Environmental effects of DME compared to other automotive fuels

INNAS

Environmental effects of DME compared to other automotive fuels

June 1999

M. van Walwijk
W.P. Troelstra

A publication of IEA/AFIS,
operating agent:
Innas BV
Nikkelstraat 15
4823 AE Breda
The Netherlands
Phone: +31-76-5424080
Fax: +31-76-5424090

The IEA Automotive Fuels Information Service (IEA/AFIS) is an information service that can produce reliable and objective information regarding road transport fuels. IEA/AFIS operates on commercial terms and conditions, under the auspices (kindly patronage and guidance) of the IEA Advanced Motor Fuels Agreement (IEA-AMF). Innas BV is the main operating agent of IEA/AFIS. Atrax Energi AB is co-operating agent of IEA/AFIS.

Support from the IEA Advanced Motor Fuels Agreement stems from six countries:

Belgium	VITO
Finland	VTT
Netherlands	NOVEM
Sweden	STEM
UK	Department of Transport
USA	Department of Energy

Innas BV
Nikkelstraat 15
NL 4823 AE Breda
The Netherlands
Phone: +31 / 76 5424080
Fax: +31 / 76 5424090
E-mail: innas@wxs.nl

Atrax Energi AB
Ekmansgatan 3
S 411 32 Göteborg
Sweden
Phone: +46 / 31 167850
Fax: +46 / 31 207460
E-mail: anders.elam@atrax.se

Summary

The goal of this report is to provide a clear, consistent understanding of the environmental effects that dimethyl ether (DME) would have as a mainstream motor transportation fuel, compared to other fuels. The comparison is made on the basis of the complete well to wheel fuel chain, i.e. feedstock production, feedstock transport, fuel production, fuel distribution and finally the use of the fuel in vehicles.

The comparison is based on existing data. Data from literature are supplemented with data that stem from practical experience of parties working in the field of automotive fuels and DME. Conclusions are drawn on the basis of all the data that thus are made available. The co-operating parties in this project are Amoco, Haldor Topsøe, Innas, Natural Resources Canada, Renault, Statoil, TNO-Road Vehicles Research Institute and Volvo Truck Corporation.

The well to wheel fuel chains of gasoline, diesel, CNG (compressed natural gas), LPG from oil and gas fields and LPG as a refinery product, methanol produced from natural gas and DME from natural gas are compared on energy consumption and emissions. Synthetic diesel and LNG (liquefied natural gas) are addressed qualitatively. Although DME can be produced from biomass, biofuels are not included in this report. DME produced from natural gas is expected to be the preferred option during its introduction as an automotive fuel.

It appears that the results are strongly dependant on the fuel chain scenario that is used and for some stages of some fuel chains, data are scarce. This means that all results should be considered to be estimates. In spite of these sensitivities and uncertainties, some general conclusions on the well to wheel fuel chains can be drawn.

- Energy consumption is in one range for all fuels. Well to wheel DME energy consumption is average. Diesel is at the lower end of the range and methanol is at the higher end. Because all fuels are made from fossil feedstock, none of the fuels will solve the oil and gas dependency issue.
- Greenhouse gas emissions of DME produced from natural gas are in the same range as for diesel, natural gas and LPG. Gasoline and methanol from natural gas tend to show a larger contribution to global warming than the other fuels.
- NO_x and SO_2 emissions are contributors to acidification. Well to wheel NO_x emissions of all fuels are in one, large range. DME appears to be at the lower end of this range. Diesel shows relatively high NO_x emissions, mainly caused by the vehicle stage in the fuel chain. When appropriate technology is applied, NO_x emissions for the other fuels can be significantly lower than for diesel. However, technologies to reduce NO_x emissions from diesel vehicles are under development, like the deNOx exhaust catalyst. Only diesel and gasoline show significant SO_2 emissions. These are mainly vehicle tailpipe emissions resulting from sulphur in the fuel. These emissions will be reduced significantly in the near future because legislation will require lower sulphur content in these fuels.

- For diesel vehicles, particulate emissions are significantly higher than for the other fuels. For all other fuels and fuel chain stages, including DME, particulate emission levels generally are low.
- In general it can be observed that the environmental burden of gaseous fuels regarding acidification, smog, ozone forming potential, toxicity and discharges to water tends to be lower than for gasoline and diesel. Also methanol and DME score better than the conventional fuels.

Because DME will be used in modified diesel engines, DME can bring an emission advantage on particulates and NO_x emissions compared to the use of diesel fuel. However, gasoline and the gaseous fuels show this potential as well. When the technology for vehicular use of DME is developed, DME can be considered a new option beside other alternative fuels. Exploiting remote natural gas reserves may become an important reason to choose DME instead of other alternative fuels.

Contents

1
Introduction

1.1
Goal and background

The goal of this report is to provide a clear, consistent understanding of the environmental effects that dimethyl ether (DME) would have as a mainstream motor transportation fuel, compared to other fuels. For a relevant comparison of automotive fuels, the basis for comparison should be the complete well to wheel fuel chain, i.e. feedstock production, feedstock transport, fuel production, fuel distribution and finally the use of the fuel in vehicles.

At the SAE congress in 1995 DME was introduced as a new automotive fuel option. Important reasons to consider DME as an automotive fuel are it's soot free combustion while keeping a high energy efficiency when used in diesel engines. The company Haldor Topsøe in Denmark came up with a new catalyst which enables a relatively low cost production of DME from syngas. Using natural gas for syngas production is an option to spare fossil oil resources. The oil and gas industry sees DME as an option to exploit remote natural gas fields.

This potential of DME was the incentive for the International Energy Agency's Advanced Motor Fuels (AMF) executive committee to start a more in-depth study on DME. This study is performed under annex XIV, as a joint effort of some companies around the globe that are interested in the use of DME as an automotive fuel. This report on the environmental effects is one of the results of the work under this annex.

1.2
Organisation

To obtain a picture of how DME as an automotive fuel compares to other fuel options, eight parties co-operated in this project.

- Amoco (now BP/Amoco), an oil and gas production company from the USA.
- Haldor Topsøe, the company in which a new catalyst for low cost DME production was invented; based in Denmark.
- Innas, an engineering and consultancy company working on internal combustion engines and fuels; based in the Netherlands. Innas was the task leader in this project.
- Natural Resources Canada, a governmental body in Canada.
- Renault, manufacturer of light and heavy-duty vehicles in France.
- Statoil, an integrated oil and gas production and retail company from Norway.
- TNO-WT (now TNO Automotive), a road vehicles research institute in the Netherlands.
- Volvo Truck Corporation, a vehicle manufacturer from Sweden.

A number of reports on well to wheel automotive fuel comparisons are available. These reports and additional data have been used by IEA/AFIS for producing the 'Automotive fuels survey' volume 1 'Raw materials and conversion' and volume 2 'Distribution and use' [1, 2]. The results of an earlier study on the DME well to wheel fuel chain can be found in 'Global assessment of dimethyl-ether as an automotive fuel', a TNO-WT report produced in co-operation with Innas [3]. These reports have been used as the basis for this study. In this report the existing information is supplemented with data from the co-operating parties in this project. Thus a picture of the current status is build, based on current experience of different parties that are actually involved in automotive fuel production and use.

1.3
Report structure

This report concentrates on energy consumption and emissions of well to wheel fuel chains. First, the scope and starting points are addressed to clarify what the data presented stand for. Next are energy consumption and emissions per fuel, presented for each stage in the well to wheel fuel chain. Finally, the fuels are directly compared to each other on their environmental effects, using the complete well to wheel fuel chain as the basis for comparison. Some important fuel characteristics are summarised in annex C.

2
Scope and starting points

2.1
Scope of the study

To show the environmental effects of the use of DME as an automotive fuel, it is on the basis of well to wheel fuel chains compared with gasoline, diesel, natural gas, LPG and methanol, for both heavy and light-duty vehicles.

All fuels considered in this report are being produced from fossil feedstocks. This implies that the comparison of energy consumption in this report stands for a comparison in fossil energy use. Such a comparison is relevant for an effective use of the limited fossil resources.

Although DME produced from biomass seems to be an interesting and useful option for the future in certain geographical locations, it is not included in this report. The scope of this project did not allow including fuels from biomass because establishing energy consumption and emissions of the well to wheel chain of fuels from biomass is a complicated task and an unambiguous method to include energy consumption and emissions from by-products in the well to wheel chain of fuels from biomass is not existing. IEA's Implementing Agreement on energy from biomass is referred to for further details on biofuels.

Table 2.1 lists the fuels and feedstocks covered in this report. Only a limited amount of data on synthetic diesel and on LNG (liquefied natural gas) is available, so these fuels are addressed into lesser detail than the other fuels. Synthetic diesel is included because it could be a competitor for DME, being another option of bringing remote natural gas to the market.

Table 2.1 Fuels and their feedstocks addressed in this report.

Fuel	Feedstock
Gasoline	crude oil
Diesel	crude oil
Synthetic diesel	natural gas
CNG, LNG	natural gas
LPG (field)	direct LPG extraction
LPG (refinery)	crude oil
Methanol	natural gas
DME	natural gas

Emission components addressed in this project are: CO_2, CH_4 (methane), NMHC (non methane hydrocarbons), NO_x, N_2O, SO_2, CO and Pm (particulates) because these are assumed to influence global warming, acidification, smog formation and other negative environmental effects, including health effects. Because of the relatively high global warming potential of methane, CH_4 and NMHC are mentioned separately in North American emission legislation. European legislation does not make this distinction yet and only limits total hydrocarbon (HC) emissions. Because the emission data presented in this report are based on European test cycles, in most cases no NMHC emission data are available and HC emissions are presented. To obtain NMHC emission figures, CH_4 emissions should be subtracted from HC figures.

2.2
Starting points

Figure 2.1 shows the five stages of the well to wheel fuel chain, both for light-duty vehicles (LDVs) and for heavy-duty vehicles (HDVs). In this report the focus in each stage is on the fuel. This means that for example exploration and the manufacturing of off-shore platforms, refineries, refuelling stations and vehicles is not included in the energy consumption and emission figures. Only the operations that feedstock and fuel go through are being considered here.

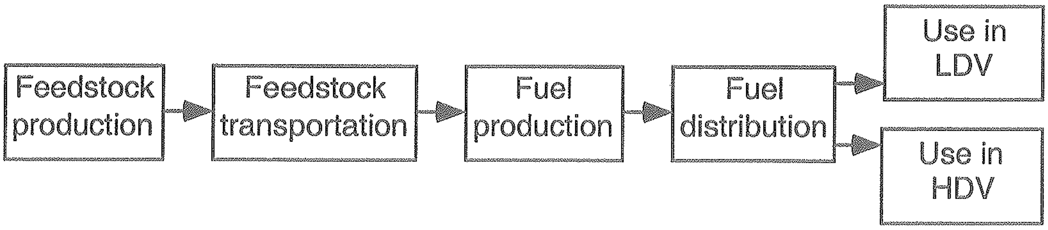

Fig. 2.1 The five stages of the well to wheel fuel chain, both for LDVs and HDVs.

To help building the picture, some remarks on each stage of the fuel chain are presented here.

- Feedstock production.
  This stage includes flaring and venting at oil and gas production sites. Oil and gas may be produced simultaneously at one production site. In that case, energy consumption and emissions from that site are allocated to oil and gas, according to the ratio of the energy content of the products.
- Feedstock transportation.
  Leaks during transportation are included in emissions, but also are considered to be an energy loss. Feedstock transportation may include transport by sea, rail, road and pipeline. Intermediate storage usually takes place between feedstock transportation and fuel production. This storage is considered part of the transportation stage.

- Fuel production.
  The output of a fuel production plant (a refinery for example) is often a product mix. An effort is made to let the energy consumption and emissions that are allocated to each product reflect the effort that is required to produce that individual product. Gasoline production is for example more energy intensive than diesel production.
- Fuel distribution.
  Gasoline, diesel, LPG and methanol distribution is usually by road tanker. It is expected that DME also will be distributed by road tanker. Using a pipeline grid is a way to distribute natural gas. Gas compression at the refuelling site is included in this stage. Evaporation, leaks or spills during distribution are included when data were available.
- Vehicle use.
  Current vehicle technology status is used. Energy consumption and emission figures for light-duty vehicles are based on the European EU 15 + EUDC (extra urban driving cycle) test cycle. The basis for comparison of LDVs is vehicle kilometre. For heavy-duty vehicles the European heavy-duty engine 13 mode cycle ECE-R49 is used. The basis for comparison of HDVs is thus per kWh engine energy output.

Second order effects are not included in this report. One example is given here to explain the meaning of this statement. A fuel can be distributed by a diesel fuelled road tanker. In this case the energy consumption and the emissions from the diesel truck are included in the well to wheel figures. Energy consumption and emissions from the refinery that produces this diesel oil are not included.

In this report the term diesel refers to auto diesel used in road vehicles. In locomotive and marine applications for example, other diesel compositions are used. These diesel qualities are not addressed here.

Current emission legislation focuses on vehicle emissions. Both fuel composition and vehicle technology develop parallel in time, to meet increasingly stringent emission levels. Developments in vehicle technology and fuels are interwoven. New vehicle technology may ask for new fuel compositions. For example exhaust catalysts require a fuel that is low in sulphur content. On the other hand, new fuels may require new vehicle technology. For example the low lubricative properties of DME require fuel pump modifications. Acceptable emission levels are expected to be lowered further in the future. New developments in fuels and vehicle technology will be the result. The data in this report are valid for the most recent technology that is available on the market as much as possible and as such should be regarded as a snapshot in time. It is recognised that in ten years time the situation will be different, but in this report no speculations about the future are being made.

During the lifetime of a vehicle, exhaust emission per vehicle kilometre may increase gradually. Both in North America and Europe, legislation on maintaining certain emission levels during the lifetime of automobiles is on its way. However, the vehicular exhaust emission figures used in this report are based on measurements on new vehicles. Deterioration effects are not included.

3

Well to wheel fuel chains

Energy consumption and emissions for the five stages of the well to wheel fuel chain are presented in this chapter, for each fuel under consideration. Data presented here are taken from existing literature and additional data are supplied by the parties co-operating in this project. The data are presented graphically. For each fuel, two pictures are presented. The first picture reflects the first four stages of the fuel chain: feedstock production, feedstock transportation, fuel production and fuel distribution. The second picture for each fuel shows vehicle data. The data from literature are considered reference data, represented by grey bars in the pictures. New data that are generated in this project are presented as dots in the pictures.

For the first four stages of the fuel chain, data in this report are presented on the basis of energy content of the fuel available at the refuelling nozzle at the refuelling station. In some literature this is also the basis, in others it is expressed per MJ fuel output of the stage under consideration. Participants in this project also supplied data on the basis of fuel output per well to wheel stage. These data are converted to figures per MJ fuel at the refuelling outlet, using the energy consumption of each fuel stage and calculating backwards from fuel distribution to feedstock production. The energy requirement of each stage is determinant for the energy output of the previous stage. The throughput of each stage to finally obtain one MJ fuel at the outlet, is determinant for the emissions of that stage. This calculation method is addressed more extensively in annex B.

The well to wheel fuel chains are compared for both light-duty and heavy-duty vehicles in chapter 4. For both types of vehicles, a reference vehicle has been chosen. For light-duty vehicles this is a gasoline vehicle (energy consumption 2.2 MJ/km) and for heavy-duty it is diesel (energy consumption 9 MJ/kWh). The reference data from literature and the data collected for this project have been used to establish the relative energy consumption of alternatively fuelled vehicles compared to these reference vehicles. The relative energy consumption is presented as a range, to reflect different vehicle and engine technologies. Due to the very limited data available on DME, for DME vehicle energy consumption the diesel data are used, in line with the current expectations for DME vehicles. This procedure has resulted in the energy consumption figures as presented in table 3.1. More background information can be found in annex A.

Table 3.1 Relative energy consumption of light-duty (LDV) and heavy-duty vehicles (HDV).

	Gasoline	Diesel	CNG	LPG	Methanol	DME
LDV	100%	75-90%	80-110%	90-110%	85-105%	75-90%
HDV	--	100%	105-140%	110-130%	100-110%	100%

It should be noted that the data presented in this chapter stems from a large number of sources, each standing for a particular well to wheel fuel chain scenario. Thus, the data should be considered to be indicative. However, the trends shown in this report are considered to be representative for the bulk of the fuel chains in the Western hemisphere. However, for deciding which fuel is best in a certain situation, data for that particular fuel chain should be gathered.

3.1
Gasoline

Theoretically, gasoline can be produced from any carbon-containing feedstock. Gasoline production via crude oil refinery is the cheapest option, so this is currently the practised production method for automotive gasoline.

Large gasoline markets are North America and Europe. The crude oil for these markets comes from, among others, Texas, Venezuela, the North Sea and the Middle East. Crude oil composition is dependent on the location of the production site. Differences occur for example in hydrocarbon composition, sulphur content and water content.

Crude oil is generally transported by sea to refineries that are located close to the market. Overland, crude oil is transported by pipeline. Sea transport takes place by large tankers or vessels. The company Ecotraffic states that energy consumption of crude oil transportation is very similar for different transport modes. Also the influence of transportation distance at sea is considered to be small, because for smaller distances smaller (relatively less energy efficient) vessels are used [4]. This Ecotraffic observation is supported by the fact that the range for reference crude oil transportation data in figure 3.1 is small.

Each market has its own gasoline specifications. Gasoline composition in North America is different from European gasoline. Different crude oil compositions combined with different gasoline composition requirements results in a range of refinery processes, each with its associated energy consumption and emission figures. Removal of sulphur from crude oil components is an energy intensive process and increases refinery energy consumption and emissions. Reformulating gasoline to be less volatile and to reduce vehicle NMOC (Non Methane Organic Compound) emission levels has several -partially counterbalancing- effects in the refinery process [5]. Reformulated gasoline is the reference in figure 3.1.

Because crude oil refineries are usually located close to the market, gasoline distribution distances are often small compared to crude oil transportation distances. Distribution distance in North America may generally be higher than in Europe. Generally, road tankers are used for gasoline distribution but in North America pipeline transportation is used as well.

In all stages of the well to wheel fuel chain of gasoline, energy is consumed and consequently emissions are being produced. Emissions may stem from sea going vessels, electricity production (pumps in pipelines may be powered by electrical energy and refineries consume electricity) and road tankers for example. Evaporative emissions (mainly light hydrocarbons) during loading, storage and unloading of gasoline cannot be neglected either.

In figure 3.1 reference data from literature on some American and European gasoline fuel chains are presented. Because different fuel chains are considered, the reference data are presented as a range, shown with bars in figure 3.1. Although many different fuel chains are included, the dispersion in reference data appears to be small. Comments on the dots in figure 3.1 are given below.

The gasoline energy consumption and emission data obtained in this project (represented by the dots in figure 3.1) reflect a general situation in the USA [6], one Amoco crude oil production site and a Statoil scenario typical for Norway.

Amoco emission data on feedstock production stand out. NO_x, CO and to a lesser extent CH_4 values are relatively high. The reason behind this is that this data represents a crude oil field where a large amount of associated gas is produced and most of this gas is reinjected, which makes energy consumption of this production site relatively high compared to other sites. In this case, approximately 75% of the energy consumption of feedstock production is for associated gas compression. The Amoco emission figures are not measured but are estimates. However, the relatively high energy consumption of this type of oil production does not stand out in the energy consumption graph of figure 3.1. This can be explained by the fact the average of measured energy consumption figures is shown here. The measured energy consumption values were lower than the estimated energy consumption. Gas reinjection is currently practised in a minority of the crude production sites, so it is not included in the reference values of figure 3.1. Gas reinjection is expected to increase in the future, to extend production from oil fields nearing depletion and because countries ban flaring. Reinjection increases energy consumption and its associated emissions of crude oil production.

In general, the data obtained in this project tend to somewhat enlarge the ranges of the energy consumption and emission data of the first four stages of the gasoline fuel chain, as were found in literature. CO and particulate emissions obtained for fuel production are significantly higher than the reference values. The data supplied here stems from a large North American refinery in 1996. There is no typical explanation for these higher values. For emission components where only limited data are available (like SO_2, particulate matter and N_2O), the data should be considered as a rough indication, based on a very limited number of scenarios.

