power station — a hydro source, coal, oil or natural gas? Hydrogen produced with hydropower electricity requires 0.86 MJ of *renewable* energy per MJ as hydrogen. If the electricity comes from a natural gas power plant the energy need per MJ hydrogen rises to 2.73 MJ natural gas. Thus, the energy-intensity range for producing hydrogen becomes wide, at some six to twenty times that of gasoline.

Fuel Distribution

Energy consumption in distribution depends on the distances between production sites and refuelling points, the transport modes and the energy consumed by vehicle refuelling itself. Evaporative losses can also occur for some fuels. Distribution of gasoline follows a chain: from refineries to terminals by ship or pipeline, transfer to road tankers, haulage to service stations and finally vehicle refuelling. Diesel oil moves very similarly, but it requires less energy per unit of energy transported because diesel has a higher energy content and less evaporative loss. Biodiesel distribution is about the same as for diesel oil, perhaps taking slightly more energy because of the fuel's somewhat lower volumetric energy content and because road tankers may have to travel greater distances from a less-developed network of production sites and terminals. LPG distribution requires more energy than gasoline. Pressurisation to liquefy it plays the biggest role; others include LPG's lower calorific value per litre, the need for heavier pressure vessels during transport and a constraint on LPG road tankers, which may not be filled to more than 85% of capacity⁷.

The energy consumption figures for natural gas distribution in Table 2 cover transportation by pipeline from production sites to refuelling stations, with longer assumed distances than those from refineries to refuelling stations. Other possible scenarios are

7 DME and LPG distribution are similar, and the lower relative distribution figures in Table 2 for DME copy the LPG values, but only for transport from terminal to service station. They also ignore DME's slightly lower volumetric energy density.

discussed above, in the subsection on feedstock transport. The energy consumption of natural gas transport by pipeline consists of energy for the compressors that push the gas; gas leaks (an energy loss of between 0.1% and 0.5% in industrialised countries); and compression at service stations to CNG (58% to 78% of the total).

As regards the alcohols, methanol can move to market in much the same way as gasoline and diesel oil. A liquid fuel, it requires no extraordinary handling precautions except corrosion-resistant materials and prevention of water contamination. Its distribution uses 1.5 to 5 times as much energy as gasoline distribution, for two reasons. First, it has less energy content. Second, it probably has to travel longer distances — from natural gas recovery sites if they are its source or, for methanol from biomass, from a limited number of production sites to a limited number of refuelling stations. More or less the same considerations apply to distributing ethanol. Its energy content is higher than that of methanol but still lower than those of gasoline and diesel. The range of figures in Table 2 arises mainly from different assumed transportation distances.

Distribution of hydrogen includes liquefaction, (sea) transport of the liquefied hydrogen and the final leg to fuelling stations. Liquefaction of hydrogen is quite energy intensive (430 MJ electricity per GJ liquid hydrogen), and evaporative losses occur. Hydrogen costs 40 to 70 times as much energy as gasoline to distribute.

Energy Consumption in Vehicles

Vehicle mass and engine size count most here. The energy consumption of alternatively fuelled vehicles thus requires comparison with their conventional counterparts. Gasoline provides the reference for LDVs and diesel oil that for HDVs, with comparisons made on the basis of energy consumption per vehicle-kilometre travelled (MJ/vkm). As noted at the outset, the energy consumption of vehicles powered by internal combustion engines lies in the same order of magnitude for all fuels, with the biggest difference smaller than a factor of 1.5.

Passenger cars ingest between three litres of gasoline per 100 kilometres for fuel-efficient prototypes and approximately 20 litres per 100 kilometres for large cars, or between one and 6.2 MJ/km. Higher octane numbers enable higher vehicle efficiencies but they also require more energy in fuel production. With present production techniques, the optimal octane number (RON) is 95, the octane number of European regular gasoline. With their higher compression ratios, diesel engines have greater efficiency. Diesel LDVs consume 78% to 96% of their gasoline-powered counterparts. Similarly, cars running on biodiesel can have up to 20% more energy efficiency than comparable gasoline vehicles. Much the same probably applies to LDVs using DME; the available data, for only a single DME car, show it comparable to its diesel counterpart. DME-fuelled HDV engines reportedly have energy efficiencies similar to diesels, but no figures for them are available.

LPG passenger cars need less energy per vehicle-kilometre than gasoline cars. Most LPG passenger cars are dual-fuel, converted gasoline cars, so their improved energy efficiency does not result from higher compression ratios possible with dedicated LPG engines. It arises first because, unlike gasoline engines, these motors do not need to add an excess of fuel at cold starts or at full load, and second because LPG has a higher octane number, which enables advanced ignition timing without the risk of engine knock. HDVs running on LPG are less energy-efficient than diesel HDVs, however, because diesel engines have higher compression ratios and on-board LPG tanks weigh more.

Natural gas engines can operate with higher compression ratios than gasoline engines but, again, with the disadvantage of greater fuel-tank weight as compared with conventional fuels. Nevertheless, the efficiency gain for dedicated natural gas cars with increased compression ratio amounts to 10% to 15%, and gasoline cars retrofitted for natural gas show an energy consumption comparable to the gasoline vehicles. As with LPG, HDVs using CNG have 10% to 40% less energy efficiency than their diesel counterparts. Diesel compression ratios can be higher, and the extra mass for CNG fuel storage in HDVs can go up to 1.6 tons for high-pressure steel tanks.

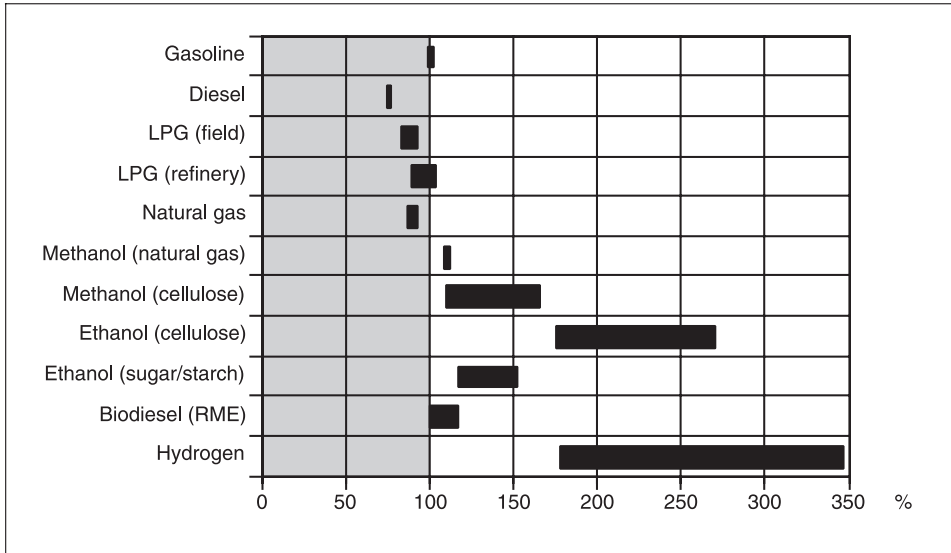
The data on methanol passenger cars refer only to flexible-fuelled vehicles, which are slightly more energy-efficient running on methanol (M85) than on gasoline. Heavy-duty methanol (M100) vehicles match their diesel competitors. While data on ethanol in LDVs with SI engines remains limited, the extant studies show comparable or slightly better fuel efficiency than in gasoline counterparts. Ethanol HDV energy consumption approximates that for diesel HDVs.

The energy efficiency of a hydrogen-fuelled internal combustion engine exceeds that of a gasoline engine of the same size. These engines can have higher compression ratios, partial loads do not require throttling and cold starting does not demand enrichment of the air/fuel mixture. Data on hydrogen HDVs is scarce. Fuel-cell vehicles (which use hydrogen) remain in a very early stage of development, making it hard to predict what their energy consumption might be when they mature. Indications are good. Research has found that the energy efficiency of a fuel-cell vehicle without regenerative braking reaches 42% to 48%, from tank to wheels; with regenerative braking, the range goes up to 46% to 55%. Both sets of numbers compare well with the 20% to 35% of gasoline and diesel vehicles.

WELL-TO-WHEEL ENERGY CONSUMPTION

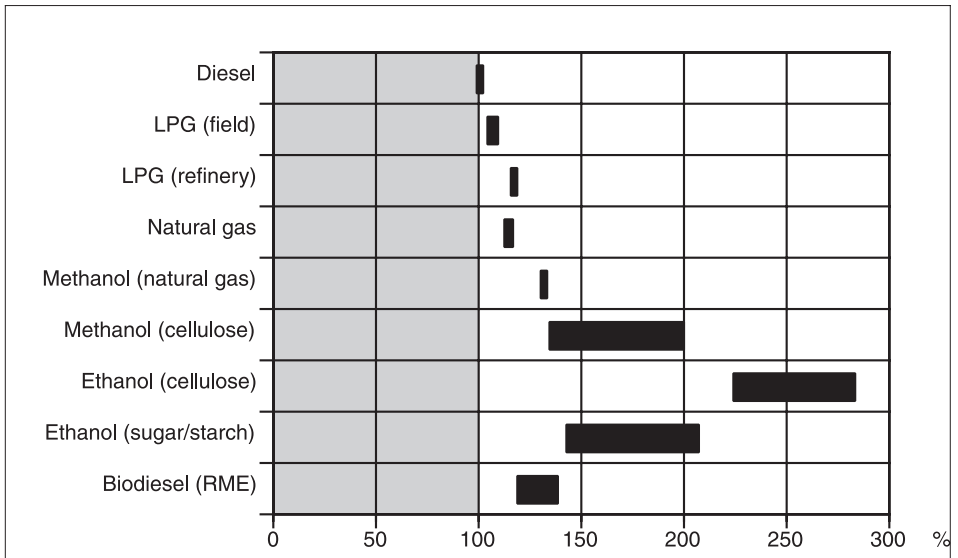
Adding up the results of the five stages of the well-to-wheel fuel chain produces the figures presented in the last two columns of Table 2 — subject to the caveats recorded in the table's notes. The reader should heed as well that particular circumstances may cause deviation from these results, and developments over time may lead to new ratios between the different fuels. Figures 1 and 2 show the results graphically.

Figure 1
**Well-to-Wheel Energy Consumption
in LDVs, Relative to Gasoline**



Source: Table 2.

Figure 2
**Well-to-Wheel Energy Consumption
in HDVs, Relative to Diesel**



Source: Table 2.

For both LDVs and HDVs, vehicles running on diesel have the lowest well-to-wheel energy consumption in the complete well-to-wheel chain, and the vehicles themselves account for 89% to 91% of that, when all the numbers are cast in terms of energy consumption per vehicle-kilometre. For biodiesel (RME), production of the raw material requires 20% to 27% of the total, conversion between 5% and 21%, and transport and distribution 1% or 2%. These relatively high numbers before biodiesel even gets to the car or truck reduce the share burned in the vehicle to between 57% and 68%. Gasoline has average well-to-wheel energy consumption compared to other fuels. The vehicle itself again takes the highest share in the total, 84% to 86%; crude-oil extraction requires 3% to 5%, refining 8% to 11% and transport and distribution together 1% to 1.9%.

Well-to-wheel energy consumption of LPG is generally lower than for gasoline but higher than for diesel, with field LPG scoring lower than refinery LPG. Vehicular energy consumption is 91% to 94% for field LPG and 84% to 86% for refinery LPG, whose energy use at the refinery is considerable, at 7% to 8%. Energy depletion in the natural-gas fuel chain compares with that for field LPG; the vehicle takes 89% to 94%. Compared to other fuels, energy use in distribution of natural gas can run relatively high (3% to 8%), mainly for compression to CNG.

Methanol dissipates more energy in the chain than either gasoline or diesel. Because of the energy intensities of conversion, production accounts for 28% of total energy consumption for methanol from natural gas and for 47% for methanol from cellulosic material. The other alcohol, ethanol, has one of the highest well-to-wheel energy-depletion rates per vehicle-kilometre, especially ethanol from cellulosic material. Conversion and vehicle use take the most. Making ethanol from cellulose accounts for 59% of the total energy consumption and using crops rich in sugar or starch takes between 30% and 39%, but production of these crops themselves uses much energy, some 15% of the total. The vehicles burn 36% in the case of ethanol from cellulose and 45% to 55% when they run on ethanol from crops. Although comparable with ethanol from cellulose in much of its range, hydrogen shows the highest well-to-wheel energy consumption of all fuels. Both its production from water and its distribution (liquefaction and low temperature storage) are energy-intensive processes.

EMISSIONS, STAGE BY STAGE

The vehicle's tailpipe disgorge the most important emissions in transport with conventional fuels, although emissions from the other stages in the fuel chain cannot be ignored. Ninety-nine per cent of the exhaust gases of internal combustion engines consist of nitrogen, carbon dioxide (CO₂), water vapour and possibly oxygen (depending on the air/fuel ratio used in the engine); of these, CO₂ of fossil origin causes the most concern because it contributes to global warming. The remaining 1% contains many polluting components, a few of whose emissions many countries regulate. They

include nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons or volatile organic compounds (HC) and particulates (Pm).

This analysis concentrates on the regulated components, plus CO₂. Note that CO₂ and not CO₂-equivalent emissions are covered, in contrast to the treatment in Volume Three of the *Automotive Fuels Survey* (3). The focus rests on only the most important, not all features, and the caveats about the data expressed previously apply here as well. At all stages of the fuel chain, gasoline generally serves as the reference for LDVs and diesel for HDVs. Each fuel has a range of data; the authors believe that these ranges typify situations around the world, but individual fuel chains with unique conditions could reveal differences. The presentation follows the format of the preceding section on energy consumption, with the data gathered in Table 3, subsections on emissions during each of the five stages of the fuel chain and a final review of emissions from a well-to-wheel perspective.

Feedstock Production

For fuels derived from crude oil and natural gas, venting and flaring of associated gas remain substantial at many production sites. Apart from energy wastage, they represent the most significant emission sources at the feedstock production stage, causing emissions of carbon dioxide, light hydrocarbons and sulphur dioxide when the gas contains sulphur. Emissions from producing agricultural biomass stem from tractors and other equipment used in cultivation (mainly NO_x, CO, HC, Pm and CO₂) and the production and use of fertilisers (predominantly CO₂ and N₂O). Cellulosic material generally requires less energy input and may need less fertiliser than agricultural feedstocks, yielding lower emissions.

Feedstock Transportation

Emissions occur in shipping crude oil, from the ships' engines and (as HC) through evaporative losses during loading, unloading and transport. The same kinds of emissions occur when LPG feedstock crude oil moves by sea, but they are relatively low because gas-tight tankers carry the trade. When field LPG gets processed at the gas-recovery site, no feedstock transportation and hence no emissions occur, just as with natural gas, which usually is processed if necessary at the extraction location. For biomass, on the other hand, transport emissions form a significant part of the well-to-wheel total, making it important to minimise feedstock transport; emissions depend on the distance to the processing plant and the moisture content of the feedstock.

