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Global assessment of Dimethyl-ether as an automotive fuel

(second edition)

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Abstract

This report studies the feasibility of Dimethyl-ether (DME) as an automotive fuel. The report is aimed at putting DME in a wide perspective. Subjects included are production of the fuel, emissions, engine design, market introduction, safety and the possible position of DME in the future world-wide energy supply.

DME is a liquid gas with handling characteristics very similar to propane and butane. It is currently used as a very safe and environmental friendly propellant for spray cans, primarily for the cosmetics industry.

Position DME in world-wide energy supply:

DME is intended as a clean alternative automotive fuel. DME can be made from a variety of carbonaceous energy sources. Among these are natural gas, coal, crude oil, oil sands and renewable sources such as wood, straw and crop residues. From a CO₂ emissions point of view, DME can best be made out of biomass or natural gas.

For future energy supply, it will be necessary to start exploring "remote" natural gas sources and transport this over longer distances than economically possible by pipelines. This kind of transport is now already taking place; Japan is for a part of its energy supply relaying on LNG shipments from other countries in South East Asia. DME and also methanol are alternatives to LNG. DME (and methanol) are especially interesting when the energy is needed or desired as a transportation fuel and when it has to be transported over increasingly long distances.

It is also necessary to use more energy from renewable sources and to find an economic way to use associated gas from crude oil production. This gas, with an energy content of about 2.5% of the crude oil production, is now wasted. Conversion into DME can be a way to use this energy.

Exhaust emissions DME:

DME appears to be an excellent fuel for diesel-cycle engines (compression ignition). Companies which have been developing and testing the DME engines reported for both light and medium duty engines exhaust emission levels which fulfil the American ULEV standards. The particulates emission of the DME engine appears to be almost as low as with otto engines.

The reasons why DME is an ideal diesel-cycle fuel are:

- it has a low auto-ignition temperature,
- it is an oxygenated fuel, which reduces particulates (soot) formation,
- it is a gas, which helps establishing a good air-fuel mixture and consequently prevents particulates formation.

The largest advantage is however that it makes NO_x reduction possible through fuel injection "rate-shaping" and EGR (Exhaust Gas Recirculation). These technologies are also being investigated for future (conventional) diesel engines, but are more complex due to the characteristics of diesel fuel.

With rate-shaping of the DME engine a very smooth combustion can be achieved with gradual pressure build up and lower maximum pressures and temperatures. This reduces NO_x and noise. NO_x can be further reduced with EGR (exhaust gas recirculation).

The published exhaust emissions data for DME engines are compared with those of other fuels. For light duty engines the comparison is made with 1993 series production engines fuelled with diesel, gasoline, LPG and CNG (LPG and CNG are retrofit conversions). It turned out that the DME engine can have the same NO_x emission level as the otto engines with 3-way catalyst.

With medium and heavy duty engines the NO_x emission of the DME engine over the European R49 test cycle is in the same range as the lean-burn gas engines.

The CO and HC emissions levels are very low when an oxidation catalyst is used. However, without catalyst they are somewhat higher than the diesel engine.

With respect to non-regulated exhaust emissions components, the following remarks can be made:

- * Because of the simple molecular structure of DME it is expected that no significant emissions of PAH (polycyclic aromatic hydrocarbons) and Benzene, Xylene and Toluene take place (just like LPG, natural gas, methanol and ethanol).
- * Because of the oxygen atom in the DME molecule, there is a risk of emission of lower aldehydes (just like methanol and ethanol).
- * SO_2 emission will be low, because of the absence of sulphur in DME.

Well to wheel comparison:

With respect to energy efficiency and CO_2 emissions, a well to wheel comparison was set up using different fuels.

The energy efficiency with DME is lower than with diesel fuel, because of the relatively high losses (almost 30%) with the production of DME from natural gas. Compared to other fuels there is however compensation because of the high diesel-cycle efficiency.

For light duty vehicles the overall energy efficiency of DME is about the same as with gasoline and CNG, but remarkably better than methanol (16.4% versus 12.5%). With heavy duty vehicles the energy efficiency of gas engines, especially the lean-burn engines, is better than with DME. For urban bus application the numbers are: DME: 19%, CNG lean-burn 22%, LPG lean-burn: 24% and diesel 26.5%.

The CO₂ emissions are primarily dependent on the energy efficiency and the hydrogen to carbon ratio of the feed stock. When the hydrogen content is high a relative large part of the energy comes available with the oxidation of hydrogen, which does not lead to CO₂ emission. Fuels with a high hydrogen content in the feed stock are natural gas, DME and methanol. In the well to wheel comparison we see consequently that DME has a low CO₂ emission. With light duty vehicles DME together with diesel fuel and CNG are the lowest CO₂ emitters. With heavy duty engines DME is still about equal to diesel fuel, but CNG and LNG are 5%-12% lower (urban bus application).

The lowest CO₂ emissions are naturally achieved when the fuel is made out of renewable feed stock. This is possible for DME, methanol and ethanol. In that case the net CO₂ emission drops to 20%-40% of the diesel fuel value.

DME engine concept and market introduction:

A DME engine is characterized by a low pressure fuel injection system and -if well tuned- a smoother combustion process.

This can lead to a lighter and cheaper engine design than the conventional diesel engine. Especially for medium and heavy duty engines this difference is expected to grow, when diesel engines have to comply with lower NO_x limits (in Europe in 2005 60%-70% reduction compared to 1995 value). EGR and SCR-DeNO_x (Selective Catalytic Reduction) are so far the only technologies for the diesel engine to comply with the expected 2005 emissions requirements. For both technologies this will lead to a significant cost increase of the diesel engine.

The strong points of DME, low NO_x and particulates emissions, are most appreciated in urban areas when DME engines replace diesel engines. Vans and city buses have been identified as most suitable vehicle groups for market introduction, because they drive a large proportion of their time in urban areas and they can usually be refuelled from a central filling station.

Barriers against market introduction are:

- a) There is no large scale DME production, which makes demonstration programs and the first phase market introduction very costly.
- b) The emissions legislation is not stringent enough such that alternative fuels are required. This is especially the case for medium and heavy duty engines.

The current emissions legislation for these categories follows the best available technology of diesel engines.

A possible market niche might however be created, when more stringent emission requirements are introduced for certain vehicle categories such as for example the EEV program for cities (Enhanced Emissions Vehicles).

A strong point of DME as an automotive fuel is that the overall performance with respect to environment, operational aspects and economics is good. It does not show the serious disadvantages, that are sometimes seen with other alternative fuels. Examples are the storage and fuel quality variation (CNG, LNG) and the necessity of ignition improver (diesel cycle methanol & ethanol). For light duty vehicles it is a disadvantage that dual fuel operation with DME is much more difficult than with methanol, LPG and CNG.

It is estimated that the DME fuel costs will range between 100% to 135% of the diesel fuel costs (corrected for vehicle efficiency). This is primarily based on the production costs of methanol. Larger scale production of fuel grade DME could lead to a cost reduction of about 10%. Compared to methanol fuelled vehicles, there is a clear advantage in fuel costs. For heavy duty vehicles this is because of the (high) costs of ignition improver. For light duty it is because of the difference between diesel-cycle and otto-cycle efficiency.

With respect to safety, it is determined that DME is in most aspects very similar to LPG:

- The fire and collision safety of DME fuelled vehicles is good. Fuel tanks are very strong and never explode.
- DME is virtually non toxic with respect to direct inhalation.

Recommendation for further research:

In order to be able to make definite decisions for introduction of DME as an automotive fuel, further research is needed.

The following subjects need further assessment:

- * Investigation of barriers for market introduction of DME and alternative fuels in general.
- * Investigation of the technical and economical possibilities to produce DME from associated gas from crude oil.
- * Assessment of DME production from biomass, including a costs analysis and a comparison with methanol and ethanol from biomass.

- * Evaluation of possible DME role with respect to the Enhanced Emissions Vehicles program (EEV: stringent exhaust emissions requirements for cities):
 - comparison with other alternative fuels,
 - comparison with clean diesel engine concepts.

- * Possibilities to make DME available for the first phase market introduction for a reasonable price.



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1 Introduction

Haldor Topsøe came a few years ago with the idea to use Dimethyl-ether (DME) as a fuel for combustion engines. Together with the University of Denmark, they tested the fuel in a very small diesel engine of a generator set [24]. During that initial work they found out that DME is an excellent diesel-cycle fuel. Much lower NO_x and particulates emissions could be reached than characteristic for conventional diesel engines. Also the NO_x could be reduced considerably by applying EGR (Exhaust Gas Recirculation).

That initial work apparently interested the companies Amoco, Navistar, AVL and the US DOE, and test programs were started with larger engines, such as a Navistar 7.6 litre engine and the AVL single cylinder and AVL-leader test engines.

This work and the work of Haldor Topsøe and the University of Denmark led to a series of publications of both emission measurements and production of DME at the February 1995 SAE congress.

With these publications the possibilities to achieve ULEV exhaust emission levels for both light and medium duty engines were made credible.

DME can be made out of natural gas or biomass. From an automotive point of view it can be considered as an alternative to methanol. The production process is for both fuels very similar. With a different catalyst in the last stage of the production process, DME can be produced instead of methanol.

The objective of this report is to critically assess all aspects of DME as an automotive fuel. This includes production, emissions, safety, market introduction and the possible position of DME in the future energy supply.

The composition of the report is as follows. In Chapter 2 the properties of DME are compared to those of other fuels. Chapter 3 describes the production process of DME, while in Chapter 4 the energy efficiency and the emissions of DME are compared to those of other fuels. Chapter 5 evaluates DME engine concepts, also in comparison to the diesel engine. In Chapter 6 the exhaust emissions of DME engines are compared to those of other engines. Chapter 7 comprises a well-to-wheel comparison of energy efficiency and CO_2 production, while Chapter 8 deals with the safety aspects of DME. An assessment of the automotive market introduction and the possible position of DME in the world-wide energy supply are dealt with in Chapter 9 respectively 10, after which the report is finalized with conclusions and recommendations.

The comparison with other fuels usually includes diesel fuel, gasoline, LPG (propane/butane), natural gas and bio-ethanol and sometimes methanol. Some variation exists depending on the subject and on whether it concerns light duty vehicles or medium and heavy duty vehicles.



2 DME properties

DME, chemical formula $\text{CH}_3\text{-O-CH}_3$, is gaseous and invisible under ambient conditions. Because of this it requires special handling. DME is heavier than air and will therefore concentrate on the floor of a room. When the DME is pressurised to about 5 bar it will condense to a fluid that looks like water and which has two third of the density of water. The vapour pressure is roughly the same as LPG and therefore desires the same kind of handling and storage. Even though water is heavier than liquid DME it will not concentrate on the bottom of a tank since up to six mass percentage water can dissolve in DME. Commercial grade DME will contain water as well as methanol. Although the contents are small, the effect of a small amount of methanol on the solvability of water in DME is very large (Figure 2.1). Almost the entire gasphase will exist of pure DME independent of the fluid composition.

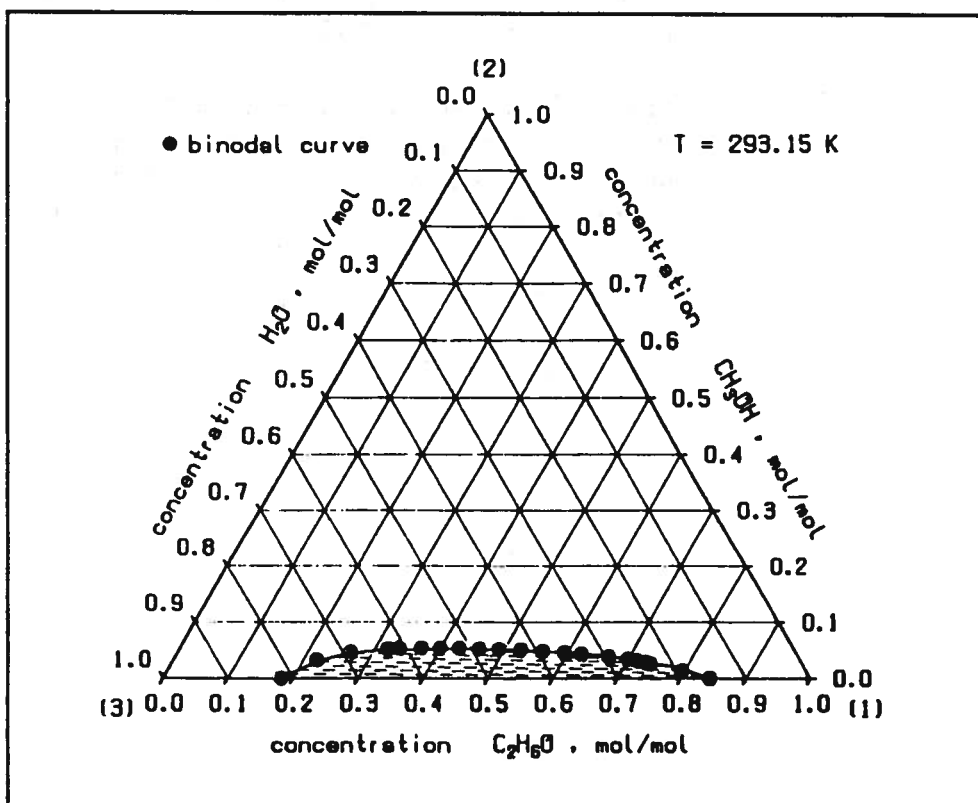


Figure 2.1: Liquid phase-equilibrium diagram of the ternary system; DME-Methanol-Water

Dimethylether is the simplest ether compound, it has been shown to be non-toxic and environmentally benign. Low concentrations (a few volumepercent) of gaseous DME hardly have any odour and cause no negative health effects. Very

high concentrations (>10 volumepercent) still don't effect human health but cause narcotic effects after long exposure and can be recognised by their odour. This narcotic effect is also seen with propane and butane at comparable concentrations.

Burning DME displays a visible blue flame over a wide range of air/fuel ratios, similar to natural gas. This is an important safety characteristic.

Dimethylether has a high cetane number which makes it ideal for use in a compression ignition (CI) engine. This characteristic lines up with the low auto ignition temperature of the oxygenated fuel. The low liquid density and the low calorific value (due to the bound oxygen) require a high volume of DME to be injected compared to gasoil. A quick evaporation of the fuel after injection and a short ignition delay result in a smoke free combustion of DME.

Although DME is non-corrosive, ethers are not compatible with most elastomers. For that reason a careful selection of seal materials is necessary to prevent deterioration after prolonged exposure to DME. Sealings of DME filled cans can for example be made of PTFE.

In Table 2.1 the properties of DME are listed and compared to a range of other fuels. LPG is split up in its components; propane and butane. The composition of LPG varies in practice between 30% and 70% propane and the remainder butane.

Table 2.1: Properties of DME compared to other fuels.