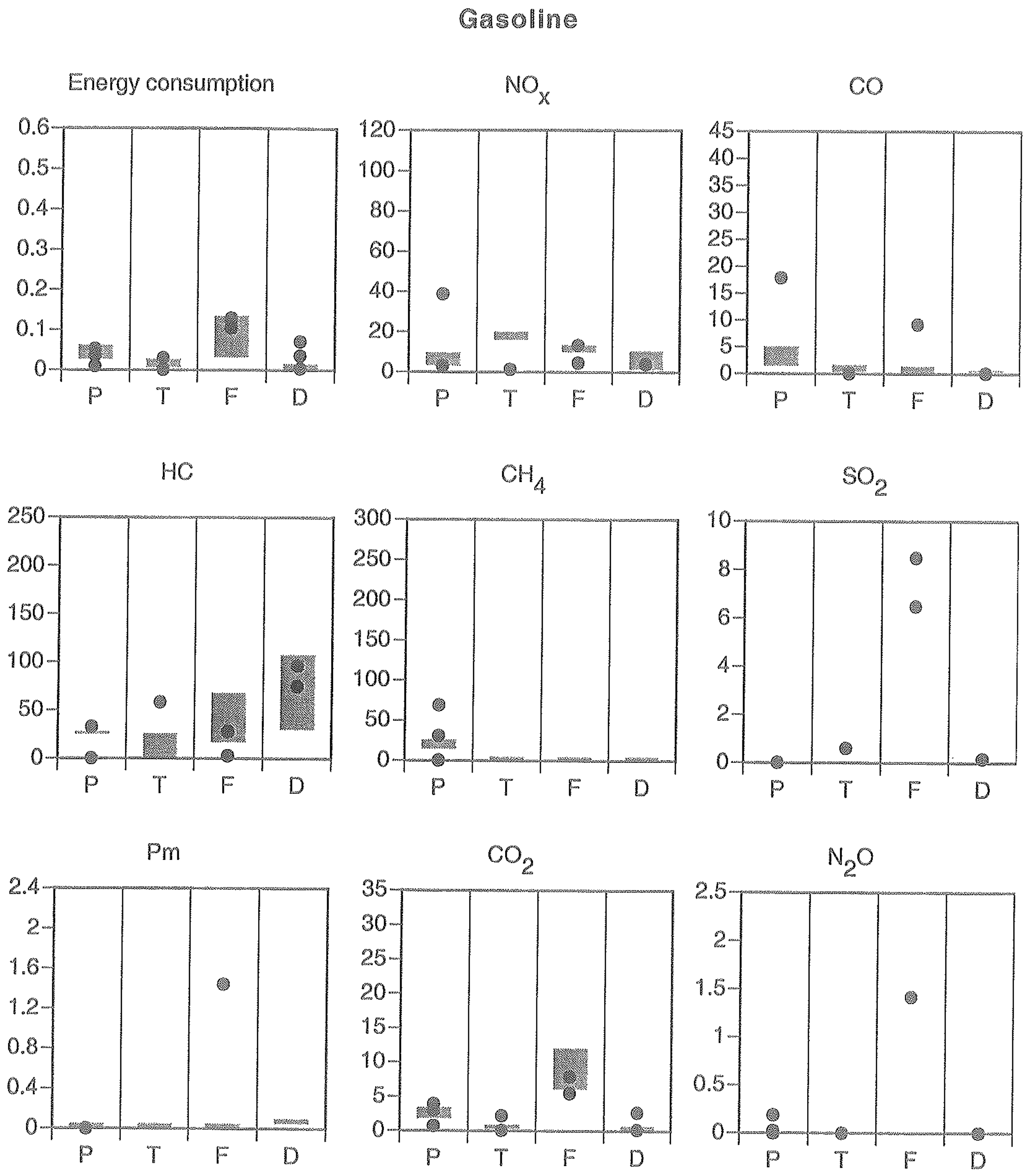

Fig. 3.1 Energy consumption and emission of the first four stages of the well to wheel fuel chain of gasoline, per MJ fuel available at the refuelling station.
Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show reference data from literature. Dots show new data obtained in this project.
P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

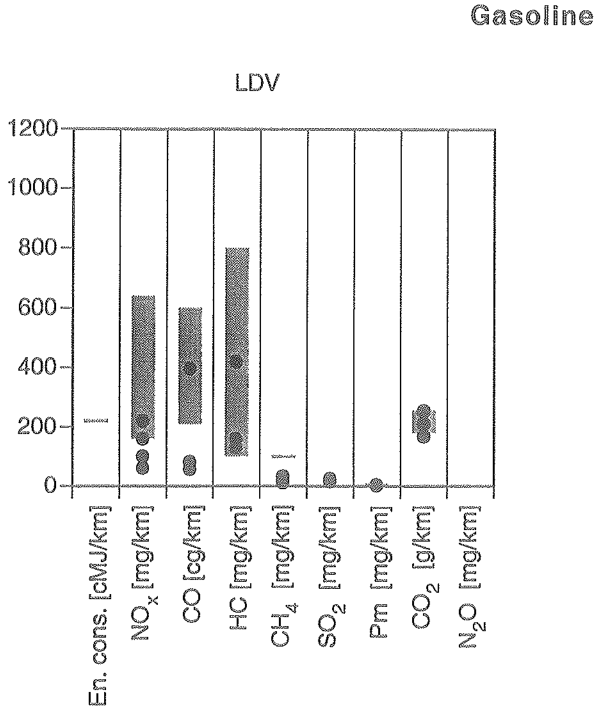

Fig. 3.2 Energy consumption and emissions of gasoline light-duty vehicles (LDV). Grey bars show reference data from literature. The energy consumption bar is the LDV reference value. Dots show new data obtained in this project. (1 cMJ = 0.01 MJ)

Figure 3.2 shows energy consumption and emission data for modest size (1.5- 2 litre engine) American and European light-duty vehicles, equipped with three way exhaust catalysts. Because today's vehicle technology is the basis for the data supplied in this project, these emissions values are generally at the lower end of the reference data range, because it is inevitable that data from literature are a few years old.

3.2
Diesel

The first four stages of the well to wheel fuel chain for diesel are very similar to the gasoline fuel chain, so the gasoline section is referred to for more information.

The most significant differences between diesel and gasoline occur in the fuel production stage. Diesel production requires less energy than gasoline production, resulting in lower refinery emissions per MJ fuel produced. However, diesel composition requirements tend to lower the acceptable sulphur level in the fuel, to meet vehicle emission standards. Sulphur removal is an energy intensive process which increases refinery energy consumption and emission figures. Still, current diesel production energy consumption is below that of gasoline production. This gap is expected to narrow in the future.

Diesel is less volatile than gasoline, resulting in lower evaporative emissions during loading, storage and unloading of diesel. In fact, evaporative hydrocarbon emissions from the diesel fuel chain are negligible.

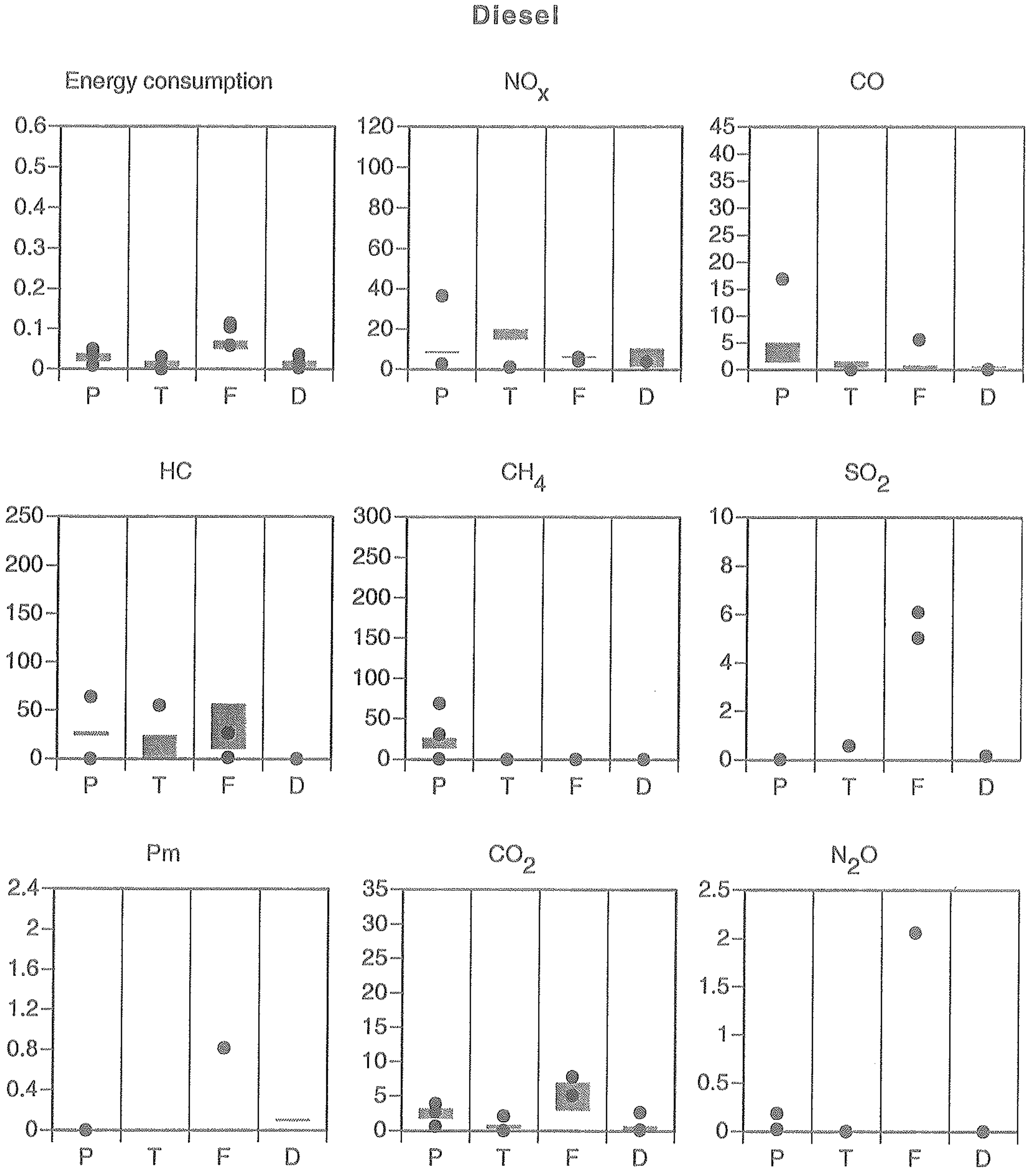

Fig. 3.3 Energy consumption and emission of the first four stages of the well to wheel fuel chain of auto diesel, per MJ fuel available at the refuelling station.
Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show reference data from literature. Dots show new data obtained in this project.
P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

Just like the gasoline data, diesel data in figure 3.3 represent a range of actual fuel chains of American and European auto diesel. The ranges in reference data are relatively small.

The diesel energy consumption and emission data obtained in this project reflect a general situation in the USA [6], one Amoco crude oil production site and a Statoil scenario typical for Norway.

Similar as for gasoline, the Amoco figure of a crude oil production site with a high rate of gas reinjection stands out.

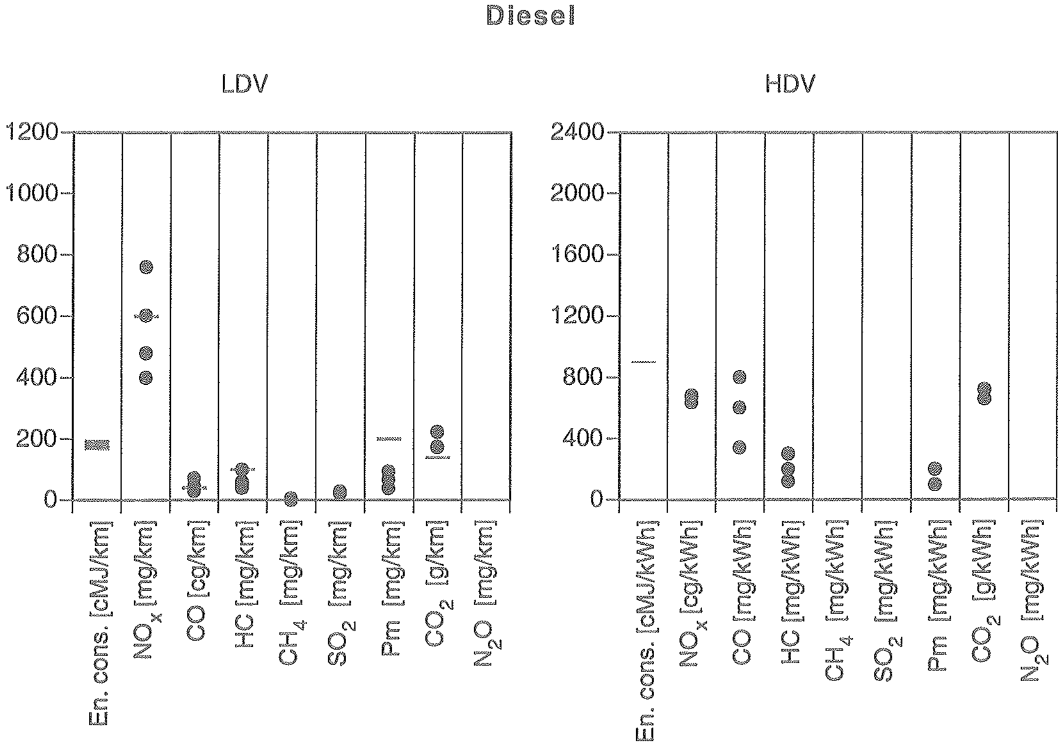

Fig. 3.4 Energy consumption and emissions of diesel light-duty vehicles (LDV) and heavy-duty vehicles (HDV).
Grey bars show reference data from literature. The LDV energy consumption bar is relative to the reference gasoline vehicle defined in this report and includes new data obtained in this project. The HDV energy consumption bar is the reference value. Dots show new data obtained in this project. (1 cMJ = 0.01 MJ)

Hardly any diesel light-duty vehicles are in operation in North America, so all LDV data in figure 3.4 stem from European vehicles. Also the HDV diesel data are based on European vehicles only, because the European ECE-R49 13 mode cycle is used as the basis for comparison and no data of American heavy-duty engines tested according to this cycle are available.

3.3
Synthetic diesel

In order to meet future diesel vehicle emission legislation, companies like Shell, Exxon, Syntroleum, Rentech and Sasol are working on synthetic diesel fuel. Instead of crude oil, natural gas or coal is the feedstock of this fuel. Here, only synthetic diesel production from natural gas is addressed, because this fuel can be seen as a competitor to DME from remote natural gas. Producing synthetic diesel at a remote natural gas recovery site may be another way of bringing this gas to the market.

To produce synthetic diesel, natural gas is first converted into syngas. Second, a Fischer-Tropsch synthesis is used to convert syngas into long hydrocarbon molecules (waxes). In the third and final production step, these waxes are cracked and then distilled into molecules with smaller hydrocarbon molecules, being diesel. This process results in an almost sulphur free diesel quality, which also is low in aromatics and has a lower density than conventional diesel. Because Fischer-Tropsch diesel is in an early state of development, data are still scarce. That is why synthetic diesel is addressed less extensively than the other fuels.

Feedstock production and transportation will be similar to what is described under natural gas. Producing synthetic diesel near a natural gas recovery site will ease transportation of the product of such a site to the market. The theoretical maximum energy efficiency of Fischer-Tropsch diesel fuel synthesis from natural gas is 77%, far below conventional diesel production from crude oil. Practice is still quite far from this theoretical maximum. The Shell SMDS (Shell Middle Distillate Synthesis) plant in Malaysia operates for example at an energy efficiency of approximately 64% [7]. Production energy efficiency is expected to gradually improve in the near future.

Producing syngas requires significant volumes of water. Water is a by-product of the Fischer-Tropsch synthesis, which may be used to reduce the overall water consumption. Other by-products leave the FT synthesis with the reaction water, so this water has to be treated before it can be released. The by-products are mostly oxygenates, predominantly alcohols. Catalysts that have been used for the FT synthesis need to be handled with care to reduce environmental impact. However, this is not different from common practice in the oil industry [8]. Recycling of those catalysts is possible.

Fischer-Tropsch diesel has been tested in heavy-duty diesel engines. Test results of American transient tests and European steady state tests have been published. The results are shown in table 3.1. Note that transient and steady state test results can not be compared directly. Also, the reference fuel for the transient test (American 2-D diesel) was different than for the steady state tests (European RF 73 reference diesel). Finally it should be noted that engine technology has a large influence on emission results.

Using Fischer-Tropsch diesel results in a peak torque loss of a few percent and also in a fuel consumption penalty of a few percent.

Table 3.1 Emission reductions for heavy-duty engines running on Fischer-Tropsch diesel compared to conventional diesel.

Reference	[9]	[10]	[11]
Engine	DDC series 60 (1991) 12.7 litre DI, TC, IC	DDC series 60 (1991) 11.1 litre DI, TC, IC	MB OM 360 (1992/93) 6 litre, DI, TC
Test	Transient (USA)	Transient (USA)	Steady state (EU)
Reference fuel	2-D (USA)	2-D (USA)	RF 73 (EU)
HC	49%	46%*	14%
CO	33%	47%*	20%
NO_x	27%	9%*	16%
Pm	21%	32%*	18%

** = maximum reduction that has been measured*
DDC = Detroit Diesel Corporation
MB = Mercedes Benz
DI = direct injection
IC = intercooling
TC = turbocharged

From table 3.1 it can be seen that Fischer-Tropsch diesel enables a large emission reduction of HC and CO, which are already relatively low for diesel engines. Emission reduction for NO_x and Pm is smaller but still significant. NO_x and Pm are considered the emission components of diesel engines for which a large emission reduction still is required. It should be noted that the figures as presented in table 3.1 are based on first trials of synthetic diesel used in prototype diesel engines. Optimisation of fuel and engines may lead to further emission reductions.

Because synthetic diesel and DME are two different ways to bring remote natural gas to the market, comparison of the fuel chains is useful. However, due to a lack of information, only HDV emissions can be compared for those fuels. Currently, both NO_x and Pm emissions of DME HDVs are even lower than for HDVs that run on synthetic diesel. It should be noted that both fuels are still in an early stage of development, so for both fuels further improvements are possible.

Handling of synthetic diesel is similar to conventional diesel. Issues requiring attention are lubrication properties, seal compatibility and cold performance characteristics [11]. Biodegradability of Fischer-Tropsch diesel in (sea) water is good.

3.4
Natural gas

Natural gas can be stored on board a vehicle either as CNG (compressed natural gas) or as LNG (liquefied natural gas). CNG is usually the preferred option. Relatively few vehicles operate with LNG. LNG vehicles are mainly used in Japan, but also in North America some LNG vehicles are in operation. Differences between the well to wheel fuel chains of CNG and LNG are mainly in the fuel production (gas compression respectively liquefaction) and distribution stages. Because LNG is being used on a very limited scale compared to CNG vehicles, little data on the LNG fuel chain are available. That is why this section concentrates on CNG. LNG is addressed briefly and qualitatively at the end of this section.

Natural gas composition is dependant on its recovery site. Differences in methane (the main constituent) content, heavier hydrocarbon content, calorific value and level of contaminants occur. In general, the gas needs only limited processing before it can be used in vehicles but dedicated natural gas engines will put requirements on gas composition (see the paragraph on engine use, further down in this section). Gas processing may take place at the recovery site. Important steps of processing are removal of heavy components, hydrogen sulphide and water. Flaring of waste products at the recovery site are a source of emissions and stand for an energy loss as well. Flaring at the production of North Sea gas is limited, and for example lower than in the Middle East.

Natural gas is recovered onshore and off-shore. The location of the recovery site relative to the location of the gas market is determinant for mode of transportation. North Sea gas is transported by pipeline to the European main land and to the UK. Another example is Malaysian off-shore gas that is transported to Japan as LNG (liquefied natural gas) by sea going vessels. The gas has to be kept at low temperature to remain in the liquid phase. Boil off losses are used to propel the ship's engines. After landing, regasification of LNG takes place before it is pipelined to the final market.

Most natural gas vehicles operate with CNG (compressed natural gas) storage. Gas distribution for CNG vehicles is done via the (in many countries already existing) grid. CNG vehicle fuelling is either by slow fill or fast fill. Slow fill can be done overnight to fill the vehicle tanks up to 200 bar tank pressure. For fast fill, high pressure (250 bar) storage at the refuelling station in necessary. To save on energy consumption at the refuelling site, cascade storage at different pressure levels is used. Fast fill also results in 200 bar vehicle tank pressure. Gas distribution for LNG vehicles can be done in liquefied form. It requires well isolated tanks and some boil off losses can not be avoided.