Fuel Production

Refineries generate both evaporative HC losses and emissions from energy use when they convert crude oil to gasoline and diesel. Diesel requires less processing and has smaller emissions. Because refinery LPG is a by-product or co-product from crude oil

Table 3
Emissions Along the Fuel Chain

| Fuel | NO _x | CO | HC | Pm | CO ₂ |
|------------------------------------|----------------------|---------------------|-----------------------|-----------------|----------------------|
| A. Feedstock Production | | | | | |
| Gasoline | 100 (= 8.4-9.5 g/GJ) | 100 (=1.5-5.1 g/GJ) | 100 (=25.6-27.8 g/GJ) | 0 | 100 (=1.8-3.4 kg/GJ) |
| Diesel | 95-100 | 93-100 | 94-100 | 0 | 94-100 |
| LPG | | | | | |
| Field | 83-100 | 87-100 | 93-100 | 0 | 85-100 |
| Refinery | 100-131 | 100-127 | 100-131 | 0 | 100-129 |
| Natural gas | 43-100 | 63-67 | 121-236 | 0 | 47-100 |
| Methanol | | | | | |
| Natural gas | 95 | 98 | 320 | 0 | 100 |
| Cellulose | 229-833 | 314-587 | 16-36 | 100 (=3.3g/GJ) | 49-583 |
| Ethanol | | | | | |
| Cellulose | 595-750 | 196-275 | 25-32 | ND | 528-611 |
| Sugar/starch | 716-1845 | 980-1827 | 49-94 | 312 | 180-1611 |
| Biodiesel | 1464-1568 | 490-3300 | 76-235 | 600 | 695-1167 |
| B. Feedstock Transportation | | | | | |
| Gasoline | 100 (=16-20 g/GJ) | 100 (=0.4-1.7 g/GJ) | 100 (=1-26.1 g/GJ) | 0 | 100 (=0.6 kg/GJ) |
| Diesel | 94-100 | 94-100 | 93-100 | 0 | 100 |
| LPG | | | | | |
| Field | 0-89 | 0-88 | 0-2 | 0 | 0-83 |
| Refinery | 100-131 | 100-129 | 100-130 | 0 | 100-131 |
| Natural gas | -- | -- | -- | -- | -- |
| Methanol | | | | | |
| Natural gas | -- | -- | -- | -- | -- |
| Cellulose | 160-186 | 500-524 | 4-106 | 100 (=2.4 g/GJ) | 324-333 |
| Ethanol | | | | | |
| Cellulose | 80-250 | 250-2500 | 70-700 | ND | 167-1833 |
| Sugar/starch | 102-150 | 288-500 | 2-100 | 54 | 177-333 |
| Biodiesel | 68-105 | 194-250 | 2-100 | 38 | 118-167 |

Table 3 (continued)
Emissions Along the Fuel Chain

| Fuel | NO_x | CO | HC | Pm | CO₂ |
|-----------------------------|-----------------------|---------------------|------------------------|-----------------|-----------------------|
| C. Fuel Production | | | | | |
| Gasoline | 100 (=10-13.4 g/GJ) | 100 (=0-1.4 g/GJ) | 100 (=17-67.9 g/GJ) | 0 | 100 (=6.1-12 kg/GJ) |
| Diesel | 49-60 | 0-57 | 59-84 | 0 | 49-58 |
| LPG | | | | | |
| Field | 0-50 | 0-214 | 0-153 | 0 | 0-8 |
| Refinery | 60-105 | 0-93 | 65-137 | 0 | 67-107 |
| Natural gas | 0-56 | 0-150 | 0-371 | 0 | 0-10 |
| Methanol | | | | | |
| Natural gas | 1100 | 1427 | 376 | ND | 67 |
| Cellulose | 100-212 | 186-1286 | 47-257 | 100 (=0.5 g/GJ) | 372-808 |
| Ethanol | | | | | |
| Cellulose | 880-1300 | 5500-17500 | 335-676 | ND | 0 |
| Sugar/starch | 549-700 | 514-10714 | 127-376 | 700-3400 | 0-687 |
| Biodiesel | 95-156 | 79-2586 | 25-146 | 0-1320 | 0-196 |
| Hydrogen | 1100-5951 | 0-5824 | 0-1292 | 11700 | 1750-4181 |
| D. Fuel Distribution | | | | | |
| Gasoline | 100 (=1.6-10.6 g/GJ) | 100 (=0.4-0.7 g/GJ) | 100 (=30.3-107.9 g/GJ) | 100 (=0.1 g/GJ) | 100 (=0.2-0.7 kg/GJ) |
| Diesel | 94-100 | 100 | 1 | 100 | 100 |
| LPG | 356-550 | 229-425 | 0-9 | 500 | 200-357 |
| Natural gas | 17-631 | 0-225 | 206-207 | 0 | 714-1600 |
| Methanol | 198-731 | 143-875 | 13-20 | 1000 | 200-382 |
| Ethanol | 142-538 | 143-650 | 10-13 | 700 | 143-281 |
| Biodiesel | 94-344 | 101-400 | 0-1 | 500 | 100-179 |
| Hydrogen | 1132 | 639 | 18 | ND | 771 |

Table 3 (continued)
Emissions Along the Fuel Chain

| Fuel | NO _x | CO | HC | Pm | CO ₂ |
|---|---------------------|---------------------|---------------------|-----------------|----------------------|
| E. Vehicular Emissions: LDVs | | | | | |
| Gasoline | 100 (=0.2-0.4 g/km) | 100 (=2.1-6.0 g/km) | 100 (=0.1-0.8 g/km) | ≈ 0 | 100 (=181-256 g/km) |
| Diesel | 305 | 20 | 57 | 100 (=0.2g/km) | 77 |
| LPG | 100-110 | 25-46 | 43-71 | ≈ 0 | 79-89 |
| Natural gas | 67-100 | 23-25 | 75-129 | ≈ 0 | 68-83 |
| Methanol | 81-100 | 69-100 | 79-145 | ≈ 0 | 82-95 |
| Ethanol | 33 | 40 | 100 | ≈ 0 | 100 |
| Biodiesel | 367 | 18 | 50 | 87 | 78 |
| Hydrogen | 25 | ≈ 0 | ≈ 0 | 0 | 0 |
| DME | 39 | 12 | 4 | ≈ 0 | ND |
| F. Vehicular Emissions: HDVs | | | | | |
| Diesel | 100 (=14.1-16 g/km) | 100 (=0.5-4.3 g/km) | 100 (=0.4-0.5 g/km) | 100 (=1.1 g/km) | 100 (=885-1195 g/km) |
| LPG | 20-25 | 200-500 | 200-209 | 24 | 98-100 |
| Natural gas | 15-34 | 100-620 | 150-646 | 15 | 87-103 |
| Methanol | 43-50 | 81-400 | 59-614 | 19 | 81-96 |
| Ethanol | 81-90 | 107-400 | 140-145 | 19 | 83-100 |
| Biodiesel | 106-115 | 67-100 | 80-96 | 67 | 102-106 |
| G. Well-to-Wheel Emissions: LDVs | | | | | |
| Gasoline | 100 (=0.3-0.6 g/km) | 100 (=2.1-6.0 g/km) | 100 (=0.8-1.1 g/km) | 0 | 100 (=209-307 g/km) |
| Diesel | 130-221 | 7-21 | 15-40 | 100 (=0.2 g/km) | 52-74 |
| LPG | | | | | |
| Field | 96-110 | 25-47 | 17-71 | 1 | 71-82 |
| Refinery | 114-117 | 25-47 | 65-66 | 1 | 78-93 |
| Natural gas | 56-79 | 23-25 | 111-115 | 0 | 65-78 |
| Methanol | | | | | |
| Natural gas | 158 | 101 | 155 | ND | 80 |
| Cellulose | 119-142 | 71-102 | 76-117 | 11 | 30-110 |
| Ethanol | | | | | |
| Cellulose | 81-117 | 17-24 | 27-41 | ND | 10-16 |
| Sugar/starch | 122-154 | 22-52 | 32-104 | 24-45 | 24-55 |
| Biodiesel | 189-346 | 8-26 | 12-47 | 112-120 | 13-32 |
| Hydrogen | 79-864 | 0-12 | 2-339 | 0-113 | 5-362 |

Table 3 (continued)
Emissions Along the Fuel Chain

| Fuel | NO_x | CO | HC | Pm | CO₂ |
|---|-----------------------|---------------------|---------------------|-----------------|-----------------------|
| H. Well-to-Wheel Emissions: HDVs | | | | | |
| Diesel | 100 (=14.5-16.7g/km) | 100 (=0.6-4.3 g/km) | 100 (=1.1-1.8 g/km) | 100 (=1.1 g/km) | 100 (=977-1363 g/km) |
| LPG | | | | | |
| Field | 22-32 | 199-445 | 69-177 | 24 | 94 |
| Refinery | 25-32 | 200-436 | 154-177 | 24 | 104-106 |
| Natural gas | 16-35 | 99-530 | 255-588 | 15 | 87 |
| Methanol | | | | | |
| Natural gas | 64 | 405 | 497 | ND | 98 |
| Cellulose | 50-61 | 87-434 | 158-300 | 28 | 3-135 |
| Ethanol | | | | | |
| Cellulose | 94-103 | 577-1075 | 160-256 | ND | 16-26 |
| Sugar/starch | 103-104 | 119-891 | 114-235 | 55 | 34-67 |
| Biodiesel | 118-127 | 81-212 | 68-120 | 90-98 | 28-44 |

Sources: 1, 2, 6, 8.

Notes: In sections A through D, emissions are based on the energy content of the fuel. The gasoline data are all in g/GJ, except for kg/GJ for CO₂. For all other fuels the numbers are percentages, *i.e.* index numbers where the gasoline value = 100. For section A, B and C, methanol from biomass is used as the reference for particulate emissions (Pm), because Pm emissions for gasoline are negligible. In sections E through H, the reference fuels are gasoline for LDVs and diesel for HDVs, with emissions expressed in g/km. Because Pm emissions from gasoline are negligible, diesel becomes the Pm reference fuel for LDVs. «ND» indicates no or insufficient data. A double dash (--) indicates «irrelevant or negligible». Hydrogen from electrolysis of water (the only form considered) is not listed in parts A and B because emissions from feedstock production and transport are zero or negligible. In part C, the emissions for hydrogen reflect generating electricity for hydrolysis, assuming a natural-gas power station and the UK power-generation mix (coal, oil, nuclear, gas and hydro). Throughout the table, where DME is not listed separately there are no data; in feedstock production, feedstock transport and fuel production its emissions are similar to those of methanol from natural gas, while in distribution they resemble those of LPG.

refining, part of the refinery emissions should be allocated to it. Analysts differ on the emissions from producing field LPG. One source considers them negligible because processing is only marginal; another assumes emissions during fractionating and purifying the extracted gas liquids. Differences in processing generate the wide range in the natural gas production-emission data. Depending on feed-gas composition, they vary between nil and considerable HC losses, mainly of methane (CH₄), when the gas requires purifying and drying.

For the alcohol fuels, the main emissions in methanol production stem from the energy used for the synthesis process. For methanol from natural gas, wet gas is the fuel; besides its emissions, HCs also escape in methane leakages. Because no commercially sized plants exist to convert biomass to methanol, emissions data are sparse. Net CO₂

emissions in production might be nil if biomass serves as the fuel for the conversion process, because it takes equal amounts of CO₂ from the atmosphere during its growth. Ash is a by-product of the wood-to-methanol process. Emissions from ethanol production depend on the fuels used for the necessary steam and electricity. As with methanol from biomass, net CO₂ emissions may be nil with biomass fuel. Emissions for ethanol conversion from cellulosic material are higher than from feedstocks rich in sugar or starch because it requires more energy.

Biodiesel has lower production emissions than the other biomass fuels because conversion is less energy-intensive. If straw replaces fossil fuel in the process, net CO₂ emissions are negligible. In contrast, the energy-intensive electrolysis of hydrogen depends heavily on how the electricity gets generated. Hydropower plants have no emissions, natural-gas plants yield considerable ones and coal-fired power stations are worst.

Fuel Distribution

Distribution emissions arise mainly from the transport mode and the energy content of the fuel carried; a fuel with half the energy content of gasoline needs two road tankers to move the same quantity of energy. Specific fuel characteristics also play a role. For example, most of the HC emissions from gasoline distribution come from the evaporation of light hydrocarbons. Vapour-return systems used during loading and unloading of road tankers and car refuelling can reduce these losses. Diesel is not as volatile as gasoline and evaporative emissions are small. Its distribution emissions stem from the transportation fuel. Although diesel has a slightly higher energy density than gasoline, distribution emissions (except HC) are similar per energy unit. The same applies to biodiesel, except as longer transport distances may raise emissions.

In general, LPG has higher distribution emissions than gasoline; its lower calorific value requires more transport energy, the pressure tanks weigh more and energy gets consumed in liquefaction and compression. HC emissions are lower because gas-tight couplings cut evaporative losses. The natural gas figures in Table 3 reflect distribution by pipeline from recovery sites to vehicle-refuelling stations. Transportation distances exceed those for gasoline and diesel. The emissions come from making electricity to power the compressors that pump the gas through the grid, gas leaks (CH₄) and gas compression at service stations.

Distributing alcohols resembles gasoline and diesel distribution. The combination of methanol's lower energy content and the longer distances make emissions during its transport higher, but ethanol, with its greater energy content, does better. Its emissions fall below those for methanol but exceed those from gasoline distribution. Hydrogen's emissions depend on what powers the transport mode — a truck engine in liquid transportation or a pipeline's pumps.

Vehicular Emissions

Many factors influence vehicle emissions, which vary considerably. They include different vehicle technologies, variant fuel composition, driving behaviour, the numbers of cold starts and trip lengths. Moreover, vehicle emission legislation develops continuously, with acceptable emission levels lowered every few years⁸. For at least the coming decade, gasoline and diesel likely will remain the predominant automotive fuels. With increasingly stringent legislation, emission levels of conventionally fuelled vehicles will go down; alternative fuels will have to follow this trend. Thus the figures for the reference fuels in Table 3 represent only a snapshot of a moving reference.

Gasoline vehicle emissions consist mostly of exhaust gases. Evaporation contributes significantly to relatively high HC emissions as well. Changing fuel properties can help: reformulated gasoline may bring reductions of up to 20% for the regulated emission components. Because diesel engines run on lean air/fuel mixtures (excess of air) under all load conditions, they usually have low CO and HC emissions, but incomplete combustion at cold starts results in higher HC emissions. Diesel engines also have relatively high NO_x emissions, and the presence of excess oxygen in the exhaust gases impedes using three-way catalysts to reduce them, although de-NO_x catalysts are under development. Low-sulphur diesel helps to reduce high Pm emissions compared to other fuels and facilitates the introduction of exhaust catalysts. Biodiesel emissions resemble those of fossil diesel in most respects and in both LDVs and HDVs, although they tend to be lower in HDVs for emissions categories other than CO₂ and NO_x.

An LDV running on LPG has NO_x emissions comparable to gasoline but lower CO and HC emissions, due especially to LPG's advantage in cold starts, which requires no addition of excess fuel and thus avoids unburned fuel in the exhaust gases. LPG vehicles also emit less CO₂ than gasoline cars because LPG contains less carbon. LPG HDVs have lower NO_x and particulate emissions than their diesel counterparts, comparable CO₂ emissions, higher CO and HC emissions and negligible Pm emissions.

Compared to gasoline and diesel, natural gas puts high levels of methane (CH₄) into its exhaust gases, difficult to oxidise in an exhaust catalyst because methane molecules are chemically stable. Notwithstanding their high HC emissions, natural-gas cars do emit less CO and CO₂ than gasoline LDVs and their NO_x emissions are comparable with gasoline cars. Natural-gas HDVs emit less NO_x and particulates than diesel HDVs, CO emissions are comparable or higher, CO₂ emissions are comparable or slightly lower and HC emissions are much higher because of the CH₄.

Aldehydes form during combustion of alcohols, whereas conventional fossil fuels have very low vehicular aldehyde emissions, which explains why many countries do not yet regulate them. Formaldehyde may cause headaches and has cancerogenous properties. Methanol vehicles have aldehyde emission levels high enough (three to twenty times

⁸ An example is the upcoming EURO IV emission legislation for heavy duty vehicles.

as high as gasoline or diesel engines) to cause serious health problems were methanol to enter into large-scale use. Ethanol vehicles produce mainly acetaldehyde and some formaldehyde.

Otherwise, emissions from the alcohol fuels compare quite well with gasoline and diesel. They are the same or lower in methanol LDVs for all the regulated components except HC, which come from unburned methanol. Methanol HDVs have lower NO_x , Pm and CO_2 emissions than their diesel counterparts, while CO and HC emissions may go above or below, depending on vehicle technology. Ethanol LDVs match gasoline for HC and CO_2 emissions, and do better for NO_x and CO. Using ethanol in HDVs reduces NO_x and particulate emissions but often raises CO and HC output relative to diesel.

In a combustion engine operating on hydrogen, water vapour and NO_x form the bulk of exhaust emissions other than unused air. The NO_x results from the high combustion temperatures and the presence of nitrogen in air. Traces of CO and HC also occur; they come from the lubrication oil.

Extremely limited data on DME emissions in LDVs come from a single DME passenger car and are indicative at best. The regulated emission components of DME vehicles seem to be relatively low. The CO_2 emissions of the test car are not recorded but probably resemble those of an LPG equivalent.

WELL-TO-WHEEL EMISSIONS

As in the previous discussion of energy consumption, one can combine information about emissions in the five stages of the fuel chain to obtain a picture of how the various fuels perform in the well-to-wheel fuel chain as a whole — but with the same caveats. Note especially that the numbers in the last two sections of Table 3 do not come directly from adding the individual figures in each stage of the fuel chain. Moreover, a high percentage in one step of the fuel chain, even a very high one, does not necessarily imply a high figure for the full chain, because the emissions of that stage may form only a small part of well-to-wheel emissions. Remember too that developments continue, for conventional as well as alternative fuels. Improvements come and emissions targets move.

Nitrogen Oxides

LDVs running on gasoline have relatively low well-to-wheel NO_x emissions, and only natural gas can improve on them. LPG and ethanol from cellulosic material perform about the same as gasoline, and methanol, ethanol from sugar or starch, diesel and biodiesel spew more well-to-wheel NO_x than a gasoline-fuelled LDV. For hydrogen, whether emissions are much lower or much higher depends very much on the manner of hydrogen production and the energy source used to make the electricity for electrolysis.

A slightly different picture emerges for HDVs. Natural gas still has the lowest well-to-wheel NO_x emissions but LPG-fuelled trucks are comparable. HDVs running on methanol outperform diesel HDVs, but those using ethanol discharge about the same amounts of NO_x . Biodiesel HDVs have the highest NO_x emissions, as with LDVs and somewhat higher than conventional diesel emissions.

Carbon Monoxide

Hydrogen generates the lowest well-to-wheel CO emissions in LDVs, gasoline and methanol the highest. The other fuels all perform better than gasoline, to roughly the same degree. In HDVs the data show much more dispersion. Diesel generally has the lowest CO emissions. Biodiesel and methanol from cellulosic feedstock may discharge slightly less CO but probably more. The other fuels all greatly exceed diesel's CO output; ethanol tops the list at nine or ten times that of diesel.

Hydrocarbons

Diesel and biodiesel LDVs show the lowest total HC emissions, with natural gas and methanol the highest, mainly as methane (CH_4). Hydrogen bifurcates; it performs best of all the fuels when the electricity for electrolysis comes from renewable energy, but worst when fossil fuels are used. In HDVs and excluding hydrogen (no data), the fuels perform about the same as in LDVs, although the index numbers differ because diesel is the reference fuel.