	Unit	DME	diesel	Propane	Butane	CNG	Methanol	Ethanol	Gasoline	Hydrogen
Liquid density	kg / m ³	667	831	500.5	578.8	-	795	789	750	-
Relative gas density (air=1)	kg / m ³	1.59	-	1.52	2.07	0.56	-	-	-	0.07
Cetane number		>55	40-55	-	-	-	-	40 / 50	-	-
Metane number		-	-	-	-	75	-	-	-	0
RON		-	-	112.1	91.8	120	106	107	98	-
Chemical structure		CH ₃ -O-CH ₃	-	C ₃ H ₈	C ₄ H ₁₀	CH ₄ +rest	CH ₃ OH	C ₂ H ₅ OH	-	H ₂
Stoich. A/F Ratio	kg / kg	9.0	14.6	15.68	15.46	16.86	6.46	9	14.7	34.2
Boiling point	°C	-25	180 / 370	-42	-0.5	-162 / -88	65	78	30 / 190	-253
C	% wt.	52.2	86	82	83	76	37.5	52	85	0
H	% wt.	13	14	18	17	24	12.5	13	15	100
O	% wt.	34.8	0	0	0	0	50	35	0	0
Velocity of sound	m / s	980	1330	-	-	-	-	-	-	-
Kinematic viscosity (liquid)	cSt	<1	3	-	-	-	-	-	-	-
Modulus of elasticity	N/m ²	6.37E+08	1.49E+09	-	-	-	-	-	-	-
Discharge coeff. at sprayhole	C _{hyd}	-	0.75	-	-	-	-	-	-	-
	C _{sph}	0.53	0.62	-	-	-	-	-	-	-
Cavitation factor	K _{lim}	0.1	0.68	-	-	-	-	-	-	-
LCV	MJ / kg	28.8	42.7	46.35	45.72	49	19.8	26.4	43.2	120
Ignition limits	λ	0.34 / 1.92	0.48 / 7.35	0.42/2.0	0.36/1.84	0.7 / 2.1	0.34 / 2.0	0.3 / 2.1	0.4 / 1.4	0.5 / 10.5
Ignition limits	% gas in	3.4/18.6	0.6/6.5	2.0/9.5	1.7/8.6	5.0/15	5.5/26	3.5/15	-	-
Vapour pressure [293 K]	kPa	530	?	830	210	-	37	21	45 / 90	-
Molwt.	g / mol	46.069	170	44.09	58.12	17	32.04	46.07	98	2.01
Min. ign. energy (λ = 1)	mJ	0.29	?	0.305	0.38	0.32	0.215	0.65	?	0.019
Auto Ignition temperature	°C	235	250	470	365	650	450	420	?	?
Kg (Max. pressure rise during	Bar	96	-	77	46	-	-	-	-	-
Maximum explosion pressure	Bar·m /	7.9	-	7.7	7.5	-	-	-	-	-
Max. laminar burning velocity	m / s	0.54	?	0.46	0.41	?	?	?	?	?
Liquid specific heat	kJ/kg·K	?	2.2	2.5	2.4	0.63	2.6	2.5	2.4	-
Gaseous specific heat	kJ/kg·K	2.99	1.7	1.67	1.68	2.2	1.72	1.93	1.7	1.44
Heat of vapourisation	kJ / kg	467.13	300	372.00	358	510	1110	845	420	460

Table 2.1 shows that the viscosity of DME is much lower than the viscosity of diesel fuel. This is likely to cause problems with the injection equipment commonly used for diesel fuel, because the thin DME will leak along the plungers which rely on a small clearance for sealing. Also the poor lubrication characteristics might cause wear problems with the injections equipment. A lubricity additive like Lubrizol probably can solve these problems.

3 DME production

This chapter starts with an overview of DME production methods. The most favourable methods for large scale DME production are discussed in more detail. Finally, the production method which is most suitable for automotive DME is chosen.

3.1 Introduction

Currently, most DME is being produced by dehydrogenation of methanol. Relatively small quantities are produced in this way. World wide production ranges between 100,000 and 150,000 tonnes per annum [1,2]. DME is being used to substitute chlorofluorocarbons (CFC's) as propellant in spray cans.

Besides the production of DME from methanol, other production routes for DME exist. Figure 3.1 gives an overview of the production routes which can be considered for large scale DME production. Other production routes, for example the simultaneous production of dimethyl ether and dimethyl sulphide, are not considered suitable for the large quantities which are required for automotive use. Consequently, these other production methods are not addressed in this report. This Figure shows that DME can be produced from different carbonaceous feedstocks.

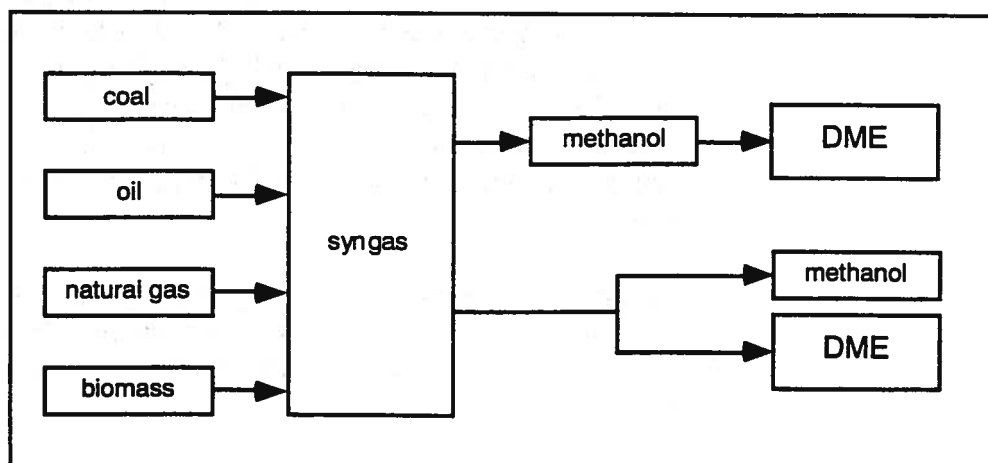


Figure 3.1: Product routes to DME, using different feedstocks

The first step of the DME production process is the conversion of the feedstock to syngas. Figure 3.1 shows that both fossil and renewable feedstocks can be used for the production of syngas. For the production of DME from syngas, two routes are possible:

- Production of methanol from syngas, followed by dehydration of methanol to DME. This is the conventional route.
- Simultaneous production of DME and methanol from syngas is the other option. The DME/methanol ratio can be chosen. DME content lies between 0% and 100%.

Not shown in Figure 3.1 is the final step in the production of DME, the purification of the raw product which contains methanol and water. This step is determining for the final product quality. Increasing product purity requirements will increase DME production costs. DME containing low percentages of methanol and water does not show problems when used in combustion engines [1,2].

The production of syngas is discussed in section 3.2. The subsequent section describes the methanol route. Finally, section 3.4 is about the simultaneous production of DME and methanol from syngas.

3.2 Production of syngas

Syngas is short for synthesis gas, which is a mixture of hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2). It may also contain impurities like methane (CH_4).

Feedstocks for syngas production as mentioned in Figure 3.1 are coal, oil, natural gas and biomass. The terminology is meant to represent groups of feedstocks. Beside coal, lignite can be used as well. Oil includes crude oil, heavy refinery residues, etcetera. Natural gas stands for a mixture of gases, predominantly consisting of methane. Natural gas composition varies between different gas fields and can be adjusted by purification. Biomass represents a wide range of carbon containing products. Just a few examples are vegetable oils, wood and straw.

The process technology of the conversion of coal, oil and biomass to syngas is partial oxidation by gasification with pure oxygen. Processes for gasification of coal and oil are commercially available. Biomass gasification processes are in the demonstration stage.

Steam reforming is the most common process to convert natural gas into syngas. Because natural gas is expected to be the cheapest feedstock for large scale DME production for many years to come, the production of syngas from natural gas is discussed here in more detail.

Haldor Topsøe proposes three different technologies for the conversion of natural gas to syngas [2]:

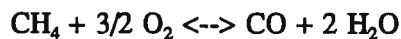
- Conventional one-step steam reforming.
- Autothermal reforming.

- Two-step reforming.

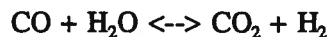
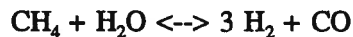
According to [2], based on production capacity of a single production unit, autothermal reforming is the preferred process for the large scale production which is required for the use of DME as an automotive fuel. Other important advantages of autothermal reforming are the compact design of the production unit, very low NO_x-emissions and low capital costs.

Before natural gas is fed to the autothermal reformer, purification may be necessary. Sulphur-containing gas has to be desulphurised before being fed to the autothermal reformer, to avoid poisoning of the reformer catalyst. Beside that, to ensure the production of soot free synthesis gas, it is necessary to convert heavy hydrocarbons in the gas before it is being fed to the reformer.

Natural gas, steam and oxygen are fed to the autothermal reformer. The conversion consists of two steps. The first step is a partial combustion of natural gas.

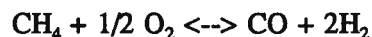


Two reactions in which hydrogen, carbon monoxide and carbon dioxide are being formed take place in the second step.



The composition of the syngas is defined by the amounts of steam and oxygen added and the exit temperature and pressure [2]. The produced syngas has a high temperature. It has to be cooled before it can be used in subsequent processes. The waste heat can be used to produce steam for power generation.

DSM has proposed to make syngas via catalytic partial oxidation (CPO) instead of via conventional steam reforming or a combination of steam reforming and partial oxidation [29]. According to DSM this will lead to an energy input saving of about 7% compared to the combined process. With catalytic partial oxidation syngas is prepared via the reaction :

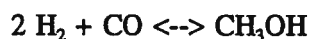


To avoid transportation of natural gas, the syngas production plant can be located at the natural gas recovery site.

3.3 The methanol route to DME

This section describes the production of methanol from syngas which is followed by the production of DME from methanol. Produced in this way, DME is intrinsically more expensive than methanol, because an additional step in the production process is required. On the other hand, using this production method, it is not required to produce methanol and DME at the same location. Methanol can be transported to a DME production plant.

Methanol synthesis from syngas is a mature technology. The nominal synthesis temperature is 250°C [5]. The methanol synthesis is carried out at 80 to 120 bar [4]. The process takes place in the presence of a catalyst. The catalysts which are being used are almost all copper based. Methanol (CH₃OH) is produced from hydrogen (H₂) and carbon monoxide (CO), which is shown in the following equation.



The methanol produced is in its liquid phase. The reaction is thermodynamically equilibrium limited and exothermic. The synthesis catalyst is slurried in an inert hydrocarbon oil, which effectively absorbs the heat of reaction. The catalyst is deactivated when it is overheated. That is why the conversion ratio per pass is limited. Additionally, a high methanol concentration in the liquid phase limits the synthesis reaction. A reduction in methanol concentration increases the kinetic driving force of the reaction [5, 7].

The next step is dehydration of methanol to DME (CH₃OCH₃). The following equation shows the molecular formulas.



This reaction takes place in the presence of a another type of catalyst. This catalyst can be for example alumina or a zeolite [5,6]. The end product is DME, which is contaminated with water and methanol. Depending on the application of DME, purification may be necessary.

3.4 Direct conversion of syngas to DME

To avoid the syngas to methanol conversion from stopping due to an increasing methanol concentration as described in section 3.3, the methanol concentration can be reduced by the conversion of methanol to DME. The two steps methanol production and methanol dehydration to DME can take place in one reactor, when the applicable catalysts are being used. Additional advantages of combining the methanol and DME production are [4,5,6,11]:

- The equilibrium constraints of methanol conversion are avoided, resulting in an increase in reactor productivity compared to methanol synthesis alone.
- High CO conversion ratio's.
- Synergetic effects, for example on catalyst efficiencies (as discussed below) and relieve of pressure level.
- DME yield is greater than from sequential processing.
- DME and methanol can be produced in any fixed proportion, from practically pure DME to pure methanol, by choosing the applicable process parameters. The productivity can be considered to be almost 100%.
- One reactor instead of a series of reactors for each process step offers advantages in capital investment and operating costs.

A lot of research has been done on this subject. Just four examples of groups and companies who have performed research in this field are Air Products [5,9], Amoco and Haldor Topsøe [2,4,10], CSIR (South Africa) [6] and The university of Akron together with the Electric Power Research Institute in Palo Alto (USA) [3,7,8]. Of these groups, Amoco and Haldor Topsøe currently do a lot of work to develop DME as a vehicle fuel.

The simultaneous production of DME and methanol can take place either with or without recycling of syngas. Figure 3.2 shows both processes. The waste gas which is produced in the 'once through' process (fig. 3.2.b), can be used for power generation. Even the produced methanol can be used for this purpose. However, for the production of large quantities of DME it is more applicable to use the process in which syngas is being recycled, to obtain a maximum DME yield. So this section concentrates on the latter production process.

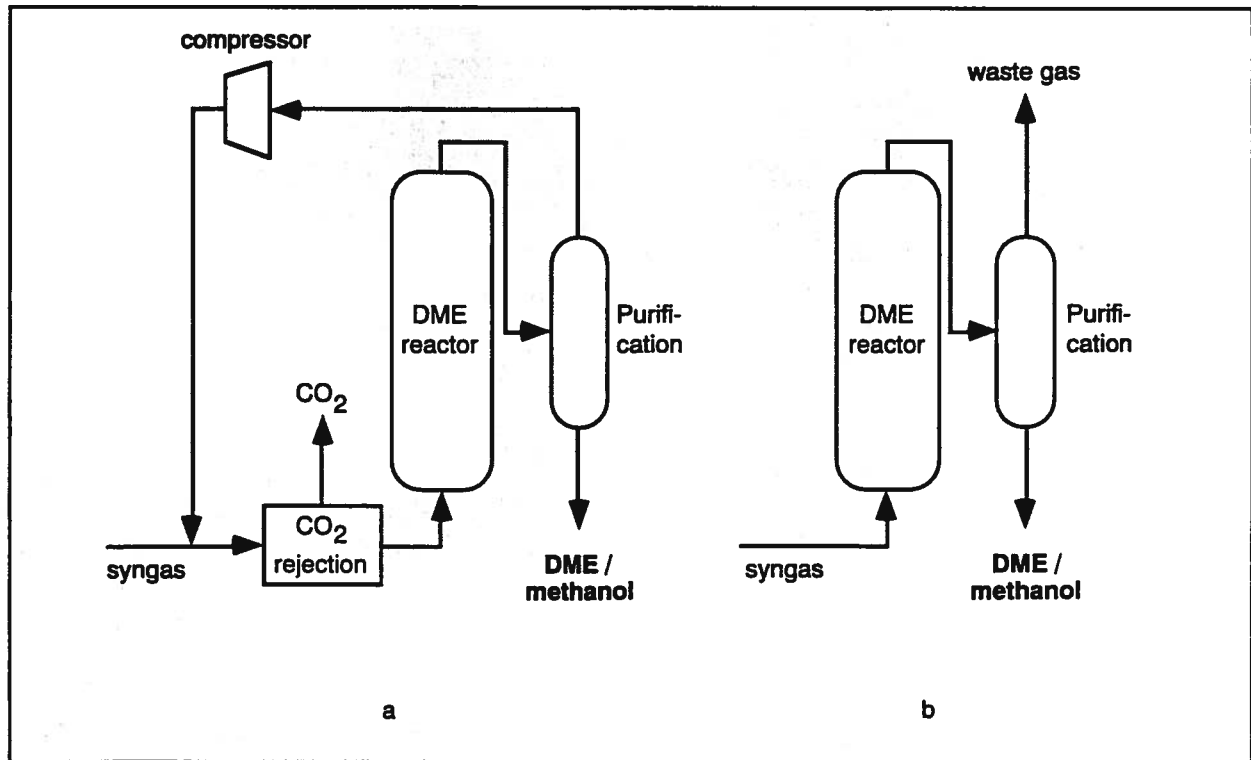
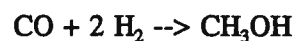
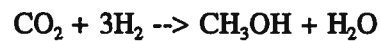


Figure 3.2: Process schemes for simultaneous DME and methanol production

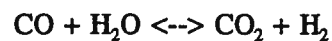
Two different reactions are possible to produce methanol from syngas, depending on syngas composition:



or



To obtain an adequate ratio of hydrogen to carbon oxides, a water gas shift reaction may be required:



Finally, methanol is dehydrated to DME:



The water gas shift, methanol synthesis and dehydration of methanol to DME can take place simultaneously in one reactor, when the appropriate catalysts are being used.