The CNG distribution emission figures produced in this project (shown in figure 3.5) are based on the assumption that gas compression is the dominant source of energy consumption. No liquid gas phase is included in this scenario. Gas compression is assumed to be done by using electrically driven pumps. Emission data for the European electricity mix (1996) from literature have been used [12]. The electricity production emission figures per MJ have been multiplied by the minimum and the maximum gas compression energy consumption values, being 0.023 MJ/MJ and 0.025 MJ/MJ. These values are supplied by Ho & Renner (earlier Amoco research) and Renault respectively. The Amoco value of 0.148 MJ/MJ is considered to be too high to be representative. For NO_x, CO and CO_2 this has resulted in values that are in the range of the reference data. (The high CO_2 emission value shown for the distribution stage is connected to the high energy consumption dot for this stage.) SO_2 distribution emissions (12.8 mg/MJ and 13.9 mg/MJ) are higher than the maximum axis values, so these do not show in figure 3.5. PM emissions calculated this way are higher than the reference value. HC emission data for the European electricity production are not available. Further emission components that are not mentioned could not be calculated. The differences between the calculated values and the reference data ranges show some sensitivity of CNG distribution data for assumption on electricity production fuel mix and energy consumption of gas compression.

Combustion engines are sensible to gas composition. A range of gas qualities can be used in engines, but each engine is tuned to one specific gas composition, so natural gas composition influences engine and motor management specifications. Dutch natural gas has up to 14 vol% nitrogen content and for example Russian gas may have a methane content above 98 vol%. Hydrocarbon content of the gas is important for the calorific value and thus for engine performance. The octane number of the gas is important for engine knock. Gas composition directly affects engine out emissions, so local gas composition may require local vehicle adaptations to obtain high energy efficiency combined with low tailpipe emissions. These vehicles do not perform optimal when travelling in other regions or other countries. This means that taking a natural gas vehicle across country borders in Europe, may result in difficulties with the engine. That is why in the USA one standardised gas quality is used for automotive applications. Methane content of this automotive natural gas is 98%. This may require additional processing besides gas cleaning, when methane content at the recovery site deviates from this 98%. International standardisation of natural gas composition for vehicle use is under consideration. Natural gas can be considered a safe fuel for use in vehicles.

Data on feedstock transportation are scarce, because in most scenarios this stage is avoided. Fuel production consists mainly of cleaning of the gas, which is usually done at the natural gas recovery site, so feedstock transportation does not occur.

In general, emissions for the natural gas fuel chain are low compared to other fuels. However, HC and CH_4 emissions are relatively high, due to gas leaks from the distribution grid.

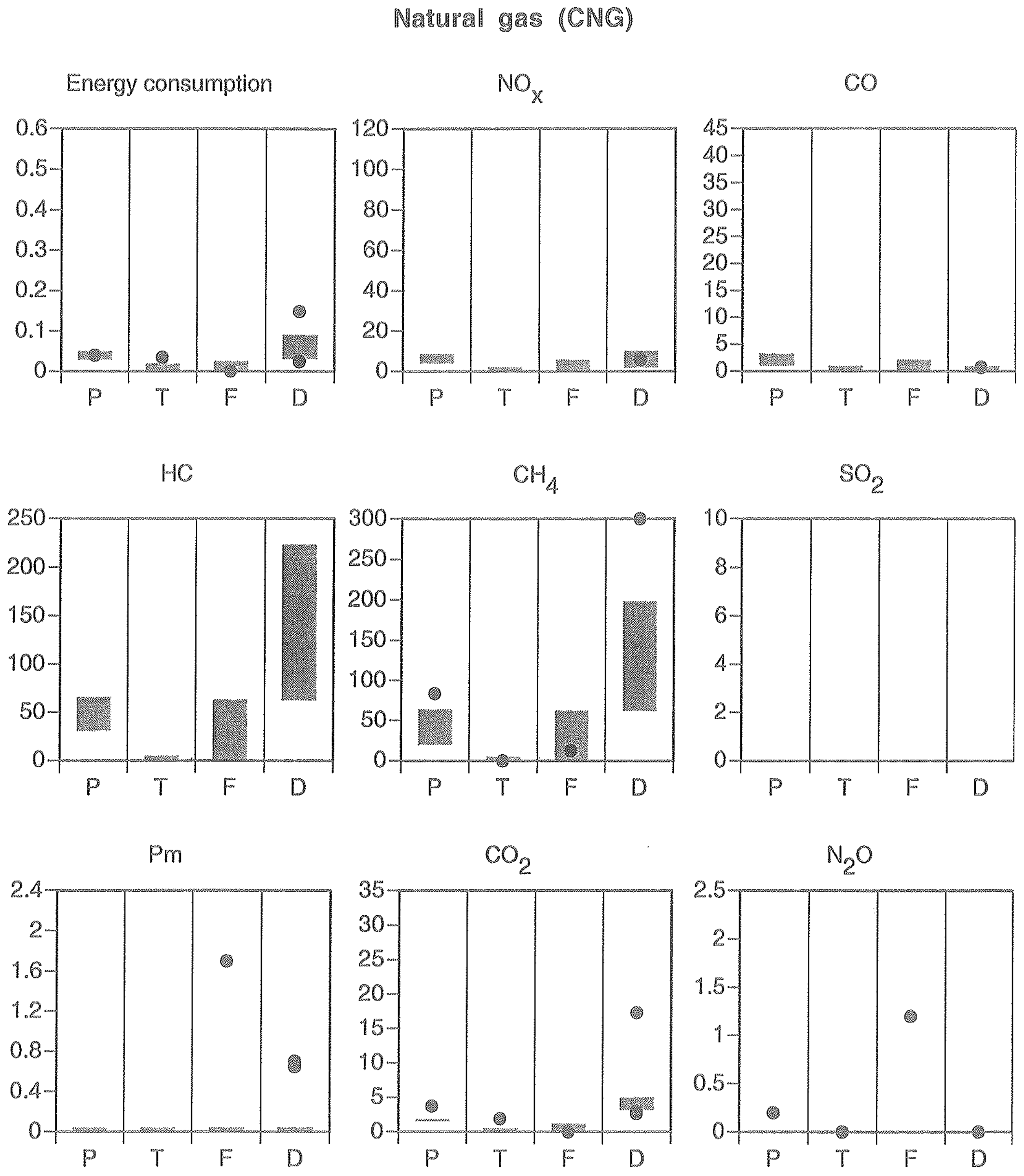

Fig. 3.5 Energy consumption and emission of the first four stages of the well to wheel fuel chain of natural gas (CNG), per MJ fuel available at the refuelling station.
Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show reference data from literature. Dots show new data obtained in this project.
P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

Natural gas (CNG)

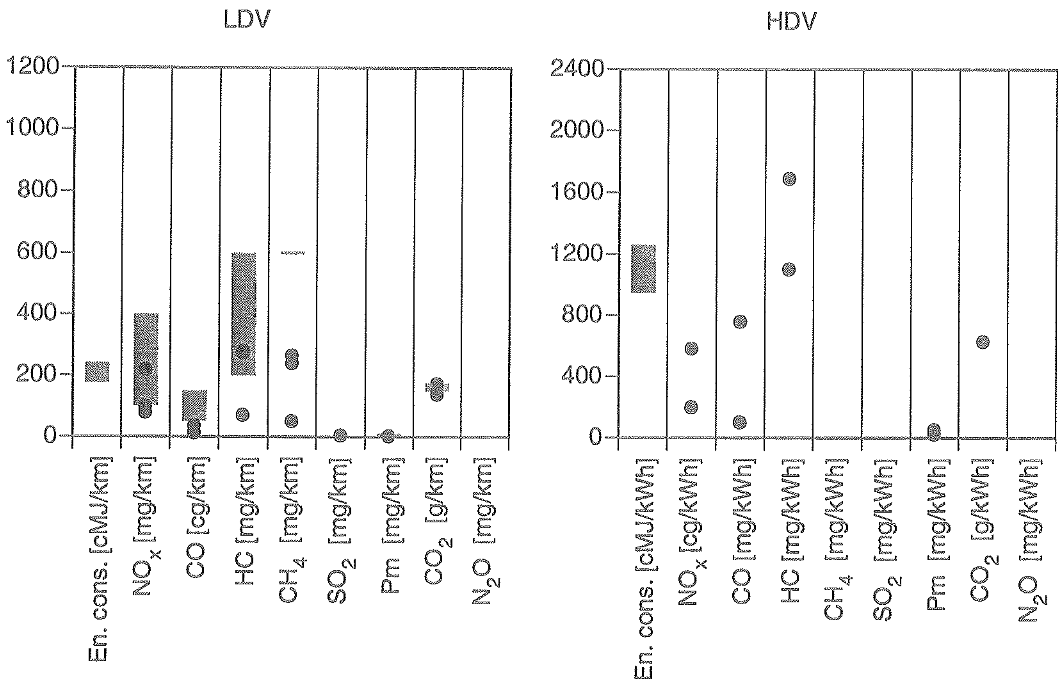

Fig. 3.6 Energy consumption and emissions of methanol light-duty vehicles (LDV) and heavy-duty vehicles (HDV).
Grey bars show reference data from literature. Dots show new data obtained in this project. Energy consumption bars are relative to the reference vehicle defined in this report and include new data obtained in this project. (1 cMJ = 0.01 MJ)

Because methane is the predominant constituent of natural gas, vehicle emissions of methane (CH_4) are significant and consequently total hydrocarbons (HC) emissions are relatively high. Vehicular methane emissions are negligible for all other fuels under consideration in this report.

Light-duty vehicle (LDV) emissions reported in this project tend to be at the lower end of the LDV emission values as reported in the literature. This may reflect technological developments that result in lower emissions for newer vehicles. Information from literature is inherently older than the latest data that have been supplied by the participants in this project.

LNG (liquefied natural gas) is still used on a very limited scale for automotive propulsion. On board fuel storage can be advantageous over CNG because higher energy storage density is possible with LNG [13]. However, liquefaction is an energy intensive process. An LNG production plant consumes an amount of fuel that is equivalent to 9-10% of the LNG that is being produced [4, 14, 15].

3.5
LPG

LPG (autogas) is a mixture of propane and butane and a small amount of other hydrocarbons. LPG is produced in two ways:

- Field LPG.
  Natural gas liquids (ethane, propane and butane) are by-products of oil and gas production. Propane and butane are extracted from North Sea natural gas liquids in onshore terminals and gas separation plants in the UK for example.
- Refinery LPG.
  LPG is one of the oil refinery products. This LPG is often used as fuel in the refinery processes. However, in some countries a share of the refinery LPG is used to fuel road vehicles. The feedstock recovery and feedstock transport stages of the refinery LPG fuel chain are the same as for gasoline and diesel. These stages are described in more detail in the gasoline section.

Generally the LPG sold to customers is a blend of field and refinery LPG. Because significant differences between the two production routes exist, both routes are presented separately in this section and in figures 3.7 and 3.8 respectively. Energy consumption of the refinery LPG route is higher than for field LPG. Differences occur mainly at the feedstock production and the fuel production stages. Per MJ of LPG product, oil production is more energy intensive than natural gas liquids production. Producing LPG in a refinery costs more energy than the separation of LPG from well fluids. Consequently, emissions in these stages are in general also higher for refinery LPG than for field LPG.

In most cases, LPG distribution is done by road tanker. The LPG is pressurised to 6-8 bars to keep it in the liquid phase at ambient temperatures. Intermediate storage at distribution terminals may be included in the fuel distribution stage.

The propane/butane ratio of LPG depends on the local situation. The local climate is an important factor. Generally holds that with lower temperatures, the propane content must be higher. In North America and Scandinavia for instance the percentage of propane is 90 to 95 wt%. In the Netherlands it varies between 40 and 70 wt% propane and in Greece LPG contains just 20 wt% propane. The reference data presented in figure 3.7 are based on US, Swedish and British data that all contain 90% propane or more. The influence of LPG composition on vehicle energy consumption and emissions is discussed below.

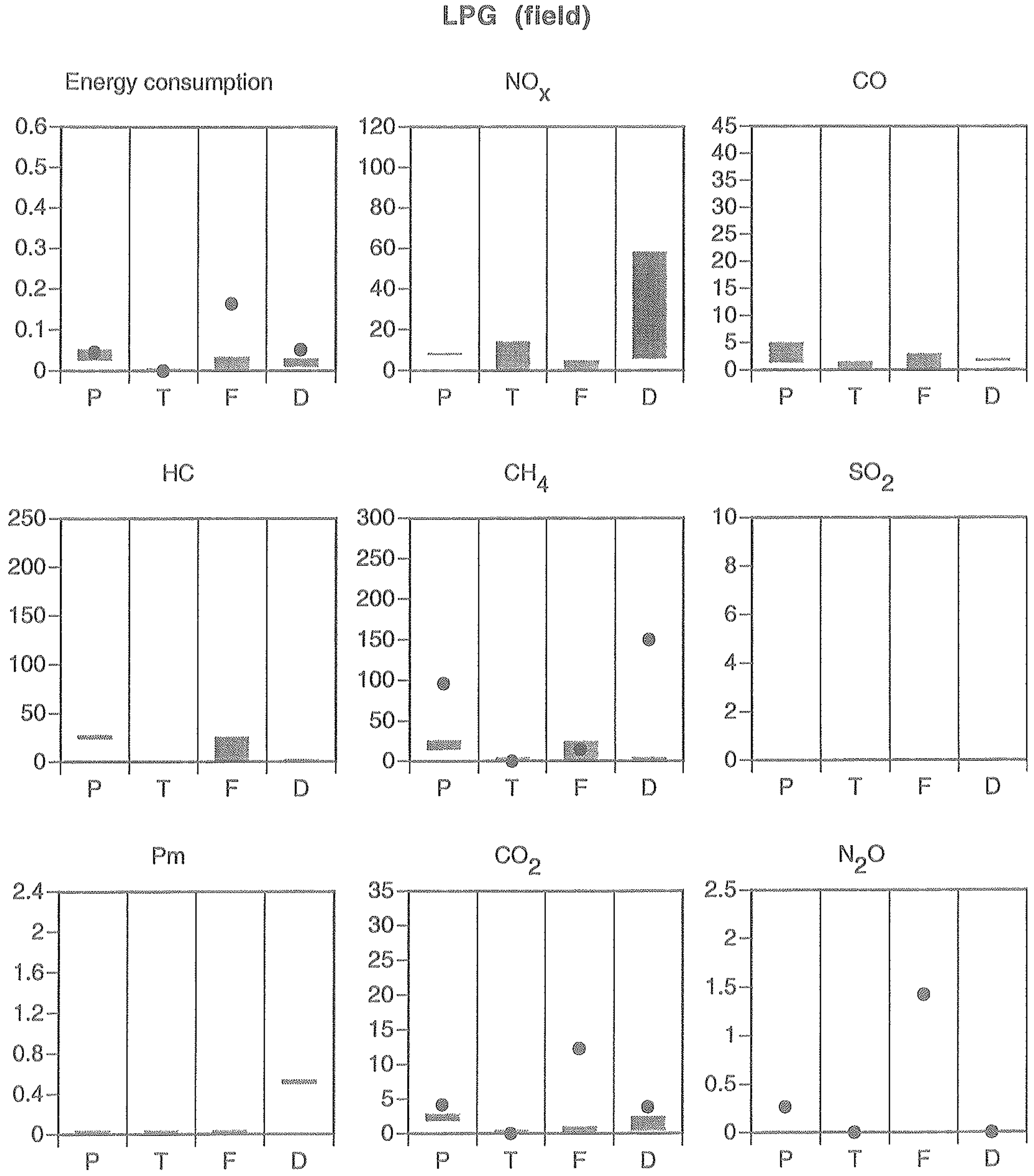

Fig. 3.7 Energy consumption and emission of the first four stages of the well to wheel fuel chain of field LPG, per MJ fuel available at the refuelling station.
Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show reference data from literature. Dots show new data obtained in this project.
P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

New data in figure 3.7 for field LPG stem from one source, that describes a scenario in the USA [6]. The figures are generally higher than the reference data. There is no particular explanation for this. It shows that different scenarios result in different data ranges and as such helps in building a data range.

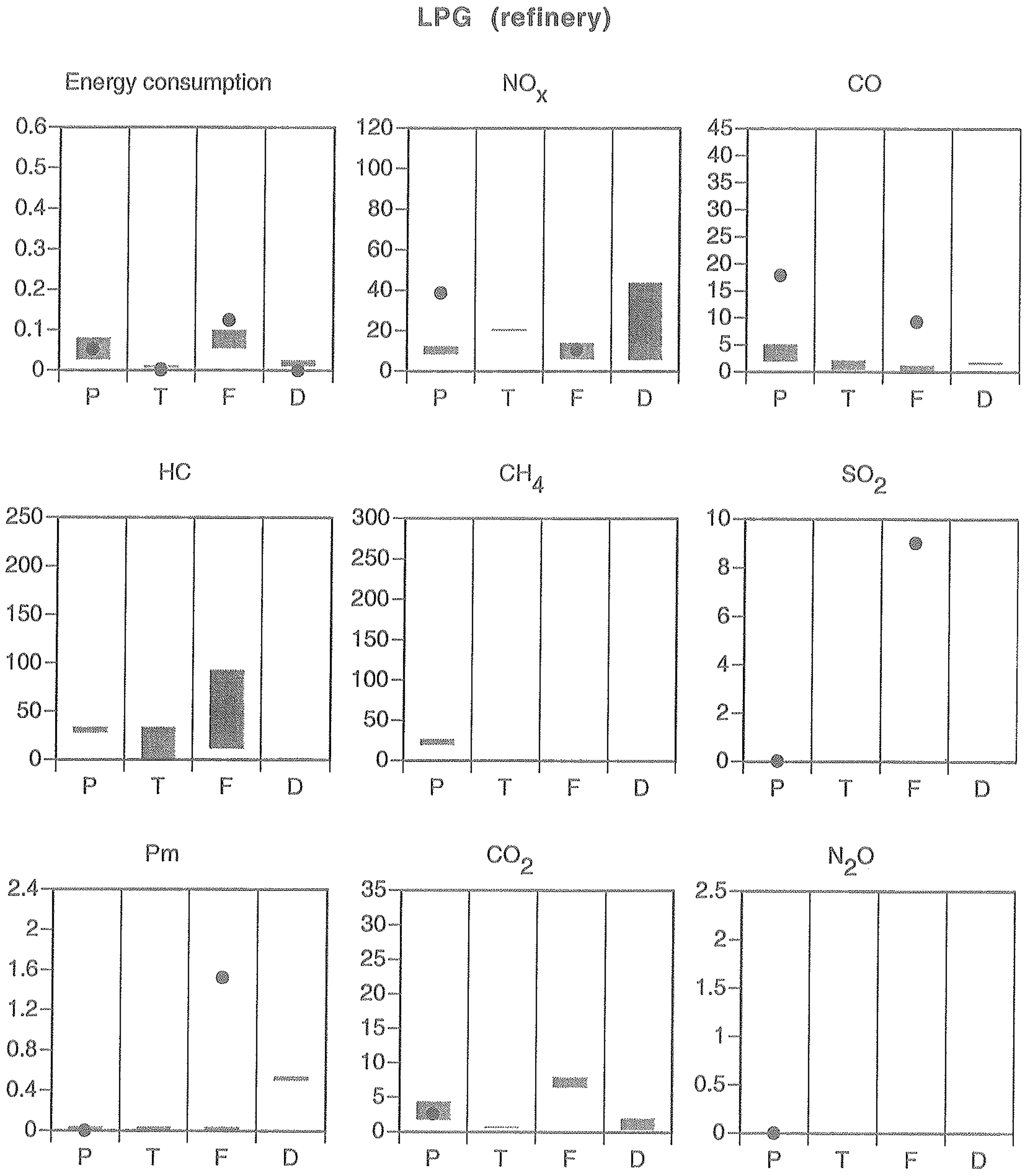

Fig. 3.8 Energy consumption and emission of the first four stages of the well to wheel fuel chain of refinery LPG, per MJ fuel available at the refuelling station.
Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ.
Grey bars show reference data from literature. Dots show new data obtained in this project.
P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

Similar to field LPG, the new data for refinery LPG are from one source only. In this case it is Amoco. Again, the explanation for the differences in data is that different scenarios are being considered.