Particulate Matter

Only a few fuels — diesel and biodiesel (largely from vehicle discharges), and hydrogen produced with fossil electricity — generate significant well-to-wheel Pm emissions in LDVs. Pm outputs from gasoline, LPG, natural gas, methanol and hydrogen made with electricity from renewable sources all are negligible. HDVs, however, have much higher well-to-wheel Pm emissions, with diesel and biodiesel again the highest. The other fuels outperform the reference fuel (diesel in HDVs), but with differences generally smaller than in LDVs.

Carbon Dioxide

Fuels produced from renewable sources have the lowest CO_2 emissions. With fossil energy used for conversion, CO_2 emissions can escalate. Different energy sources, for example, explain the dispersion in the data for hydrogen and methanol from cellulosic material. Vehicle engine efficiency also plays an important role in well-to-wheel CO_2 emissions of fossil fuels: efficient motors like diesel engines discharge less CO_2 . These generalisations apply to both LDVs and HDVs.

FUEL COSTS

This chapter looks at the expected relative costs of the fuels under review in both the short term (one to five years) and the long term (15 to 25 years). Reversing the orientation of the previous chapter, it begins with an overall view of well-to-wheel costs, then discusses the elements that can affect them in the various stages of the fuel chain.

Several caveats are in order. Assumptions and estimates lie behind practically all of the cost figures. One key assumption builds in decided increases between the short term and the long term in the costs of all fuels except those derived from cellulose; they mostly track anticipated rises in feedstock prices. Another takes no account of current crude-oil prices, which in real terms sit at lows not seen since before the oil crises of the 1970s. Note also that the analysis ignores costs other than fuel costs that may affect fuel choices, including notably those of the different types of engines or vehicles which different fuels may require.

In comparisons of new and conventional fuels one cannot always link costs and established market prices, and *vice versa*. Several of the feedstocks for automotive fuels have long held the status of commodities traded world-wide at prices established on major exchanges, even if they are not used primarily to manufacture automotive fuels or priced on that basis. Grains offer a good example, except where internal production subsidies and offsetting export bounties complicate matters. Other feedstocks, however, trade only on limited and often local markets and have no world market prices. Local conditions, such as values relative to more established raw materials and local or national taxation, often determine the local prices of such feedstocks.

For commodities, global supply and demand establish world market prices, which may have a tenuous relation, at best, to production costs. For example, it may cost less than US\$ 1.00 to produce a barrel of crude oil from a fully depreciated oil field in the Middle East, but an identical barrel from a new Arctic oil field may cost US\$ 15-20. Nevertheless, the market prices of both these barrels are equal, after corrections for quality and transportation costs. Despite the focus here on costs, prices rather than costs have been chosen as representative in such situations.

Table 4 presents the estimates for well-to-wheel fuel costs in both LDVs and HDVs, calculated by adjusting estimated costs from well to service station by a coefficient of vehicle efficiency to arrive at “effective driving costs”. Bear in mind that fuel cost at the pump usually does not equal fuel price, because it abstracts from the taxes and duties that governments may use along with vehicle and road taxes to steer fuel choice. The two sets of data reveal that diesel stands first or second in rank order (from lowest to highest cost) in both the short and the long term for both vehicle types, with CNG

a close cost competitor. Methanol from cellulose does well for HDVs in the long term⁹. DME competes closely with gasoline and even pulls well ahead for HDVs in the long term. The rankings of effective driving costs are as follows (“ND” means “no data”):

| | <i>LDVs</i> | | <i>HDVs</i> | |
|------------------|-------------------|------------------|-------------------|------------------|
| | <i>Short Term</i> | <i>Long Term</i> | <i>Short Term</i> | <i>Long Term</i> |
| Gasoline | 3 | 4 | 4 | 7 |
| Diesel | 2 | 1 | 2 | 1 |
| LPG | | | | |
| Field | ND | ND | ND | ND |
| Refinery | 5 | 5 | 5 | 6 |
| CNG | 1 | 2 | 1 | 3 |
| Methanol | | | | |
| Natural Gas | 6 | 7 | 3 | 5 |
| Cellulose | 8 | 6 | 8 | 2 |
| Ethanol | | | | |
| Cellulose | 10 | 9 | 9 | 8 |
| Starch | 8 | 6 | 7 | 10 |
| Biodiesel | 7 | 8 | 6 | 9 |
| Hydrogen | ND | ND | ND | ND |
| DME | 4 | 3 | 4 | 4 |

COSTS ALONG THE FUEL CHAIN

Feedstocks

Crude oil dominates feedstocks for automotive fuels today. Its nominal market price has fluctuated in recent years around US\$ 17-US\$ 20 per barrel, equal to around US\$ 3.00-US\$ 3.50 per GJ in energy terms. Current prices are 35% to 40% lower. Common opinion holds that crude oil prices eventually will rise as demand increases force exploitation of gradually more expensive oil reserves, but the timing remains at the least obscure¹⁰.

Natural gas gets priced on the basis of its heating value because generating heat and power represent its primary uses and it competes with oil products for them on consumer markets; its use as an automotive fuel remains marginal. The wellhead *market* price currently fluctuates between US\$ 2.00 and US\$ 3.00 per million Btu

9 But see the discussion of cellulosic feedstocks on p. 48. The drop in cellulose (wood) costs represents less a “forecasting” assumption than an exercise to see how much costs would have to drop to bring fuels from this feedstock into a range competitive with other fuels.

10 Oil from tar sands and asphalt now costs more than crude oil, but it could become competitive in the long term. It receives no consideration here.

Table 4
Well-to-Wheel Fuel Costs

| | <i>Total Well-to-Service-Station Costs¹ (US\$/GJ fuel)</i> | | <i>Vehicle Efficiency (%)</i> | <i>Effective Driving Costs (US\$/GJ vehicle performance)²</i> | |
|-----------------------------|---|------------------|-------------------------------|--|------------------|
| | <i>Short Term</i> | <i>Long Term</i> | | <i>Short Term</i> | <i>Long Term</i> |
| A. LDVs | | | | | |
| Gasoline | 9.75 | 17.95 | 25 ³ | 39 | 72 |
| Diesel | 8.90 | 16.30 | 28 | 32 | 58 |
| LPG | | | | | |
| Field | ND | ND | 20 ⁴ | ND | ND |
| Refinery | 9.90 | 16.20 | 20 ⁴ | 50 | 81 |
| CNG | 4.30 | 14.20 | 20 ^{4,5} | 22 | 71 |
| Methanol | | | | | |
| Natural gas | 11.40 | 18.20 | 20 | 57 | 91 |
| Cellulose | 24.30 | 16.80 | 20 | 122 | 84 |
| Ethanol | | | | | |
| Cellulose | 41.10 | 25.20 | 20 | 206 | 125 |
| Starch | 26.60 | 37.50 | 20 | 133 | 188 |
| Biodiesel (RME) | 18.90 | 29.50 | 28 | 68 | 105 |
| Hydrogen⁶ | ND | ND | 25 | ND | ND |
| DME | 13.20 | 20.00 | 28 | 47 | 71 |
| B. HDVs | | | | | |
| Gasoline | 9.75 | 17.95 | 24.6 | 40 | 73 |
| Diesel | 8.90 | 16.30 | 33.6 | 26 | 49 |
| LPG | | | | | |
| Field | ND | ND | 24.4 | ND | ND |
| Refinery | 9.90 | 16.20 | 24.4 | 41 | 66 |
| CNG | 4.30 | 14.20 | 23.9 | 18 | 59 |
| Methanol | | | | | |
| Natural gas | 11.40 | 18.20 | 29.1 | 39 | 63 |
| Cellulose | 24.30 | 16.80 | 29.1 | 84 | 58 |
| Ethanol | | | | | |
| Cellulose | 41.10 | 25.20 | 33.3 | 123 | 77 |
| Starch | 26.6 | 37.50 | 33.3 | 79 | 113 |
| Biodiesel (RME) | 18.9 | 29.50 | 33.3 ⁵ | 57 | 89 |
| Hydrogen⁵ | ND | ND | 25 | ND | ND |
| DME | 13.20 | 20.00 | 33.3 | 40 | 60 |

Sources: 2, 3, 15.

Notes: 1. Costs per unit of energy of the fuel available at the filling station. 2. Costs on the basis of mechanical energy performed by the vehicle, which has a direct relation to the driving distance. The transportation performance is the ultimate basis for comparison, since this is why the vehicle is used. 3. Direct injection. 4. Using a stoichiometric air/fuel mixture in a combustion engine. 5. Estimated. 6. Internal combustion engine. ND = No data.

(MMBtu) — or roughly the same per GJ — and this study assumes that the differential against crude oil will drop to about US\$ 0.50 per GJ in the long term. For gas fields under development, however, sellers and buyers frequently *negotiate* prices on a long-term project basis before a project is implemented. These prices apply to defined geographic markets and include often considerable pipeline costs.

The study also assumes that gas used as a feedstock for making automotive fuels like methanol and DME will be “remote natural gas” from fields not easily connected by pipeline to major markets. Remote natural gas may be priced at less than US\$ 1.00 per MMBtu (about the same per GJ); the prohibitive cost of transporting it to a developed market gives it no alternative value. Yet it can receive conversion on site to methanol or DME, or to LNG, before shipping to established markets. If it arrives as LNG, its assumed price after regasification will be competitive with pipeline gas.

Costs of feedstocks for most renewable fuels still depend heavily on local circumstances and no world market prices exist. Wood has only limited use as a fuel on an industrial or commercial scale, although some countries have introduced systems that use it (largely branches, roots and other residues from lumbering) for district heating and electric power. In the medium to long term, forest plantations could produce wood for energy on an industrial scale. Costs depend on the species grown, productivity, climate, availability and access to water and nutrients, and similar factors. This analysis assumes short-term costs of US\$ 3.50 per GJ, which decrease over time because of productivity gains and increased efficiency in handling and transportation (also assumed). Cellulose is in fact the only raw material to which the study assigns a cost reduction, to illustrate better the reductions required for cellulose to become able to compete with fossil fuels. The exercise is disputable, and reduced costs do not necessarily mean that prices will drop.

In agriculture as opposed to forestry, the crops with the largest potential for making automotive fuels include plants abundant in starches and sugars, from which to extract glucose for fermentation into ethanol, as well as oilseeds for the manufacture of biodiesel esters like RME (rapeseed methyl ester) and REE (rapeseed ethyl ester) by reaction with alcohols such as methanol or ethanol. Also, several crop by-products — molasses, corn fibre, bagasse, wheat and rice straw, and grasses — are potential automotive fuel feedstocks.

Grains, as internationally traded commodities, have world market prices that cannot be entirely obscured by local agricultural policy devices such as subsidies. This study assumes that the short-term production costs of grains (wheat and corn) lie at around US\$ 10.00 per GJ. Their determinants include the costs of fertilisers and pesticides, fuel for machinery, drying and transport, and labour costs. Most of these depend on oil prices. As they rise, farming costs will increase. The same points apply to oilseeds, although the focus shifts to vegetable oils themselves because oil yields vary among different oilseeds. Vegetable oils also have market prices, currently at about US\$ 15 per GJ. While genetic engineering may develop high-yielding oil seeds suitable for extracting vegetable oils for motor fuels, this study ignores that possibility and assumes

that vegetable oil costs will rise at the same rate as those for grains. The agricultural by-products consist mainly of cellulose, so the assumption for them equates their cost per GJ to that for cellulose from forest plantations, and takes no account of their potential as raw materials for automotive fuels.

Fuel Production

This analysis¹¹ makes the general assumptions that feedstock-processing costs will rise in line with oil costs, with investment holding constant in real terms except for new capital to exploit major technological changes. It also takes into account the values of by-products from fuel manufacture when establishing the cost per GJ of the final fuel.

Refineries make gasoline, diesel and LPG simultaneously and together with other petroleum products. Their total costs, which may vary considerably among refineries, are easily known, but allocation to individual products is at least partly arbitrary. Based on a technical judgement that 25% by weight (wt-%) of a refinery's output is gasoline, the cost of gasoline after manufacturing reaches US\$ 5.90 per GJ of final fuel. Assuming a 35 wt-% diesel yield, with slightly lower capital and operating costs than for gasoline, diesel's costs work out to an estimated US\$ 5.40 per GJ of final fuel. Refinery LPG requires limited processing relative to most other products and its production is in fact difficult to avoid; hence, one can argue that making it demands no capital and only small operating costs. On this basis its assumed cost becomes US\$ 4.20 per GJ of final fuel. Field LPG is a by-product of extraction. In some situations it is flared when no economic use can be found for it.

For use as an automotive fuel natural gas requires compression to CNG or liquefaction to LNG. CNG holds favour currently, especially in Europe. Upon compression, it is ready for the fuel tank, so "production" here includes both conversion and distribution. Its estimated cost amounts to US\$ 4.30 per GJ of final fuel. LNG, which must have a competitive price *vis à vis* CNG, receives no further consideration, although the United States and Japan are testing it. Liquefaction normally occurs in the exporting country, with its cost included in the price.

It makes sense to produce methanol from remote natural gas at the gas recovery site to reduce transportation costs. On the assumption that this occurs, methanol's estimated cost becomes US\$ 5.00 per GJ final fuel, before transportation, the same as for producing DME from natural gas in a very similar process.

The crucial steps for making methanol from wood involve gasification of the feedstock and subsequent gas purification to syngas. Despite a number of technologies now under development, no established or proven technology yet exists. In the absence of reliable experience data on capital or operating costs for wood gasification, one can say that a

¹¹ Cost figures for large-scale production of hydrogen by electrolysis of water are not available.

wood-to-methanol plant should yield approximately 55% methanol on an energy basis, with 25% recovered as steam and total estimated internal fuel consumption and losses of 20%. Based on anticipated wood feedstock costs and revenues of US\$ 3.50 per GJ for steam, the assumed short-term cost comes to US\$ 18.40 per GJ methanol, before the expected longer-run *decrease* in feedstock costs takes place.

No commercial plants now make ethanol from wood, for the same reasons as for wood-to-methanol. A plant might yield about 20% of ethanol on an energy basis, with some 50% recovered as lignin fuel (for steam and/or electricity) and internal fuel consumption and losses estimated at 30%. A feedstock cost of US\$ 3.50 per GJ and co-product revenue of US\$ 4.00 per GJ for lignin fuel would set the assumed cost of ethanol at US\$ 36.00 per GJ of final fuel. Under an assumption that the yield structure for ethanol-to-wood will improve, these long-run conversion costs also will drop.

Ethanol yields from farm crops depend on the feedstocks' potential sugar content. A 35 wt-% yield from grain would put the estimated cost per GJ of final fuel at US\$ 21.50. With the technology already established, no significant cost reduction from technological advancements is likely, so the only upward cost pressures in the long term will come from net feedstock and operating costs moving in line with oil prices.

Converting vegetable oils to the corresponding esters is a simple, low-cost process, with an assumed yield of close to 100%. The cost per GJ biodiesel would be US\$ 15.50, increasing in the long term like costs of all other fuels except those from cellulose, as feedstock and energy costs for conversion rise.

Fuel Distribution

Fuel distribution costs¹² (at least for the liquids) relate primarily to volume rather than weight. An element based on value enters as well, because moving a fuel from its manufacturing site to the filling station and then selling it to drivers take time and hence working capital, which has an interest cost. The several cost components will include most or all of the following:

- Sea, road or rail transport from the refinery gate or plant to depots;
- Depot storage;
- Administration and handling in wholesale trade;
- Transport from depot to filling station;

¹² Because a detailed analysis of future distribution costs was beyond the scope of Volume 3 of the *Automotive Fuels Survey*, a single cost figure is used here for both the short and the long term. This cannot capture any rise that takes place, but if one assumes that distribution costs will increase in a fairly uniform way, the differentials between the fuels will not change markedly.

- Filling-station storage;
- Administration and handling in retail trade;
- Emergency and strategic storage; and
- Interest on working capital.

Table 5 summarises the total distribution costs. Note that, for methanol, they depend on the feedstock. Methanol from remote natural gas costs much more to transport over the longer distances involved than methanol from wood (cellulose). Both of the ethanol feedstocks, however, are biomass; no reason exists to posit significant differences in production plant location.

Table 5
Distribution Costs

| | <i>US\$ per GJ</i> |
|-------------------------------|--------------------|
| Gasoline | 3.85 |
| Diesel | 3.50 |
| LPG | 5.68 |
| CNG | n.a. ¹ |
| Methanol (natural gas) | 6.41 |
| Methanol (cellulose) | 5.88 |
| Ethanol | 5.12 |
| Biodiesel | 3.39 |
| Hydrogen | 15 ² |
| DME (natural gas) | 8.16 |

Source: 3.

Notes: 1. *Not applicable. CNG distribution costs are included in conversion costs.* 2. *Rough estimate.*

Vehicle Use

Direct comparisons of fuel costs in driving can occur only when the fuels themselves enter as the only cost variable. Yet, especially as seen from the drivers' perspective, the costs of vehicles, their engines and their maintenance and operating costs may well differ according to the fuels they burn. More important, fuel consumption and hence fuel cost vary considerably with the different efficiencies achievable. Only fuel costs are addressed in this chapter.