Parameters influencing the syngas to DME/methanol conversion process are (among others) type of reactor, impeller speed, temperature, pressure, type of catalyst, volume and type of oil, flow rate of syngas, flow and removal of inert [3,5]. Some important parameters are discussed here briefly:

- Temperature.

A high temperature is attractive for a high methanol production rate. However, an increasing temperature deactivates the methanol synthesis catalyst and the thermodynamic equilibrium yield of DME falls with increasing system temperature. At a methanol synthesis temperature of 250°C, the DME yield is high [5].

- Pressure.

The pressure range for the process is approximately 14 to 140 bar [5]. On its own, the methanol synthesis must be carried out in the pressure range of 80 to 120 bar [4]. However, the dehydration of methanol to DME reduces the need for pressurised operation [5]. Pressures of 30 to 70 bar (depending on type of catalyst) are mentioned for the simultaneous synthesis of DME and methanol from syngas [3,6].

- Catalysts.

Two functionally different catalysts are slurried in an inert liquid phase, using an inert hydrocarbon oil [5,11]. Many types of catalysts are being used for each reaction of the process. Methanol synthesis catalysts are almost all copper based. Alumina and zeolites are examples of catalysts for the dehydration of methanol to DME [5,6,11]. An increasing temperature deactivates the methanol synthesis catalyst [5]. A gamma-alumina dehydration catalysts showed a positive effect on the methanol synthesis catalyst. The dual catalysts showed a higher activity and these activities are sustained over a longer catalyst on stream life [11]. Catalysts reactivity diminishes when catalyst life increases [2,11].

- Flow rates.

A large inert flow has a cooling effect which can avoid overheating of the methanol synthesis catalyst. In doing so, a decrease in catalyst activity is avoided.

CO₂ builds up in the process loop. The removal of CO₂ from the loop is an important operating variable. By removing CO₂, both DME productivity and product selectivity can be improved [5].

3.5 DME from natural gas

Both from a costs and product yield point of view it can be concluded from the previous sections that the synthesis of DME directly from syngas is the preferred route for large scale production. Significant energy savings are claimed for this conversion process with higher conversion rates [6]. However, these savings are not quantified.

DME can to a certain extent be qualified as a renewable fuel when the syngas is produced from renewable feedstocks. However, Haldor Topsøe's analyses show that natural gas will be the cheapest feedstock for DME production [4].

So the most cost effective route is DME production by direct synthesis of syngas (with methanol as an intermediate step or co-product), using natural gas as the feedstock. Haldor Topsøe claims that this also represents the lowest energy alternative. The energy consumption of stand alone plants is expected to be approximately 5% lower than for methanol plants [2].

Beside building new facilities for DME production, large scale production of DME can also be realised by converting methanol plants to the production of DME [2]. This can be an attractive option when a large production capacity has to be realised in a limited amount of time.

4 Comparison of DME production and the production of conventional fuels

4.1 Energy balance

In this section the energy consumption of the production of automotive fuels is being addressed. The energy consumption consists of two parts: the energy content of the feedstock and the energy consumption of feedstock recovery and fuel production. Both types of energy consumption are addressed in this section. First, the energy consumption of DME production is established. Next, this is compared to the energy consumption of petrol, diesel and LPG (autogas).

Haldor Topsøe supplies data on the energy consumption of DME production (using an autothermal reformer) compared to that of methanol production, for plants with a similar production capacity. These plants have a capacity of 2500 metric tons per day (MTPD), which is relatively small for large scale DME use. The figures of Haldor Topsøe are on a methanol equivalent basis, which stands for carbon content. On this methanol equivalent basis, the energy consumption of DME production is 5% lower than for methanol production. The energy consumption figures include the energy content of the natural gas that is used as feedstock [2]. These figures can be converted to an energy equivalent basis. The following data is used for this calculation:

- the energy consumption of methanol production is 30.6 GJ per metric ton of methanol [2],
- the energy consumption of DME production is 29.1 GJ per metric ton of methanol equivalent [2],
- 719 kg DME contains the same amount of carbon as 1000 kg methanol,
- the lower calorific value of methanol is 19.8 MJ/kg [14],
- the lower calorific value of DME is 28.8 MJ/kg [2].

The results of this calculation is presented in Table 4.1. It is concluded that on an energy basis, the production of DME is 9% more efficient than the production of methanol. According to Haldor Topsøe, a small amount of electrical energy is produced as a by-product. It is less than 1% of the energy consumption of the methanol and DME production processes and neglected in this report. Excess process heat can be neglected as well. It is not clear whether the energy consumption of oxygen production (oxygen is required for DME production) is included in these figures.

Table 4.1: Energy consumption (including energy in feedstock gas) of methanol and DME production, calculated from figures supplied by Haldor Topsøe [2]

	[MJ/MJ]
Methanol	1.55
DME	1.41

DeLuchi, Ecotrafic and a previous TNO report give energy consumption figures of petrol, diesel and LPG production [12, 13, 21]. DeLuchi and Ecotrafic also present figures on methanol production, which are used here to check the comparability with the figures calculated above. The background of these figures is described first. Next, Table 4.2 presents an overview.

DeLuchi considers the situation in North America [13]. An energy consumption figure for natural gas transportation is presented in Table 4.2, but for comparison reasons it is not included in the total energy consumption.

Ecotrafic concentrates on the Swedish situation and assumes that the methanol production plant is located at the natural gas recovery site, so natural gas transportation is omitted. According to Ecotrafic, the conversion of gaseous hydrocarbons to methanol is the result of an optimisation with regard to the (future) price of the gas, the investment cost and the economic environment (e.g. financing, CO₂ release fee). When producing methanol, a small surplus of electricity is also produced. This electricity production is not quantified [12].

Table 4.2: Energy consumption of the production of methanol from natural gas, in MJ per MJ methanol

Reference	DeLuchi [13]	Ecotrafic [12]	Haldor Topsøe [2]
Natural gas recovery	0.0788	0.03	--
Natural gas transport	(0.0217 ¹)	0	--
Methanol production, including energy in natural gas	1.5405	1.40	1.55
Sum	1.6193	1.43	1.55²

1) Not included in sum.

2) Without energy consumption of natural gas recovery

From Table 4.2 it can be seen that Haldor Topsøe's value is a reasonable average for the energy consumption of methanol production. Because this figure can be compared directly with Haldor Topsøe's DME production figure, 1.55 MJ/MJ is used in this report. Accordingly, the energy consumption figure for DME in this report is 1.41 MJ per MJ DME (see Table 4.1). These figures include the energy content of the feedstock.

Average values for the energy consumption of petrol, diesel and LPG can be calculated with figures from the references mentioned above. This is shown in

Appendix B. With the assumption that the energy content of the crude oil of which these fuels are produced is 1 MJ per MJ fuel, the Figures in Table 4.3 can be created.

Table 4.3: Energy consumption of the production of petrol, diesel, LPG and DME, including the energy content of the feedstock. Energy consumption of feedstock recovery and transport are included in these Figures. The DME production plant is considered to be at a natural gas recovery site, so natural gas transportation is omitted.

	Gasoline	Diesel	LPG	DME
Energy consumption of production, including energy content of the feedstock [MJ/MJ]	1.20	1.10	1.11	1.41

4.2 CO₂-emissions

The three references from the previous section also supply figures on CO₂ emissions of fuel production and distribution [12,13,21]. Table 4.4 gives an overview. Background information on these figures can be found in section 4.1 and in Appendix C.

Table 4.4: CO₂ emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are grams CO₂ per MJ of fuel produced

[g/MJ]	DeLuchi [13]	Ecotraffic [12]	TNO [21]
Petrol	33	15.4	12.7
Diesel	--	10.4	8.1
LPG	22	11.4	8.1
Methanol	48	11.8	--

DME 15.3 *production*

The differences in CO₂ emission values between the USA and Europe are much larger than the differences in energy consumption figures. Additionally, according to DeLuchi, CO₂ emissions of methanol production and distribution are larger than petrol while Ecotraffic presents an opposite effect. Larger transportation distances may explain part of the difference. From the fact that DME production requires more energy than petrol production (Table 4.3) and similarities between the production of methanol and DME from natural gas, it is expected that CO₂ emissions from DME production are also larger than from petrol production. It is not possible to quantify the difference with the available figures.

According to Haldor Topsøe, CO₂ emissions of DME production are 0.44 tons per ton DME [2]. Using a lower calorific value of 28.8 MJ/kg for DME, this

figure can be converted to 15.3 grams of CO₂ per MJ DME. Recovery and transportation of the feedstock and DME distribution are not included in this figure.

*NG supply 9.5 g CO₂/MJ DME
distribution 1.4 g CO₂/MJ DME*

4.3 Regulated emissions

Carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulates are regulated emission components. These emission components are dealt with in this section. From information of Haldor Topsøe it can be concluded that unregulated emissions of DME production can be neglected [2].

DME production from natural gas takes place in a pressurised, closed system. Consequently, emissions of the process itself will be negligible. Emissions from DME production consist of the emissions of power and heat generation. According to Haldor Topsøe the only emissions of concern are CO₂ and NO_x [2]. CO₂ emissions are dealt with in the previous section. NO_x emissions of DME production are 70 grams per ton methanol equivalent (carbon content). Using 719 kg DME is one ton methanol equivalent and a lower calorific value of 28.8 MJ per kg DME results in a NO_x emission figure of 3 mg/MJ for DME production. A comparison with NO_x emissions of the production of conventional fuels is given in Table 4.5. Recovery and transportation of the feedstock and fuel distribution are not included in these figures. Appendix C gives more data on regulated emission components of fuel production.

Table 4.5: NO_x emissions of fuel production in milligrams NO_x per MJ of fuel produced

[mg/MJ]	Ecotrafic [12]	Haldor Topsøe [2]
Petrol	10	--
Diesel	6	--
LPG	6	--
DME	-	3

4.4 Feedstock transportation and fuel distribution

4.4.1 Feedstock transportation

Over the next 30 years transportation of natural gas over long distances will become more important [18]. There are basically three options for this transportation: by pipeline, by LNG tanker and by methanol or DME tanker (after natural gas to liquid fuel conversion).

According to an IEA report [19], the most economical transport depends on the distance: up to 3000 miles a pipeline is most economical, from 3000 to 7000 miles LNG and above 7000 mile via methanol (DME is not considered). Refer to appendix D.

Approximately three quarters of international natural gas trade is currently pipeline gas. The remainder is LNG, with Japan by far being the largest importer. Most LNG for Japan stems from Indonesia, Brunei, Malaysia and Australia [20]. The largest part of the energy consumption of this type of transportation is the energy requirement of the liquefaction process. Ocean shipment and regasification have their respective energy consumption as well. Evaporative losses cannot be neglected by this type of transportation. LNG has to be kept at a temperature of -161°C . Boil-off losses of cryogenic tanks are reported to be 0.15% per day. These losses occur both at storage and during sea transport. During sea transport, these losses can be used as fuel for the tanker. Adding up these effects, the energy consumption of LNG transport by sea tanker (including liquefaction) is considered to be approximately 0.18 MJ per MJ gas [12]. The transportation distance is not mentioned.

Specific energy densities for DME, methanol and LNG per unit of mass and volume are summarized in Table 4.6. The table shows, that the energy per unit of mass and volume for DME are respectively 45% and 23% higher than for methanol. A disadvantage of DME is that it has to be transported under a pressure of about 5 bar to keep it liquid. This leads to a higher mechanical load on the tanks, which leads to heavier tanks. This effect is considered to be small compared to the difference in energy content per mass of fuel. So the transportation of DME is favoured over the transportation of methanol (and LNG).

In Chapter 3 it was concluded that from a production point of view, a direct synthesis of DME from syngas is preferred over DME production with an intermediate methanol step. So it is concluded that the direct conversion of syngas to DME and consequently (sea) transportation of DME will be the preferred option for large scale DME production.

Table 4.6: Comparison energy densities of DME, methanol and LNG

	DME	Methanol	LNG
Lower calorific value [MJ/kg]	28.8	19.8	49
Lower calorific value (liquid, 20°C) [MJ/l]	19.2	--	--
Lower calorific value (15°C) [MJ/l]	--	15.6	--
Lower calorific value (liq., -161°C) [MJ/l]	--	--	22.2
Density (liquid, 20°C) [kg/l]	0.67	--	--
Density (15°C) [kg/l]	--	0.79	--
Density (liquid, -161°C) [kg/l]	--	--	0.45

Transport of associated gas

Gas to liquid fuel conversion might be the best option to transport associated gas from crude oil production. In that case it will not be wasted. The quantity of gas being flared-off world wide equals to 8-10 million GJ energy per day. This equals to 2 to 2,5% of the energy content of the crude oil. An overview of flare-off sites is presented in Appendix D, page 2.

4.4.2 DME distribution

Transportation, storage and dispensation of DME as a liquid fuel are similar to LPG or propane. See also Chapter 8. Consequently, the infrastructure for DME distribution will be very similar.

DME is being transported as a liquid, because this requires less volume than gaseous transportation. To keep DME in the liquid phase at ambient temperatures, it has to be pressurised. It's vapour pressure is approximately 5.1 bar at 20°C [2,36].

DME is currently being transported by rail and by road tankers. This is expected to become common practice when DME is used on a large scale for vehicle use. To estimate the energy of road transportation, it is assumed that the average load of a road tanker is 20 tons of DME. The diesel oil consumption of such a truck is considered to be 33 litre per 100 km. An average calorific value of diesel oil is 36 MJ per litre [14]. Using 28.8 MJ/kg (Table 4.6) as the calorific value of DME, the energy consumption to transport DME by road tanker over 1000 km can be calculated as 0.02 MJ per MJ DME. Note that loading and unloading is not included in this figure. Neither is the return trip of the truck.

For small quantities in remote areas, transportation of DME in refillable bottles can be considered.

Energy consumption and emissions from transportation depend on the transportation mode and the technology of the vehicle being used. When electric trains are used for DME transportation, then the energy consumption and emissions stem from electrical power generation. When diesel trains or diesel trucks are used, the energy consumption is diesel oil consumption and the emissions are tailpipe emissions of these vehicles. In a mature situation, DME can be used instead of diesel oil in these vehicles. NO_x and particulate emissions of DME vehicles will be lower than for diesel. Except in emergencies, no DME evaporates or is being vented during transportation. Consequently, in this respect no energy losses or emissions occur.

Safety measures similar to LPG are required for DME transportation and storage. LPG is placed in the category of dangerous goods. Transportation of these goods is subject to certain regulations. These regulations include for example [17]:

- Particular routes must be used for transportation.
- Relief valves at tankers and storage tanks.
- Breaker couplings in filling hoses and emergency stop switches.
- Storage tanks must be underground or in a mound.
- A minimum distance between storage tank and buildings is required.

It is clear that strict rules apply for planning LPG -and consequently also DME- refuelling stations. The demands can easily be met for refuelling stations along motorways, but in other places this can be difficult. Especially for public transport depots in urban areas, it can be difficult to meet the demands because of adjacent buildings [17].