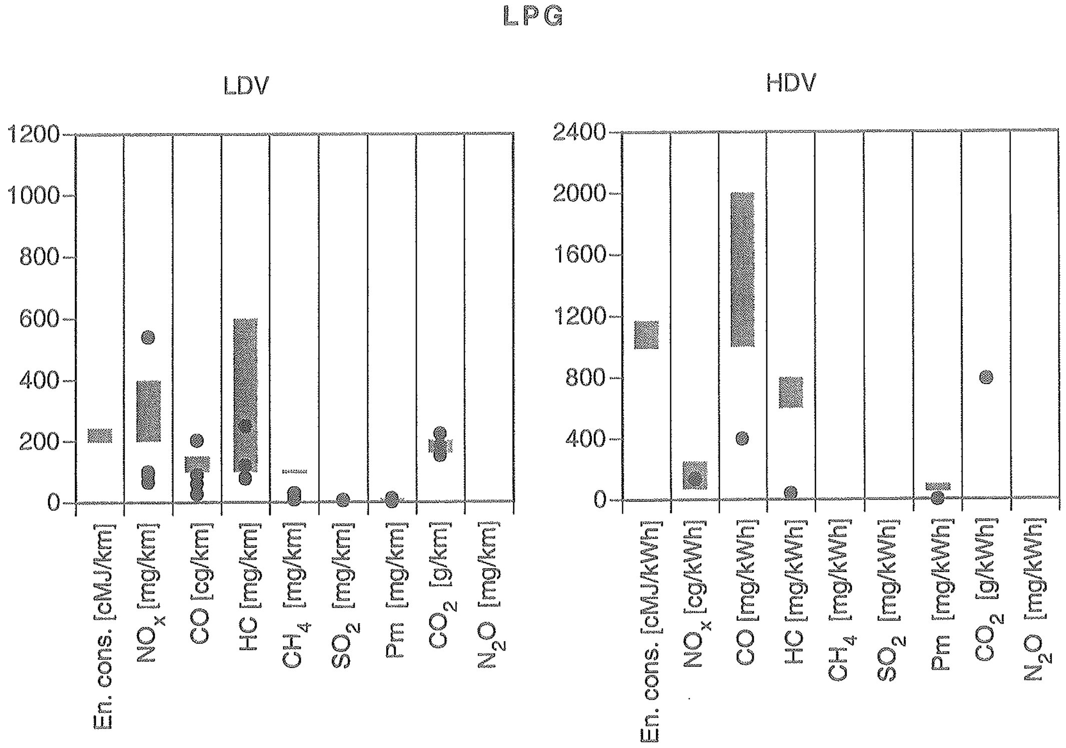

Fig. 3.9 Energy consumption and emissions of LPG light-duty vehicles (LDV) and heavy-duty vehicles (HDV).
Grey bars show reference data from literature. Dots show new data obtained in this project. Energy consumption bars are relative to the reference vehicle defined in this report and include new data obtained in this project. (1 cMJ = 0.01 MJ)

The LPG used to obtain the vehicle emission data varies in composition from more than 90% propane for the reference data down to 50 wt% propane for the LPG used in Renault's emission tests. Different studies have shown that the influence of changes in LPG composition on emissions is ambiguous and relatively small. HC and CO emissions tend to decrease and NO_x emissions tend to increase with increasing propane content [2].

For light-duty vehicles, new emission figures tend to be lower than for the reference vehicles. This can be explained by the ongoing technical developments in vehicle emission reduction technology. Latest technology LPG vehicles are equipped with third generation LPG systems, which have electronically controlled multi-point fuel injection and a three way exhaust catalyst.

Data on heavy-duty LPG vehicles -tested according to the European ECE-R49 13 mode test- show that emission levels of the newest technology engines have come down compared to the reference values.

3.6
Methanol

Methanol is a commodity in the chemical industry and traded on a large scale, so the technology for production and distribution is mature. Methanol is predominantly produced from natural gas, although many carbon containing feedstocks may be used. Natural gas may be transported by pipeline to a methanol production plant. For remote natural gas, methanol production at the gas recovery site is favoured because it lowers transportation costs. Depending on gas processes used, it may be necessary to remove undesired components like sulphur initially, since sulphur can poison catalysts used in subsequent process steps. Gas quality is depending on the location of production. North Sea gas for example is relatively 'clean' and does not require much processing.

Methanol transportation and distribution is by sea going vessel and road tanker. Volumetric energy density of methanol is half that of gasoline, so twice the volume of methanol has to be transported for an equal amount of energy. The fuel tank of a methanol vehicle is almost twice the size of a gasoline vehicle tank for the same driving range, because the energy efficiency of a dedicated methanol engine is slightly higher than for a gasoline engine. The use of methanol as an automotive fuel is mainly concentrated in North America. A fleet of flexible fuelled vehicles (FFVs) is running on M85, a methanol/gasoline blend with 85 vol% methanol. Heavy-duty methanol vehicles predominantly run on pure methanol (M100). Methanol vehicle emissions are very similar to gasoline vehicle exhaust emissions, except for hydrocarbons. Relatively more oxygen containing hydrocarbon compounds are produced during the combustion of methanol. Formaldehyde emissions are relatively high but may be reduced to acceptable levels by applying an exhaust catalyst.

Some general remarks on using methanol as an automotive fuel are:

- Methanol (in presence with water) affects certain steel qualities, aluminium and plastics (including elastomers). Materials that will come in contact with methanol have to be carefully chosen.
- Methanol has low lubrication properties. Measures have to be taken to avoid wear problems in fuel systems.
- Mechanics working on methanol vehicles have to take precautions to avoid methanol contact with skin and eyes.

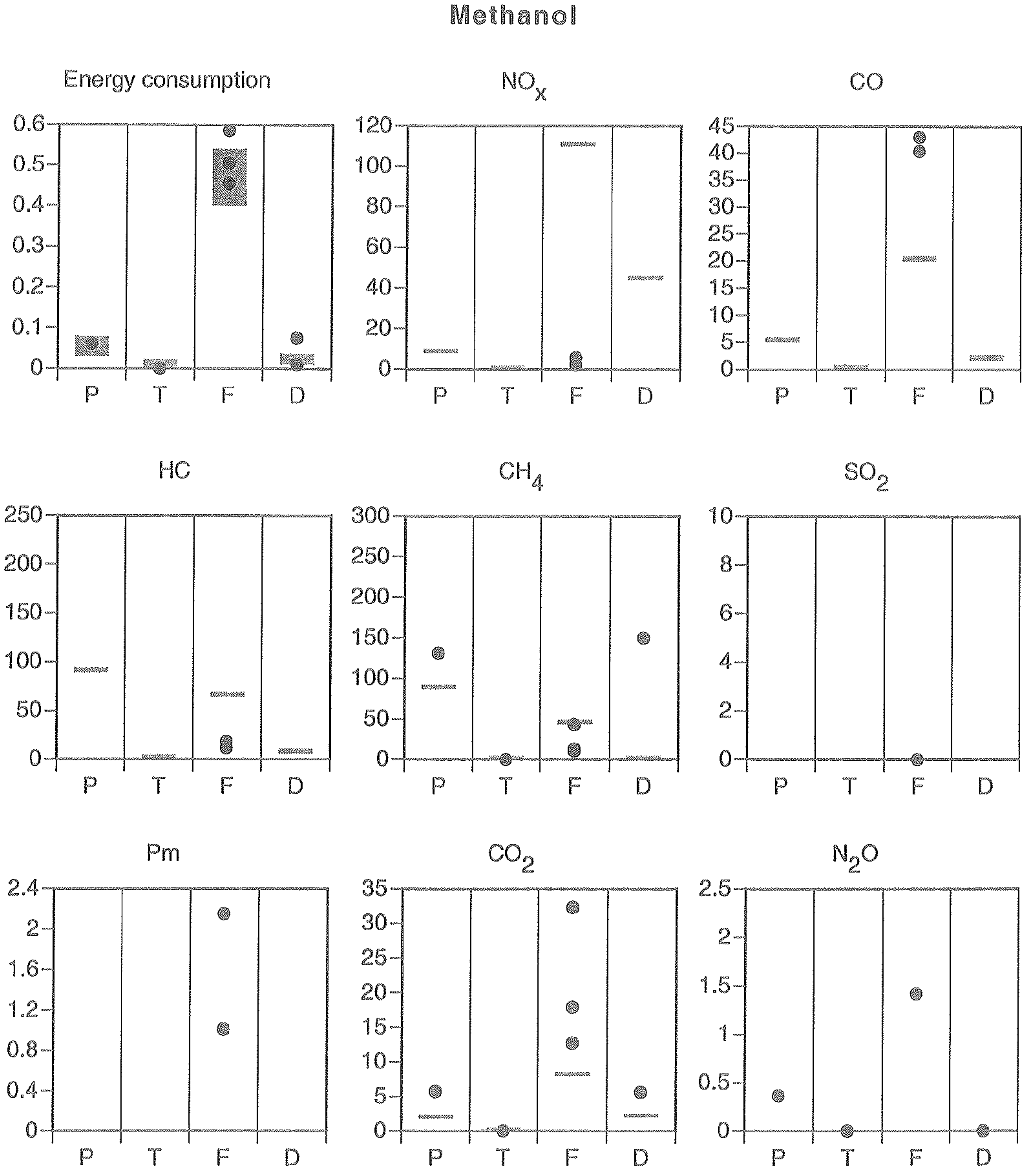

Fig. 3.10 Energy consumption and emission of the first four stages of the well to wheel fuel chain of methanol (produced from natural gas), per MJ fuel available at the refuelling station. Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show reference data from literature. Dots show new data obtained in this project.

P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

In figure 3.10 it can be seen that NO_x emission data for the methanol production stage differ largely between the reference and the new data. Reasons for this difference are that only one reference that stems from 1992 is available and that the new data are for a modern plant incorporating autothermal reforming with no open flames and auxiliary heaters equipped with low NO_x burners.

Energy consumption of feedstock transportation is zero when methanol is produced at the natural gas recovery site, just like DME from remote natural gas.

Compared to gasoline and conventional diesel, methanol fuel production is relatively energy intensive. This results in relatively high NO_x, CO and CO_2 emissions for the fuel production step as well.

CH_4 emissions of feedstock production are somewhat higher than for most other fuels because natural gas is the feedstock.

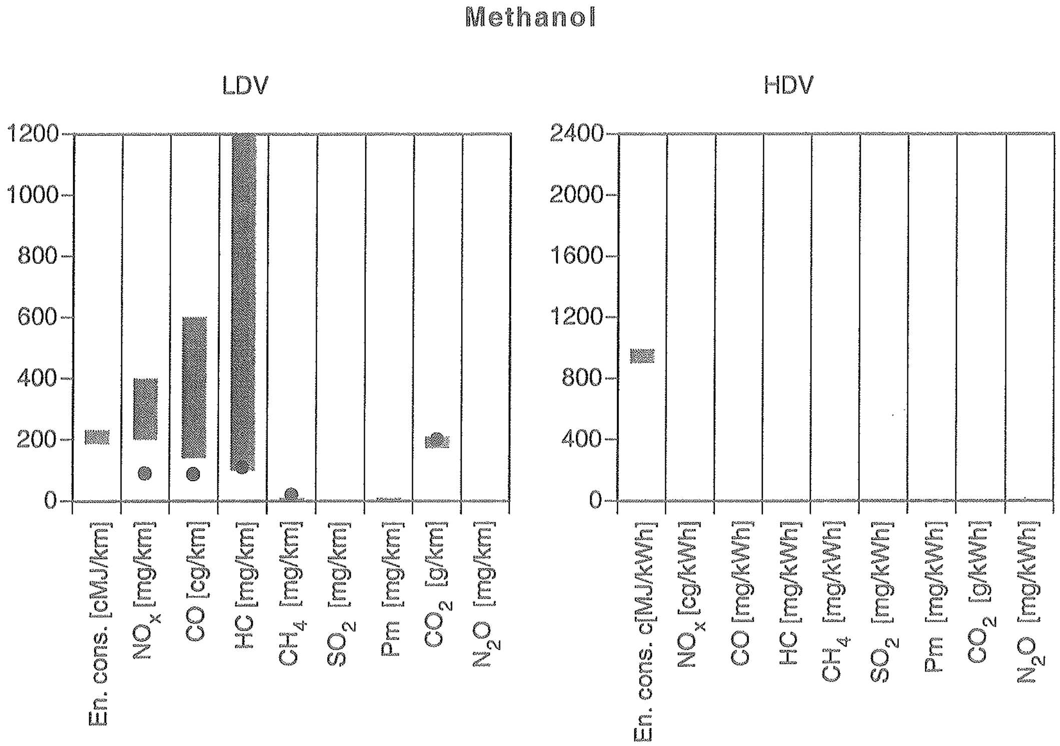

Fig. 3.11 Energy consumption and emissions of methanol light-duty vehicles (LDV) and heavy-duty vehicles (HDV).
Grey bars show reference data from literature. Dots show new data obtained in this project. Energy consumption bars are relative to the reference vehicle defined in this report and include new data obtained in this project. (1 cMJ = 0.01 MJ)

HC emissions of methanol light-duty vehicles tend to be higher than for the other fuels, but a new technology LDV is at the lower end of the range. Also for other LDV emission components, the new methanol vehicle is at the lower end of the range, showing that technology improvements still are being implemented.

3.7

DME

DME can be produced from carbon containing feedstocks, as long as these can be converted into synthesis gas (syngas). Like for methanol, syngas is the intermediate step in DME production. An important reason for oil companies to show interest in DME as an automotive fuel is finding an outlet for remote natural gas. Further in the future, DME may be produced from biomass as well. Supplying data on the biomass production route would be too speculative so it is not included in this report. Only production from natural gas is addressed here.

Because selling remote natural gas is the driving force for using DME as an automotive fuel, this is expected to be the predominant scenario for an automotive DME market. Therefore this section concentrates on DME from remote natural gas.

Because transporting liquids is cheaper than transporting gas, DME will be produced at the natural gas recovery site. First, natural gas is converted into syngas, for example by steam reforming. When DME is being produced in large quantities in very large plants, the synthesis gas will be generated by autothermal reforming. In the next step syngas is catalytically reacted to form DME. Transport of DME may be by sea tanker or by pipeline. After sea transport, pipeline transport to a storage depot may be necessary before final distribution by road tanker. To keep DME in the liquid phase at ambient temperatures, it is slightly pressurised, just like LPG. Also on other aspects than pressurising, handling of DME is very similar to handling of LPG.

On board storage of DME is similar to LPG. The tank is larger and heavier than a gasoline or diesel tank. Energy efficiency of DME combustion in the vehicle engine is similar to diesel engine efficiency. DME combustion is soot free and noise level is at a gasoline engine level. Lubrication properties of DME are worse than those of diesel. Fuel pumps have to be modified to avoid wear problems, for example. Compressibility of DME is higher than for diesel oil, which affects fuel injection rates and may lead to pressure waves in fuel lines. Fuel system modifications are required to compensate for these effects.

For this report, Haldor Topsøe supplied energy consumption and emission (except N_2O) data for DME production. Data for feedstock production, feedstock transport and fuel distribution are not available so these have been estimated as is described below. No speculations about N_2O emissions are made here.

- Feedstock production is natural gas production at a remote location. Because natural gas is the feedstock for methanol production as well, the total data range for methanol has been used here. Because no data for SO_2 and Pm emissions for methanol feedstock production are available, these emissions are not calculated for DME. However, these SO_2 and Pm emission levels may be expected to be low.

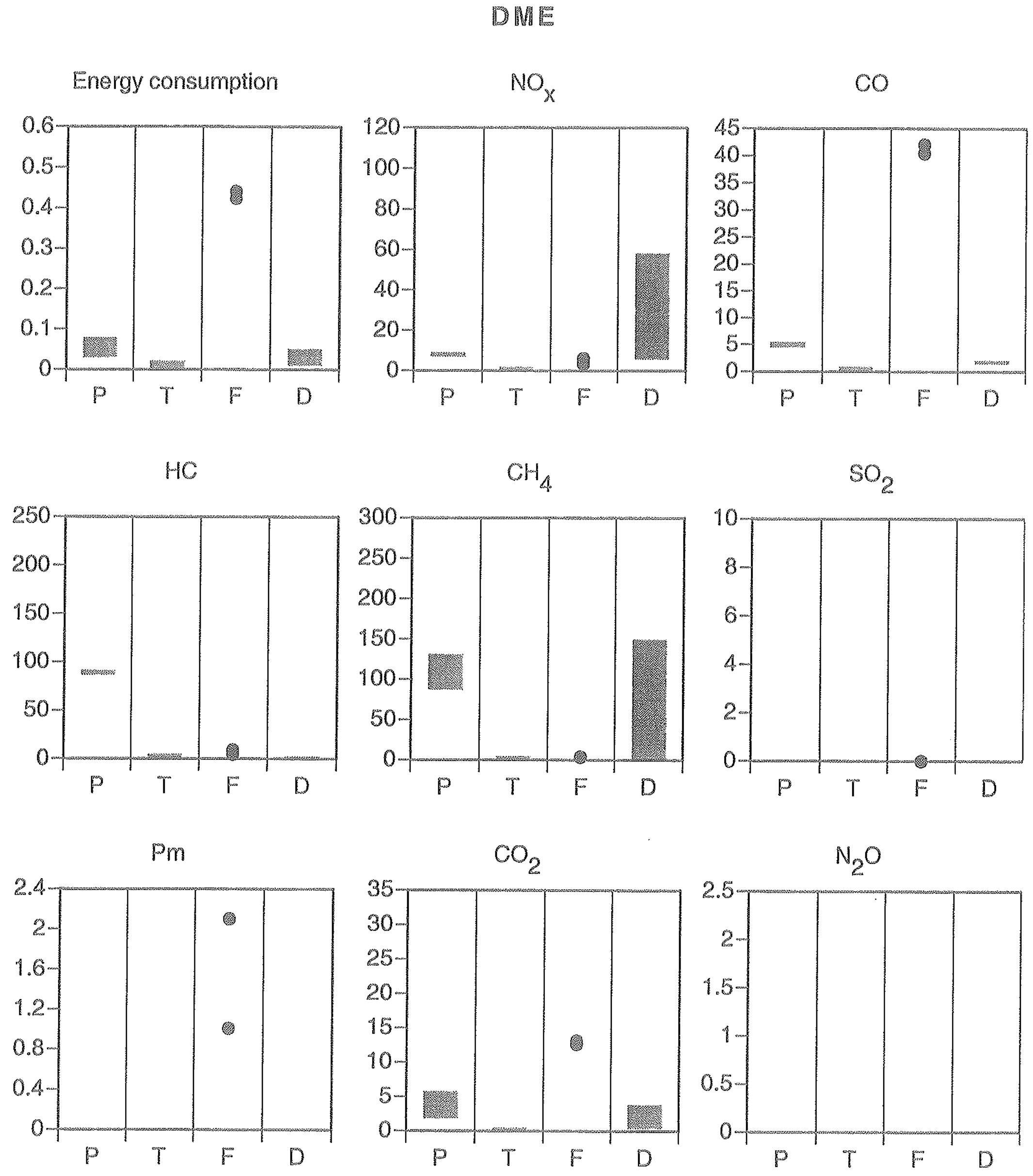

Fig. 3.12 Energy consumption and emission of the first four stages of the well to wheel fuel chain of DME (produced from natural gas), per MJ fuel available at the refuelling station. Energy consumption is in MJ/MJ. Emissions are in mg/MJ except CO_2, which is in g/MJ. Grey bars show estimates as described in the text. Dots show new data obtained in this project.

P = feedstock production
T = feedstock transportation
F = fuel production
D = fuel distribution

- Because DME is to be produced at the natural gas production site, energy consumption and emissions for feedstock transportation are estimated to be negligible. Again, SO_2 and Pm emission data are not available and the emission levels may be expected to be low.
- Handling of DME is very similar to handling of LPG, so for fuel distribution the total data range for field LPG has been used. In a scenario with DME production at a remote natural gas recovery site, energy consumption and emissions may be higher than the figures that are presented here. No speculations about such a scenario are made here. The figures supplied here must be considered a lower limit for energy consumption and emissions of distribution.

The results are shown in figure 3.12.

No LDV emission data for the European test cycle are available yet. However, AVL did some steady state emission measurements on a 2 litre direct injection, turbocharged and intercooled compression ignition engine [16]. Based on these steady state results, AVL was able to project the emission results for the American FTP 75 test cycle. Diesel emission figures for a reference vehicle are also available for this FTP cycle. Using this information, estimates for LDV emission data according to the European test cycle have been made, using the following method. DME LDV emission result are expressed as a percentage of the diesel LDV emission results for the FTP cycle. With these percentages and the total range of diesel LDV emission figures presented in this report (see figure 3.4), the emissions for LDV DME vehicles have been calculated. The resulting ranges are shown in figure 3.13. The way in which they have been obtained makes clear that those ranges only should be seen as a first, rough indication.