For both LDVs and HDVs, this report measures fuel costs in US dollars per GJ of work performed by the vehicle. Thus it must correct fuel costs for the relative efficiencies of the fuels, which appear in the middle column of Table 4. The figures for LDVs apply to a mixed urban, suburban and motorway driving cycle, a reasonable representation of real conditions. Note that the LDV gasoline figure may be optimistic because it

applies to direct-injected (DI) engines, which only recently have become available. The figures for HDVs apply to an urban bus driving cycle, probably not representative of most HDVs — but one can assume that the ratios of the efficiency numbers to one another do lead to valid comparisons of effective well-to-wheel driving costs, which constitute the main message in Table 4.

PART B

COMPARING AUTOMOTIVE FUELS: THE SEARCH FOR THE ULTIMATE FUEL

EMISSIONS

INTRODUCTION

We now embark upon direct fuel comparisons, from national and global perspectives most likely to interest policy makers. This chapter focuses on local and greenhouse emissions. Chapter Six looks at fuel costs and the potential of different fuels to reduce dependency on oil, then concludes by combining all the possible bases for fuel choice under the rubric of “The Search for the Ultimate Fuel”. The comparisons are based on strict, if sometimes hypothetical, policy criteria that facilitate clear conclusions — verdicts perhaps too “black and white”, but nevertheless shorn of the “greys” which obscure distinctions with meaning. Readers interested in only a quick survey may safely concentrate on these two chapters of Part B, with perhaps a glance at Chapter One for familiarisation with the orientation of the study and, with the remainder of Part A at hand only for reference and background¹.

Comparisons and judgements like these always remain subject to challenge and alternative formulations, although the authors believe that they faithfully represent well-to-wheel fuel chains in most parts of the world. Nevertheless, the setting for fuel choices is not static. New technical developments appear almost daily; national legislation develops along a continuum; societal views and demands change constantly. For all these reasons the data presented and the points made here aim at a moving target and thus take on an indicative rather than definitive flavour.

LOCAL EMISSIONS

Local emissions influence the direct surroundings of the emission source and thus affect urban areas, where they concentrate, the most. Exhaust emissions may cause health problems or material damage to buildings. Noise and vibration may become local nuisances. Box 3 summarises all the local effects of the most important emission components, concentrating on those that deteriorate local air quality.

Reducing emissions per vehicle kilometre to improve local air quality can occur in three main ways: a change in vehicle technology, the use of alternative or reformulated fuels, or a modification of driving patterns. Technological changes and new fuel compositions have already reduced emissions enormously. The introduction of the three-way-catalyst in gasoline vehicles reduced HC, CO and NO_x emissions by approximately 90%. The reformulation of gasoline and diesel to an optimised composition compared to the fuels used during the mid 1990s has already lowered vehicle emissions in several countries².

- 1 Much more detail appears in the three volumes of the IEA's *Automotive Fuels Survey* (1, 2, 3). Volume 3 serves as the basis for this and the following chapter (Part B).
- 2 Emissions from the production and distribution of fuels, usually generated outside cities, are not included in local emissions here because in cities vehicle emissions are far more important.

| <p style="text-align: center;"><i>Box 3</i></p> <p style="text-align: center;">Local Effects of Automotive Emissions</p> | |
|---|---|
| Direct Toxic and Nuisance Effects | <p>CO causes short term toxicity, blocking the uptake of oxygen by haemoglobin. This problem occurs mainly in confined areas like garages.</p> <p>NO₂ causes respiratory problems in the lungs.</p> <p>Particulate matter mechanically overloads the lungs; soot in combination with SO₂ forms an acute toxic.</p> <p>Aldehydes irritate the bronchi and other mucous membranes, and are acute toxics, especially the aldehydes with the lower molecular weights.</p> |
| Summer Smog (ozone) | <p>Ozone causes respiratory problems and irritation of the mucous membranes, damages biomolecules and probably diminishes resistance to virus infections. Ozone and other photochemical oxidants are formed by volatile organic compounds (VOC) and NO_x under sunlight.</p> |
| Long-term Toxicity | <p>Benzene, a haematotoxic, is also a suspected carcinogen. Toluene and xylene are less toxic.</p> <p>Each of the Polycyclic Aromatic Hydrocarbons (PAHs) in exhaust gases has some mutagenic and carcinogenic activity.</p> <p>Soot is mutagenic and carcinogenic and increases allergenic reactions.</p> <p>SO₂ causes cell destruction.</p> <p>Lead affects the psychic development of children.</p> |
| Material Damage | <p>Soot fouls buildings. SO₂, in combination with nitrogen compounds and photochemical oxidants, generates material damage.</p> <p>Vibrations may damage buildings.</p> |
| Stress | <p>Noise causes irritation, sleep disturbance and stress. These effects probably lead to heart and vascular diseases.</p> |
| Winter Smog | <p>Particulate matter and SO₂ together cause winter smog.</p> |

Judgements of fuels' ability to reduce local emissions emerge from four comparisons which examine separately their potential in light duty vehicles (LDVs) and heavy duty vehicles (HDVs) in both the short and the long term³. Because no standardised way exists to aggregate all local effects of vehicle emissions, the different emission components need separate handling, with the focus here on four regulated ones — NMHC, CO, NO_x and Pm⁴.

Test methods, test circumstances, the vehicle and the fuel all influence measured emission data, rendering comparisons of emissions from different fuels difficult. With

³ As in Part A, the short term refers to one to five years and the long term to 15 to 25 years.

⁴ Europe regulates all the hydrocarbons (HC); the United States regulates HC excluding methane, or non-methane hydrocarbons (NMHC); and both regulate CO, NO_x and Pm. Because methane is non-toxic and has a relatively low ozone-forming potential, NMHC is used here.

one test method in a given vehicle, a fuel may emit less than the reference fuel, but a different test method may reverse the result. On the road, as well, a change of fuel will not always have the same effect on emissions, because the effect depends not only on fuel choice but also on driving style, vehicle model and climate. Hence the outcome of a fuel switch cannot be pinned down to an exact percentage of improvement or deterioration in emissions, and only a range emerges.

In the comparisons, gasoline is the reference fuel for LDVs and diesel oil is the reference for HDVs, because these are the most common fuels currently used in the two types of vehicles around the world. The criteria for meaningful emission reductions from each of the fuels take the following forms:

- **Short-term, in LDVs:** at least one regulated emission component improves (drops) by more than 50% relative to gasoline, while none of the others goes to over 110% of its gasoline equivalent (considered a minor change);
- **Short-term, in HDVs:** NO_x and Pm emissions improve more than 50% while CO and HC emissions (which are low from diesel engines) deteriorate no more than 100%, *i.e.* no more than double;
- **Long-term, in LDVs:** the fuel can meet the California ultra low-emission vehicle (ULEV) standards (see Table 6); and
- **Long-term, in HDVs:** the fuel can reduce NO_x and Pm emissions simultaneously, without the trade-off between the two that constitutes the chief problem of emission reduction in diesel-fuelled engines.

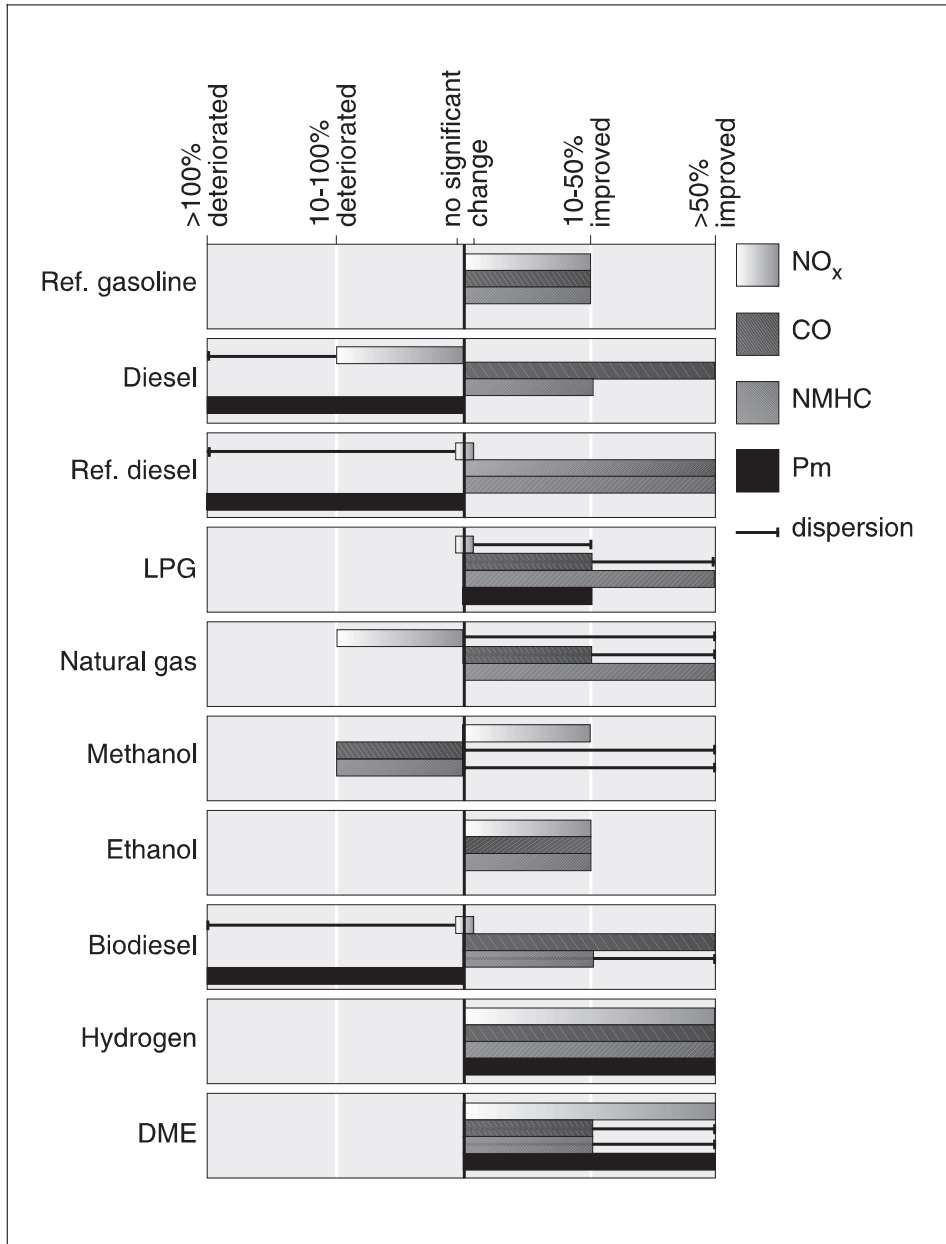
Table 6
ULEV Standards (Measured in the US FTP test cycle, in g/mile.
Values between brackets are g/km.)

| | CO | NMOG⊗RAF* | NO _x | Formaldehyde |
|-------------|-----------|--------------|-----------------|---------------|
| ULEV | 1.7 (1.1) | 0.04 (0.025) | 0.2 (0.12) | 0.008 (0.005) |

* NMOG⊗RAF measures the ozone reactivity of organic gas emissions. Reactivity adjustment factors (RAF) allow estimation of the ozone reactivity of vehicles without measuring the whole non-methane organic gas (NMOG) composition of the exhaust.

LDVs, short-term: Figure 3 shows that LPG, and especially DME and hydrogen, meet the criteria for all components and can improve local emissions *vis à vis* standard gasoline. Natural gas or methanol may lead to improvements but, depending on vehicle and conditions, some components might deteriorate more than 10%. Reformulated gasoline and ethanol improve emissions only moderately, while reformulated diesel and biodiesel have high Pm emissions, and their NO_x emissions deteriorate relative to gasoline.

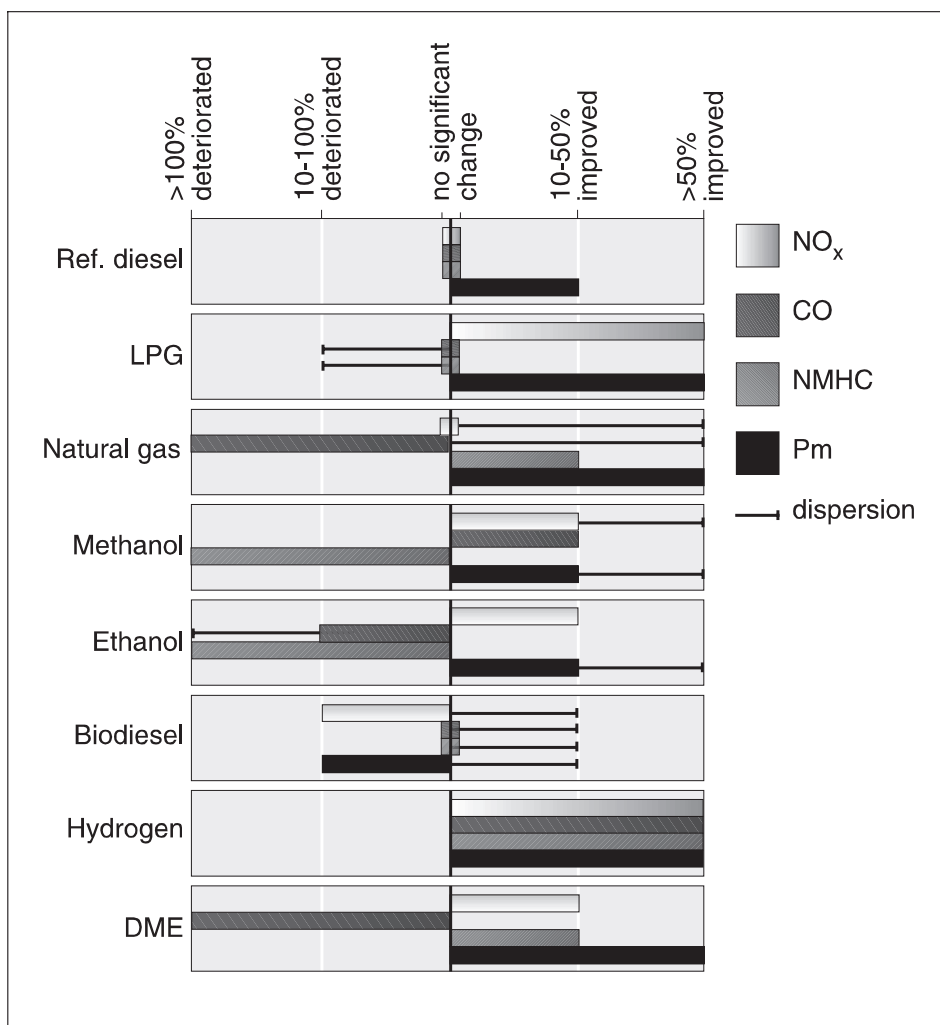
Figure 3
**Emissions of LDVs Relative to their Gasoline Counterparts
in the Short Term**



Where no bar is shown, no data are available. Note that the axes for deterioration and improvement are scaled differently. Hydrogen and DME data are based on a limited number of prototype vehicles. "Ref." = Reformulated.

HDVs, Short-Term: Emission reduction for HDVs focuses on NO_x and particulate matter because diesel engines emit relatively little HC and CO. Although most fuels improve HDV emissions of some components relative to diesel, only LPG and hydrogen clearly fulfil the 50% criterion for NO_x and Pm (Figure 4). Natural gas and methanol can do so as well, but only if the technology and circumstances are right. Reformulated diesel reduces Pm emissions and none of the other emissions deteriorates, but the improvement is relatively modest compared to the other fuels.

Figure 4
**Emissions of HDVs Relative to their Diesel Counterparts
in the Short-Term**



Where no bar is shown, no data were available. Note that the axes for deterioration and improvement are scaled differently. Hydrogen and DME data are based on a limited number of prototype vehicles. "Ref." = Reformulated

| <p style="text-align: center;"><i>Box 4</i></p> <p style="text-align: center;">Non-Regulated Emissions and Noise</p> | |
|---|---|
| PAH | Emissions of aromatics and poly-aromatic hydrocarbons (PAH) are almost negligible for fuels with small molecules, like LPG, natural gas, methanol, ethanol, hydrogen and DME. Biodiesel and especially fossil diesel emit relatively large amounts of PAH. |
| Reactivity of HC and organic gases | The reactivity with ozone (and other oxidants) of the hydrocarbons and organic gases differs greatly between fuels. Reactivity of the exhaust gases of LPG, natural gas and alcohols is 40% to 60% lower than that of gasoline, diesel, biodiesel and hydrogen. |
| Aldehydes | Diesel, biodiesel and alcohol-fuelled cars emit relatively large amounts of aldehydes, twice to seventeen times as much as gasoline for the alcohols and about eight times as much for diesel. Biodiesel emits 90% to 175% of the diesel level. Exhaust catalysts can reduce these aldehyde emissions. |
| Toxicity of particulate matter | Although biodiesels like RME have Pm emission levels comparable to diesel vehicles, their composition is different. RME contains a low concentration of PAH and no sulphate or nitrate, and thus is less detrimental to health. Its mean Pm particle size is ten times that of diesel emissions, which reduces the likelihood of inhalation and deposits in the lungs. |
| Lead | Lead-containing chemicals are still used in some countries as an anti-knock additive in gasoline, but in most their phaseout is fast diminishing lead emissions. Gasoline is the only fuel using lead containing additives. |
| Noise | <p>Rapid variations in pressure cause noise, and CI engines have higher noise levels than SI engines. CI engines use diesel, biodiesel, alcohols (only in heavy-duty applications) and DME. The fuels with short ignition delays generate less noise. DME in a CI engine is almost as silent as gasoline in an SI engine.</p> <p>Gasoline, LPG, natural gas, alcohols (in light-duty and some heavy-duty motors) and hydrogen burn in SI engines, which makes LPG, natural gas and hydrogen attractive to reduce noise from buses in cities.</p> <p>Fuel-cell vehicles (on hydrogen, methanol or gasoline) are even quieter; the reformer, fuel cell and electric motor all produce little noise.</p> |

LDVs, Long-Term: Vehicle technology is set to realise large emission reductions in the near future. Gasoline vehicles emitting less than half of today's emissions standards have already been developed. For the long term, therefore, alternatively fuelled LDVs require assessment of their ability to fit into this established trend. Most fuels suitable for internal combustion engines or fuel cells can in fact already reach ULEV standards for LDVs. Only for diesel, biodiesel and ethanol does it remain unproved that ULEV vehicles can be built. In ethanol trials, the NMOG⊗RAF emissions continued to be too high, but not by much. For this reason, and because ethanol technology and emissions compare with those of methanol, ethanol can bear a "might make it" assessment. For diesel and biodiesel, ULEV levels stay elusive.