5 Engine concepts for DME

DME has appeared to be an excellent fuel for a "diesel cycle" engine because of its low auto-ignition temperature and its instantaneous vaporization when it is injected in the cylinder.

5.1 Fuel injection system

Just like diesel fuel DME needs a fuel injection system, that injects the fuel into the cylinder at the end of the compression stroke. There are however a few key differences:

- a) DME only requires an injection pressure of 200 to 300 bar, compared to 500 to 1500 bar for modern direct injected diesel engines. This low injection pressure can be explained from the characteristics of the fuel. First of all it is an oxygenated fuel and secondary it is a gas at the conditions (temperature and pressure) in the cylinder at the time of injection. So even though injected as a liquid, it immediately gasifies. Diesel fuel on the other side has to be injected at a high pressure, so that fine droplets can form a homogeneous mixture and soot formation can be controlled.
- b) DME is much less viscous than diesel fuel. This is bound to cause problems in relations to the small clearance sealing principle of the plungers of diesel fuel injection equipment. The literature [22] mentions leakage rates of DME along the plungers of 40% to 50% of fuel. Without special measures this leaked DME will vent into the atmosphere which is unacceptable. With conventional fuel injection pumps it might be possible to improve the seals of the driving mechanism casing to take the high pressure necessary to keep DME liquid (necessary to feed it back to the tank or pump inlet). The high leakage rate along the plungers probably also causes accuracy problems with respect to the dosage of the fuel.

For HD engines the leakage along the plungers is much more a problem than for LD engines, because the drive mechanism is engine oil lubricated. This is necessary to meet the live requirements of these engines. Because of this the pressure can probably not be raised sufficiently. Also the oil will be solved in DME and eventually be combusted in the engine.

- c) The lubricity of DME is less than that of diesel fuel:
The lower lubricity can probably be solved with a lubricity additive [22]. It might also be possible to adapt the materials of bearing surfaces and plunger/barrel to the low lubricity of DME without additive. The experience gained in the past with methanol fuel injection pumps will probably be useful.

Difference (a) is an advantage, while from (b) can be concluded that current diesel fuel injection equipment -especially for heavy duty engines- is less suitable for DME.

It is not known whether the modifications of conventional fuel injection systems suggested under (b) and (c) can lead to a DME fuel injection system, that can be used in practise for light or heavy duty engines.

AVL has started the development of a "common rail" fuel injection system for DME. This is probably the best solution for a dedicated DME engine. Currently common rail fuel injection systems are also being developed for diesel fuelled engines. In such a system a higher pressure pump delivers the fuel to a rail or manifold, in which a constant high pressure is maintained. Electromagnetically controlled fuel injectors are connected to the rail.

Although a special, common-rail, fuel injection might be the best solution for a dedicated DME engine, for demonstration purposes it might be more cost effective to convert conventional fuel injection equipment.

5.2 Dedicated DME engine

The favourable characteristics of DME makes the DME engine very suitable for optimization through rate shaping of the injection event. By reducing the amount of fuel injected during the ignition delay, it is possible to get a very gradual pressure build up. This results in low peak pressures (and temperatures) and consequently lower NO_x and noise [25].

This also leads to lower load of the engine crankshaft, bearings, crankcase and cylinder head. The overall engine design can be kept lighter which saves fuel in two ways:

- a] the engine efficiency rises when bearing diameters can be decreased, and
- b] the vehicle weight goes down.

It is also reported that the excess air ratio can be decreased [1]. This is logical because a DME engine does not have a particulates emission "problem" like the diesel engine. The lower possible excess air ratio of DME can be used to improve the transient response of the engine. It can also be used to raise the specific power output of the engine (provided that the thermal load remains below the limit).

5.3 Dual-fuel and Retrofit

Dual-fuel and retrofit are two methods to stimulate the introduction of DME for a broad public.

Retrofit is possible for both light and heavy duty vehicles. It should be noted however that for HD vehicles the requirements with respect to reliability and live

are so high, that a definite involvement of the manufacturer of the engine is necessary in both the design and (endurance) testing of the retrofit package. This might in practice be difficult to realise.

The NO_x output and the efficiency of a retrofit engine will not be as good as a "dedicated" engine, because with the latter more combustion optimization will take place. The dedicated engine will probably also be lighter and it probably has a better matched turbocharger characteristic.

The dual-fuel principle is successfully applied in the Netherlands with LPG. Cars running on LPG can also run on gasoline. It is also the case with the introduction of light duty methanol vehicles in the US. An estimated 10.000 of these vehicles have been sold in the US. The advantage of the methanol-gasoline FFV's (flexible fuel vehicles) is that the methanol and gasoline can be stored in one tank. The engine management system with fuel composition sensor adapts automatically the fuel-air mixture to the methanol-gasoline ratio.

With DME the dual-fuel principle is much more difficult, because of the different characteristics of DME and diesel fuel and the need for in-cylinder injection. The injection parameters such as pressure and nozzle area deviate widely between the two fuels.

It might be possible to develop a DME-LPG dual fuel injection system. These fuels can be stored in the same tank, provided that a sensor can be developed to determine the mixture ratio. When the DME content falls below a certain percentage some kind of ignition assistance will be necessary. The possibilities for this are an ignition improving additive (mixed with the fuel from a separate tank) or glowplug or sparkplug assistance.

6 Comparison exhaust emissions DME engines with other engines

6.1 Introduction

One of the most important reasons for the world wide interest in DME as an automotive fuel is, that DME appears to be a fuel which combines "diesel cycle" efficiency with very low exhaust emissions.

Very low NO_x and particulate emissions results of diesel engines running on DME have been reported by AVL (Graz, Austria), the University of Denmark and Haldor Topsøe [1, 10, 22, 24, 25]. In these publications compliance with the American ULEV limits for both light and medium duty engines is made plausible.

In Paragraph 6.2 and 6.3 the published exhaust emissions data with DME are compared to the emissions data with diesel and gasoline fuel and alternative fuels. The latter group includes LPG and natural gas and for heavy duty engines also bio-ethanol. For heavy duty engines the comparison is also expanded to future diesel engine concepts.

Paragraph 6.4 deals with the non-regulated exhaust emissions of DME and other fuels, while Paragraph 6.5 handles toxic and environmental effects due to regulated and non-regulated emissions.

Paragraph 6.6 finally contains a projection of the contribution of different vehicle categories to emissions in urban areas. This is to select suitable vehicle categories for replacement by DME or other clean vehicles.

6.2 Light-duty engines

Table 6.1 contains a comparison of exhaust emissions results over the US-FTP test cycle with DME, diesel fuel, gasoline, LPG and CNG. These results are graphically presented in Figure 6.1. The DME results, which come from AVL [25], are presented with and without an oxidation catalyst.

Table 6.1: Comparison exhaust emissions light-duty engines over US-FTP75 test cycle using different fuels, in grams/mile

	DME ¹⁾ EGR	DME ¹⁾ EGR, ox.cat	Diesel EGR ox.cat	Diesel	Gasol.	LPG	CNG
NO _x	0.2	0.20	0.93	1.18	0.24	0.34	0.21
CO	6.0	0.04	0.16	1.07	1.79	1.46	0.72
HC	0.4	0.04	0.16	0.22	0.24	0.19	0.58
PM			0.11	0.15	0.02	0.01	0.04

1) AVL test results, calculated from steady-state test results

2) Particulates matter

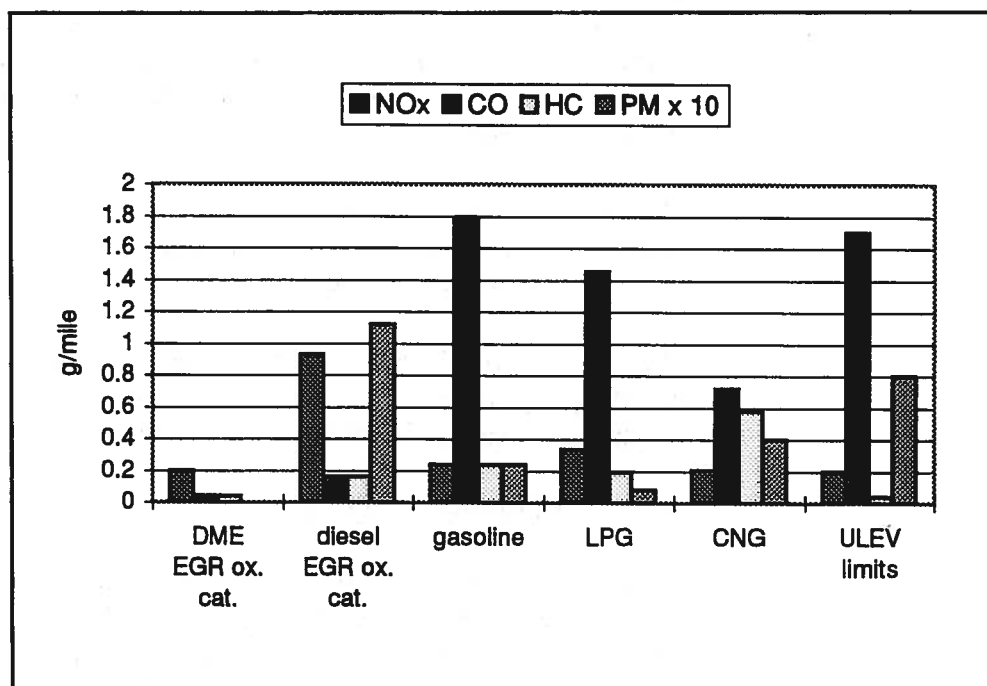


Figure 6.1: Comparison exhaust emissions light-duty engines over US-FTP75 test cycle. Source AVL & TNO

The emissions data of the other fuels originate from a measurement program carried out at TNO in 1993 [27]. In this study regulated and non-regulated emissions were measured of almost new vehicles generally equipped with modern technology. The otto cycle engines were all equipped with microprocessor and lambda controlled fuelling system and 3-way catalyst. Two diesel engines were equipped with EGR and 3 with an oxidation catalyst. The LPG and CNG cars used retrofitted fuelling systems.

For the diesel fuel a separate result is presented for a diesel engine with EGR and an oxidation catalyst. This is a Mercedes 250 D Turbo. The other diesel result and the results for gasoline and LPG are the average of five vehicles. The CNG result is the average of 2 vehicles.

The DME results are calculated from steady-state (engine dynamometer) test results. Different studies have demonstrated that for diesel (cycle) engines, there is indeed a reasonable correlation between calculated and measured results over transient test cycles. CO and HC results with oxidation catalyst should however be judged as indicative only, since the US-FTP includes a cold start phase during which catalyst efficiency is lower. This is very difficult to project from steady-state results.

The very low NO_x-level with DME is according to [25] obtained by applying high EGR rates. EGR reduces the NO_x formation, because it reduces the oxygen concentration while maintaining or even increasing the cylinder charge mass. Because of this (local) combustion temperatures and consequently NO_x formation are reduced. EGR is a common technology for light duty diesel engines and also otto engines to decrease NO_x emissions.

The current and future US Federal and the future European emission limits for light duty engines are presented in Table 6.2. The test cycles for US and Europe are respectively the US-FTP75 and the ECE 15 + EUDC (Extra Urban Driving Cycle). For the latter the first 40 seconds idle are included in the emissions measurement, which is not the case for the current European Emissions legislation. Noted should be that in Europe there are different limits for gasoline and diesel cars. Only the gasoline limits for Europe are presented in the Table. For diesel cars the Stage 2000 and Stage 2005 NO_x limits are respectively 0.37 and 0.28 g/km.

The US Federal "Tier II" NO_x and CO limits are the same as the Californian ULEV limits. ULEV is however more stringent regarding (non-methane) HC and particulates (0.04 g/mile for both).

Comparison of NO_x limits in Table 6.2 shows that the European Stage 2005 limit is actually more stringent than the US Tier II limit. According to TNO's experience the different test cycles do not lead to significant differences in the emissions in grams per km or mile.

Table 6.2: US current and future and European future emissions legislation for light duty vehicles

	US g/mile		Europe g/km (gasoline)	
	Tier I 1996	Tier II 2004 ¹⁾	Stage 2000 ²⁾	Stage 2005 ²⁾
NO _x	0.4	0.2	0.15	0.08
CO	3.4	1.7	2.3	1.0
HC			0.2	0.1
NMHC ³⁾	0.25	0.125		
PM	0.08	0.08		

1) Proposed introduction date

2) Proposed limits

3) Non Methane Hydro Carbons.

When comparing Table 6.1 and 6.2, it can be concluded that the 1993 series production gasoline and CNG vehicles already fulfil the 2004 US Tier II requirements (NMHC of CNG engines is not measured but according to our experience very low). This is also the case for the (laboratory) DME engine with oxidation catalyst.

Without oxidation catalyst the CO and HC levels of the DME engine are quite high and exceed the current US emissions legislation.

6.3 Medium and Heavy Duty engines

Haldor Topsøe, AVL, Navistar and Amoco have published exhaust emissions results based on two engines; a 7.6 liter turbocharged V8 Navistar engine and a single cylinder 2 liter AVL test engine [1, 10]. All tests were carried out at the AVL facilities in Graz Austria.

With the Navistar engine a NO_x emission was achieved of approximately 2 g/bhp.hr over the US heavy duty transient test cycle by applying EGR. This data is projected from steady state test results. The regulated emissions of this engine complied with the 1998 California ULEV requirements for medium duty engines. With the AVL single cylinder test engine a NO_x level over the US HD transient was reached of 1 g/bHp.hr

In Table 6.3 and Figure 6.2 the ECE 13-mode emission results of two DME engines are compared to those of a diesel engine, two CNG engines and a bio-ethanol engine. The diesel engine is a standard series production engine, which complies with the EURO-2 emissions legislation. EURO-2 has been entered into

force in 1995. The CNG values are from a 9.5 litre, 270 kW turbocharged Iveco engine, which was tested in a lean-burn and a stoichiometric version [23]. The LPG engine is a 12 litre, naturally aspirated DAF engine [38]. The bio-ethanol values are from a 12 litre naturally aspirated Mercedes engine, which has been used in a 3 year demonstration project with 3 buses in Groningen, the Netherlands [30]. An ignition improver was mixed with the bio-ethanol so that the engine could run as a diesel engine (compression ignition).

Table 6.3. Comparison exhaust emissions heavy duty engines over ECE R49 13-mode test cycle using different fuels, in g/kWh

	DME ¹⁾	DME ¹⁾	Diesel Euro-2	CNG lean-burn	CNG stoich.	LPG lean-burn	bio-ethanol
Engine	Navistar	AVL single cyl.	DAF	Iveco	Iveco	DAF	Mercedes
Emission reduction	EGR	EGR	-	oxi.cat.	3-way catalyst	-	oxi.cat.
NO _x	3.85	2	6.92	2.5	0.8	3.6	4.86
CO	2.2		0.68	0.2	0.4	4.1	0.27
HC	0.2		0.23	1.0	0.4	0.9	0.76
PM	0.05 estim	0.02	0.11	<0.02	<0.02		0.04

1) AVL test results, resp. [1] en [10].