Heavy-duty DME engine data of two different engines are available. The reference data in figure 3.13 were measured on a Navistar 7.3 litre direct injection turbo truck engine. Measurements were done by AVL using their 8 mode test. The result for the European ECE R49 test are calculated from their results [17]. Volvo supplied data on their recently developed first DME engine. The emissions of particulate matter are reported to be below 0.05 g/kWh. This engine was equipped with an oxidation catalyst to reduce CO emissions. The data supplied here must be considered as a first upper limit for the emission levels that are possible with compression ignition DME engines, because for both engines holds that these are first prototypes, which means that getting the engine running was more important than achieving the lowest emissions possible. So optimisation of those engines is expected to lower the emission levels. For example exhaust gas recirculation (EGR) will reduce NO_x emissions. Also energy consumption, and consequently CO_2 emissions, are expected to be lowered in the future.

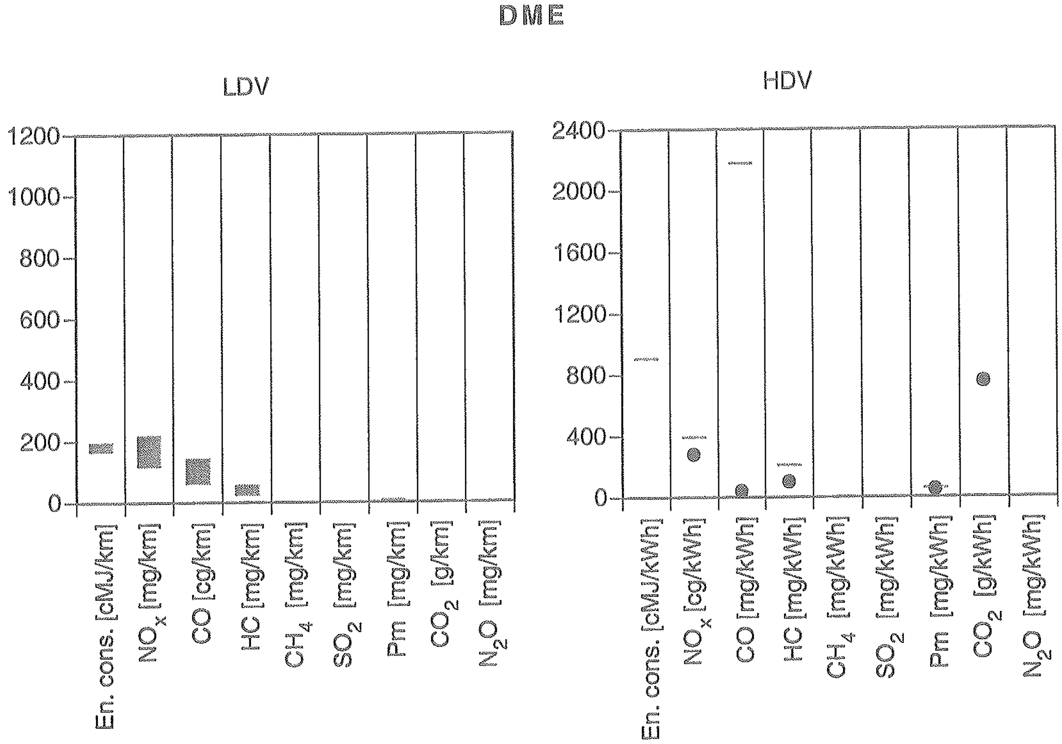

Fig. 3.13 Energy consumption and emissions of DME light-duty vehicles (LDV) and heavy-duty vehicles (HDV).
Grey bars in the LDV graph show data that have been calculated from literature. Grey bars in the HDV graph show reference data from literature. Energy consumption bars are relative to the reference vehicle defined in this report. Dots show new data obtained in this project. (1 cMJ = 0.01 MJ)

For all fuels, latest technology vehicles are close to meeting Euro III (to be introduced in the year 2000) emission limits. Although still immature, DME already meets the Euro III requirements, except for LDV NO_x emissions in some cases. All fuels under consideration here may be expected to meet the Euro III emission requirements, and also for the future Euro IV emission limits no fundamental barriers are foreseen. Because DME is still in its infancy as an automotive fuel, there is still much room for improvement of engine exhaust emission levels.

4
Comparison of fuels

In this chapter, the automotive fuels under consideration are compared to each other on energy consumption and emissions over the complete well to wheel fuel chain. The complete well to wheel fuel chain is used because it is considered a fair basis to compare automotive fuels and because it is a relevant basis for many cases where decisions on fuel choice have to be made. In this chapter, first an overall comparison is made on the basis of energy consumption and emissions simultaneously. Next, energy consumption and the environmental effects of the emissions are addressed, each in its own section.

A remark must be made on the interpretation of the pictures that are presented in this chapter. The pictures show data ranges for energy consumption and emissions. This makes sense because many different well to wheel fuel chain scenarios are in operation around the globe and many different technologies are being used, so presenting only one value would not be appropriate and would not have general applicability. However, the influence of technology cannot be determined from the data ranges. If a certain technology is at the upper or at the lower end of the data range is not shown. Consequently, comparing the same technology for different fuels is not possible with these pictures. In general it can be stated that the most recent and advanced technology results in values at the lower end of the data range.

4.1
The overall picture

The well to wheel energy consumption and emissions comparison is made for light-duty and for heavy-duty vehicles separately in this section. The figures for the five stages of the fuel chain as presented in chapter 3 have been used to obtain the total well to wheel data for each fuel under consideration. In chapter 3, data on the first four stages of the fuel chain are presented per MJ fuel available at the refuelling station. These figures are multiplied by the vehicular energy consumption to obtain the "well to refuelling nozzle" figures for the vehicle under consideration. To obtain the well to wheel figures, upstream and vehicular figures are added. Because for most stages a range of data is presented in chapter 3, the data for the complete fuel chain are also ranges. The total range represented by the grey bar and the dots in the pictures of chapter 3 is used as the data range to build the pictures in this chapter. The data for the complete fuel chain are presented for each fuel in a spider web (figures 4.1 and 4.2). The data ranges are shown as dark shaded areas in these figures. Although included in chapter 3, SO_2 and N_2O are not shown here, because not sufficient data are available to produce figures for the total well to wheel fuel chains.

In this subsection the total energy consumption and emissions picture of the well to wheel fuel chains are placed beside each other, to enable a general comparison of the fuels. After some general remarks, the comparisons for light-duty vehicles and heavy-duty vehicles are made separately in this subsection. Some of the emission components that are included here are also addressed separately in the subsequent subsections.

It appears that for both light and heavy-duty vehicles the data ranges are relatively large, in particular for NO_x, CO, HC and Pm emissions. This is mainly due to a large spread in vehicle emission data. In general it can be stated that the more recent the vehicle technology is, the more the data will be at the lower end of the range. Today's exhaust gas catalyst technology results in low values for these emission components. The large data ranges also reflect the fact that all data should be considered as indicative. It can be noticed that DME data ranges are relatively small, although DME technology is still in an early stage of development. The small data ranges are caused by the limited number of figures that are currently available. Because DME is in an early stage of development, for some emission components there is not enough data available to establish relevant well to wheel figures.

Light-duty vehicles

Figure 4.1 shows the well to wheel comparison for fuels in light-duty vehicles. It shows that CO, HC and CH_4 emissions and energy consumption for diesel fuel are relatively low. On the other hand, particulate emissions for diesel are high compared to the other fuels. CO_2 emissions for gasoline and methanol are higher than for the other fuels. Also energy consumption of methanol from natural gas is relatively high. DME shows the potential to have low NO_x emissions. Although not shown in figure 4.1 due to a lack of data, Pm emissions of methanol and DME may be expected to be small and in the same order of magnitude as for the gaseous fuels and gasoline. For all fuels, including DME, it can be stated that total well to wheel emissions are strongly dependant on the vehicle exhaust catalyst technology. Appropriate technology will result in low emissions for all fuels. CO_2 emissions are not affected by the exhaust catalyst.

Heavy-duty vehicles

Because no CH_4 emission data are available for heavy-duty vehicles, CH_4 is not shown in figure 4.2. Energy consumption for diesel and DME are below average; methanol is higher than average. Particulate emissions of diesel are higher than for the other fuels, but the difference is not as large as for LDVs. NO_x emissions for diesel are relatively high. Natural gas shows the potential to have relatively low CO_2 emissions. Data for methanol from natural gas are very incomplete. Just like for LDVs, Pm emission for methanol and DME may be expected to be smaller than for diesel and similar to the gaseous fuels. DME shows the potential to have lower NO_x emissions than diesel. However, the other fuels show this potential as well.

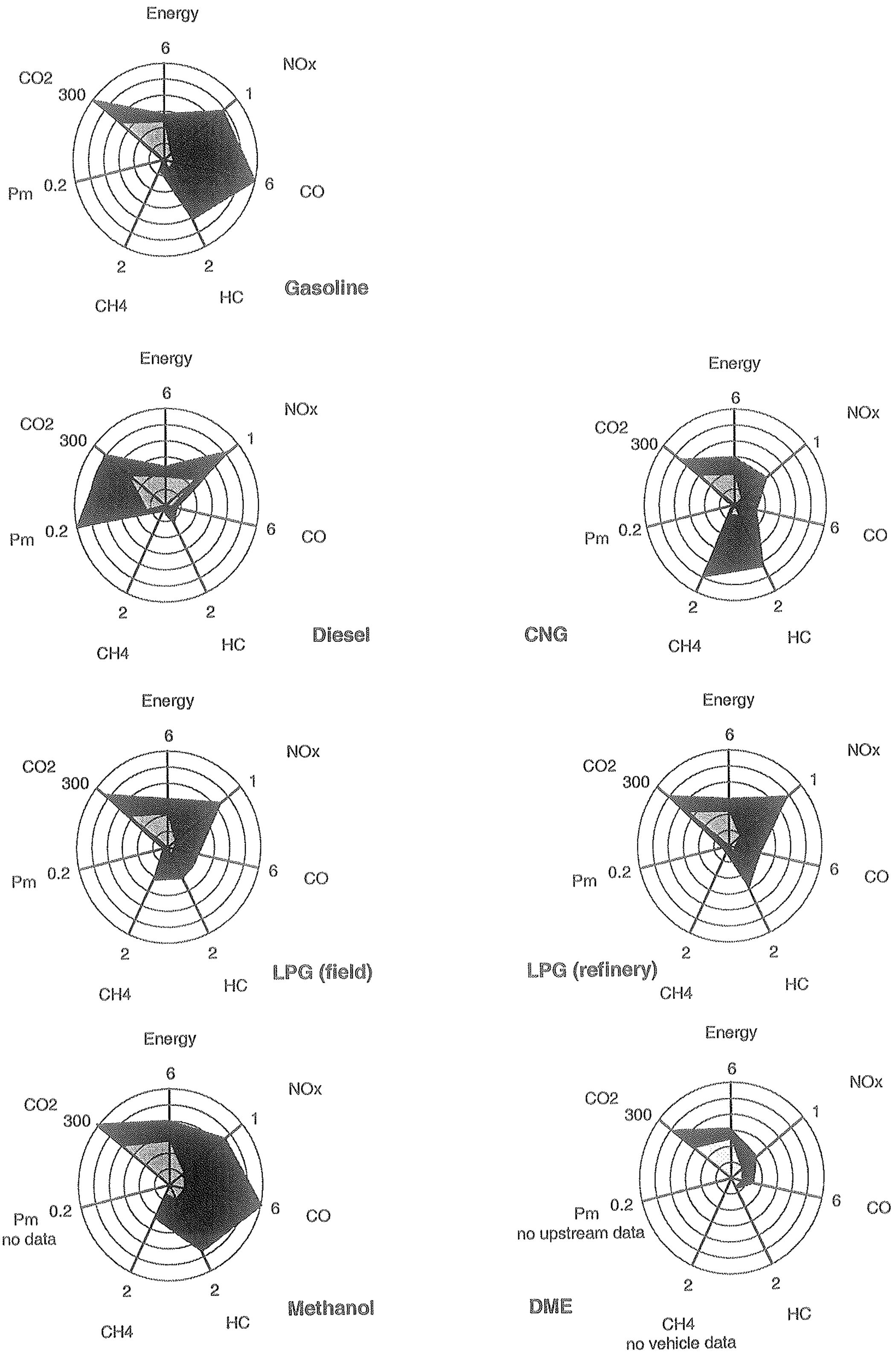

Fig. 4.1 Well to wheel energy consumption and emissions of light-duty vehicles (LDVs). Energy consumption is in MJ/km, emissions (except N_2O) are in g/km. Dark shading is the data range.

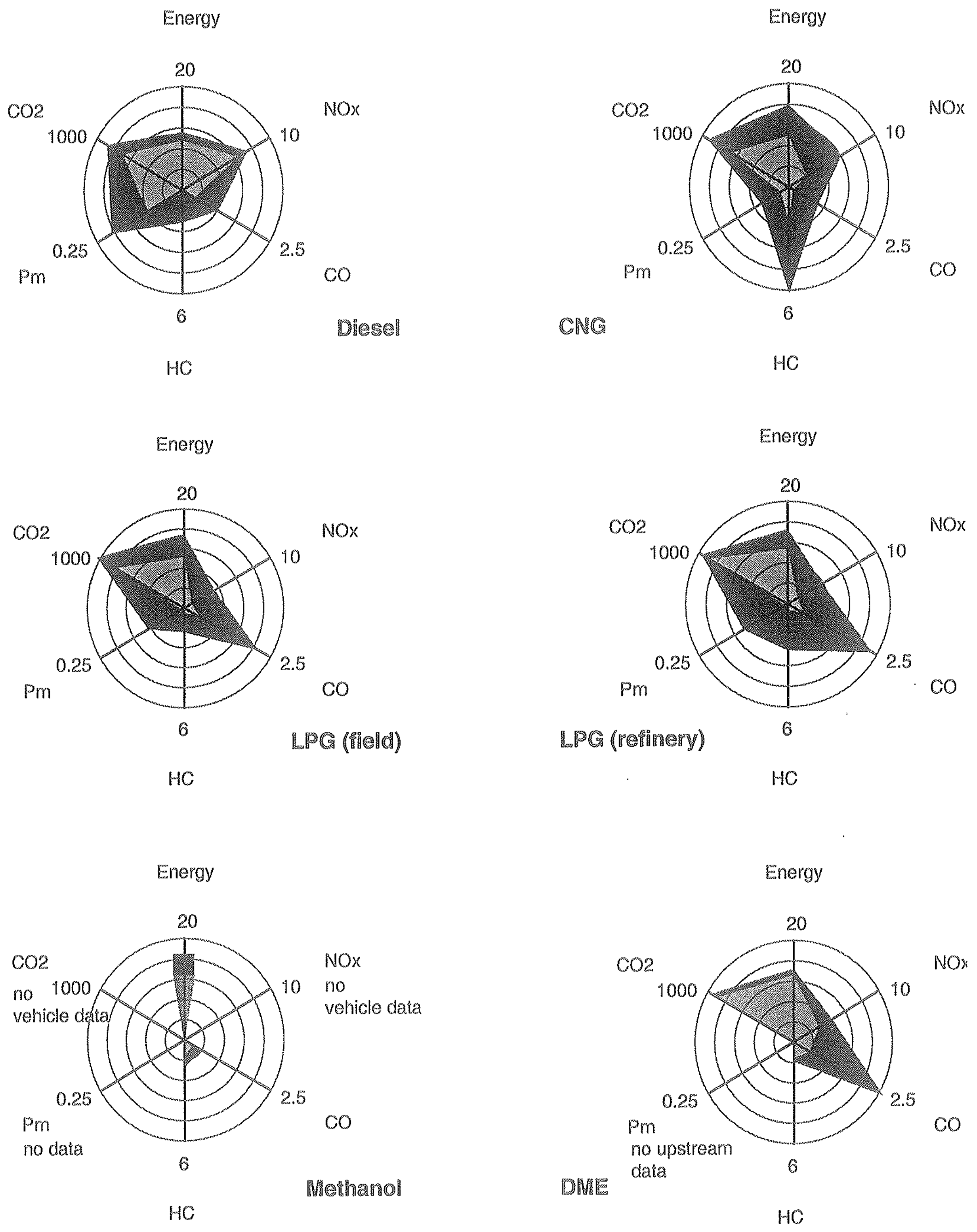

Fig. 4.2 Well to wheel energy consumption and emissions of heavy-duty vehicles (HDVs). Energy consumption is in MJ/kWh, emissions are in g/kWh. Dark shading is the data range.

Conclusions

From the fuel comparison on the basis of well to wheel energy consumption and emissions, it can be concluded that there is not an absolute winner with significantly lower values than the other fuels. Data ranges for different fuels are in general very similar. Some trends that can be observed are:

- Diesel shows the lowest energy consumption. Methanol from natural gas the highest. DME from natural gas appears to have an average energy consumption.
- Particulate emissions from diesel are relatively high. Particulate emissions for all other fuels are significantly lower and mutually in the same range.
- NO_x emission levels for diesel are the highest. All other fuels have the potential to result in lower NO_x emissions.
- CO_2 emissions are directly related to energy consumption and to carbon content per energy content of the fuel. Diesel shows the lowest CO_2 emissions, methanol from natural gas the highest. DME CO_2 emissions are in the same order of magnitude as the gaseous fuels.
- The other emissions components look very similar for all fuels. Appropriate vehicle exhaust catalyst technology will results in low emission levels, including methane from natural gas vehicles.

4.2
Energy consumption

Energy consumption of light-duty vehicle (LDV) fuel chains are shown in figure 4.3. The total fuel chain is first split in an 'well to refuelling nozzle' part and a vehicle part, which are shown separately. The lower third of the picture shows the total well to wheel fuel chain values. Data ranges are presented in this figure. Each bar stands for a data range. Looking at DME for example, it can be read from the figure that energy consumption of 'well to refuelling nozzle' activities for this fuel is between 0.7 and 1.1 MJ/km. DME vehicular energy consumption is between 1.7 and 2 MJ/km and the total well to wheel energy consumption for DME LDVs is between 2.4 and 3.1 MJ/km. The well to wheel bar shows the sum of the well to refuelling nozzle and vehicle bars.

Well to refuelling nozzle in figure 4.3 includes feedstock production, feedstock transportation, fuel production and fuel distribution. Energy consumption of methanol and DME, both produced from natural gas, in this section of the fuel chain stand out. Fuel production is the main reason for this relatively high energy consumption, because both fuels require an energy intensive synthesis process. Because these processes are very similar, methanol and DME data ranges are also similar. The data range for DME is smaller than for methanol because a smaller number of data points is available for DME and methanol production includes some older, less energy efficient, manufacturing processes. Well to refuelling nozzle energy consumption for the other fuels is well within one range. Vehicular energy consumption is similar for all fuels except diesel and DME, which fuels show lower vehicular energy consumption values. Energy consumption of DME LDVs is assumed to be equal to diesel LDVs. When well to refuelling nozzle and vehicular energy consumption figures are combined, then it shows that most fuels are in the same range. Diesel is at the lower end of this range and methanol from natural gas is clearly higher. DME turns out to be similar to gasoline.

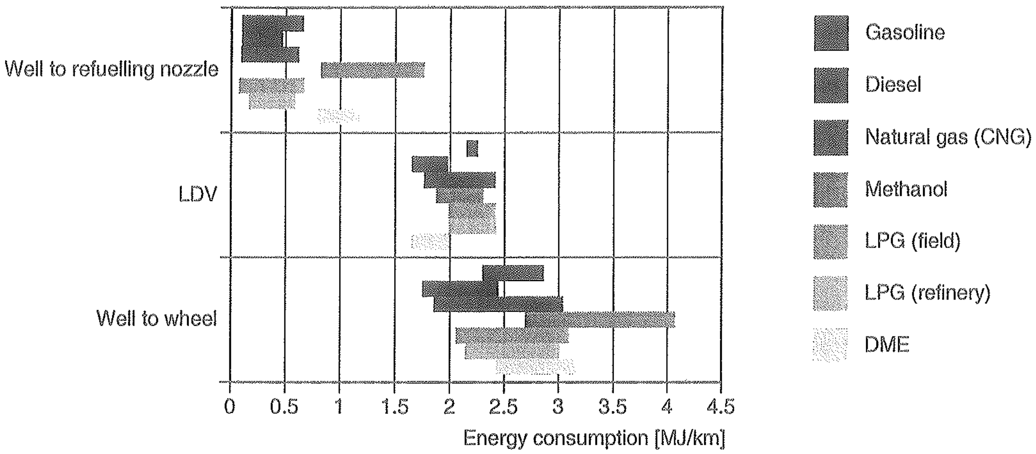

Fig. 4.3 Data ranges for LDV well to wheel energy consumption. Three ranges are shown. LDV bars show the energy consumption of the vehicle only. Note that 2.2 MJ/km is a gasoline reference vehicle. Well to wheel is the sum of the well to refuelling nozzle and LDV values.