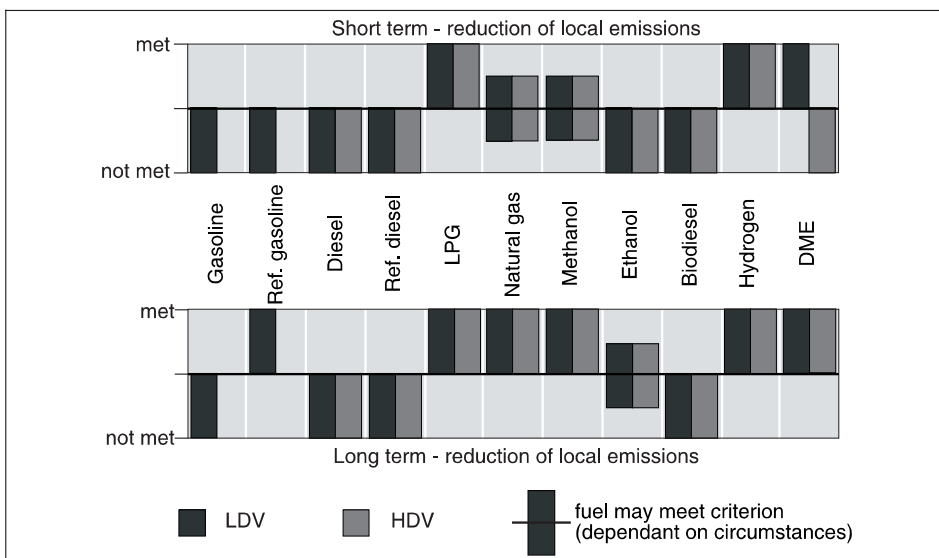
HDVs, Long-Term: Diesel emissions can be brought down — if often at the cost of reduced engine efficiency — with the help of several techniques: EGR, water injection, particulate traps and deNO_x catalysts. These technologies do not depend much on the fuel used, however, and only fuel-related emission characteristics are compared here, to see which fuels can reduce NO_x and Pm emissions simultaneously, abstracting from technologies that accomplish the same end.

Almost all fuels except diesel and biodiesel meet the criterion and could give large emission advantages in the future. LPG, natural gas, methanol, ethanol, hydrogen and DME all have soot-free combustion, so no trade-off between NO_x and soot occurs, and their non-soot Pm emissions are also low compared to diesel. Gaseous-fuel Pm emissions are very low and those from methanol generally less than a third of those of the equivalent diesel HDV. Ethanol probably has potential to meet the criterion, but so far, the data do not prove it can. Its measured emission advantage for Pm in HDVs still varies from only 10% to a more promising 80%.

Non-Regulated Emissions and Noise: Although not the primary focus of this analysis, these aspects should not be neglected. Box 4 summarises some information about them and how different fuels can contribute to their amelioration.

Some Conclusions for Local Emissions: Switching to alternative fuels can indeed reduce emissions considerably and thus improve local air quality. Figure 5 summarises these findings. To profit most from such fuel shifts, technological adaptations often become necessary. In fact, appropriate technological and legislative changes should always accompany the introduction of “clean” fuels, to raise the certainty of reaching emission-reduction targets.

Figure 5
How Fuels Meet the Criteria for Reducing Local Emissions



Large-scale introduction of ethanol or DME in LDVs, and of LPG and hydrogen in both LDVs and HDVs, would reduce the emissions of regulated components significantly. Using hydrogen in fuel-cell vehicles would even lead to *zero* emissions of the regulated components. Emissions would also drop when natural gas or methanol is used, if the appropriate technology were applied. In the long term all fuels except perhaps diesel, biodiesel and ethanol in both LDVs and HDVs can contribute to a significant improvement in local air-quality.

The conclusions of Figure 5 also hold for the non-regulated components, except for the alcohol fuels, which have high aldehyde emissions compared to gasoline. Special catalysts can reduce these emissions to the level of diesel vehicles, which is still significantly higher than for gasoline cars. The noise production of most alternatively fuelled HDVs falls below that of diesel engines.

GREENHOUSE GAS EMISSIONS

Transport accounts for more than a fifth of CO₂ emissions from human activity world-wide. If current trends continue, that share will increase. Automotive fuels emit not only CO₂ but also other gases that contribute directly or indirectly to global warming. They include N₂O, NO_x, CH₄, NMOG, CO and H₂O. For fossil fuels the CO₂ emissions are most important, whereas for some renewable fuels the non-CO₂ emissions form the larger part. Emissions from a given fuel can be added up, using a different weighing factor for each gas, to obtain a CO₂-equivalent value to represent the global warming potential (GWP) of that fuel.

Water vapour (H₂O) in tailpipe emissions is a greenhouse gas, but all the water vapour generated by all human combustion of fossil fuels represents only 0.0013% of current global evaporation, an amount negligible compared to natural water evaporation. Even if all vehicles were hydrogen-propelled, H₂O emissions per vehicle km would double from present levels, an insignificant boost to global warming⁵.

Air conditioning in vehicles does play a role in global warming. In 1987 about 48% of all new cars, trucks and buses manufactured world-wide had air conditioners. So did 80% of all new cars sold in the United States in 1995. Air conditioners in road vehicles increase greenhouse gas emissions in two ways. They require extra energy (about 10% during use); and most refrigerants (which are released through leakage or during servicing) have a global warming potential.

5 A hydrogen car with a combustion engine emits approximately 230 g H₂O per km; a diesel car emits approximately 110 g H₂O per km.

Stopping the probable process of global warming requires a decrease or at least a stabilisation of greenhouse-gas emissions. Yet mobility, as measured by vehicle numbers and vehicle use (mileage), is bound to increase. Reduction or stabilisation of the transport-related contribution to the greenhouse effect thus must involve a significant reduction of CO₂-equivalent emissions per vehicle kilometre, along the entire well-to-wheel fuel chain, not just from tailpipes.

The criterion by which this section evaluates the different fuels is a simple one: reduce well-to-wheel CO₂-equivalent emissions per vehicle kilometre to 50% of the current level. The analysis looks at short-term and long-term possibilities and limits itself not only to LDVs⁶ but also to single vehicles, leaving aside fleets, where only a gradual introduction of alternatively fuelled vehicles is possible. Gasoline is the reference fuel. The criterion may be too modest. There are conflicting views on how much reduction is actually necessary to stop global warming. Difficulties abound in translating an overall reduction target into specific goals for transport or for individual vehicles. It is clear that a 50% reduction of CO₂-equivalent emissions per vehicle kilometre would have little effect if only a few such cars were driving around. Even if half the number of cars on the road met the goal, total emissions would still increase if mobility doubled.

In both the short-term and the long-term analyses, the notion of a “technology gap” has relevance for fuels that do not meet the emission-reduction criterion. Figure 6 illustrates its general outlines: when application of the fuel alone will not result in a 50% reduction of CO₂-equivalent emissions, a technology improvement resulting in lower emissions becomes necessary. The improvement could occur in the vehicle, its engine, the fuel or somewhere in the well-to-wheel chain (e.g. fuel production or vehicle use). The size of the technology gap differs by fuel. For one, only minor improvements might suffice, while for another the fuel has no or a negative effect on emissions and so the reduction of emissions depends completely on technology.

The Short Term: Which fuels meet the 50 % reduction criterion, compared to a gasoline passenger car and based on today’s technology? Based on an extensive survey of many studies, Figure 7 shows greenhouse gas emissions of all fuels relative to gasoline. Although dispersion in the data is high, the figure clearly shows that fossil fuels cannot hit the target in the short term. For the renewable fuels, it appears feasible, although not all studies support that conclusion. The most likely candidates are biodiesel and both methanol and ethanol from wood (cellulose).

6 The authors believe that the results for HDVs may be very similar.

Figure 6
The Technology Gap

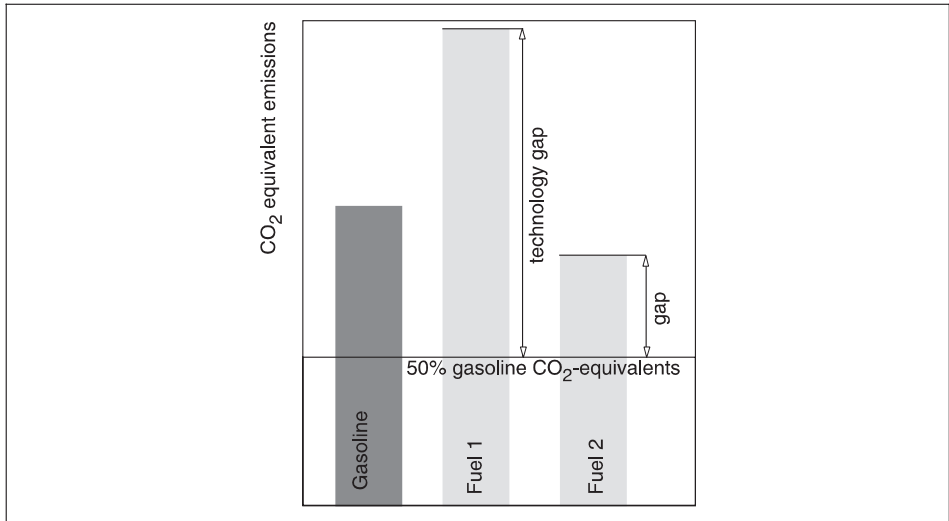
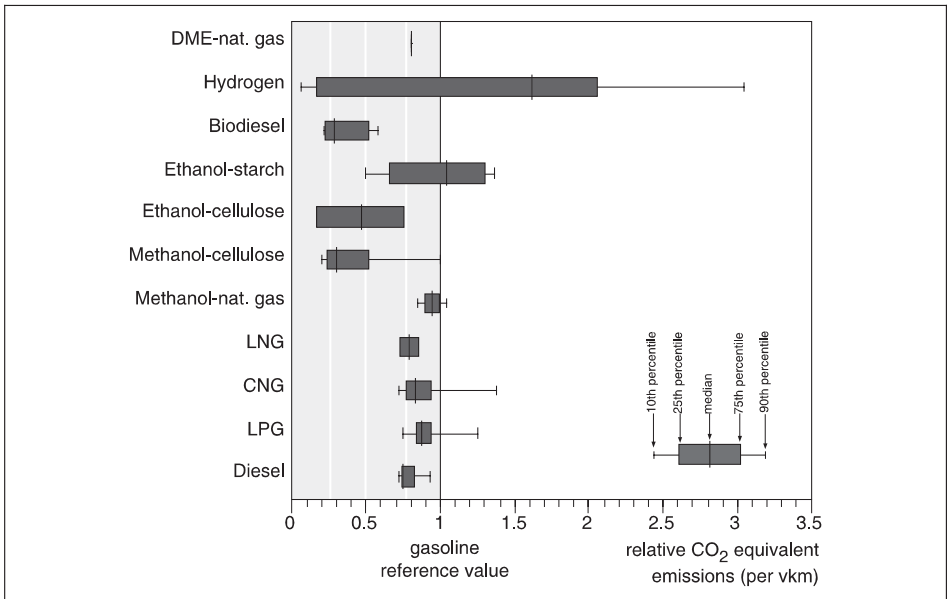


Figure 7
Short-Term CO₂-Equivalent Well-to-Wheel Emissions of LDVs on Different Fuels



Source: 3.

Notes: Performance relative to a 1996 gasoline LDV. The gasoline reference value is 1; 0.5 marks 50% of the CO₂-equivalent emissions of the reference vehicle. Ranges in data result from local variations between fuel routes and differences in technology, which may occur at all stages of the well-to-wheel fuel chain.

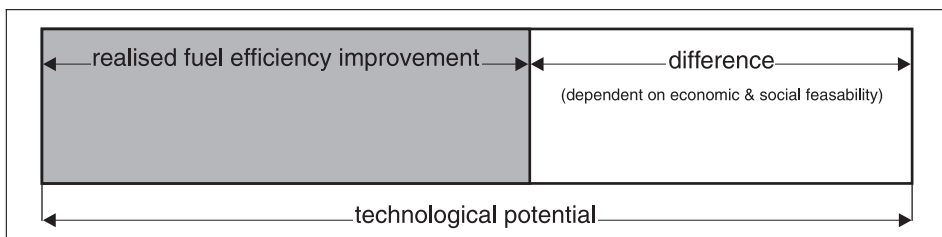
The Long Term: Which fuels can bridge the short-term technology gap in the future, based on developments now expected? Improved fuel efficiency can occur through technological advances and/or changes in consumers' technology preferences. The factors that play a role include (see Figure 8):

- Technical potential: the maximum level of technological development possible;
- Economic feasibility: the economic viability of technologies; and
- Social acceptability: legislation, attitudes towards the environment and non-renewable resources, fuel prices.

These factors have a high degree of interdependence. Social acceptability can interfere strongly in economic feasibility; stricter legislation (if politically attainable) makes higher costs acceptable. Knowledge of the technological potential can help decide where intervention would be most effective, but the economic and social factors together influence how much of intervention will in fact be realised and how it will be used. When technology enables construction of lighter vehicles, for example, producers will decide, based on consumer preferences and the laws, whether to use the weight reduction to reduce fuel consumption or to use it to make bigger cars without raising fuel consumption.

Do not forget the fuel chain. The contribution of each step of the fuel chain to well-to-wheel emissions, and therefore the emission-reduction potential, differ among fuels. Fewer emissions in production and distribution have only a small effect on the total for a fuel like gasoline, where these steps in the chain hold only a small share. For fuels made of biomass and for hydrogen, however, efficiency improvements in fuel supply become significant. Moreover, efficiency improvements in vehicle use have an impact on both vehicular and supply emissions. If, for example, only half the fuel is needed to drive a given distance, only half has to be produced and distributed. Thus, improving vehicular fuel economy offers the best way to reduce greenhouse gas emissions. It can occur in two major ways: (1) by increasing the efficiency of the drive train (engine, axles and transmission); and (2) by reducing the driving resistance/effort required to move the vehicle.

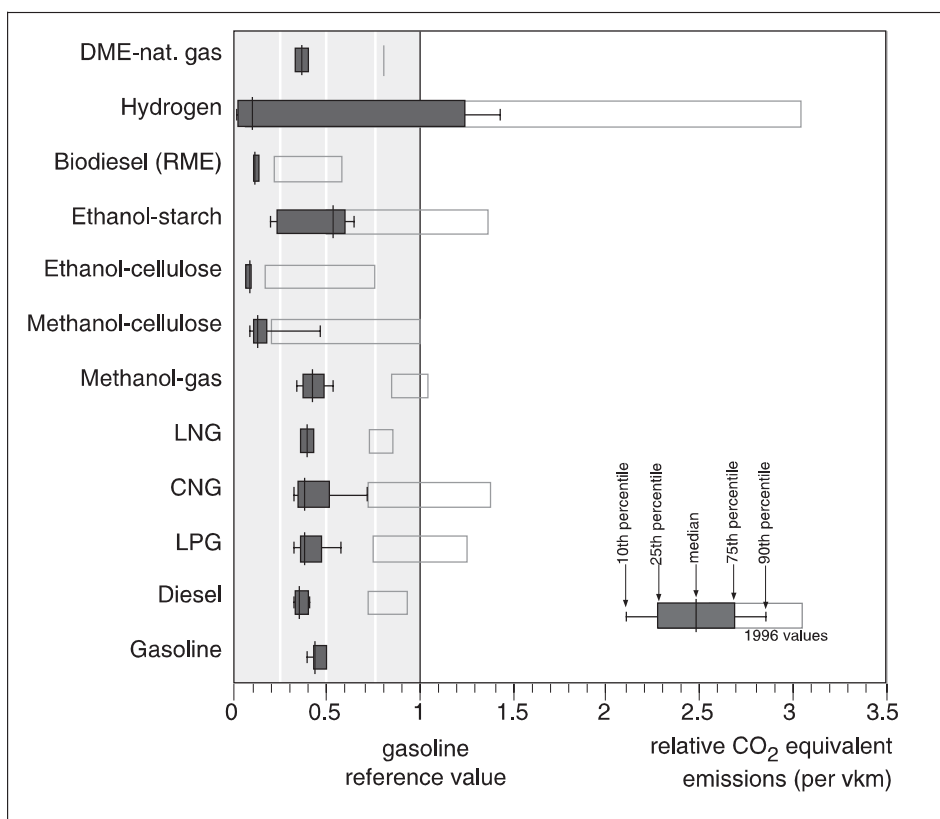
Figure 8
Technical Potential and Realised Fuel Efficiency



A lack of information prevents any quantification of technological potentials for emission reductions by fuel and stage of the fuel chain. Assumptions must intervene, and they are the same for all fuels: an efficiency improvement of from 5% to 10% in fuel supply (production and distribution); and one of 50% to 55% in vehicular efficiency, for all fuels used in 3-litre combustion engines. With these assumptions, almost all fuels can meet the 50% emission-reduction criterion in the long term (Figure 9). Whether hydrogen does so depends very much on how the electricity for electrolysis is generated. Ethanol produced from starch may have difficulties.