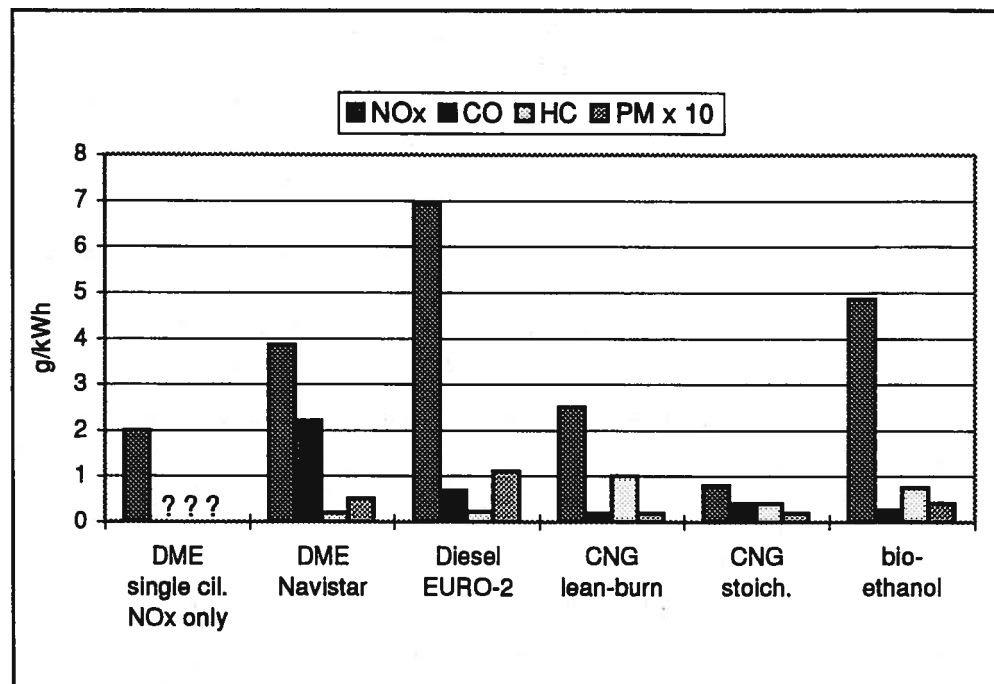


Figure 6.2: Comparison exhaust emissions heavy duty engines over ECE 13-mode test cycle. Source AVL & TNO.

Comparison of the NO_x emission levels from Table 6.3 learns that all alternative fuelled engines show considerable lower NO_x values than the standard diesel engine. The DME engines produce NO_x emissions of 2 to 4 g/kWh. With this range the NO_x emission is comparable to that of the lean-burn gas engine and 40% to 70% lower than the current production diesel engine.

It should be noted that the results with DME over the steady-state European test cycle are not as good as those over the transient test cycles (appr. 1.5 g/kWh over the US HD-transient). One of the reasons for this is probably the higher average load of the European test cycle. At higher loads it is usually more difficult to create high EGR percentages and consequently the NO_x emission will be higher.

For the diesel engine there are two technologies to reduce the NO_x emission by 60% to 70% and be in the range of the lean-burn gas and DME engines. These are EGR and SCR-DeNO_x (Selective Catalytic Reduction). TNO and others have confirmed the effectiveness of these technologies. The TNO results of recent projects are published in respectively [31] and [32]. Along with the (expected) European emissions legislation these results are presented in Table 6.4.

For SCR-DeNO_x an ammonia (releasing) reagent is injected before the catalyst. For transportation application urea instead of ammonia is recommended because of safety reasons. The quantity of the reagent solution is about 5% of the fuel volume.

Table 6.4. ECE 13-mode results for low NO_x diesel engine concepts and European emissions legislation (also ECE 13-mode test procedure), in g/kWh

	Diesel EGR	Diesel DeNO _x ¹⁾	EURO-2 1995	EURO-3 ²⁾ 1999/2000	EURO-4 ²⁾ 2004/2005
NO _x	2.42	2.2	7.0	< 5.0	< 3.0
CO	0.6	0.018	4.0	2.5	1.0
HC	0.2	0.012	1.1	0.7	0.5
PM	0.107	0.10 ³⁾	0.15	< 0.10	< 0.10

1) aqueous ureum reagent injected in exhaust system

2) expected values and introduction date

3) estimated

When comparing the 13-mode NO_x Figures of Table 6.3 and 6.4 the following can be concluded:

- A DME engine with EGR shows similar low NO_x levels as the lean-burn gas engine or the diesel engine equipped with EGR or SCR-DeNO_x.
- The stoichiometric gas engine with 3-way catalyst shows the lowest NO_x emission levels.

The following can be concluded for the other emission components:

- The particulates emissions of the DME engines is at least 50% lower than that of the diesel engines (also when they are equipped with a low NO_x system).
- Little information is available on CO en HC emissions of DME engines. The CO emission of the DME engine are higher than the CO emission of the other engines. CO and HC can usually be reduced by mounting an oxidation catalyst (Refer to the light duty DME engine, Paragraph 6.2)

With a particulates filter (or trap) the particulates emissions of the diesel engine can be reduced to the level of the alternative fueled engines. These filters are however costly and appear to have reliability problems. A new design trap like the CRT (continuously regenerating trap) might reduce or even overcome these problems.

It should be noted that both the DME engines and the low NO_x diesel engine use EGR to control NO_x emission. The diesel engine however will require higher EGR quantities, because the necessary NO_x reduction is higher. Because of this and because of the soot emission of the diesel engine, the EGR system of the diesel engine will be more complex and is possibly more prone to failure.

The following can be said with respect to the costs of a heavy duty DME engine in relation to the future diesel engine:

Advantages of the DME engine are:

- It does not need a very complex EGR system or DeNOx aftertreatment system.
- The diesel engine needs a very expensive, high pressure fuel injection system to keep the particulates emissions within the future requirements.

A disadvantage of the DME engine is, that it might need an oxidation catalyst. This is a relative expensive part, because of the noble materials needed.

6.4 Non-regulated exhaust emission components

Sulphur dioxide [SO₂]

Since DME does not contain any sulphur, also no SO₂ can be formed during the combustion proces.

Standard diesel fuel contains up to 2000 ppm (by weight) sulphur, while for a low sulphure diesel fuel the maximum is 500 ppm. Low sulphure fuel leads for an average passenger car to a SO₂ emission of appr. 0.1 g/kWh (a small proportion is converted into SO₄). The maximum sulphure content of unleaded gasoline is around 100 ppm.

Lower aldehydes:

Because of the molucular structure of DME, it is probable that some formaldehyde (CH₂O) is formed. AVL reported a formaldehyde emission of the Navistar engine of about 10% of the non-methane hydrocarbon emission [1]. The University of Denmark reported a formaldehyde emission of only about 1% of the hydrocarbon emission [24].

Polycyclic Aromatic Hydro carbons [PAH] and Benzene, Xylene & Toluene [BTX]:

Because of the simple molucular structure of DME with only few carbon atoms, it is expected that no significant emissions of PAH and Benzene, Xylene and Toluene take place (just like LPG, natural gas, methanol and ethanol) [27].

6.5 Environmental effects

The environmental effects are divided into:

- direct toxic and nuisance effects,
- long term toxic effects, and
- regional environmental effects (smog and accidification).

Direct toxic and nuisance effects:

CO, NO₂, PM and lower aldehydes:

Good in relation to diesel engines, because of the low NO_x and particulates emission. Care has to be taken with respect to the probably higher CO and aldehyde emissions. If this appears to be a problem, it is recommended to use an oxidation catalyst.

Long term toxic effects:

PAH, BTX and lower aldehydes:

Good, because of low PAH and BTX relative to diesel and gasoline engines. An oxidation catalyst might be necessary to control the aldehyde emission.

Regional environmental effects:

* Summersmog

C_1 - C_{12} , aldehydes, CO and NO_x :

The contribution of NO_x to summersmog depends on the local background NO_x concentration. The contribution can vary from very high (low NO_x in background) to summersmog reducing (high NO_x in background, bad situation).

In normal situation the summersmog potential of the ^{DME}diesel engine will be better than that of the diesel engine (because the NO_x emission is lower), but not as good as the otto engines (especially with 3-way catalyst).

With oxidation catalyst, the DME engine might come close to the otto engines.

* Wintersmog

Related to total PM and SO_2 emissions:

The contribution of DME to wintersmog is small, because of the low particulates and SO_2 emission. The SO_2 emission is very low, because DME-like LPG and natural gas- contains hardly any sulphure.

* Acidification

NO_x and SO_2 :

DME has a 50% to 75% advantage over diesel fuel, because of the lower NO_x and SO_2 emission. Acidification effect is comparable to that of otto engine with 3-way catalyst.

Conclusions

An overall comparison of toxic and environmental effects of the different fuels is presented in Table 6.5.

Table 6.5: Overview environmental effects of different fuels.

	Petrol	LPG	CNG	Diesel	DME
Direct Toxic	o	o\+	+\\++	-\\-	+
Long term Toxic	-\\o	o\+	+	-	o\+
Summersmog	+	+	+	--	o
Wintersmog	o	o\+	o	-	o\+
Acidification	-\\o	o\+	o\+	-	o

++ much better than average

+ better than average

o average

- worse than average

-- much worse than average

From the evaluation above, the toxic and environmental effects of DME can be summarized as follows:

- DME scores better than diesel fuel on all toxic and environmental effects,
- DME is comparable to the otto engines with respect to wintersmog and acidification,
- When the aldehyde and CO emissions can be controlled, possibly through the use of an oxidation catalyst, DME can be as good as CNG and LPG with respect to toxic effects and summersmog.

6.6 Emissions in urban areas

This paragraph contains a projection of the contribution of different vehicle categories to the emissions in urban areas.

In this way the influence on emissions can be determined of replacement of certain vehicles by DME vehicles.

The vehicles are categorized in cars, vans, trucks and buses and for each -when applicable- the different fuels gasoline, diesel and LPG.

The contribution per vehicle class is determined by using statistical data (for the Netherlands) with respect to number of vehicles and city-kilometrage and simulation programs which calculate emissions in g/km for respectively passenger cars, vans/trucks and city buses. For this simulation driving parameters and/or cycles are used characteristic for urban use. For trucks and buses the characteristic cycles used are respectively the Urban part of the FIGE cycle and the (Dutch) Urban Bus driving cycle [28]. These cycles are presented in Appendix E.

The emissions input data used in these programs are based on a large number of passenger cars, vans, trucks and buses tested in in-use compliance test programs

carried out for the Dutch ministry of the environment [43]. These data are extrapolated to the year 2000 [45].

Table 6.6: Vehicle classes and (Dutch) statistical data used for emissions projection in urban areas

Vehicle category	Fuel	Annual kilometrage km	City kilometrage %	Number of vehicles in 1991	Number of vehicles in 2000
Cars	Gasoline	12980	33.9	4349696	5330508
	Diesel	27760	16.8	623266	647334
	LPG	26620	17.6	595892	671300
Vans	Gasoline	12508	80.5	144127	280620
	Diesel	24679	80.5	272885	255683
	LPG	22091	80.5	21801	33045
Trucks < 16 tons GVW	Diesel	23100	22	69890	82750
Trucks > 16 tons GVW	Diesel	83800	22	45000	53280
Articulated trailers	Diesel	93448	20	38464	45541
Busses + Coaches	Diesel	61000	52	12427	17398

Via a spreadsheet program, which combines the statistical data with the g/km data, the contribution per vehicle category to the total emission is calculated. This is for NO_x and particulates presented as percentage of the total emissions in urban areas in Figure 6.3. The projection of the emissions and fuel consumption in urban areas in g/km is presented in Appendix E page 3.

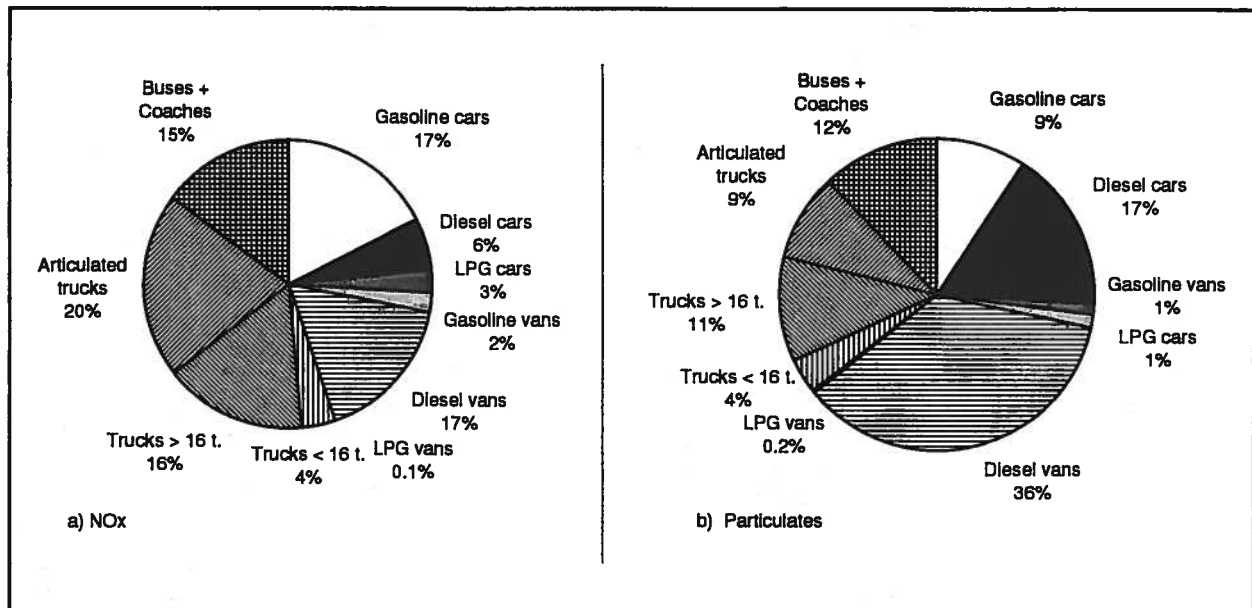


Figure 6.3: Contribution of different vehicle categories to the total emissions of NO_x (a) and particulates (b) in urban areas

The following conclusions can be drawn from Figure 6.3:

- The NO_x emission is for 85% produced by the categories: gasoline vehicles, trucks heavier than 16 ton GVW, articulated trucks and buses. The NO_x production is equally divided over these categories.
- The particulates emission is for 36% emitted by diesel vans. Other large producers are diesel cars (17%), trucks (29%) and buses (12%).

Assuming that DME vans would have a 4 times lower NO_x and particulates emission (this is slightly less optimistic than presented in Table 6.1), it can be concluded that when 50% of the diesel vans are replaced by DME vans, the total NO_x and particulates emissions in the city are decreased by respectively 6% and 13%. For buses 50% replacement would lead to NO_x and particulates reductions of respectively 4% and 5%.

This is assuming that with DME buses the NO_x and particulates emissions would be respectively 2 times and 4 times lower than diesel buses (year 2000: new diesels: 5 g/kWh NO_x, DME 2,5 g/kWh NO_x).

7 Energy efficiency and emissions from well to wheels

7.1 Introduction

The well to wheel energy efficiency and the CO₂ emissions for DME and other fuels are investigated in this chapter. The energy efficiency is expressed as percentage of the total energy input (feed stock, manufacturing, evaporation, transportation, filling).

The fuels included in this comparison are presented in Table 7.1, which also specifies the engine types used in combination with the fuels.

Table 7.1: Fuel engine type combinations used for comparison.

Fuel	Engine type
Fossil:	
DME	diesel
Diesel	diesel
Gasoline	otto
LPG	otto, $\lambda=1$ and lean-burn
CNG	otto, $\lambda=1$ and lean-burn
LNG	otto, lean-burn
Methanol	otto, diesel
Renewable fuels:	
DME	diesel
Bio-ethanol	diesel

Table 7.1 includes two renewable fuels; DME renewable and bio-ethanol. These fuels are only included in the CO₂ emissions comparison. DME renewable can just like methanol be made from wood, straw and crop residues.