The upstream energy consumption picture (figure 4.4) for heavy-duty vehicles (HDVs) is very similar to the LDV picture. The synthetic fuels methanol and DME show the highest well to refuelling nozzle energy consumption. This way of presentation does not show that for a similar production process, energy consumption of DME is lower than for methanol.

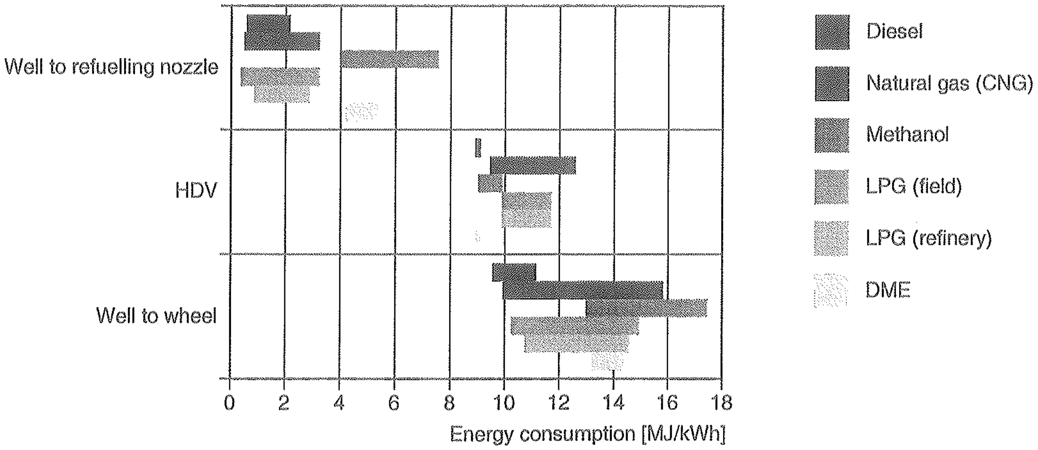

Fig. 4.4 Data ranges for HDV well to wheel energy consumption. Three ranges are shown. HDV bars show the energy consumption of the vehicle only. Note that 9 MJ/kWh is a diesel reference vehicle. Well to wheel shows the sum of the well to refuelling nozzle and HDV values.

Diesel and DME HDVs are most efficient in vehicular energy consumption. Just like with LDVs, energy consumption of diesel and DME HDVs is assumed to be the same. Methanol HDVs are just slightly higher. Well to wheel energy consumption for HDVs is in one large range, with diesel clearly at the lower end and methanol at the higher end of the range.

Looking at the well to wheel energy consumption for both light and heavy-duty vehicles, it can be concluded that all fuels under consideration are not very far apart. Diesel well to wheel energy consumption is relatively low and methanol produced from natural gas shows a relatively high energy consumption. Relatively low vehicular energy consumption values for DME are being offset by a relatively high fuel production energy consumption. For the total fuel chain, energy consumption of DME is average.

4.3
NO_x emissions

NO_x emissions are important because they contribute to acidification and summersmog (see also section 4.6). Well to wheel NO_x emissions of light-duty vehicles are shown in figure 4.5. This picture shows that the data ranges are large, especially for vehicular NO_x emissions. It appears that technology and scenario have a large influence on NO_x emissions. It also can be observed that for low NO_x emitting vehicles, the upstream section of the fuel chain can be the major emission source. Looking at the well to wheel NO_x emissions, it shows that all fuels are within one large data range. Diesel is clearly at the higher end of this range because of the relatively high vehicular NO_x emissions, natural gas tends to be relatively low and DME is clearly at the lower end of this range. Both the well to refuelling nozzle and vehicular emissions of DME are at the lower end of the data ranges.

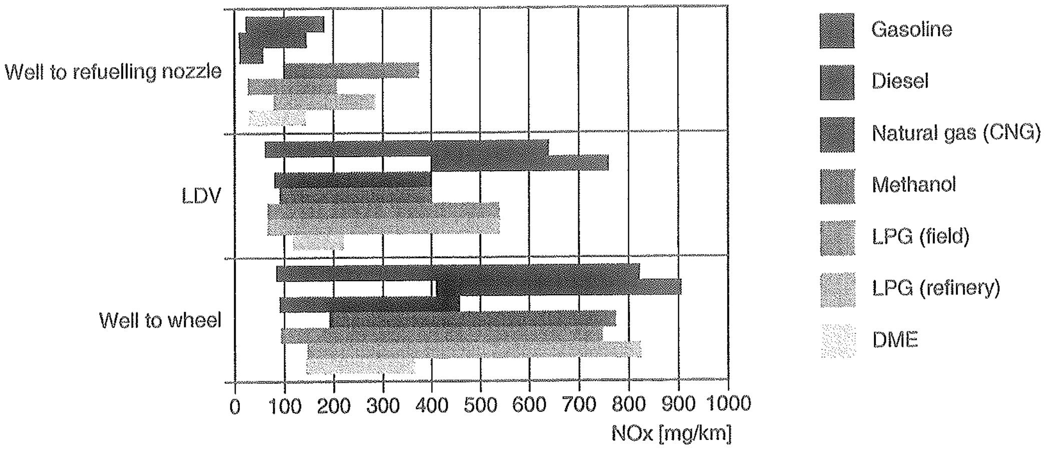

Fig. 4.5 Data ranges for LDV well to wheel NO_x emissions. Three ranges are shown. LDV bars show NO_x emissions of the vehicle only. Well to wheel is the sum of the well to refuelling nozzle and LDV values.

Emissions of diesel heavy-duty vehicles are highest in the NO_x picture (see figure 4.6). Also natural gas HDVs may have relatively high NO_x emissions, but with appropriate technology (stoichiometric fuel combustion combined with a three way catalyst), natural gas vehicles can also be at the lower end of the vehicle emission range. What cannot be read from figure 4.6 is that these lower NO_x emissions come with a higher fuel consumption. Methanol HDV data for the European 13 mode cycle are not available. For methanol HDVs in North America, NO_x emission levels of 44-84% of diesel HDVs have been reported [2]. Using these values here would result in methanol well to wheel NO_x emission levels of approximately 50-100% of diesel levels. For HDVs it can be concluded that well to wheel NO_x emissions of diesel vehicles are the highest. All other fuels have the potential to halve these emission, when appropriate vehicle technology is used.

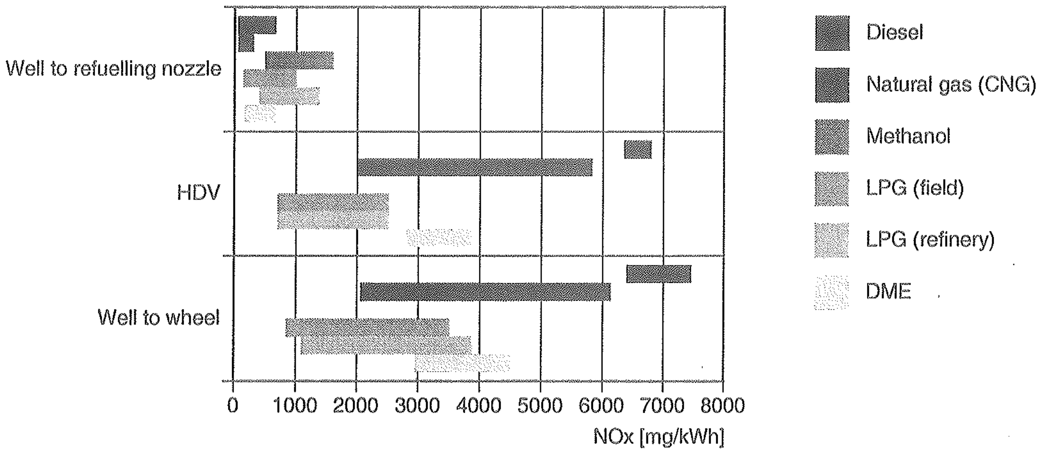

Fig. 4.6 Data ranges for HDV well to wheel NO_x emissions. Three ranges are shown. HDV bars show NO_x emissions of the vehicle only. Well to wheel is the sum of the well to refuelling nozzle and HDV values. No methanol HDV data are available.

In general it can be concluded that well to wheel NO_x emission levels of diesel are relatively high. Vehicular emissions are the main source of these high levels. That is why research on deNOx catalysts is currently being undertaken. All other fuels under consideration here show the potential to roughly halve well to wheel NO_x emission levels compared to diesel, when appropriate vehicle technology is applied. The advantage for DME LDVs can even be larger.

4.4

Emissions of particulate matter

There are two reasons to address emissions of particulate matter separately here. One is that emissions of particulate matter (Pm) are undesirable because of their carcinogenic properties. The other reason is that DME engines are promising very low particulate emission levels and these should be compared with other fuels.

For both light and heavy-duty vehicles, upstream particulate emissions of natural gas stand out. Electricity consumed for gas compression in the fuel distribution phase is the main cause for this high level. Gas compression is relatively energy intensive and particulate emissions stem from production of the electricity. Unfortunately, for DME only heavy-duty vehicle data are available, so it is not possible to establish well to wheel figures for DME. For methanol no data on particulate emissions are available.

For light-duty vehicles, well to wheel particulate emissions of diesel vehicles are significantly higher than for the other fuels (see figure 4.7). No large differences exist between the well to wheel particulate emissions for using the other fuels in LDVs.

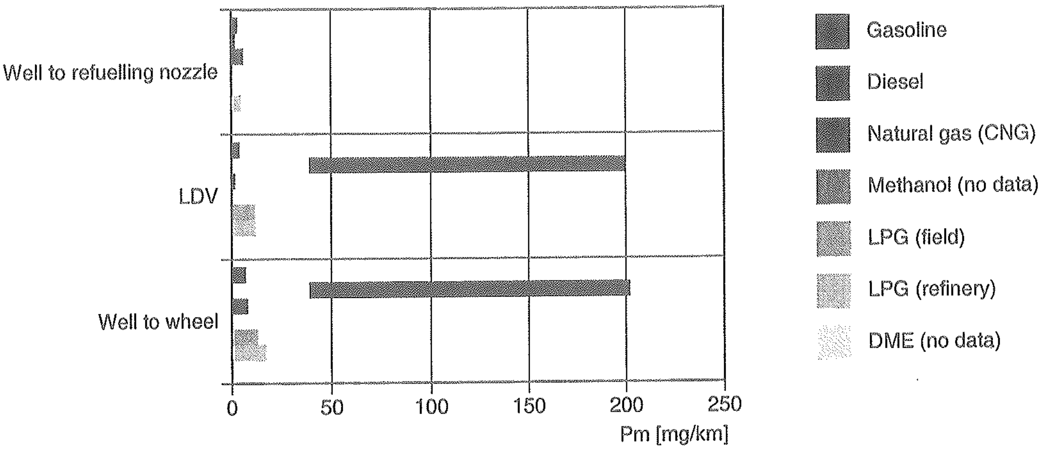

Fig. 4.7 Data ranges for LDV well to wheel Pm emissions. Three ranges are shown. LDV bars show Pm emissions of the vehicle only. Well to wheel is the sum of the well to refuelling nozzle and LDV values. No methanol and DME data are available.

For heavy-duty vehicles, particulate emissions are highest for diesel fuel. However, due to increasingly stringent emission legislation and due to the fact that modern diesel engines are considered, the differences between diesel HDVs and alternatively fuelled HDVs is smaller than for LDVs. Another reason for the smaller difference can be the fact that alternative fuelled HDVs are behind on LDVs, when looking at technological developments. This would mean that particulate emissions of alternatively fuelled HDVs still have potential to be reduced further.

From the limited amount of data available, it can be expected that particulate emissions of DME vehicles will be similar to gaseous fuelled vehicles, which is significantly lower than for diesel vehicles. Because DME is a synthetic fuel, energy consumption of fuel production is higher than for conventional and gaseous fuels. This results in a somewhat higher energy consumption for the upstream stages of the fuel chain, compared to those other fuels (see figures 4.3 and 4.4). Therefore it may be

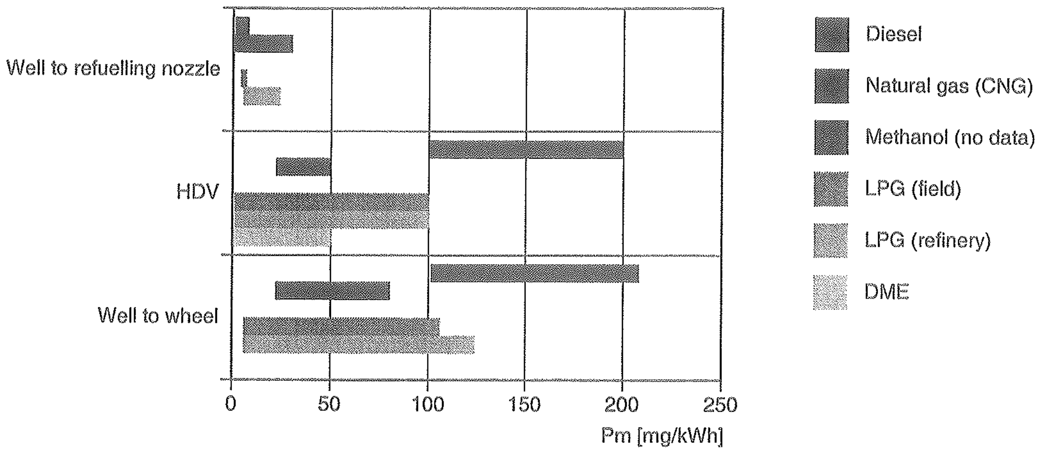

Fig. 4.8 Data ranges for HDV well to wheel Pm emissions. Three ranges are shown. HDV bars show Pm emissions of the vehicle only. Well to wheel is the sum of the well to refuelling nozzle and HDV values. No methanol data are available. DME well to refuelling nozzle data are not available.

expected that particulate emissions for the well to refuelling nozzle stages of the DME fuel chain will be slightly higher than for gasoline, diesel and LPG. It can be concluded that well to wheel particulate emissions of DME may be expected to be significantly lower than for diesel and slightly above the other fuels.

4.5
Global warming potential

A build up of certain gases in the atmosphere may lead to a world-wide climate change with a rising average air temperature. This is called the 'greenhouse effect' or 'global warming'. Although the greenhouse effect is not scientifically proven yet, there are strong indications that it exists and policy makers generally take it as a serious threat. Road transport is one of the important anthropogenic sources of greenhouse gas emissions.

The assumed greenhouse impact of a gas depends on its concentration in the atmosphere, its effectiveness in absorbing heat and its average lifetime. Conversion factors have been established by the Intergovernmental Panel on Climate Change (IPCC) to estimate the global warming potential of a component in comparison to CO_2. As gases have a limited lifetime, their global warming effect diminishes in time. In general the effects for a 100 year time horizon are presented. The global warming potential factors presented in table 4.1 are IPCC values for a 100-year time horizon. The factor 21 for CH_4, for example, means that 1 gram of CH_4 has a greenhouse effect equivalent to 21 grams of CO_2. Although the factors are quoted as single values, the typical uncertainty is still + or -35%. Non-methane hydrocarbons, CO and NO_x emissions are also suspected to contribute to the greenhouse effect and global warming factors for these gases have been published in the past. However, the IPCC concluded that these figures suffered from too many uncertainties so they are not published any longer.

Table 4.1 Global warming potential factors of emission components, on a mass basis. Figures are for a 100 year time horizon. By IPCC, version 1995 [18].

	CO_2	CH_4	N_2O
GWP	1	21	310

The global warming potential of the automotive fuels considered in this report can be calculated by adding the well to wheel CO_2, CH_4 and N_2O emissions of the fuels, using the weighing factors from table 4.1. However, because none of these emission components are legislated yet, data are scarce. Although beginning to receive attention in recent years, particularly vehicular N_2O emissions are almost non-existent. It is not possible to calculate the global warming potential using all three emission components. In spite of its high weighing factor, a sensitivity analysis with estimated vehicular N_2O emissions shows that the influence on the total global warming potential of this emission component is small. It does not affect the ratio between the different fuels significantly. The sensitivity analysis is shown in annex D. So here the global warming potential of the fuels is presented on the basis of CO_2 and CH_4 emissions only. This shows a representative picture of how the different fuels compare to each other concerning their global warming potential. Figure 4.9 shows this comparison for light-duty vehicles. Because the CO_2 and CH_4 emissions for LDV fuel chains are expressed in grams per vehicle kilometre, the global warming potential is also expressed in g/km. CO_2 emissions for DME light-duty vehicles have been calculated (see annex D).

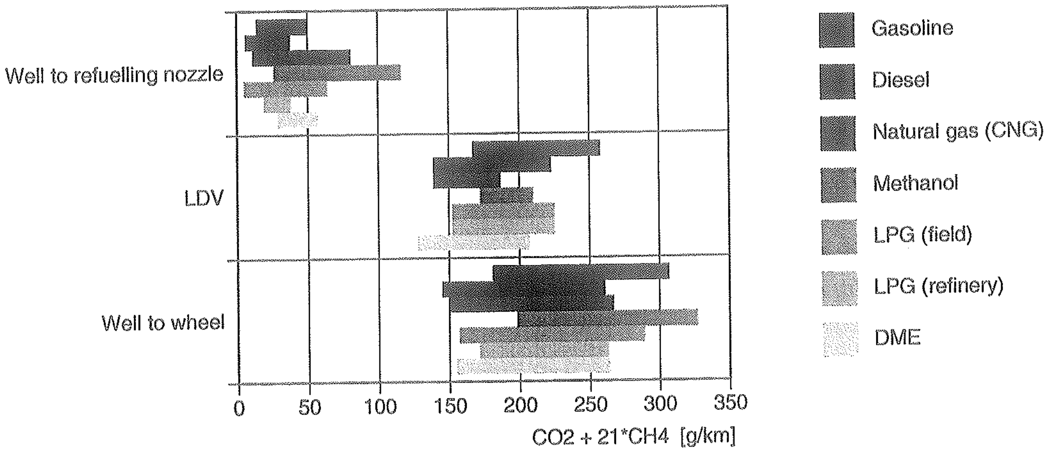

Fig. 4.9 Comparison of global warming potential, based on CO_2 and CH_4 emissions.

From figure 4.9 it can be concluded that on a well to wheel basis, the global warming potential of the different fuels does not differ substantially. The maximum difference between fuels is in the same order of magnitude as the data range per fuel. Gasoline and methanol produced from natural gas tend to have a higher global warming potential than the other fuels. DME does not stand out. It is in the same range as diesel, natural gas and LPG. These conclusions are very similar to what Fleisch and Meurer presented in 1995 [19].

When exploiting remote natural gas reserves is the motive for using methanol and DME as automotive fuels, the upstream global warming potential of these fuels will show more similarity than is shown in figure 4.9, because the fuel will be produced at the natural gas recovery site and the fuel production processes are very similar. The small data range that is shown in figure 4.9 for the upstream DME global warming potential is mainly caused by the limited number of data points that are available.

For heavy-duty vehicles there are not enough data available to paint a separate picture for the global warming potential. However, from the HDV data that are available, it can be concluded that the trend is expected to be similar to the LDV picture.

4.6
Other environmental effects

In this section acidification, smog, ozone forming potential, toxicity and discharges to water are addressed qualitatively. Those environmental effects were not addressed by the project team mentioned in section 1.2, so the information that is presented here stems predominantly from literature that is available in the public domain. This literature concentrates on vehicular emissions. Information on the first part of the fuel chain -from feedstock until refuelling nozzle- is mostly estimated here.

acidification

Acidification is a term for 'acid rain', which has a negative effect on the growth of plants and which harms buildings. SO_2 (sulphur dioxide) and NO_x emissions are the most important contributors to acidification.