Conclusions on Greenhouse Emissions: Any substantial reduction of greenhouse-gas emissions depends heavily on technological developments. Figure 10 illustrates that only biomass fuels and hydrogen from “clean” electricity *may* be able to reduce such

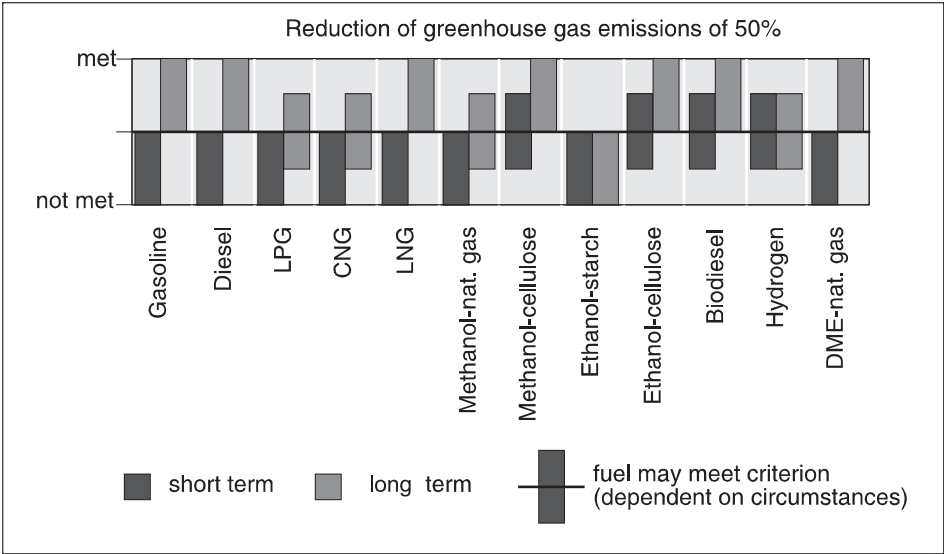
Figure 9
**Long-Term Well-to-Wheel CO₂-Equivalent Emissions
of LDVs On Different Fuels**



Data are displayed per vehicle kilometre and relative to a 1996 gasoline LDV. The gasoline reference value is 1; 0.5 indicates 50% of the CO₂-equivalent emissions of the reference vehicle. The data ranges result from differences in expectations, local variations among fuel routes and differences in technology, which may occur at all stages of the fuel chain.

emissions by 50% in the short term. Figure 9 has already shown that fuels from biomass (except ethanol from grain), and hydrogen, can reduce emissions per vehicle kilometre by more than 75% in the long term, but only with considerable technological improvement.

Figure 10
Feasibility of Greenhouse-Gas Emission Reduction



OIL DEPENDENCY, COSTS AND THE SEARCH FOR THE ULTIMATE FUEL

REDUCING OIL DEPENDENCY

The world depends on oil for more than 30% of its energy. Because reserves are unevenly distributed, many countries import much of their oil and so come to depend on the few places in the world where petroleum is abundant, mainly the Middle East. The OECD countries use almost half of their crude oil consumption as gasoline or diesel in road transport; gasoline and diesel together provide 99% of the fuel consumed in road transport. This reliance on oil will not diminish in coming decades because petroleum remains abundant and cheap, and energy consumption for transport will increase. World-wide automotive energy consumption reached an estimated 52.5×10^{18} J in 1990, and is projected to grow to 79×10^{18} J around the year 2025 (3).

Countries may have several reasons to reduce their oil consumption. They may aim for more self-sufficiency and less dependence on the few oil exporters, many of which lie in politically unstable regions; this reasoning influenced the US ethanol programme and the Dutch policy on LPG. Some countries may simply wish to cut imports and stimulate the use of alternative domestic resources, as was the case for Brazil's programme, based on ethanol from sugar cane. Others may seek to guarantee affordable transport-energy supplies in the long term when, as is the common expectation, oil prices will rise as production moves to more costly sites and methods. Some countries prepare for sudden future oil-price increases by studying and gradually introducing alternative fuels. Finally, the environmental burden posed by oil consumption provides a powerful stimulus to reduce it. Vehicle technology can diminish most of the local and regional pollution from automotive fossil fuels, but increased greenhouse emissions remain inherent in their use.

An alternative fuel can reduce oil dependency only if it can meet a significant part of world-wide automotive-fuel demand. Its potential depends on (1) feedstock production and fuel-conversion capacity; (2) the availability of a distribution infrastructure; and (3) its suitability for application in vehicles. This section analyses these three issues in turn, in light of the following policy criterion: a fuel must be capable of substitution for 10% of the world-wide automotive fuel consumption projected for the short and the long term.

Feedstock Production and Fuel Conversion Capacity

For what non-oil fuels can industry recover and convert enough feedstock to meet the 10% criterion? In precise terms, this means, for each fuel, finding and processing feedstocks sufficient to produce 5.25×10^{18} J of automotive fuel within five years and

7.9×10^{18} J fifteen to twenty-five years from now. The long-term conversion goal is assumed to be reachable only if no major technological problems currently remain. Figure 11 shows that natural gas, methanol from natural gas and hydrogen can meet the criterion for feedstock supply in the short term, with enough feedstocks becoming available in the long run for LPG, DME, and perhaps ethanol from sugar and methanol from cellulosic material. Figure 12, however, reveals that sufficient short-term conversion capacity exists only for LPG and natural gas. In the long term, enough conversion capacity can be built for all fuels except non-oil gasoline, non-oil diesel and ethanol from cellulosic material. For these exceptions, conversion remains experimental.

Biofuels: The production of feedstock for biofuels resembles the raising of such crops for food or industrial uses, although the breeding varieties usually differ. Cellulosic materials for methanol or ethanol may be by-products, such as straw and wood waste or they come from sources like short-rotation coppice. Most of the feedstocks of concern here are already produced on a commercial scale, and the technology for making biofuels exists.

Figure 11
Meeting the Feedstock Recovery Capacity Criterion

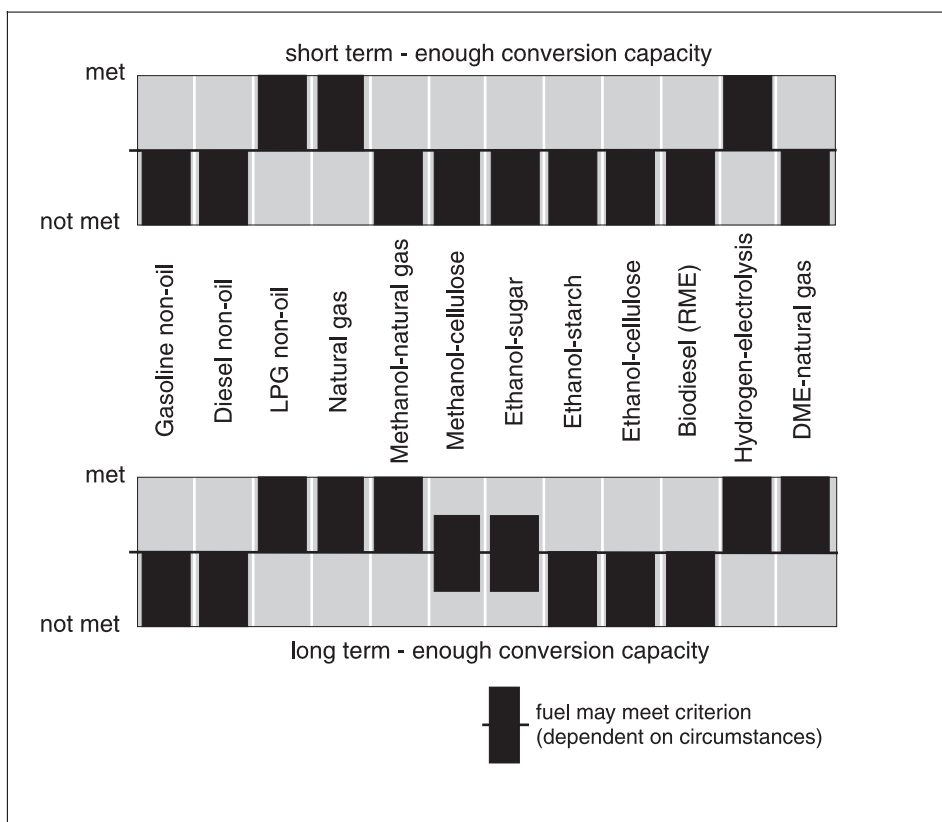
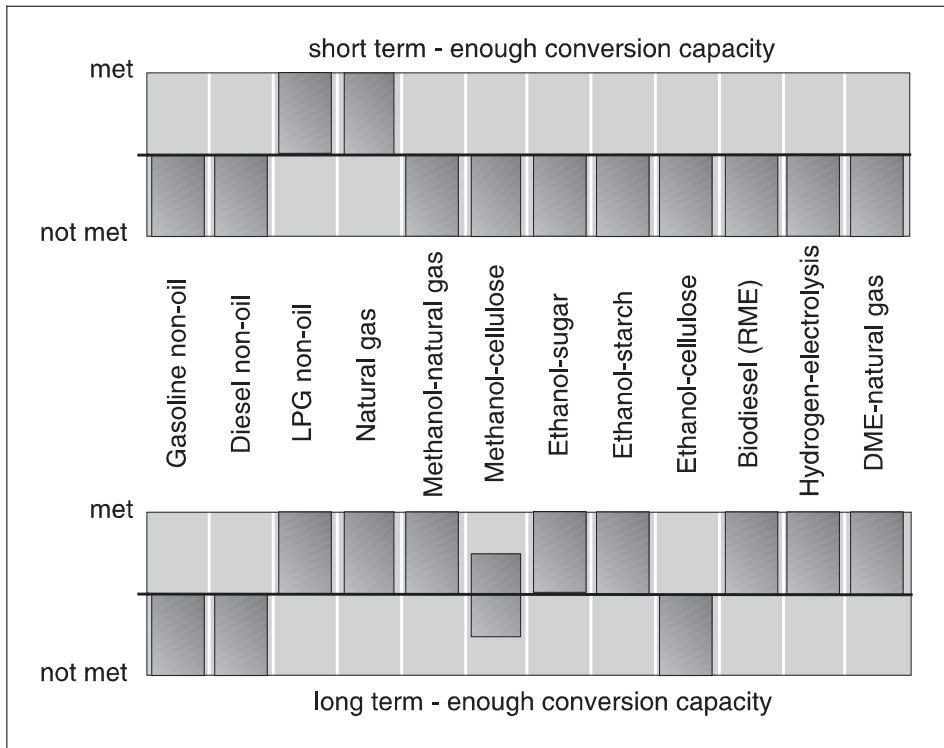


Figure 12
Meeting the Feedstock Conversion Capacity Criterion



But is the necessary land available to grow these crops? Table 7, with its estimates of the agricultural territory needed to meet the 10% criterion for each biofuel, shows that land is indeed a heavy constraint. Given the enormous acreages involved, only in the long term could just two fuels — ethanol from sugar beets or other high-sugar feedstocks and methanol from cellulosic materials — substitute for 10% of automotive fuel demand. The feasibility of such a shift in global land-use patterns raises other questions; many economic and non-economic factors would influence it. The other fuels simply require too much land for any reasonable expectation that they could meet the criterion.

Several factors might mitigate the land constraint; while others might exacerbate it. A significant increase in yields would increase biofuels' chances. Higher yields have increased agricultural production enormously in recent decades. Yet this trend may not last, because large areas have already been irrigated and fertilised, water shortages may emerge. Both erosion and irrigation cause farm yields to decline. Genetically engineered plants may lead to renewed increases, but their technical potential is not yet fully

Table 7
**Land Needed to Produce Feedstocks
for Biofuels under the 10% Substitution Criterion**

(In units of 10^7 ha and as percentages of total world cropland of 144×10^7 ha in 1992)

| | <i>Short Term</i> | | <i>Long Term</i> | |
|------------------------------------|-----------------------------|----------|-----------------------------|----------|
| | <i>10^7 ha</i> | <i>%</i> | <i>10^7 ha</i> | <i>%</i> |
| Methanol from Cellulose | 5.6 | 4 | 8.4 | 6 |
| Ethanol from Cellulose | 9.7 | 7 | 14.7 | 10 |
| Ethanol from Starch (wheat) | 10.3 | 7 | 16 | 11 |
| Ethanol from Sugar Beet | 3.7 | 3 | 5.6 | 4 |
| Biodiesel | 12 | 8 | 17 | 12 |

Notes: These are, of course, rough estimates. They derive from European data on yields per hectare, feedstocks needed for a ton of fuel and the energy content of that fuel. Production-capacity calculations assume that enough good-quality hectares exist for production of the crop or similar crops with comparable yields per hectare. The estimates of the areas required assume constant yields.

known and they have encountered societal resistance in some places. Finally, note that the production capacity of different biofuels depends on the area already claimed by others, because each influences others' production capacity. The introduction of more than one biofuel simultaneously on a scale sufficient for each to meet the criterion posed here would multiply the crop-area burden. Introducing just one bio-fuel could absorb land now claimed by others.

LPG: Field LPG is not an oil-based fuel; oil is not its feedstock and part of it is still wasted by flaring⁷. Its current production could meet the short-term criterion as an automotive fuel, but it is partly used in other applications. This puts the criterion out of reach for the moment. In a just slightly longer perspective, however, brighter prospects emerge. Production of LPG has a proven technology and is not difficult to expand. It will increase because of increased natural gas production and decreased flaring, while other feedstocks could meet demand in non-automotive applications. LPG also can be made with synthesis gas from coal, gas or biomass, although at relatively high costs. On balance, therefore, LPG production capacity does not form a

⁷ LPG production in refineries stems from crude oil and is therefore oil-based. It is not included in this analysis.

barrier to meeting the 10% criterion either in the long term or, except for perhaps a brief delay, the short term.

Natural Gas: World-wide, enough natural gas is available to meet the criterion in the short term and in the future. Gas production sites presently operate at maximum capacity for only part of the year. World supplies exceed proven oil reserves by 22%⁸. For similar reasons, feedstock capacity for *methanol from natural gas* poses no immediate or future problems. Whether enough conversion capacity exists to produce 5.25×10^{18} J of methanol within five years is more difficult to assess. Some current excess capacity may make a quick increase possible, but more capacity is probably needed to reach the criterion target. In the long term, no problem exists.

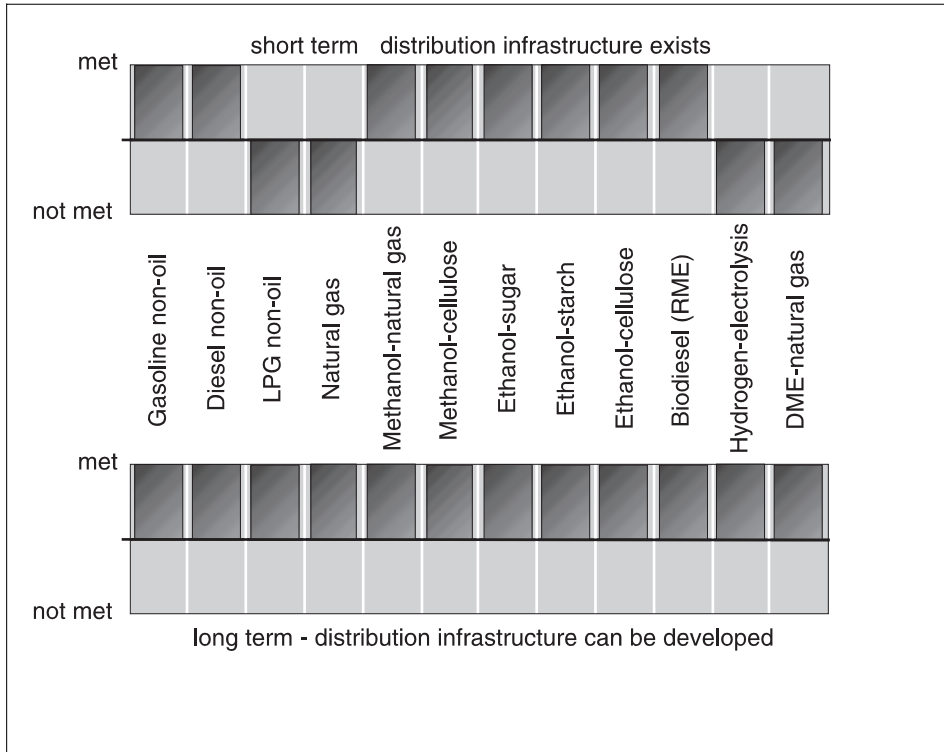
Hydrogen and DME: Both of these fuels are good prospects for the long term but not the short. Hydrogen, with abundant feedstocks, enjoys current production on a large scale for the chemical industry. Today's output equals 7% of the energy consumed by road vehicles. Although it probably cannot expand sufficiently in the short term to meet the criterion, the long term presents no difficulty. Like methanol, DME can be produced from any hydrocarbon-containing feedstock, which makes its feedstock capacity comparable to methanol's. Because some methanol plants have overcapacity, they could be retrofitted to DME production in the medium term. Moreover, a new, efficient production process invented by Haldor Topsøe probably will produce DME from natural gas in the future. DME production from biomass represents another future option, although no tests have yet estimated its feasibility.