For light duty methanol is always used as otto-cycle fuel (spark ignition) while for heavy duty engines it is usually combusted in diesel-cycle engines. This is only possible, when an ignition improver is added to the fuel or with glow-plug assistance. The first one is generally applied. A draw back of the ignition improver are the high costs.

The vehicle types used for the well to wheel comparison are:

- urban buses and,
- light duty vehicles.

7.2 Energy efficiency from well to filling station

The route from recovery to filling station is split up in:

- Recovery & transport:
Includes (sea) transport to production facility
- Fuel production:
Refinery or plant
- Distribution:
 - sea transportation (only DME and methanol)
 - transport to filling station
 - energy necessary to fill the vehicle (especially with CNG considerable compressor work is required).

The energy losses include evaporation losses of fuel during transport and storage.

For Diesel, gasoline and LPG the well to wheel route is somewhat different than for DME and methanol. For the first group there is usually sea transportation in the form of crude oil, then refinery and then distribution of the fuels over land. For DME and methanol it is assumed that the production takes place at or close to the natural gas recovery site, consequently the actual fuel is transported over sea and distributed over land.

For natural gas there are two possibilities:

- A Transportation and distribution is completely land based and via pipelines. There is an option of CNG or LNG operation.
- B Conversion of natural gas to LNG at or close to the recovery site and then transportation of LNG over sea (for example from Indonesia, Brunei, Malaysia and Australia to Japan [20]). It is then efficient to distribute the gas as LNG (by truck or train) to the filling stations, where both LNG and CNG vehicles can be filled.

For this energy efficiency comparison, the CNG options are based on A and the LNG option is based on B. The energy efficiency of LNG under A or B are however expected to be about similar.

The well to filling station efficiencies for the different fossil fuels are summarized in Table 7.2. The break down in the different parts is given in Appendix F, page 1.

Table 7.2: Well to filling station efficiency of different fossil fuels

Fuel / engine	Well to filling station efficiency
Diesel	90%
DME	67%
LPG	89%
CNG	85%
LNG	80%
Methanol	62%
Gasoline	82%

For diesel, gasoline, LPG and DME the numbers for recovery, transport and production are based on the numbers presented in Paragraph 4.1 and Appendix B (for diesel, gasoline and LPG the average of the numbers published by [12, 13, 21]). For CNG, LNG and methanol these numbers are based on [12].

An overview of the well to filling station efficiency separated in recovery & transport, fuel production and distribution is presented in Appendix F, table 1.

The distribution energy loss of most fuels originate from [12]. The distribution energy loss for DME is extrapolated from LPG based on the energy equivalent mass of fuel. On top of that 1% loss is added for sea transportation.

With respect to CNG, the energy consumption of the filling station is based on the "fast filling" option. The energy consumption in that case is approximately 8.5% of the energy content of the fuel. For slow fill (over night) this would be about 2% lower.

7.3 Energy efficiency of vehicles

The energy efficiency of vehicles from fuel energy to mechanical energy at the wheels is dependant on engine efficiency, transmission & rear axle (if applicable) efficiency and power consumption of auxiliaries (fans, air compressor, steering pump).

In order to be able to make a good comparison between the different vehicles, also a correction factor is included for the weight of the vehicle. Especially CNG vehicles weigh more because of the required large and heavy fuel tanks.

7.3.1 Heavy duty vehicles

The engine efficiency for the bus engines running on the different fuels are derived from 13-mode test data. This is done by using special weight factors for urban bus application [28]. In Table 7.3 these weight factors are compared with the official ECE R49 13-mode weight factors.

Table 7.3. Comparison ECE R49 13-mode weight factors with weight factors for urban bus application

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13
ECE R49	0.083	0.08	0.08	0.08	0.08	0.25	0.083	0.10	0.02	0.02	0.02	0.02	0.083
Urban bus	0.171	0.028	0.061	0.114	0.095	0.105	0.171	0.047	0.018	0.012	0.005	0.003	0.171

The heavy duty engine efficiencies for the different fuels are presented in Table 7.4. The values for the diesel-cycle engines are based on a for the Netherlands customary 12 litre diesel engine. For diesel fuel the engine efficiency is expected to go down somewhat to comply with future low NO_x emissions legislation. For EURO-4 legislation TNO estimates a (minimum) fuel consumption increase of some 2.5% [31]. Others are projecting higher increases of up to 8% [35].

For LPG and CNG both lean-burn and stoichiometric engine variants are presented. The values for the otto cycle engines are based on dedicated, 8-10 litre, turbocharged otto engines. Compared to the usual diesel engine conversions, these engines are characterised by a better part load efficiency.

Table 7.4: Heavy-duty average engine efficiencies for urban bus application with different fuels and engine technology.

Fuel	Engine	Engine efficiency	Engine efficiency diesel =100
Diesel, DME, methanol, bio-ethanol	diesel	35%	100
LPG, gasoline	otto, $\lambda=1$	29%	83
LPG, CNG,	otto, lean-burn	32%	91
CNG, methanol	otto, $\lambda=1$	30%	86

The transmission efficiency (including auxiliaries power consumption) is estimated based on chassis dynamometer measurements with city buses carried out at TNO. According to these measurements transmission and auxiliaries represent losses of respectively 12% and 4%, which leads to an efficiency of 84%.

7.3.2 Fuel tank size

The fuel tank size of DME and other fuels is estimated a] to make a correction on the energy efficiency with respect to the weight of the vehicle and b] to get an impression of the lay-out and the operational aspects.

An estimated engine weight is also included in the weight projection of the bus.

The comparison is based on a city bus, with the "Dutch Urban Bus Driving Cycle" as representative test cycle [28].

The tank volume and weight projection is based on the following assumptions:

- LPG and DME are filled to maximum 80% of the tank volume.
- Light weight (composite) tanks are used for CNG storage (specific weight 0.6 kg per litre volume).
- Insulation of LNG tanks is not included in the volume.
- The otto cycle engines weigh 200 kg (approx. 20%) less than the diesel engine, because of the higher (possible) specific power. The DME engine has an 100 kg advantage over the diesel engine, because of the lighter injection system, cylinder block, etc.

The results of the calculations are shown in Table 7.5. The parameters shown are:

- Tank volume,
- Weight bus; including a 50% filled fuel tank,
- Weight correction factor; correction factor for energy efficiency relative to diesel engine.

The weight correction factor is calculated with TNO's simulation program for city buses "Cube" [28].

Table 7.5: Tank volume, weight city bus and weight correction factor for different fuels and engine technologies.

Fuel / engine	Tank Volume (dm ³)	Weight bus relative to diesel (kg)	Weight correction factor
Diesel	250	-	1
DME	590	+ 170	0.99
LPG lean-burn	500	- 20	1
LPG stoich.	550	+ 10	1
CNG lean-burn high calorific	1340	+ 600	0.97
CNG stoich low calorific	1890	+ 950	0.95
LNG	450	+ 40	1
Methanol, diesel	580	+ 150	0.99
Methanol, otto	670	+ 100	0.99
Gasoline	340	- 170	1.01
Bio-ethanol (E95)	450	+ 100	0.99

7.3.3 Light duty vehicles

The engine efficiencies for the different fuels are derived from a comparative measurement program TNO conducted in 1994 with three fuels diesel, gasoline and LPG [33]. The measurements were carried out on a chassis: dynamometer over test cycles which were specially recorded in practise for urban, sub-urban and motorway use. In this study it was determined that the engine efficiencies of gasoline and LPG were respectively 17% and 18% below diesel. This is the average over urban, sub-urban and motorway driving. From this, it is projected that the efficiency of the diesel-cycle engines is 28% and those of the otto cycle engines 23%. The transmission efficiency (for all fuels) is estimated to be 89% (including auxiliaries).

7.4 Well to wheel energy efficiency

The results of the energy efficiency projections from the previous paragraphs are summarized in Table 2 and 3 of Appendix F for respectively heavy and light duty vehicles. The parameters presented in these tables are:

- Well to filling station efficiency:
Energy in fuel divided by total energy input (feed stock, transport, processing, distribution, etc.)
- Vehicle efficiency:
Energy delivered at rear wheels divided by energy input via the fuel. Included is a weight correction factor for the total weight of the vehicle (Paragraph 7.3.2). The same weight correction factor for the bus is also used for light duty.
- Well to wheel efficiency:
Energy delivered at rear wheels divided by total energy input.

The results are graphically presented in the Figures 7.1 and 7.2.

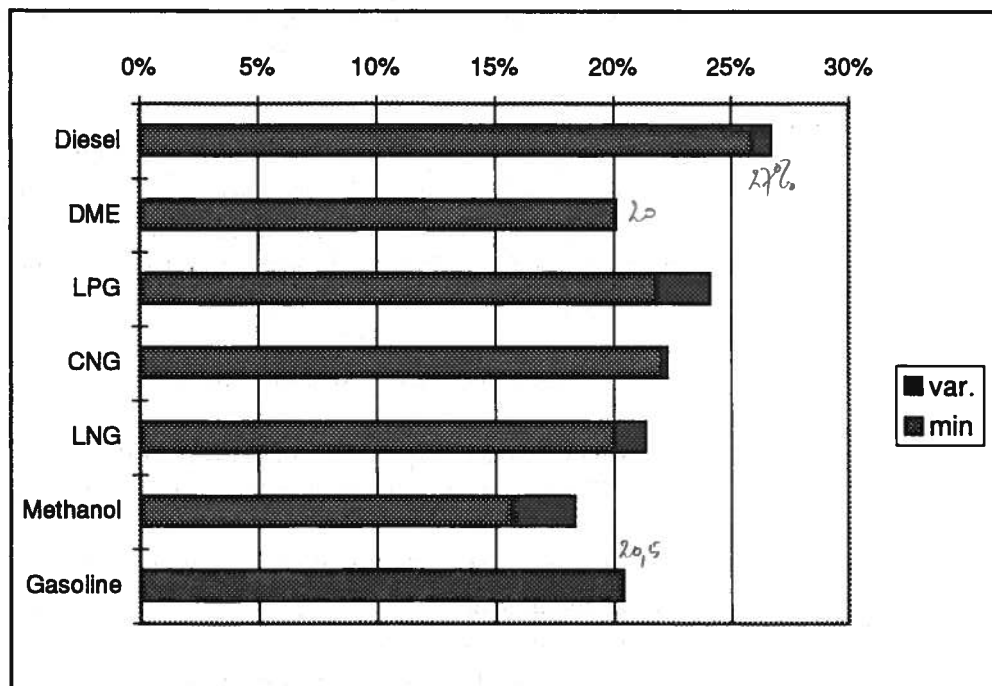


Figure 7.1: Energy efficiency from well to wheel, urban bus application. Range indicates differences in engine type

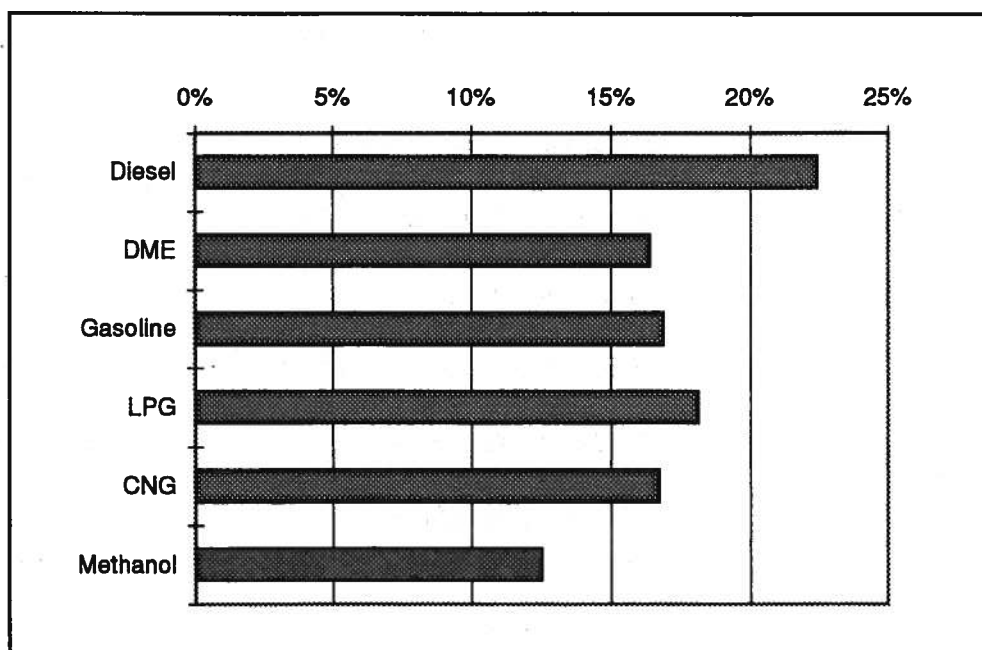


Figure 7.2: Energy efficiency from well to wheel, light duty application (mix of urban, sub-urban and motorway)

From the figures can be concluded that the energy efficiency of DME is one of the lowest. Only methanol is lower and LNG is equal (light duty) or equal to larger depending on the engine type used (heavy duty). The lower energy efficiency is due to the lower efficiency of the fuel production. Refer to Table 7.1 and Appendix F.

7.5 Well to wheel exhaust emissions

The well to wheel CO₂ emission comparison includes both fossil and renewable fuels. The renewable fuels chosen are DME and bio-ethanol.

The CO₂ emission of the fossil fuels from well to wheel (in grams per vehicle km) is determined by:

- the CO₂ emission during the production and distribution of the fuel,
- the CO₂ produced during the combustion of the fuel, and
- the vehicle efficiency (engine, transmission, weight).

The CO₂ emission during the production is primarily determined by the energy supplied for the production of the fuel (heat & power), but also CO₂ can be emitted due to molecular changes in the process of making fuel out of feed stock.

The CO₂ emission during the combustion is determined by the carbon content (in mass%) of the fuel. The carbon content of fuel ranges from 38% for

methanol to 88% for gasoline. When CO₂ emissions are compared it is customary (and necessary) to express the CO₂ emission in grams per MegaJoule energy. For the combustion this can simply be determined by multiplying the carbon content with 3.67 (ratio molecular weight CO₂ and C) and dividing it by the lower heating value of the fuel. Refer to Chapter 2. The values that are then obtained range from 55 g CO₂ per MJ for natural gas to 75 g CO₂ per MJ for gasoline.

The net CO₂ emission of renewable fuels is only determined by the fossil fuels that are used during the production and distribution of the fuel. The CO₂ that is emitted during the combustion of the fuel was already absorbed during the growth of the feed stock. The production of the fuel includes cultivation, harvesting, transportation and conversion (from feed stock to fuel). The energy necessary for the conversion is usually large in relation to the energy content of the fuel. Consequently it is important to use renewable energy sources, like straw and wood, for this.

The production of DME as a renewable fuel is almost the same as for methanol. First synthesis gas is produced by gasification of wood or straw. This then can be converted to DME or methanol. Refer to Paragraph 3.4.

Bio-ethanol can be made out of different feed stocks with considerable differences in CO₂ production for the conversion process. For this comparison two processes are chosen; the "three residues process" which uses sugar, wheat and straw as feed stock and a process which uses only wheat and straw [12].