In chapter 3 can be seen that information on SO_2 emissions is scarce. In well to wheel fuel chains, vehicle emissions form the largest share in the total emissions. This also holds for SO_2. All vehicular SO_2 emissions stem from combustion of sulphur in the fuel. Except for gasoline and diesel, all fuels addressed in this report can be considered to be sulphur free. Feedstocks for these other fuels may contain traces of sulphur, but this sulphur is removed during fuel production. Besides, sulphur has to be removed from natural gas when it is used as a feedstock for synthetic fuels, to avoid poisoning of the synthesis catalyst. So only gasoline and diesel vehicles emit significant amounts of SO_2. However, gasoline and diesel sulphur levels have been reduced in recent years and will be reduced further in the near future. Table 4.2 presents future maximum sulphur levels that have been agreed upon in Europe as an example.

Table 4.2 Maximum sulphur levels in European gasoline and diesel [20].

from year onwards	2000	2005
Gasoline	150 ppm	50 ppm
Diesel	350 ppm	50 ppm

SO_2 emissions in the well to wheel fuel chain before vehicle use are strongly dependant on the energy carriers used in those stages. Low grade, high sulphur fuel oil used in sea going vessels or in refineries for example results in more SO_2 emissions than when low sulphur fuels are used. Because of environmental concerns, sulphur levels tend to decrease in all fuels.

Concerning SO_2 it can be concluded that the diesel fuel chain shows the highest emission levels. Gasoline is next. The SO_2 emissions of the other fuels can be neglected. The vehicle is the major source of SO_2 emissions in the well to wheel fuel chain. Because sulphur levels in gasoline and diesel are required to decline in the near future, SO_2 emission levels of these fuels will lower proportionally.

Well to wheel NO_x emissions are addressed extensively in section 4.3. When the results of that section are combined with the information on SO_2, it can be concluded that diesel use gives the highest acidifying emissions. When appropriate technology is used, acidification from the use of the other fuels is far less. The differences among the other fuels then is relatively small. The development of deNOx catalysts for diesel vehicles and the reduction of sulphur content in gasoline and diesel fuel will reduce the gap between diesel and the other fuels in the future.

smog

For the smog forming potential two different types must be distinguished: summer smog and winter smog. The reactivity of the emission components are determinant for the summer smog potential. Winter smog is caused by particulates and SO_2 emissions.

TNO has determined the summer smog potential of two gaseous and two liquid fuels [21]. It was concluded that the summer smog potential in ascending order is CNG, LPG, gasoline and diesel. Here it is estimated that synthetic diesel is expected to be in between conventional diesel and gasoline. The reactivity of exhaust gases of methanol is lower than those of gasoline and diesel (see also the subsection on ozone forming potential below). The summer smog potential of methanol is expected to be similar to the gaseous fuels. It is estimated here as a first indication that the summer smog potential for DME will be similar to the gaseous fuels as well.

Because winter smog potential is based on particulate and SO_2 emissions, it can be concluded that diesel stands out in a negative sense. Because synthetic diesel is sulphur free, the winter smog potential of synthetic diesel is lower than for conventional diesel but because of the particulate emissions it is higher than for the other fuels. The other fuels, including DME, will show a similar winter smog potential, significantly lower than the diesel fuels.

ozone forming potential

Tropospheric (the first 10 kilometres of the atmosphere above the earth's surface) ozone is harmful to humans and plant life. The presence of volatile organic compounds (VOC) and NO_x emissions in the atmosphere plays an important role in the ozone forming process.

In volume 3 of the Automotive Fuels Survey it is quoted that the reactivity of exhaust gases of LPG, natural gas and alcohols is much (40-60%) lower than those of gasoline and diesel [22]. This trend is confirmed by the Oak Ridge National Laboratory report and addendum for IEA's Alternative Motor Fuels Agreement [23]. The latter indicates that natural gas show the lowest ozone forming potential of those fuels. Depending on VOC emission composition, synthetic diesel may have a somewhat lower ozone forming potential than conventional diesel. The ozone forming potential of DME may be expected to be in the same order of magnitude as the other fuels, below the gasoline and diesel levels. The Oak Ridge report states that applying an exhaust catalyst at the vehicle has a much larger ozone reducing effect than fuel choice.

toxicity

Toxicity of emission components can be split in direct toxic effects and long term toxic effects. Direct toxic are CO (supplants oxygen in the blood), N_2O (nuisance), particulates (carcinogenic) and lower aldehydes (nuisance). Lower aldehydes are for example formaldehyde, acetaldehyde and acrolein. Long term toxic effects are caused by certain poly-nuclear aromatic hydrocarbons (PAH) species, lower aromatics like benzene, toluene and xylene (BTX) and the lower aldehydes [21]. Because of the large number of emission components that play a role, it can be concluded that toxicity is a complicated issue. That is why only some general trends can be presented here.

- From TNO's comparison of gasoline, diesel, LPG and CNG on direct toxic and nuisance effects it was observed that [21]:
  - Gasoline is high in CO.
  - Diesel is high in NO_2, particulates and lower aldehydes.
  - LPG scores best on particulates.
  - CNG scores best on CO, NO_x and lower aldehydes.
- A comparison of gasoline, diesel, LPG and CNG on long term toxic effects resulted in [21]:
  - Gasoline shows the highest BTX emissions.
  - Diesel is high in PAH and lower aldehydes.
  - Gaseous fuels score consistently low.

- Methanol scores high in aldehyde emissions, because during the combustion of alcohols aldehydes are formed [2].
- From the molecule structure of DME it can be concluded that it is probable that some formaldehyde is formed during its combustion. First measurements show that aldehyde emission levels are much lower than hydrocarbon emissions [3]. This means that aldehyde emission from DME will be much lower than for methanol.
- Aldehyde emissions from diesel engines can be reduced by using an oxidation catalyst [22].
- Because a DME molecule contains only two carbon atoms, it may be expected that emissions of PAH, benzene, toluene and xylene from DME combustion are negligible [3]. This effect has already been shown for other fuels with small molecules. The emissions of aromatics and PAH from LPG, natural gas and methanol can be neglected [22].
- HC emissions from DME engines are predominantly DME molecules, which are considered to be harmless.

discharges to water

This subsection briefly addresses water pollution from well to wheel fuel chains, in order of the stages of the fuel chain.

Crude oil is often accompanied by water when it surfaces at the well. The water can be naturally present or it can have been injected to enhance oil production. The water is separated from the oil and cleaned before it is discharged to surface water. An example of a limit value for oil concentration in discharge water is 40 milligrams per litre [24]. For off-shore oil production there is always a certain risk of sea water pollution from oil spills. Natural gas production has a lower risk of water contamination than crude oil production.

Water pollution from feedstock transport by ship will not differ significantly from shipping of other goods. Only in case of accidents with crude oil tankers, locally high pollution levels will occur. Sabotage of feedstock pipelines results in water pollution when crude oil reaches the (ground) water. Sabotage of gas pipelines will not go with water pollution.

Small quantities of oil are discharged with cooling water from crude oil refineries. Shell mentions a typical value of 12 grams of oil per tonne of feedstock [24]. Fuel synthesis from natural gas may result in water pollution from cooling water as well. However, the amount cannot be quantified here.

Water pollution from fuel distribution and use will only occur in case of accidents. For normal operation, the effect of fuel spills can be minimised by leak tight flooring and other measures.

In general it can be stated that discharges to water can be minimal for all fuels, when appropriate measures are taken. Significant water pollution will than only occur from casualties.

conclusions

In general it can be observed that the environmental burden of gaseous fuels and DME, regarding acidification, smog, ozone forming potential, toxicity and discharges to water tends to be lower than for gasoline and diesel. Also methanol scores better than the conventional fuels.

Vehicle emissions are the main contributor to the well to wheel emissions discussed in this section. Vehicle technology has a larger impact on vehicular emissions than fuel choice.

4.7
Epilogue

In this chapter automotive fuel options have been compared on energy consumption, emissions and environmental effects. These issues are usually the main motives to consider other fuels than gasoline and diesel. However, it hardly matters how good alternative fuels score on these issues, if on other aspects insurmountable barriers exist, the alternative fuel will not be used on a large scale in the automotive market. Examples of such aspects are costs -both investment costs and operating costs-, safety, storage volume and vehicle range. Concerning DME, for example sealing, lubrication and wear problems have to be solved before reliable application in vehicle fuel systems is possible. For a final decision on fuel choice, these aspects should be taken into account as well; energy consumption and emissions should not be isolated to build the picture.

In general it can be concluded that none of the automotive fuels considered in this report is the ultimate solution to all energy and environmental problems of road traffic. Even if renewable fuels would be included, there would be no ultimate solution. Each fuel has its own advantages and disadvantages, so in each individual case of fuel choice, it must be analysed what is the best suitable fuel for that specific application. So before a fuel choice is made, it must be clear what the important issues are. On environmental issues this can be for example improving local air quality or reducing the greenhouse effect. Just one example of another aspect that may be relevant is reducing oil dependency. In practice, different aspects will play a role simultaneously. Weighing these aspects will lead to the optimum fuel for each specific application. This report can help on energy consumption and emission issues. Both within and outside the IEA, reports on other issues are available.

References

[1] N. Elam. *Automotive Fuels Survey: Raw materials and conversion.* vol. 1. IEA/AFIS, Göteborg, Sweden, 1996.

[2] M. van Walwijk; M. Bückmann; W.P. Troelstra; P.A.J. Achten. *Automotive Fuels Survey: Distribution and use.* vol. 2. IEA/AFIS, Breda, the Netherlands, 1996.

[3] R.P. Verbeek; A.v. Doorn; M.v. Walwijk. *Global assessment of Dimethyl-ether as an automotive fuel.* TNO Wegtransport, Delft, the Netherlands, 1996.

[4] A. Johansson; A. Brandberg; A. Roth. *The life of fuels. Motor fuels from source to end use.* Ecotraffic AB, Stockholm, Sweden, 1992.

[5] M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity.* Centre for transportation, Energy systems div., Argonne, USA, 1991.

[6] S.P. Ho; T.A. Renner. *The global warming impact of attainment strategies using alternative fuels.* Presented at 'Air and waste management conference on tropospheric ozone and environment', Los Angeles, USA, 19-22 March 1990.

[7] Lecture given at the KIVI office by T. van Herwijnen, KIVI, The Hague, the Netherlands, 2 October 1997.

[8] A.C. Vosloo; L.P. Dancuart; B. Jager. *Environmental aspects of Sasol Fischer-Tropsch technologies and products.* Presented at '11th World clean air and environment congress', Durbin, South Africa, 13-18 September 1998.

[9] P.W. Schaberg; I.S. Myburgh; J.J. Botha; P.N. Roets; C.L. Viljoen; L.P. Dancuart; M.E. Starr. *Diesel exhaust emissions using Sasol slurry phase distillate process fuels.* SAE-paper 972898, SAE, Warrendale, USA, 1997.

[10] D.A. Montalvo. *Engine evaluation of Fischer-Tropsch diesel fuel, phase I.* Southwest Research Institute, reportno. SwRI-03-7502, San Antonio / Houston / Detroit / Washington DC, USA, 1995.

[11] J. Martin Marriott. *SMDS fuels.* Presentation at Shell, Amsterdam, the Netherlands, 1997.

[12] B. Sporckmann. *Comparison of emissions from combustion-engined and "European" Electric Vehicles.* Presented at 'EVS 12', Anaheim, California, USA, 5 - 7 December 1994.

[13] W.E. Liss; S. Okazaki; G.H. Acker; D.S. Moulton. *Fuel Issues for Liquefied Natural Gas Vehicles.* SAE paper 922360, SAE, Warrendale, USA, 1992.

[14] Anon. *Vloeibaar aardgas.* Shell Nederland BV, Rotterdam, the Netherlands, December 1992.

[15] Anon. *Economic comparisons of LNG, methanol and synthetic distillate.* Jensen Associates Inc., Boston, USA, 1991.

[16] P.E. Kapus; W.P. Cartellieri. *ULEV Potential of a DI/TCI Diesel Passenger Car Engine Operated on Dimethyl Ether.* SAE-paper 952754, SAE, Warrendale, USA, 1995.

[17] T. Fleisch; C. McCarthy; A. Basu; C. Udovich; P. Charbonneau; W. Slodowske; S.-E. Mikkelsen; J. McCandless. *A new Clean Diesel technology: Demonstration of ULEV Emissions on a Navistar Diesel Engine Fueled with Dimethyl Ether.* SAE-paper 950061, SAE, Warrendale, USA, 1995.

[18] *Website greenhousegas emissions.* www.globalchange.org/sciall/96jul1d.htm,11 November 1997, 1997.

[19] T.H. Fleisch; P.C. Meurer. *DME - The diesel fuel for the 21st Century?* Presented at 'Engine and environment - Visions for fuel consumption and emissions', Graz, Austria, 24 & 25 August 1995.

[20] N.-O. Nylund. *The EU auto-oil II programme.* Presented at 'Clean energy vehicle forum', Japan, 21 October 1998.

[21] R.C. Rijkeboer; P. Hendriksen; B. Hollemans; J.v.d. Weide. *Potential impact of four different car fuels on the Dutch environment.* SAE paper 941914, SAE International, Warrendale, USA, 1994.

[22] M. van Walwijk; M. Bückmann; W.P. Troelstra; N. Elam. *Automotive fuels survey: Comparison and selection.* vol. 3. IEA/AFIS, Breda, The Netherlands, 1998.

[23] R. McGill (Ed.), *Comparison of relative environmental impacts of alternative and conventional motor fuels.* International Energy Agency / IEA-AMF, Paris, France, 1995.

[24] Anon. *Health, safety and environment report 1997.* Royal Dutch/Shell group of companies, The Hague, the Netherlands, 1997.

Abbreviations

AMF	Advanced Motor Fuels
BTX	Benzene, Toluene and Xylene
cg	Centigram (1 cg = 0.01 gram)
CH_4	Methane
cMJ	Centi Megajoule (1 cMJ = 0.01 MJ)
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DME	Dimethyl Ether
FFV	Flexible Fuelled Vehicle
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (autogas)
M85	Blend of 85% methanol and 15% gasoline
M100	Pure methanol
MJ	Megajoule (1 MJ = 10^6 J)
N_2O	Nitrous oxide
NMHC	Non Methane Hydrocarbons
NMOC	Non Methane Organic Compounds
NO_x	Nitrogen oxides
PAH	Poly-nuclear Aromatic Hydrocarbons
SAE	Society of Automotive Engineers
SMDS	Shell Middle Distillate Synthesis
SO_2	Sulphur dioxide
SSPD	Sasol Slurry Phase Distillation
syngas	Synthesis gas, a mixture of hydrogen, CO and CO_2
vol%	Percentage by volume
wt%	Percentage by weight

Annex A
Vehicular energy consumption

Light-duty vehicles

Data on energy consumption of light-duty vehicles for this project have been supplied by Renault, TNO and Volvo. These figures have been measured using the European EU 15 + EUDC driving cycle. Additionally, LDV energy consumption data from literature have been used. Some of the data from literature have been obtained using the North American FTP driving cycle. By only using data that are available for a reference gasoline vehicle and an alternatively fuelled vehicle, LDV energy consumption can be made relative to a gasoline vehicle. The driving cycle used is than less important. It enables to use more of the available data which helps in building a sound picture of LDV energy consumption. The results are presented in table A.3 on the next page.

From the results in table A.3, ranges can be established for the energy consumption of alternatively fuelled LDVs compared to gasoline LDV. The ranges used in this report are presented in table A.1. For DME, the same range as for diesel LDVs is used.

Table A.1 Relative energy consumption of light-duty vehicles (LDVs).

	Gasoline	Diesel	CNG	LPG	Methanol	DME
LDV	100%	75-90%	80-110%	90-110%	85-105%	75-90%

Because emission figures for other stages in the well to wheel fuel chain are expressed per MJ fuel used, vehicular energy consumption in megajoules per kilometre (MJ/km) is required. In this report, the gasoline LDV energy consumption used is 2.2 MJ/km. This value is considered to be representative for a 1000 kg vehicle with a gasoline consumption of approximately 1 litre per 14 kilometres. Using this gasoline LDV energy consumption figure and the ranges from table A.1 results in energy consumption ranges for alternatively fuelled LDVs. These results are shown in table A.2.

Table A.2 Energy consumption of light-duty vehicles [MJ/km].

[MJ/km]	Gasoline	Diesel	CNG	LPG	Methanol	DME
LDV	2.2	1.65-1.98	1.76-2.42	1.98-2.42	1.87-2.31	1.65-1.98

Table A.3 Energy consumption of LDVs using different fuels, relative to gasoline. Shaded areas are only to avoid misreading.

	Gasoline	**Diesel**	**CNG**	**LPG**	**Methanol**	**DME**
Volvo	100%	76%				
Renault	100%	107%				
TNO						
BMW 3	100%	99%		105%		
Mazda 626	100%	110%		103%		
Honda Civic	100%			99%		
Lancia Thema	100%			102%		
Opel Vectra	100%		120%	109%		
Volvo 850	100%			108%		
Literature:						
AFS vol.2						
CBS	100%			96%		
Gastec	100%		84%	99%		
Switzerland	100%		80-90%			
USA 1993	100%		85%			
USA 1995	100%		82-87%			
Citroen BX	100%		83-92%			
Volvo	100%				86.5% (M85)	
BMW	100%				92% (M85)	
Audi 100 FTP		(100%)				(104%)
ETSU	100%	78%	100%	100%	85%	
Ecotraffic	100%		91%	91%	90%	
DeLuchi	100%		91%	91%	87%	
TNO glob ass	100%	84%	111%	105%	105%	84%

AFS vol.2: M. van Walwijk; M. Bückmann; W.P. Troelstra; P.A.J. Achten. *Automotive Fuels Survey: Distribution and use. vol. 2.* IEA/AFIS, Breda, the Netherlands, 1996.

ETSU: M.P. Gover; S.A. Collings; G.S. Hitchcock; D.P. Moon; G.T. Wilkins. *Alternative road transport fuels - A preliminary life-cycle study for the UK.* ETSU, Harwell, United Kingdom, 1996.

Ecotraffic: A. Johansson; A. Brandberg; A. Roth. *The life of fuels. Motor fuels from source to end use.* Ecotraffic AB, Stockholm, Sweden, 1992.

DeLuchi: M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity.* Centre for transportation, Energy systems div., Argonne, USA, 1991.

TNO glob ass: R.P. Verbeek; A.v. Doorn; M.v. Walwijk. *Global assessment of Dimethyl-ether as an automotive fuel.* TNO Wegtransport, Delft, the Netherlands, 1996.

Heavy-duty vehicles

Data on energy consumption of heavy-duty vehicles for this project have been supplied by Renault and Volvo. These figures have been measured using the European 13 mode ECE R49 cycle. Additionally, HDV energy consumption data from literature have been used. Some of the data from literature stem from other cycles than the European test cycle. By only using data that are available for a reference diesel vehicle and an alternative fuelled vehicle, HDV energy consumption can be made relative to a diesel vehicle. The driving cycle used is than less important. It enables to use more of the available data which helps in building a sound picture of HDV energy consumption. The results are presented in table A.6 on the next page.

From the results in table A.6, ranges can be established for the energy consumption of alternatively fuelled HDVs compared to diesel HDVs. The ranges used in this report are presented in table A.4. For DME, the same value as for diesel HDVs is used. Additional vehicle energy consumption due to extra vehicle weight, for example the extra weight of high pressure CNG tanks, is included in these figures.

Table A.4 Relative energy consumption of heavy-duty vehicles (HDVs).

	Diesel	CNG	LPG	Methanol	DME
HDV	100%	105-140%	110-130%	100-110%	100%

Because emission figures for other stages in the well to wheel fuel chain are expressed per MJ fuel used, vehicular energy consumption in megajoules per kiloWatt hour (MJ/kWh) is required. In this report, the diesel HDV energy consumption used is 9 MJ/kWh. This value is considered to be representative for a 10 litre engine. Using this diesel HDV energy consumption figure and the ranges from table A.4 results in energy consumption ranges for alternatively fuelled HDVs. These results are shown in table A.5.

Table A.5 Energy consumption of heavy-duty vehicles [MJ/kWh].

[MJ/kWh]	Diesel	CNG	LPG	Methanol	DME
HDV	9	9.45-12.6	9.9-11.7	9-9.9	9

Table A.6 Energy consumption of HDVs using different fuels, relative to diesel. Shaded areas are only to avoid misreading.