Distribution

If vehicles are to burn them, fuels need distribution to refuelling points. The criteria here are simplicity itself: in the short term a fuel's distribution infrastructure must be ready now or adaptable within five years; for the long term, nothing stops building a distribution system except fundamental technical problems. The analysis of both, of course, is scaled to the 10% criterion. Figure 13 makes the key points: in the short term, problems exist for only a few fuels, namely field LPG, natural gas, hydrogen and DME; the long term presents no difficulties.

8 They must eventually diminish as this fossil energy carrier gets depleted in the longer term.

Figure 13
Meeting the Distribution Infrastructure Criterion



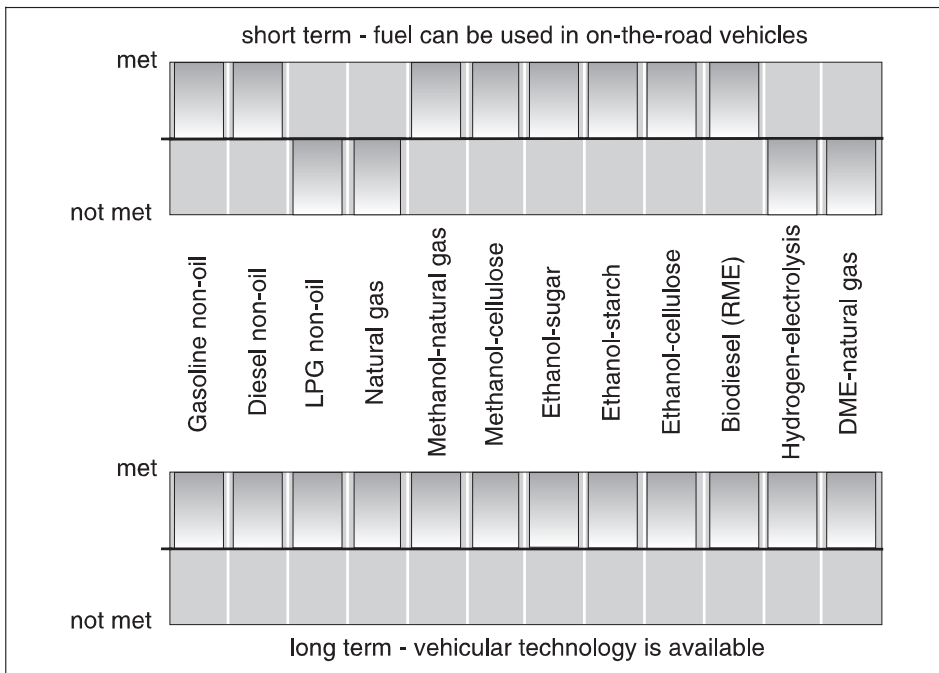
LPG distribution requires special facilities, but countries like the Netherlands and Italy already use the technology on a large scale, so others would need only time to replicate it. Natural gas can move through gas grids, if available, in which case only the refuelling appliances have to be installed and connected to the grids. Without grids, road tankers must take their place, in numbers which also require time to build, along with large-scale refuelling networks. Hydrogen-distribution technology is proven but not yet tested on a large scale. As far as the refuelling point, DME distribution can draw on experience with shipping the fuel into non-transport applications. Vehicle refuelling itself remains unproven, although DME resembles LPG and there is no reason to expect that refuelling will pose a long-term problem. As for other fuels, getting the alcohols (or alcohol-gasoline blends) to market closely resembles gasoline distribution, with the most important change involving installation of alcohol-resistant materials along the fuel chain. Newer refuelling stations are already fitted. Biodiesel offers no more difficulty than diesel fuel.

Vehicle Use

For a fuel to meet the 10% criterion in the short term, gasoline and diesel vehicles now on the road must be able to use it. Only four fuels fail the test, as Figure 14 indicates. LPG and natural gas require retrofitting. Hydrogen has not yet had extensive field testing either in internal combustion engines or fuel cells. DME use has been demonstrated, although some lubrication problems persist and fuel pumps wear too quickly.

In the long term, one can assume that enough cars can be on the road to handle the non-oil fuel or fuels chosen; no fundamental technical barriers exist. LPG and natural gas are already used fairly extensively in some markets, the former especially in the Netherlands and Italy and the latter in New Zealand and Argentina. Alcohols can now serve as gasoline additives, including up to 20% ethanol with no changes but replacement of rubber parts in older vehicles (new vehicles already are adapted). High-percentage alcohol blends can go into FFVs without major problems and they can be used in dedicated vehicles, as has been shown by extensive tests in the United States and large-scale use in Brazil. Biodiesel and diesel have no important differences; many new diesel vehicles already have biodiesel-resistant synthetic parts. DME's few remaining problems will probably find solutions within a few years because the fuel's characteristics are well known and in many respects comparable to those of LPG.

Figure 14
Meeting the Vehicle-Use Criterion



The Complete Fuel Chain

For a non-oil fuel to meet the criterion established at the start of this section — a capability to replace at least 10% of oil-based automotive fuel demand in the short and the long term — it must pass the relevant tests at all four stages of the fuel chain. The conclusions are already clear from the foregoing, but Figure 15 summarises them visually. For the next five years, matters look rather hopeless: no fuel can take even 10% of oil's place in road transport. Taking the longer view, however, one can be more optimistic. LPG, natural gas, hydrogen and DME can all satisfy the criterion. From a strictly technical point of view, two key biofuels, ethanol from sugar-rich crops and methanol from cellulose, might well do so; but they face formidable problems in the vast agricultural changes that must occur globally to make that happen.

Cost Comparisons

With knowledge in hand of the various fuels' emissions characteristics as well as the feasibility of replacing oil-based fuels with one or more fuels not derived from petroleum, one can move to the last evaluative step: comparisons of well-to-wheel fuel costs. Figures 16 and 17, drawn from Table 4 in Chapter 4 (Part A), picture these cost comparisons for the short and the long term and for both LDVs and HDVs⁹. No particular policy criterion enters here; direct comparisons suffice. Note that the figures convert ranges given in the tables to indicative fixed values; actual values depend on local circumstances. Furthermore, like all glimpses of the future, these numbers have inherent uncertainties which grow as the time horizon lengthens.

To begin with some broad generalisations, the factors which dominate in determining the cost competitiveness of the different fuels include (1) present and future feedstock costs; (2) the efficiency of fuel production and how it can improve; and (3) engine and vehicle efficiency. Moreover, high energy density in a fuel has a positive effect on its final cost, because distribution has a relatively large share in well-to-wheel costs, and the denser a fuel the less it costs to distribute.

Fuels from biomass tend to have higher costs than fossil fuels, in both the short and the long term and even under the long-term, low-cost cellulose assumptions of this study, even though the costs of methanol from cellulose fall within the same range as fossil-fuel costs in the long term. Biodiesel costs barely exceed those of fossil fuels, while ethanol looks particularly expensive. Among the fossil fuels, diesel is clearly a low-cost fuel for both LDVs and HDVs, due to its high energy density and the higher efficiency of the diesel engine. In the short term, natural gas (excluding vehicle costs) undercuts diesel, but not in the long run. Fuels produced from natural gas tend towards the upper end of the fossil-fuel range, although DME shows lower costs than methanol

⁹ Because fuel costs for hydrogen (produced by electrolysis) do not appear in Volume 3 of the *Automotive Fuels Survey* (3), hydrogen is not included here.

Figure 15
**Meeting the 10% Criterion Across
The Fuel Chain: Short and Long Term**

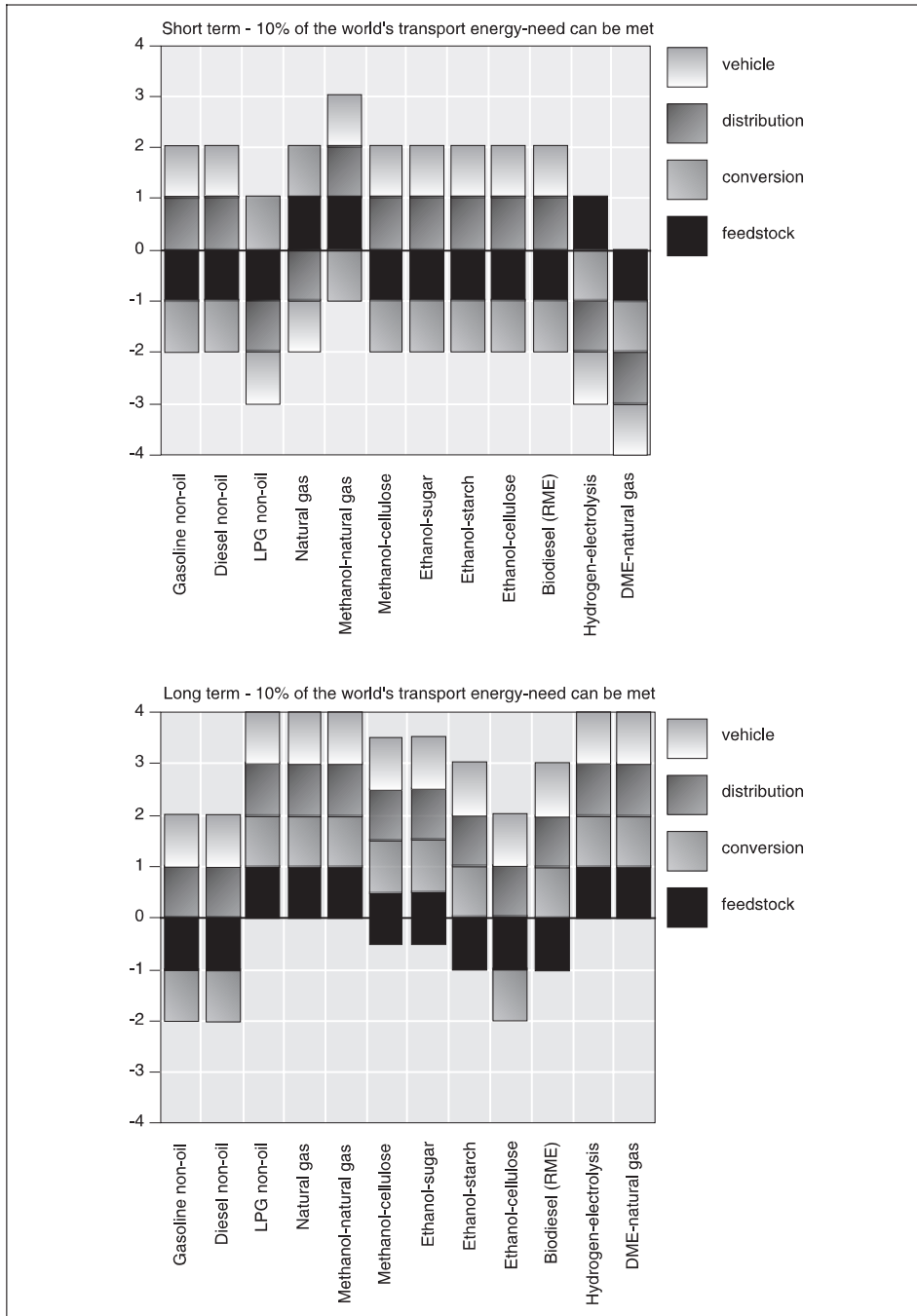


Figure 16
Well-to-Wheel Cost Comparisons for LDVs

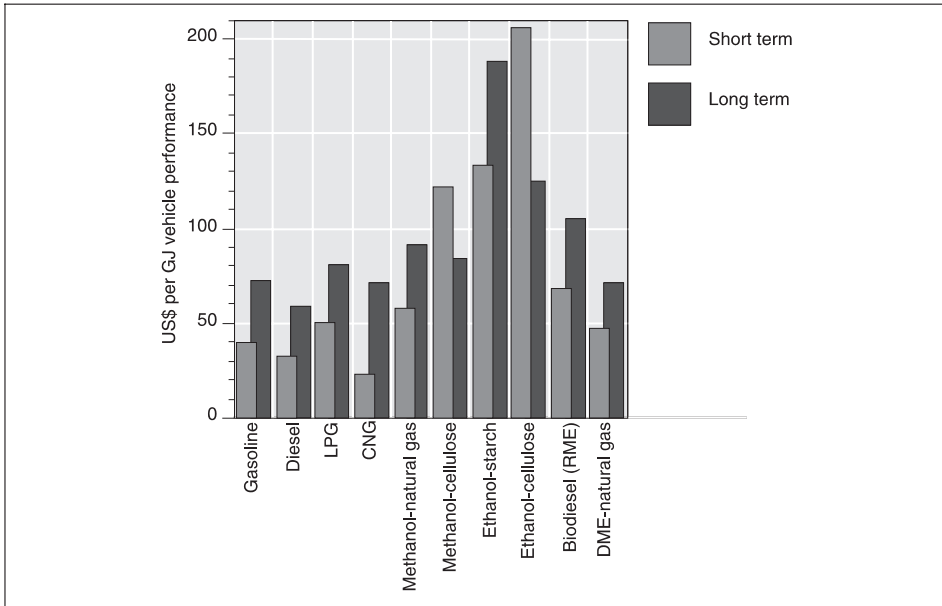
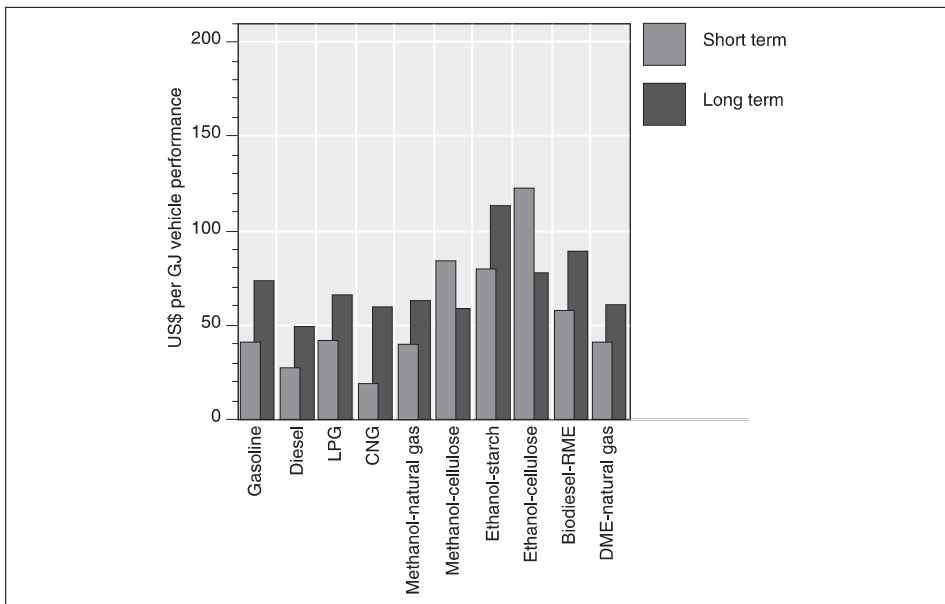


Figure 17
Well-to-Wheel Fuel Cost Comparisons for HDVs



because of higher engine efficiencies. Methanol costs relatively more in LDVs than in HDVs, mainly because the engine technologies differ; LDVs are assumed to have SI engines, while heavy-duty methanol CI engines operate with greater energy efficiency.

PUTTING IT ALL TOGETHER: THE ULTIMATE FUEL

The *ideal* fuel would combine all the advantages of today's conventional fuels with none of their disadvantages. It does not yet exist. This report explores a more modest goal, defining an "ultimate" fuel as one that simultaneously meets, at reasonable costs, the criteria introduced for emissions in the previous chapter and for reducing oil dependency in this one. This admittedly arbitrary definition reflects currently important issues. It also serves as a useful exercise — to demonstrate how decision makers might find their way in the labyrinth of automotive-fuel choices. Under real-world circumstances, different criteria may take higher priority and the facts may change substantially, but the methodology will remain valid¹⁰.