For the CO₂ emissions of the fuel production of diesel, gasoline and LPG is referred to Paragraph 4.2. For DME is referred to Haldor Topsøe [2] and for CNG, LNG, methanol and bio-ethanol is referred to Ecotraffic [12]. DME renewable is derived from bio-methanol.

The comparative CO₂ emissions for the different fuels are determined by dividing the CO₂ emissions of both production and combustion by the vehicle efficiency and then adding them up.

Full details for the CO₂ emissions calculation for both fossil and renewable fuels are presented in Appendix G. The data presented include vehicle efficiency, CO₂ emission during production and during combustion (both in g/MJ) and CO₂ emissions for the urban bus application relative to the diesel fuel.

The well to wheel net CO₂ emission is graphically presented in the Figures 7.3 and 7.4 for respectively heavy and light duty vehicles.

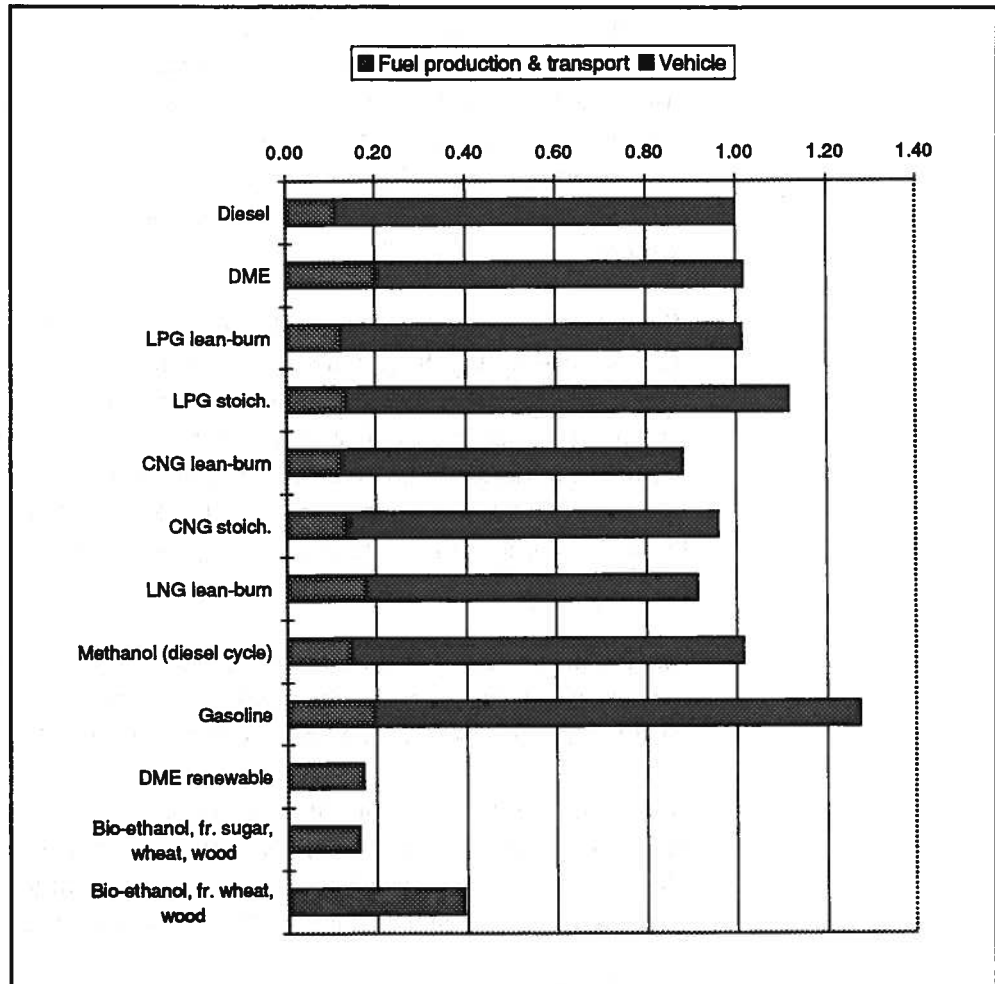


Figure 7.3: Well to wheel net CO2 emission with different fuels, urban bus application. Source Ecotrafic and TNO

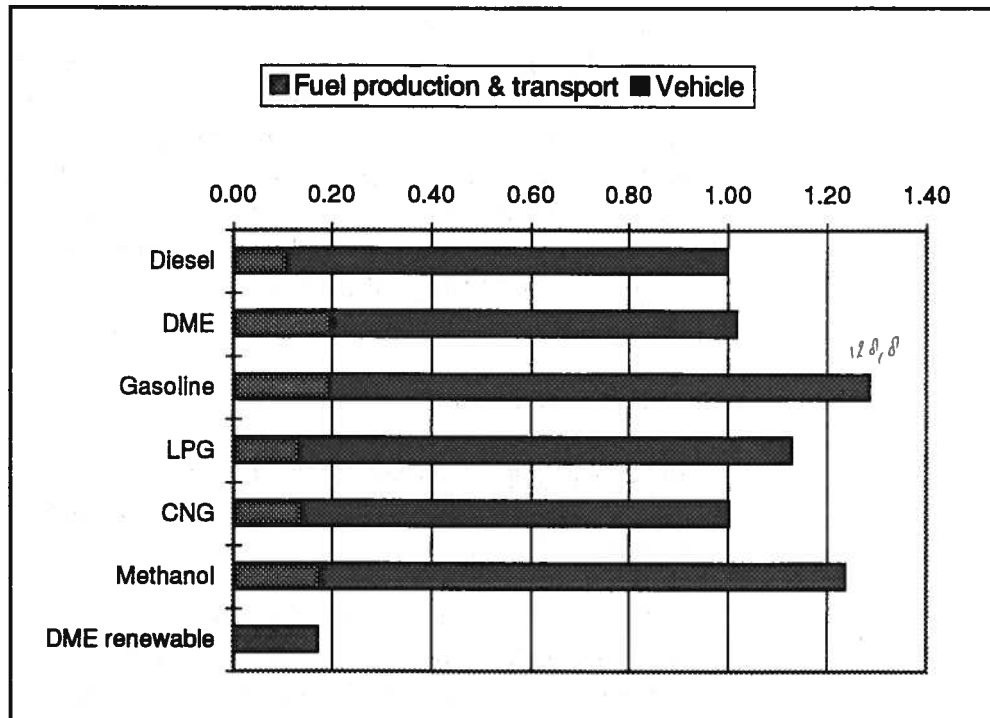


Figure 7.4: Well to wheel net CO₂ emission with different fuels, light duty application (mix of urban, sub-urban and motorway).

From the Figure 7.3 and 7.4 can be concluded that for urban bus application, natural gas has the lowest overall CO₂ emissions, followed by diesel, DME and LPG with about equal quantities.

For light duty however, diesel, DME and CNG are on the same level and LPG (and the other fuels) are higher (Figure 7.4).

The differences between light and heavy duty have two reasons:

- for light duty lean-burn variants of CNG and LPG are not included,
- the engine efficiency difference between diesel and otto cycle is for light duty larger than for heavy duty.

The renewable fuels; DME from wood and straw and bio-ethanol show very low (net) CO₂ emission figures. The CO₂ emission of renewable DME is only 18% of that of diesel fuel. Bio-ethanol shows CO₂ emissions from 17% to 38% of that of diesel fuel.

To calculate the "global warming potential" other exhaust emissions of both vehicle and fuel production, multiplied by certain factors, should be added to the CO₂ emission. The IPCC (Intergovernmental Panel on Climate Change) uses the following factors to calculate the global warming potential in a 100 year perspective: CO₂: 1, CH₄: 21, NO_x: 7, N₂O: 290, CO: 3, HC: 11.

Information regarding the contribution of non-CO₂ components can be found in [12] and [26]. According to [12] the contribution of non-CO₂ components ranges from 5% and 20% depending on the fuel and engine technology used. NO_x, N₂O and CH₄ are usually the largest contributors apart from CO₂. N₂O is produced in small quantities in cars equipped with three-way catalysts, but contributes significantly due to the high factor. According to [26] the contribution of N₂O to the greenhouse gas emission is the largest for CNG and LPG engines (15%-20%). Concluded can be that the relative position of DME in the Figures 7.3 and 7.4 will improve when the overall Global Warming Potential is considered.

7.6 Fuel costs

In this paragraph a comparison of the net fuel costs of different fuels is made. The net fuel costs are obtained by correcting the fuel costs with the vehicle efficiency.

IPCC [34] published in 1994 a list of retail costs of various regular and alternative fuels. This list is used a basis for the cost comparison. The list is presented in Table 7.6. The costs of "ethanol from sugar cane" seems unrealistic low. Other prices correlate reasonably well with the fuel cost figures published by [12, 19, 37].

Table 7.6: *Retail costs of regular and alternative fuels, without tax, in US\$ per liter gasoline equivalent. Source [IPCC]*

Fuel	Fuel cost (US\$/liter, pre-tax) gasoline equivalent
Gasoline	0.26
Diesel	0.26
CNG	0.18 - 0.24
LPG	0.19 - 0.26
Methanol from nat. gas	0.25 - 0.35
Methanol from wood	0.68 - 0.82
Ethanol from sugar cane	0.25 - 0.28
Ethanol from maize	0.94 - 1.03
Ethanol from wood	0.68 - 0.82
Liquid hydrogen	0.38 - 1.44

DME is not included in the list. The production set-up of DME is however very similar to methanol production. This applies to both the technical arrangement of the production process and the infrastructure aspects (production of liquid fuel of cheap natural gas and consequently sea transportation of the liquid fuel). Haldor Topsøe reports that the energy efficiency of production of DME is about 5% better than for DME and that the relative investment in a production plant of the same size is 4%-8% lower. The relative investment of a 2.4 times larger

plant would be about 20% lower. This concerns the production of fuel grade DME instead of a chemical grade.

Based on this, it can be projected that the production costs of large scale DME production per unit of energy could be some 10% lower than for methanol. A further cost reduction may be possible when new production technologies, such as proposed by DSM [29], prove successful.

For this comparison it is assumed that the production costs for DME ranges between equal to methanol to 10% below methanol. The costs for sea transportation and distribution are also assumed to be the same. The possible disadvantage of DME because it has to be transported under pressure, is assumed to be compensated by the fact that the energy content per unit mass and volume are higher (respectively 45% and 22% compared to methanol).

The net fuel costs are obtained by dividing the fuel costs per unit of energy by the vehicle efficiency. The fuel costs, relative to the diesel fuel costs, are graphically presented in Figure 7.5. The range per fuel is due to the range in fuel costs (Table 7.6) and differences in engine technology.

The differences in engine technology are as follows:

- Diesel:
Higher energy consumption (2.5%) due to lower NO_x limits, EURO-3 versus EURO-4 engine.
- LPG/CNG/LNG/gasoline:
Lean-burn and stoichiometric engines.
- Methanol:
Otto and diesel cycle.

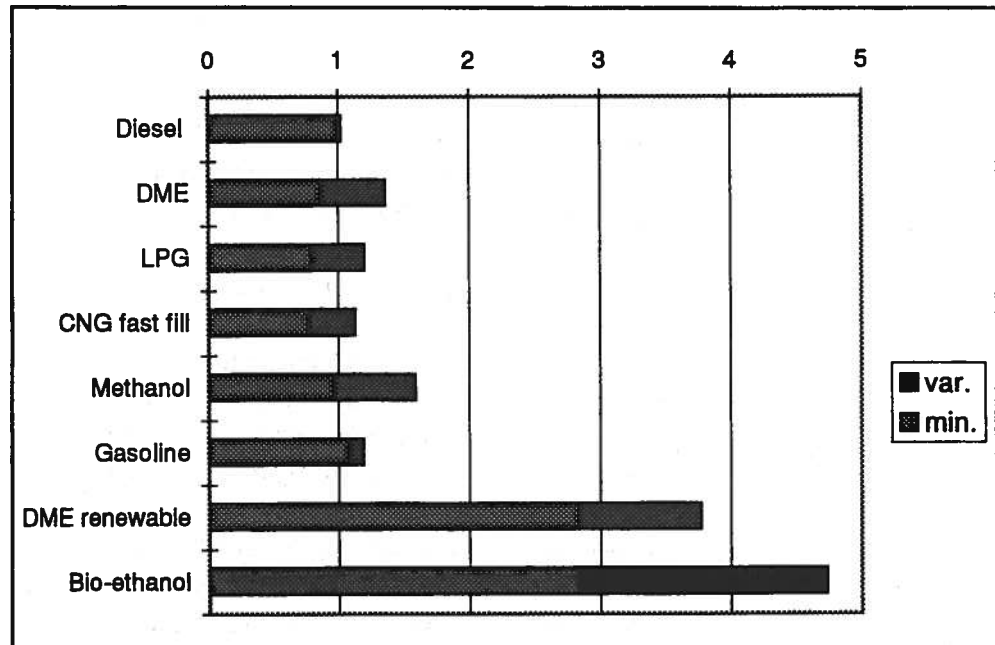


Figure 7.5: Retail fuel costs without tax, corrected for vehicle efficiency, urban bus application (diesel=1). Source IPCC & TNO

From Figure 7.5 can be concluded that the fuel costs of diesel, LPG and CNG are the lowest. The DME price range starts at 10% below diesel but ends about 35% above it.

The gasoline fuel costs are according to Figure 7.5 10% to 20% higher than the diesel fuel costs. This is fully due to differences in engine efficiency. Amoco and AVL project a price difference of gasoline and diesel of almost 90% [10]. This big difference can partly be explained by the difference in otto and diesel cycle efficiency. TNO projects a difference compared to diesel of 10% for lean-burn and about 20% for a stoichiometric otto engine, while Amoco and AVL project a difference of 40%. The projection of TNO is based on the application of dedicated, relatively highly loaded, otto cycle engines with good part load efficiencies.

8 Safety

DME safety and environmental aspects of DME were first extensively studied in the seventies. At that time the concern arose that the increasing release of chlorofluorocarbons (CFC's) possibly caused harmful effects for the ozone layer and for the health of man and environment as a result. This led both in the Netherlands and abroad for a search for an alternative. DME has been investigated in this context and is considered to be safe for use as a propellant [40, 46, 47]. Most results of this safety research work can be used to evaluate the safety of DME as an automotive fuel. The behaviour of DME can be compared to LPG (Propane + Butane) because of the similar vapour pressure (Figure 8.1). At TNO there is a lot of experience with the use and safety of LPG and CNG as automotive fuels. This experience covers for example crash safety, fire safety and type approval and can be applied to the storage and handling of dimethylether.