	Diesel	CNG	LPG	Methanol	DME
Volvo	100%	127%	136%	105%	
Renault	100%	137%			
Literature:					
AFS vol.2					
GVB	100%		109%		
TNO NL '92	100%	124%			
Gastec	100%	111%			
B.bus '95	100%	140%			
Japan '95	100%	115%			
NY bus	100%			113%	
Miami bus	100%			97%	
Ontario bus	100%			103%	
2 trucks	100%			105%	
ETSU (new bus)	100%	106%	110%	100%	
ETSU (new bus)	100%	120%			
Ecotraffic	100%	111%	110%	100%	
DeLuchi	100%	118%	118%	103%	
TNO glob ass	100%	113-123%	109-120%	101-118%	101%

AFS vol.2: M. van Walwijk; M. Bückmann; W.P. Troelstra; P.A.J. Achten. *Automotive Fuels Survey: Distribution and use. vol. 2.* IEA/AFIS, Breda, the Netherlands, 1996.

ETSU: M.P. Gover; S.A. Collings; G.S. Hitchcock; D.P. Moon; G.T. Wilkins. *Alternative road transport fuels - A preliminary life-cycle study for the UK.* ETSU, Harwell, United Kingdom, 1996.

Ecotraffic: A. Johansson; A. Brandberg; A. Roth. *The life of fuels. Motor fuels from source to end use.* Ecotraffic AB, Stockholm, Sweden, 1992.

DeLuchi: M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity.* Centre for transportation, Energy systems div., Argonne, USA, 1991.

TNO glob ass: R.P. Verbeek; A.v. Doorn; M.v. Walwijk. *Global assessment of Dimethyl-ether as an automotive fuel.* TNO Wegtransport, Delft, the Netherlands, 1996.

Annex B
Calculation of energy consumption and emissions

In this annex, the calculation method of the well to wheel energy consumption and emissions is described. This method is used for each fuel, so the results for the different fuels can be compared directly.

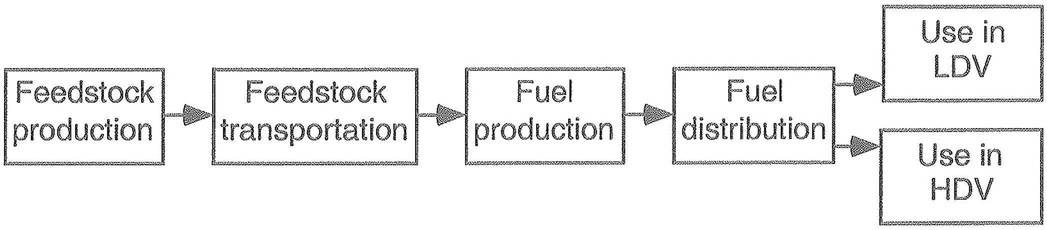

Fig. B.1 Well to wheel fuel chain.

Figure B.1 shows the five stages of the well to wheel fuel chain: feedstock production, feedstock transportation, fuel production, fuel distribution and vehicle use. Both light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) are addressed in this report.

Because the well to wheel fuel chain from feedstock until refuelling nozzle is the same for LDVs and HDVs, the total fuel chain is first divided in two sections:

1. the first four stages,
2. vehicle use.

Energy consumption and emissions for the first four stages of the well to wheel fuel chain are calculated on the basis of energy content of the fuel that is available at the refuelling nozzle (per MJ fuel available). Total well to wheel energy consumption and emissions can than be obtained by multiplying the figures of the first four stages by the energy consumption of the vehicle and adding the vehicular energy consumption and emissions. In this annex the first section is on the first four stages of the fuel chain. The next section is on vehicle use and this annex is concluded with a section on total well to wheel energy consumption and emissions.

B.1
The first four stages of the fuel chain

In this section energy consumption is addressed first. Emissions are next.

Data per stage of the fuel chain from literature are usually supplied per unit of energy available in the fuel at the refuelling station. However, because the companies that co-operated in this project each have their own field of expertise, data on energy consumption and emission were supplied per stage of the fuel chain (see fig. B.2). Each company supplied information on one ore more stages of the fuel chain on the basis of 1 MJ product output of that stage.

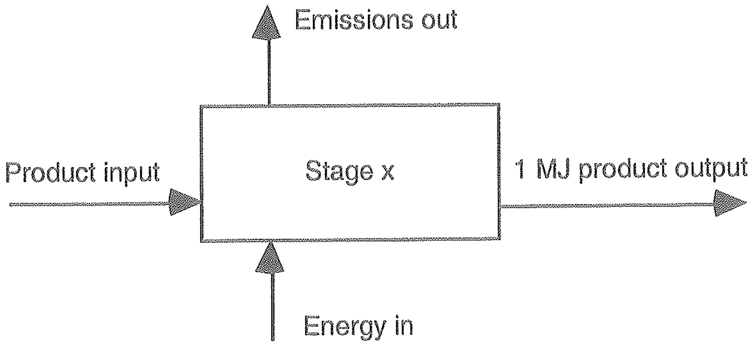

Fig. B.2 Feedstock production as an example of one stage of the well to wheel fuel chain.

For the complete well to wheel fuel chain, the information of the different companies was combined. To obtain the complete fuel chain, the product input of each stage was tied to the product output of the previous stage.

B.1.1
Energy consumption

When the input of a stage is a factor larger than 1 MJ product equivalent, the throughput and also the energy consumption and emissions of the previous stage must be multiplied by this factor.

The product input of one stage can be larger than the output because of evaporative losses or because it is used to fuel the processes of that stage. So the energy input of a stage may be supplied by the product input, it may be supplied by other energy carriers like electricity, or it can be a mix of product input and other energy carriers. For the data supplied by the companies in this project, energy consumption of most fuel chain stages is predominantly by combustion of hydrocarbons, so using the product input as the energy carrier is considered an adequate approximation. However, two exceptions should be noted:

- Data on crude oil (feedstock for gasoline, diesel and refinery LPG) transportation in North America are for pipelines. Energy consumption is electricity to drive the pumps. In North America, electricity is predominantly produced from fossil fuels so assuming that the feed is used as energy carrier for feedstock transportation is a reasonable approximation. The error caused by this assumption in the total well to wheel figures is far below the accuracy of the total fuel chain figures.
- Energy consumption of CNG distribution is predominantly electricity for the pumps that are used to obtain the high gas pressure. This energy is not considered to be taken from the gas feed of the distribution stage.

Using this working method gives the result as shown in figure B.3. For example energy consumption of fuel distribution is d, than the input of the distribution step is 1+d, to have 1 MJ fuel delivered. So the output of the previous stage (fuel production), must be 1+d as well. When the energy consumption of fuel production per MJ fuel is f, than the input of the fuel production step is (1+f)(1+d). This working method is used backwards in the fuel chain until feedstock production.

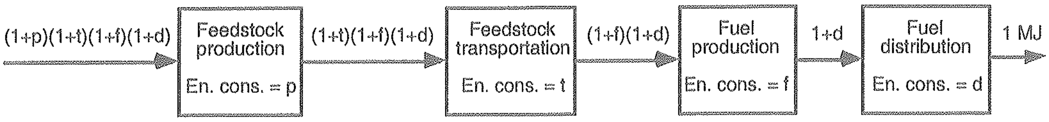

Fig. B.3 Energy consumption calculation method for the first four steps of the total well to wheel fuel chain.
En. cons. = Energy consumption per MJ output of that stage

Looking at the energy consumption (E_i) of each stage (i) in the total well to wheel fuel chain results in:

Fuel distribution $E_d = d$
Fuel production $E_f = f(1+d)$
Feedstock transportation $E_t = t(1+f)(1+d)$
Feedstock production $E_p = p(1+t)(1+f)(1+d)$

The total energy consumption for 1 MJ fuel (E_4) of the first four stages becomes:

$$\begin{aligned} E_4 &= E_d + E_f + E_t + E_p = \\ &= d + f(1+d) + t(1+f)(1+d) + p(1+t)(1+f)(1+d) = \\ &= (1+p)(1+t)(1+f)(1+d) - 1 \end{aligned}$$

Energy consumption data from literature are for each stage of the fuel chain supplied per MJ fuel available at the refuelling nozzle. This data can be used directly and does not have to be converted. The total energy consumption of the first four stages of the fuel chain can be obtained by just adding up those figures.

B.1.2
Emissions

The emissions of the first four stages of the fuel chain are available per MJ product output of each stage. So the total emissions per stage in the total fuel chain can be obtained by multiplying the emission figure per MJ with the energy content of the output of each stage, using the results of the previous subsection on energy consumption. This is shown in figure B.4. This figure holds for each emission component.

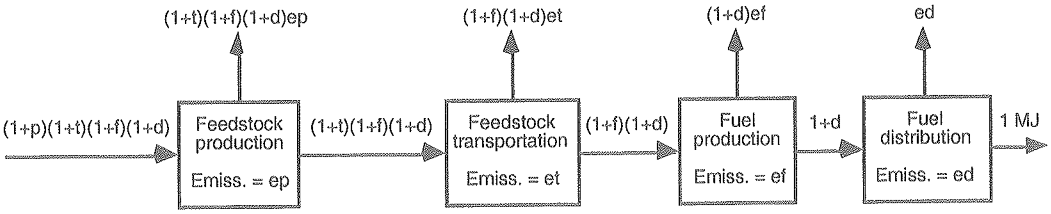

Fig. B.4 Emissions calculation method for the first four steps of the well to wheel fuel chain, using energy consumption.
Emiss. = Emissions per MJ output of that stage

From figure B.4 can be read that the total emissions (Em_i) per stage in the well to wheel fuel chain are the following (ei are the emissions of stage i per MJ output of that stage):

Fuel distribution $Em_d = ed$
Fuel production $Em_f = ef(1+d)$
Feedstock transportation $Em_t = et(1+f)(1+d)$
Feedstock production $Em_p = ep(1+t)(1+f)(1+d)$

The total emissions 1 MJ fuel (Em_4) of the first four stages become for each emission component:

$$Em_4 = Em_d + Em_f + Em_t + Em_p =$$

$$= ed + ef(1+d) + et(1+f)(1+d) + ep(1+t)(1+f)(1+d)$$

For emission data calculations on the first four steps of the well to wheel fuel chains, one exception has been made:

- Distribution of natural gas is dominated by the gas compression. Compression takes place with electric driven pumps. The European electricity mix is used to determine the emissions of this electricity production. As stated in subsection B.1.1, d (in figure B.4) is assumed to be zero, but energy consumption figures for this stage as supplied by the participants in this project have been used instead.

Emissions data from literature are for each stage of the fuel chain supplied per MJ fuel available at the refuelling nozzle. This data can be used directly and does not have to be converted. The total emissions of the first four stages of the fuel chain can be obtained by just adding up those figures.

B.2
Use in vehicles

For a fair comparison of well to wheel fuel chains for different fuels, comparable vehicles must be used. For energy consumption it is necessary to compare vehicles of the same size, because size and consequently vehicle weight have a large impact on vehicular energy consumption. Therefore, using the data that have been supplied by the companies co-operating in this project, for light-duty vehicles a gasoline reference vehicle has been defined. Energy consumption of light-duty vehicles running on other fuels is given relative to this reference vehicle. A similar procedure has been used for heavy-duty vehicles, but diesel is the reference fuel here. Gasoline heavy-duty vehicles are not addressed here. More detailed information on vehicular energy consumption can be found in annex A.

Vehicular energy consumption data from literature for alternatively fuelled vehicles have only been used if energy consumption of the reference vehicle was also available.

Vehicle emission figures have been used as they are supplied, both by the companies co-operating in this project and from literature. It is not necessary to make these figures relative to a reference vehicle, because all vehicles in one category (light-duty or heavy-duty) have to meet the same emission standards without distinguishing different vehicle sizes.

B.3
Well to wheel energy consumption and emissions

To obtain the total well to wheel energy consumption of a fuel, the energy consumption of the first four stages of the fuel chain for 1 MJ fuel (E_4) is multiplied by the energy consumption of the vehicle. This figure is added to the vehicular energy consumption, which than gives the total well to wheel energy consumption.

Well to wheel emission calculation is slightly different. Total emissions of the first four stages of the fuel chain for 1 MJ fuel (Em_4) are multiplied by the energy consumption of the vehicle. This figure is added to the vehicular emissions, which than gives the total well to wheel emissions. This is done for each emission component.

Well to wheel energy consumption and emission figures are available from a number of literature references and for a number of scenarios supplied by the companies co-operating in this project. From this data, for each stage of the fuel chain a minimum and a maximum value are available for both energy consumption and emissions. To obtain a minimum value for the total fuel chain, the minima for each stage have been added up. For the maximum value of the total fuel chain, a similar procedure has been used. Working in this way results in a range for each well to wheel chain which is considered to cover a large part of the fuel chains that are current practice in the world. Total well to wheel figures are shown in chapter 4: comparison of fuels.

Annex C
Fuel characteristics

Table C.1 Fuel characteristics [2, 9-11].

		Gasoline (EU)	Diesel	Synthetic diesel	Natural gas	LPG	Methanol	DME
Lower calorific value (15 °C)	[MJ/l]	31	35.4 - 36.1	n.d.	31.7[1]	23.4 - 26.7 [2]	15.6	18 - 19 [2]
Research octane number (RON)	[-]	95 - 97	n.a.	n.a.	120	94 - 112	106 - 115	n.d.
Cetane number	[-]	n.a.	42 - 59	70 - 75	n.a.	n.a.	<15	55 - 60

EU.	*Europe*
n.a.	*not applicable*
n.d.	*no data*
1	*MJ/m³ instead of MJ/l*
2	*liquid, 15 °C*

Annex D
Global warming potential

The global warming potential of a fuel can be calculated by adding CO_2, CH_4 and N_2O emissions, using the weighing factors as presented in table D.1. This annex concentrates on the global warming potential of light-duty vehicles (LDVs).

Table D.1 Global warming potential factors of emission components, on a mass basis. Figures are for a 100 year time horizon. By IPCC, version 1995 [18].

	CO_2	CH_4	N_2O
GWP	1	21	310

The formula to calculate the global warming potential thus becomes:

$$GWP = CO_2 + 21*CH_4 + 310*N_2O$$

The emission values are expressed in grams per vehicle kilometre, for all stages of the fuel chain. So the global warming potential is expressed in g/km here as well. For a fair comparison of automotive fuels, the emissions of the total well to wheel fuel chain should be used to calculate the global warming potential. However, vehicular N_2O emissions are hardly available and CO_2 emissions of DME vehicles are not available, so these figures are estimated.

Vehicular CO_2 emissions of DME LDVs are estimated as follows. Because DME vehicles are expected to have the same energy consumption as diesel vehicles, diesel is used as reference fuel. From the chemical composition of a fuel, the CO_2 emissions from combustion of that fuel can be calculated. Used here is:

- The lower combustion value of DME is 28 MJ/kg.
- The lower combustion value of diesel is 42.7 MJ/kg.
- 87% of diesel mass are carbon molecules.
- Energy consumption per vehicle kilometre of DME LDVs equals energy consumption of diesel LDVs.
- For both fuels it is assumed that all carbon in the fuel ends up as CO_2 after combustion. This means that the influence of CO and HC on the carbon balance is neglected.

With these starting points it can be calculated that CO_2 emissions per kilometre of DME vehicles will be 8% below diesel LDVs. The data range for DME LDVs in figure D.1 has been obtained by multiplying the diesel LDV data range by 0.92.

N_2O emissions are produced in vehicle exhaust catalyst due to high temperatures and the presence of nitrogen. The sulphur content of the fuel is important for N_2O production. A higher the sulphur level goes with higher N_2O emissions. Although an exception has been reported, a rule of thumb is that higher NO_x emission levels go with higher N_2O

levels. Using its experience from other projects, IEA/AFIS estimates N_2O emission levels for light-duty vehicles as shown in table D.2. These figures must be considered rough estimates for the European test cycle.

Table D.2 Estimates for N_2O emission levels of LDVs over the European test cycle.

	N_2O emissions [g/km]
Gasoline	25 - 40
Diesel	5 - 40
Natural gas	20
Methanol	20
LPG	20
DME	5 - 20

Using the total emission data ranges that have been obtained in this project, using the global warming potential factors from table D.1 and the N_2O LDV emission estimates from table D.2 results in the global warming potentials as presented in figure D.1. The upper part of this picture, marked 'upstream', shows data ranges for fuel production and distribution until the refuelling nozzle. 'LDV' shows the global warming potential of vehicle emissions. Combining these data ranges by respectively adding the lower boundaries and the upper boundaries results in the total global warming potential of the fuels as presented in the 'well to wheel' section of this figure. From the figure it can be read for example for gasoline that upstream processes result in a global warming potential of 15 - 50 g/km, the vehicle range is 175 - 270 g/km so the well to wheel global warming potential is 190 -320 g/km. Remember that these figures are all estimates.

Because the vehicular N_2O emissions are still speculative, the global warming potential has also been calculated by using a weighing factor of zero for the N_2O emissions. This means that the N_2O emissions of the total fuel chain are neglected. The result is shown in figure D.2.

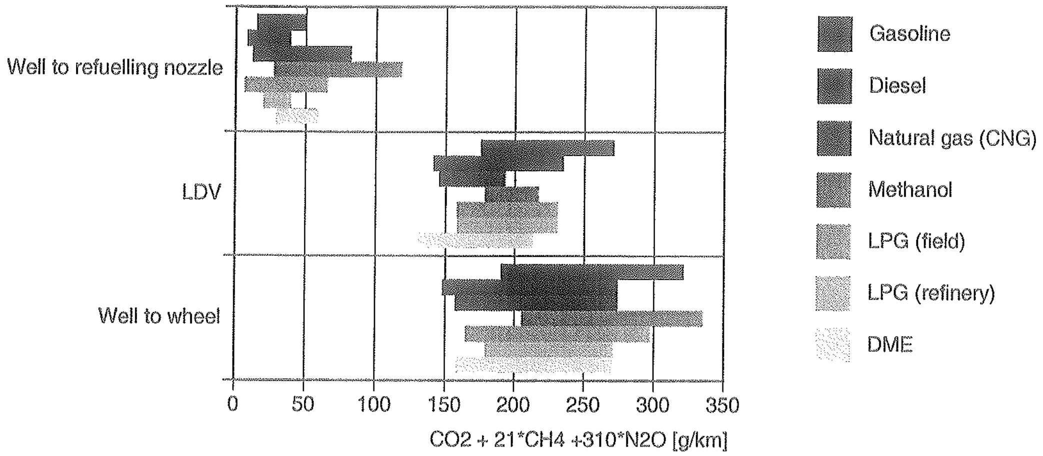

Fig. D.1 Comparison of global warming potential, based on CO_2, CH_4 and N_2O emissions.

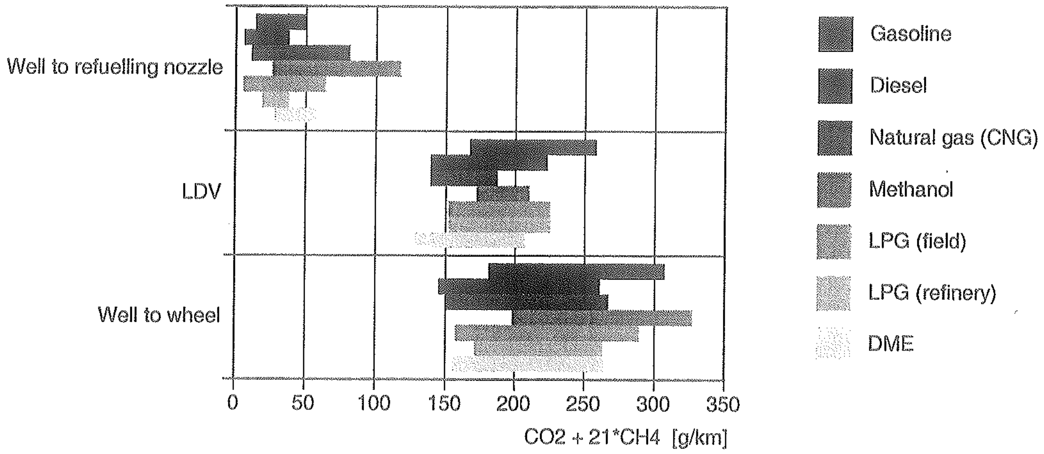

Fig. D.2 Comparison of global warming potential, based on CO_2 and CH_4 emissions.

From a comparison of figures D.1 and D.2 it can be concluded that (although the N_2O weighing factor is high) N_2O emissions only have a small influence on the global warming potential of automotive fuel chains. It also shows that how fuels compare to each other is almost independent from N_2O emissions. This means that a comparison of global warming potential can be done on the basis of CO_2 and CH_4 emissions only. Absolute values between the two methods are slightly different but the trends are the same.