In the short term some fuels show advantages, but not one comes close to being an ultimate fuel, largely because, for both LDVs and HDVs, no non-oil fuel can substitute for 10% of automotive demand. The long term offers more positive findings. Figure 18 presents a way to combine the analyses of all the issues for LDVs.

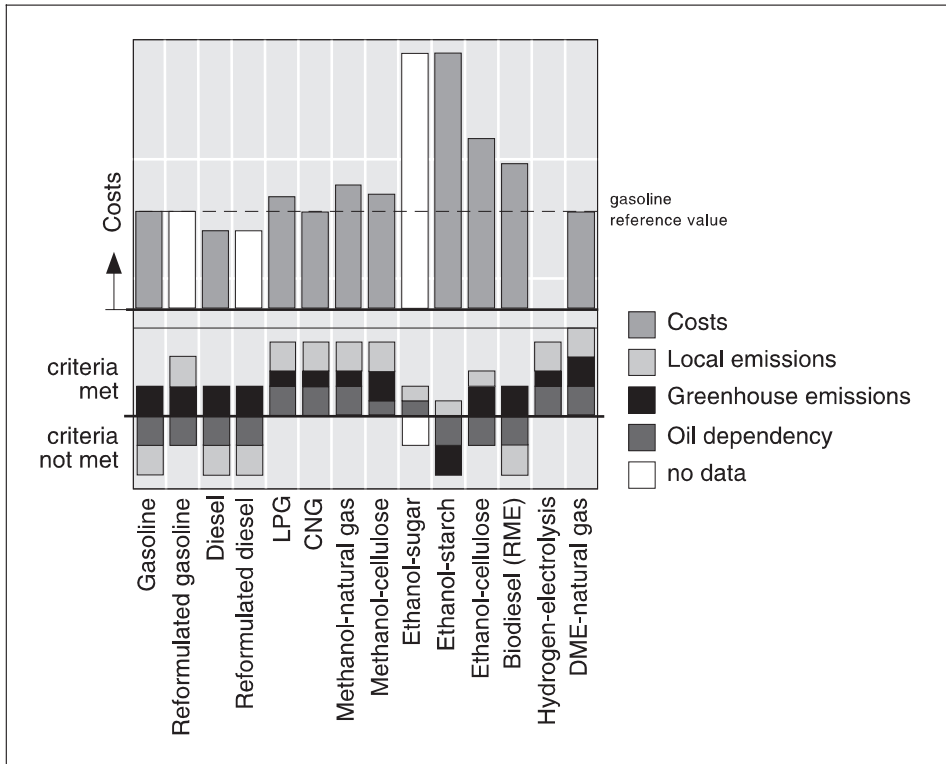
Recall that the long-term criteria for the ultimate fuel in LDVs involve the following:

- A fuel must meet the California ULEV (ultra low-emission vehicle) emission levels for *local emissions*.
- It must reduce well-to-wheel *greenhouse gas emissions* by 50% compared to gasoline vehicles.
- A fuel reduces *oil dependency* significantly if it can substitute for 10% of world-wide automotive fuel consumption.
- The reader may define his or her own *cost* criterion, say, that a fuel's well-to-wheel costs should not exceed 1.1 times those of gasoline.

DME from natural gas offers a good alternative to gasoline and diesel. It meets the criteria and should become available in the long term at a price comparable to gasoline's. LPG, CNG and methanol may meet the criteria under certain conditions. LPG, CNG and methanol from natural gas will do so when greenhouse emissions can be cut to a low level. Methanol from cellulose will do so if feedstock capacity expands

¹⁰ Other examples of combinations of criteria can be found in volume 3 of the *Automotive Fuels Survey* (3).

Figure 18
Finding the Ultimate Fuel for LDVs in the Long Term



Notes: The upper part of this figure shows well-to-wheel fuel costs relative to gasoline. The lower part shows whether fuels meet criteria on local emissions, greenhouse emissions and reducing oil dependency. Half-size blocks indicate that fuels may meet the criteria under certain conditions. For reformulated gasoline, reformulated diesel and ethanol from sugar, no cost figures are available; their long-term costs probably compare with gasoline, diesel and ethanol from starch respectively, as indicated by white bars. The absence of cost data for hydrogen precludes even guesses about its long-term costs. Ethanol from sugar lacks data on greenhouse emissions, but the result will resemble that for ethanol from starch.

sufficiently. The costs of these fuels probably will not exceed gasoline costs by very much in the long term. Hydrogen may also meet the criteria, but its long-term costs are not available.

Thus, something can indeed be said and close analysis does not go for naught. Perhaps more important, this handbook points the way to a reasonably robust methodology. It allows one to navigate the course through a fog of technical and policy conundra. Nobody knows what the long-term future will look like, but, despite its limitations, this methodology can help in setting priorities and directing automotive-fuel developments.

REFERENCES

Note: The references are cited in the text by number rather than in the usual way by author and year. Because the first three volumes of the IEA/AFIS *Automotive Fuels Survey* serve as the basis for this book's summary treatment and are cited very frequently, they are listed first and out of alphabetical order.

1. ELAM, N. (1996) *Automotive Fuels Survey: Raw Materials and Conversion*. vol. 1. IEA/AFIS, Göteborg, Sweden.
2. VAN WALWIJK, M., M. BÜCKMANN, W.P. TROELSTRA and P.A.J. ACHTEN (1996), *Automotive Fuels Survey: Distribution and Use*. vol. 2. IEA/AFIS, Breda, the Netherlands.
3. VAN WALWIJK, M., M. BÜCKMANN, W.P. TROELSTRA and N. ELAM (1998) *Automotive Fuels Survey: Comparison and Selection*. vol. 3. IEA/AFIS, Breda, The Netherlands, 1998.
4. CBS (1996), *Auto's in Nederland; Cijfers over gebruik, kosten en effecten.*, Heerlen, the Netherlands.
5. DE VOOGD, A., J.V.D. WEIDE, A. KONIG and R. WEGENER (1995) *Dedicated Natural Gas Vehicle with Low Emission*, presented at "The European Automotive Industry meets the Challenges of the year 2000", Strasbourg, France, 21-23 June.
6. GOVER, M.P., S.A. COLLINGS, G.T. HITCHCOCK, D.P. MOON and G.T. WILKINS (1995), *Alternative Road Transport Fuels – A Preliminary Life-Cycle Study for the UK*. vol. 2. ETSU, Didcot, UK, 1995.
7. HEINRICH, H., G. DECKER and R. WEGENER (1992), "Alternative Kraftstoffe – Chancen und Risiken aus der Sicht von Volkswagen", in *Aspekte alternativer Energieträger für Fahrzeugantriebe*, VDI Berichte, no. 1020.
8. JOHANSSON, A., A. BRANDBERG and A. ROTH (1992), *The Life of Fuels. Motor Fuels from Source to End Use*, Ecotrafic AB, Stockholm, Sweden.
9. KELLY, K.J., B.K. BAILEY, T.C. COBURN, W. CLARK, L. EUDY AND P. LISSIUK (1996), *Federal Test Procedure Emissions Test Results from Ethanol Variable-Fuel Vehicle Chevrolet Lumina*. SAE paper 961092, SAE, Warrendale, Pennsylvania, United States.
10. OECD/IEA (1997), *Energy Statistics of OECD Countries 1994-1995*, OECD, Paris, France.
11. OWEN, K. and T. COLEY (1995), *Automotive Fuels Reference Book*, Second ed. SAE, Warrendale, Pennsylvania, United States.

12. POULTON, M.L. (1994), *Alternative Fuels for Road Vehicles*, Computational Mechanics Publications, Southampton, UK.
13. RYAN, T.W. III, M. MAYMAR, D. OTT, R.A.L. VIOLETTE and R.D.M. DOWALL (1996) *Combustion and Emissions Characteristics of Minimally Processed Methanol in a Diesel Engine without Ignition Assist*. SAE paper 940326, SAE, Warrendale, Pennsylvania, United States.
14. VAN BLARIGAN, P. (1996), *Development of a Hydrogen Fuelled Internal Combustion Engine Designed for Single Speed/Power Operation*. SAE paper 961690, SAE, Warrendale, Pennsylvania, United States.
15. VERBEEK, R. (1997) *Workshop: Dimethyl-Ether as an Automotive Fuel*, TNO, report no. 97.OR.VM.003.1/RV, Delft, the Netherlands 1997.

GLOSSARY OF TERMS

acetaldehyde

CH_3CHO ; emission component of the exhaust gases of combustion engines; presumably carcinogenic.

additive

Additives are added to the fuel in small amounts to improve the properties of the fuel. For instance, anti-sludge additives prevent the deposits of carbon and tar on the inlet valves and other engine parts.

air/fuel ratio

Mass ratio of air to fuel inducted by an engine. See also stoichiometric ratio.

alcohol

Group of organic compounds, derived from hydrocarbons, which have one or more hydrogen atoms replaced by hydroxyl (OH) groups.

ANG

Adsorbed Natural Gas.

auto-ignition temperature

The minimum temperature at which a mixture of air and fuel ignites spontaneously without the application of an ignition source.

backfiring

An early combustion of the air-fuel mixture in the inlet manifold.

biodegradability

The capability of a substance to decompose into harmless elements.

biodiesel

Automotive fuel consisting of esterified vegetable oils like rapeseed methyl ester and soybean methyl ester.

catalyst

1. Substance that influences the speed and direction of a chemical reaction without itself undergoing any significant change.
2. Catalytic reactor which reduces the emission of harmful exhaust gasses from combustion engines.

cetane number

A measure of the ignition quality of diesel fuel based on ignition delay in an engine. The higher the cetane number, the shorter the ignition delay and the better the ignition quality. The cetane number is based on the ignition quality of cetane ($\text{C}_{16}\text{H}_{34}$) and heptamethylnonane. (a)-methyl naphthalene is also used instead of heptamethylnonane as reference fuel with a low cetane number.

CH₄

Chemical description of methane. Methane is the main component of natural gas.

CNG

Compressed Natural Gas.

CO

Carbon monoxide.

CO₂

Carbon dioxide.

compression ratio

The ratio of the volume of the combustion chamber at the beginning of the compression stroke and the volume of the chamber at the end of the compression stroke.

compression ignition engine

Internal combustion engine with an ignition caused by the heating of the fuel-air mixture in the cylinder by means of compression. This compression causes a rise in temperature and pressure which make possible the spontaneous reaction between fuel and oxygen. Also called a diesel engine.

crude; crude oil

Crude mineral oil. Naturally occurring hydrocarbon fluid containing small amounts of nitrogen, sulphur, oxygen and other materials. Crude oils from different areas can vary enormously.

DI-engine

Direct-Injected engine; combustion engine with a direct injection of fuel into the combustion chamber.

diesel engine

1. Combustion engine running on diesel oil;
2. Other name for a combustion engine with compression ignition (named after Rudolf Christian Carl Diesel (1858-1913), one of the founders of the combustion engine principle).

diesel (oil)

1. A mixture of different hydrocarbons with a boiling range between 250° and 350° C;
2. A fuel for compression ignition or diesel engines.

dimethyl ether (DME)

Chemical substance (structural formula CH₃-O-CH₃). As an additive for methanol, dimethyl ether accelerates the ignition. Dimethyl ether can also be used as an alternative motor fuel.

DME

Dimethyl ether

dual-fuel vehicle

Also called bi-fuel vehicle. Vehicle fitted with one engine and two fuel systems. The engine can operate on both fuels. An example is an LPG/Gasoline dual-fuel vehicle.

ecotoxicity

The toxicity of a substance for the environment.

ester

Chemical organic compound which is the result of a reaction between an acid and an alcohol.

ethanol

An alcohol compound; C_2H_5OH .

evaporative emission

Emission of hydrocarbons of a vehicle from sources other than the exhaust pipe. Important sources are the venting of the fuel tank and the carburettor. Evaporative losses are subdivided into:

- running losses
- diurnal losses
- hot soak losses

FFV

Flexible-Fuelled Vehicle. Vehicle able to drive on any mixture of alcohol and gasoline up to 85% alcohol.

formaldehyde

Aldehyde compound; $HCHO$; very toxic; probably carcinogenic.

FTP

Federal Test Procedure; American driving cycle defined by the Environmental Protection Agency.

fuel cell

An apparatus in which electricity is generated by a reaction between hydrogen and oxygen forming water. Water and electricity are produced after hydrogen and oxygen ions are exchanged via an electrolyte.

gasoline, gas

1. American name for petrol.
2. A mixture of more than 100 different hydrocarbons with a boiling range between 25° and 220° Celsius;
3. A fuel for ignition-compression or Otto engines.

GJ

Gigajoule; unit of energy; $1\text{ GJ} = 1.10^9\text{ Joule}$.

HC

Hydrocarbon(s).

HDV

Heavy-Duty Vehicles

hydride

hydrogen chemically bound to a metallic material.

hythane

A mixture of natural gas and hydrogen. The hydrogen content in hythane is 15% measured by volume and 5% measured by energy content.

IDI-engine

Indirect-Injection Engine; internal combustion engine (usually a diesel engine) with indirect fuel injection, for instance by way of a pre-combustion chamber or a swirl chamber.

IEA

International Energy Agency.

ignition delay

Expression usually used in connection with compression ignition engines, defined as the time between the start of the injection and the start of the ignition.

knock

Uncontrolled combustion in a spark ignition engine. Also called pinging or pin-knock.

lean mixture

Mixture of air and fuel in a cylinder of a combustion engine containing less fuel than could be burnt by the oxygen present (lambda higher than one).

LDV

Light-Duty Vehicle

liquefaction

The conversion of a gas to a fluid by lowering the temperature and or raising the pressure. LPG is a liquefied gas; natural gas and hydrogen are sometimes liquefied.

LNG

Liquefied Natural Gas; natural gas in a liquid state (only possible at temperatures below -161°C).

LPG

Liquefied petroleum gas which consists mainly of propane (C_3H_8) and/or butane (C_4H_{10}) and which can be stored as a liquid under relatively low pressure for use as a fuel.

M85

Mixture of methanol and gasoline with 85% (volume) methanol.

M100

Pure methanol.

NMOG

Non-Methane Organic Gases; collective noun for all oxygenous compounds and hydrocarbons, excluding methane.

methanol

Alcohol; CH_3OH ; very toxic; highly inflammable.

methylester

1. An ester which results from the esterification of oil with methanol.
2. Also known as biodiesel.

MJ

Megajoule; unit of energy; 1 MJ = 1.10⁶joule.

NO_x

1. Collective noun for the nitrogen oxides NO and NO₂ (N₂O or nitrous oxide is not considered an NO_x compound);
2. Description for a mixture of NO and NO₂;
3. Noxious exhaust component of combustion engines; formed under the influence of a high temperature of combustion by a direct reaction of oxygen and nitrogen present in the air. Part of the NO is further oxidised to NO₂ in the exhaust flow.

octane number

A measure for the tendency of a fuel to detonate when combusted in the cylinder of a combustion engine. The higher the octane number, the lower the tendency to detonate and the better the quality of the fuel. According to the definition of octane number, iso octane (2.2.4-trimethyl-pentane) has an octane number of 100 and n-heptane (C₇H₁₆) has an octane number of 0. Depending on the method of measuring of the octane number, a distinction is made between RON and MON values.

OECD

Organisation for Economic Co-operation and Development.

PAH

Polycyclic Aromatic Hydrocarbon(s). Aromatics of which the molecules contain several, linked benzene rings; in several cases carcinogenic.

pilot injection

Method to ignite fuels that are difficult to ignite. A more easily ignitable fuel is injected into the engine, next to an amount of the real fuel. The added fuel will ignite first and subsequently ignite the real fuel. An example is diesel pilot injection in alcohol engines.

Pm

Particulate Matter. Particles emitted from the exhaust system of vehicles.

RAF

Reactivity Adjustment Factors; a measure for the reactivity of a gas.

reformulated fuel

A fuel (especially gasoline or diesel) blended to minimise undesirable exhaust and evaporative emissions.

rich mixture

An air-fuel mixture in a combustion engine that contains more fuel than can be combusted by the air in the cylinder (lambda smaller than 1).

RME

Rapeseed methyl ester, an esterified form of rapeseed oil.

RON

Research Octane Number. Octane number which is measured by a special one-cylinder laboratory test engine called the CFR engine. This is the most frequently mentioned octane number. It is measured during rather mild circumstances, as opposed to the motor octane number (MON) which refers to high engine temperatures and high rotational speed.

spark ignition engine

Internal combustion engine with an ignition of the fuel/air mixture by means of a spark; also called otto engine.

stoichiometric air/fuel ratio

The exact air/fuel ratio required to completely combust a fuel to water and CO₂.

syngas

A mixture of hydrogen (H₂), carbon monoxide (CO) and carbon dioxide (CO₂). It may contain some impurities like methane (CH₄).

tailpipe emissions

Emissions of a combustion engine after the catalyst (as distinct from engine-out emissions which are measured before the catalytic converter).

three-way catalyst

Catalytic reactor for combustion engines which oxidises volatile organic compounds (VOC) and CO, as well as reduces nitrogen oxides.

ULEV

Ultra Low Emission Vehicle.

vkm

Vehicle kilometre.

VOC

Volatile Organic Compound(s). Collective noun for hydrocarbons which are emitted in the volatile phase by vehicles. Usually described as HC-compounds.

vol-%

Percentage by volume.

wt-%

Percentage by weight.