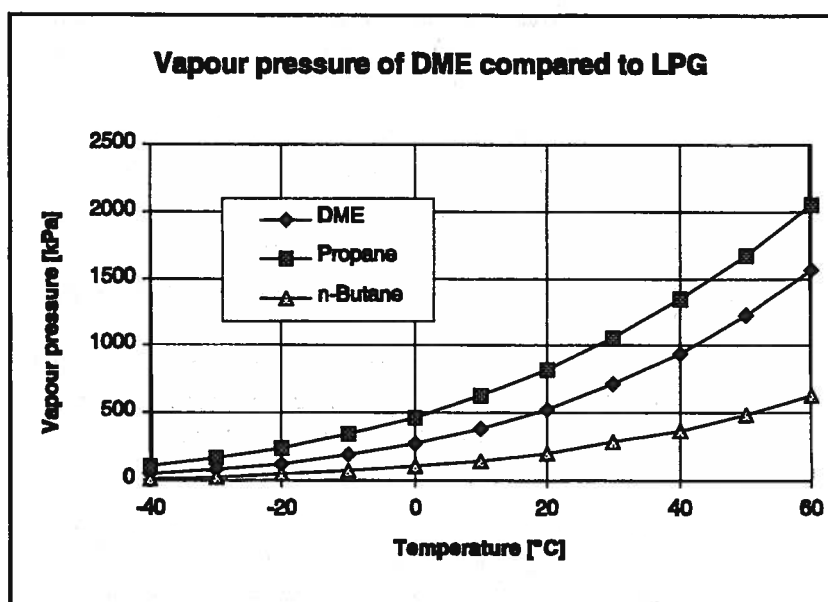


Figure 8.1: The vapour pressure of pure DME relative to Propane and Butane

8.1 DME flammability

The properties indicate a low auto ignition temperature of 235°C compared to 365-470 °C of LPG. This worse property is somewhat compensated by the fact the lower explosion limit of 3.4 vol% is almost twice that of LPG (1.7-2.0 vol%). Figure 8.2 shows that the lower explosion limit of DME goes up (which means safer) when it is diluted with water.

Because of the lower auto-ignition temperature it will be possible that a DME-air mixture in the engine compartment due to a leakage is ignited by hot engine

parts, like the exhaust manifold. For this fire hazard it is important that the fuel lines of DME are from metal, such that no sudden large quantities of DME can flow in the engine compartment due to melting of a fuel line.

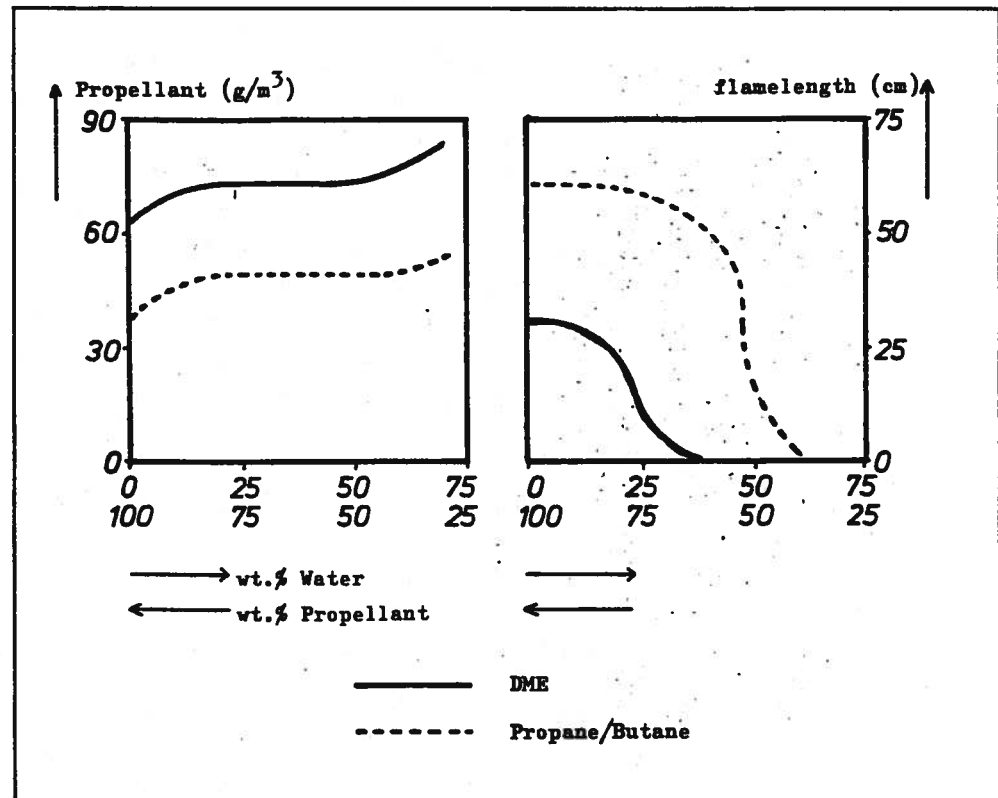


Figure 8.2: Flame lengths and lower explosion limits of a number of propellants sprayed from an aerosol can. Source [40]

Production and transportation therefore require precautions like LPG to prevent accidents like the one in 1948 in Germany (BASF). This was one of the heaviest industrial catastrophes, caused by BLEVE (= Boiling Liquid Expanding Vapour Explosion). This can happen with a fire accident causing the top of a DME tank to weaken and rupture due to the bad heat transfer of the gaseous DME in the top of the tank. In paragraph 8.4.4 it will be shown that BLEVE has never occurred in automotive accidents.

The formation of peroxides from DME in the presence of UV-light which might cause spontaneous explosions, has proven to be negligible, unlike diethylether or diisopropylether

8.2 DME behaviour in the atmosphere

If DME is released into the atmosphere it will be degraded by a photochemical reaction with OH-radicals. The most likely degradation products are carbon dioxide and water. The tropospheric half-life is 3-30 hours for the lower level in bright weather and 100-150 hours for the upper level [40]. There is no release of DME into the stratosphere.

In Europe about 4 million cans are filled with DME annually, this release does not contribute to the development of photochemical smog [40].

8.3 Toxicity of DME

About fifteen years ago most people thought dimethylether was a narcotic and toxic substance that could absolutely not be used as a propellant. A lot of research since 1977 has shown that DME does not endanger the environment nor human health in any way. However, a lot of people still associate the name "ether" with negative effects.

DME does not have to be classified as a dangerous toxic substance. The LC_{50} -values (lethal concentrations) for mice are e.g. 380.000 ppm after exposure of 30 minutes and 490.000 ppm after 15 minutes, the odour is unbearable at these concentrations.

DME is not irritating, causes no skin sensitisation and has no mutagenic or teratogenic properties at concentrations below 40.000 ppm. Pregnant rats were observed while exposed at 40.000 ppm DME from days 6-15 of pregnancy (6 hours a day), this had a toxic but no teratogenic effect. The so-called 'no adverse embryo/foetotoxic effect level' has been set at 28.000 ppm [40].

Concentrations of 80.000-120.000 ppm are mentioned as the lowest at which a narcotic effect is caused by DME. This value is slightly better than those that apply to propane and butane (50.000-100.000 ppm).

8.4 Safety of DME as an automotive fuel

8.4.1 Reliability of system components

The "basic" components of a DME-fuel system, can be of the same design and function as those of a LPG-system. The only exception in this respect are the sealings and rubber hoses, which need to be DME-proof during the lifetime of the vehicle.

Other components like the injection equipment need to operate entirely on the feed pressure level (up to 20 bar) including fuel return lines.

Below a summary is given of the Dutch safety demands of the different LPG components which could be applied for DME as well.

Filler valve

- Must withstand a pressure of 5 MPa
- Adjust sealing for DME-use

Filling hose

- Flexible rubber hose with two fixed conical connections
- Material has to be adjusted for DME-use

Maximum filling device

- Must withstand a pressure of 5 MPa
- A mechanical device closes a valve when the 80% level is reached to prevent further filling of the tank

Level indicator

- Must withstand a pressure of 5 MPa

Tank

- Max. system pressure: 2.5 MPa
- Test pressure: 3.0 MPa
- Burst pressure: > 10.0 MPa
- Ten year validity of approval
- Tank material: St 37.2 (DIN 17 100)

Safety relief valve

- Opens when tank pressure rises above 2.5 MPa (± 0.2 MPa)
- Placed in gaseous zone of tank

Take off valve on tank

- Must withstand a pressure of 5 MPa
- Closes when engine stops running
- Excess flow valve installed in case of large fuel leakage

Fuel supply pipe

- Material: seamless stainless steel / brass
- Pipe is covered with plastic or rubber to guide leaking gas towards engine compartment or via gas tight housing to the air ventilation tube mounted in the bottom of the car body
- Special attention is paid to the location of the pipe

Fuel solenoid

- Mounted in engine compartment, closes when engine stops running (switched parallel with take off valve on tank)

8.4.2 Crash safety

Extensive full-scale crash tests were conducted the past fifteen years at TNO to test the integrity and strength of a particular LPG vehicle conversion. These tests clearly indicated that vehicles equipped with LPG-systems offer a (fuel tank with) safety equal to, or greater than, original gasoline vehicles. A DME-fuelled vehicle will have a comparable fuel supply system with an even safer fuel (it takes a lot more DME to reach the lower explosion limit, see Paragraph 8.1). A DME fuelled vehicle will therefore be at least as safe as an LPG-fuelled vehicle.

From different crash tests carried out at TNO, it turned out that automotive LPG tanks can withstand very high forces and deformations without leaking. Sometimes when accessories were hit, small leakage's of these accessories occurred. Once the excess flow device in the take off valve had closed due to a fuel line rupture [48].

8.4.3 Fire safety

One of the great advantages of diesel fuel is its fire safety. Diesel fuel is not only proven to be safe but is also generally accepted as safe which is very convenient when a vehicle has to be promoted. Gasoline is also generally accepted as a safe fuel even though gasoline vehicles are involved in more fire accidents than diesel vehicles. The reason for this is the fact that the gasoline is transported and handled in tanks and tubes with no special temperature demands or collision strength though it is a much more volatile fuel than diesel. Even though LPG is used as a fuel for engines for over 40 years, many people still entitle them as dangerous. Fire tests have shown that not the LPG system but the gasoline system is most dangerous in case of fire accidents. The same can be said for a DME fuelled vehicle. The fire precautions of the DME storage and handling systems will make the use of a DME vehicle as safe as a current diesel vehicle. Vehicle fires caused sometimes by LPG leakage, gasoline leakage, or carburettor fires never created an explosion of an LPG tank. This is also due to the mandatory installation of pressure relieve valves in many countries.

Extensive tests and full-scale simulating of fire accidents at TNO have all shown the same behaviour of the LPG-fuel system [48]:

- In several minutes the tank pressure rises from about 0.5 MPa to 1.8 MPa.
- The pressure relief valve starts blowing off.
- After two minutes a stabilised situation exists with a flame of about two meter length on the outlet of the safety relief valve and a pressure of about 1.9 MPa in the tank.
- The tank does not lose its strength due to overheating because the vaporisation of the LPG consumes the heat.
- About four minutes after the fire has stopped, the safety relief valve closes again.

Comparing these LPG results with the use of DME shows that:

- It takes more heat to vaporise DME than LPG
- The lower explosion limit of DME is twice as high (safe) as LPG
- The flame length of DME is much smaller than the flame length of LPG

In a real vehicle fire situation, an accident with a DME-fuel tank will depend on:

- The position of the tank relative to the location of the fire

- The material of the tank relative to the thermal capacity and heat transfer coefficient of tank + fuel
- The dimensions of the tank and the amount of fuel in it
- The correct operation of the safety relief valve

8.5 Conclusion

DME safety:

Dimethylether handles exactly like LPG and there is no indication that the use of DME as fuel presents a danger for the environment of human health.

Environmental

- Short half-life in troposphere
- Reacts to H₂O and CO₂
- No release into stratosphere

Health

- Not a toxic, embryotoxic, narcotic or irritating substance
- No carcinogenic, mutagenic or teratogenic properties

Use

- Like LPG
- Visible flame
- Strong odour at higher concentrations
- Non-corrosive
- Small molecules with a high solubility

Collision safety:

High speed collision tests have been conducted in the past 15 years to test the integrity and strength of a particular LPG-vehicle conversion. The results of these tests and the current knowledge about DME indicate the safety is greater than gasoline vehicles and comparable with original diesel vehicles.

Fire safety:

When the same safety precautions are applied to DME as to LPG, the fire safety of DME is the same as diesel and LPG.

9 Automotive market application

9.1 Market selection

The advantages of DME compared to diesel fuel are low exhaust emissions and low noise level. These advantages are most appreciated in urban areas, when the DME vehicles replace diesel vehicles.

In Paragraph 6.6 an assessment was made of the contribution of different vehicle categories to the emissions in urban areas.

Diesel vans and buses are considerable contributors. They produce respectively 17% and 15% of the NO_x and respectively 36% and 12% of the particulates emission.

Using DME for these vehicle groups; vans and buses, will also control the problem -inherently to a new fuel- of not having a complete infrastructure of refuelling stations. Buses for public transportation always return at night to a central point for refuelling. For vans this is the case for vehicles that belong to certain fleets, like mail collection and delivery, public services and police. A third group that may qualify are taxis, which are often diesel powered.

Barriers for DME as an automotive fuel are:

- No large scale production of DME. Consequently a high price of DME during demonstration and market introduction programs (Refer to Paragraph 9.3).
- Introduction of other alternative fuels such as LPG, CNG/LNG and methanol not successful. Lack of stringent emission legislation which require cleaner fuels.

9.2 Market introduction

If the objective would be to acquire a market share with DME comparable to LPG (Netherlands 10%) the following phases would have to be gone through:

- Development of DME engines,
- Execution of demonstration programs to acquire users and public acceptance,
- Instalment of DME production capacity proportional to consumption,
- Set up of an infrastructure of DME filling stations.

It is clear that especially the first two steps cannot be taken without government support. The costs that would have to be covered can be split up as follows:

- Costs for development of DME fuel injection systems and engine optimization,
- Costs of demonstration programs:
 - project management, emission measurements and reporting

- vehicle conversion and additional maintenance.
- additional fuel costs, because of small scale (refer to Paragraph 9.3).

A possible market introduction scheme including an indicative time path is presented in Figure 9.1.

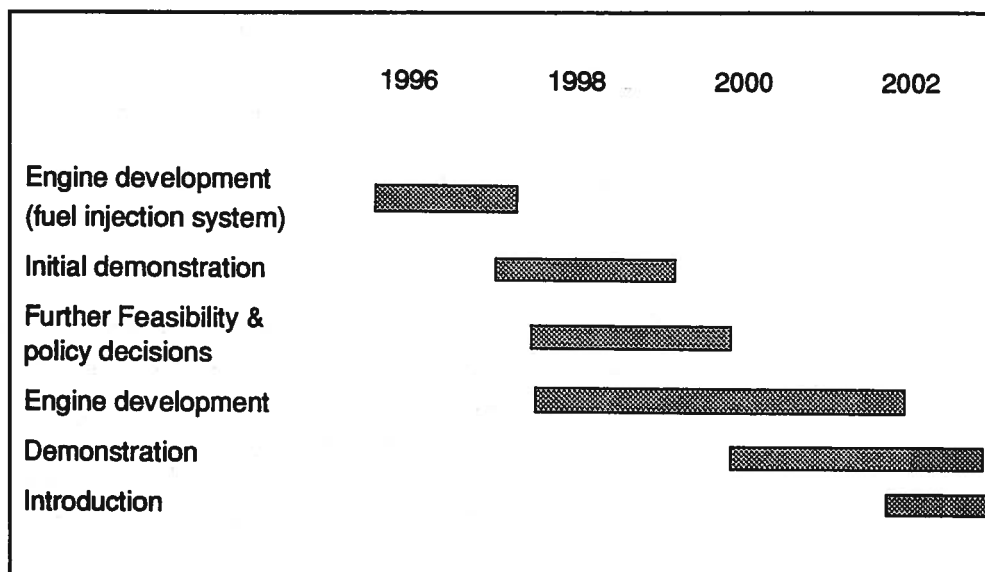


Figure 9.1: Possible introduction scheme for DME vehicles

Below follows a description of the phases:

Engine development (fuel injection system):

In the first phase engine development a dedicated DME fuel injection systems is developed or an existing diesel or methanol fuel injection equipment is adapted for DME. This is then fitted to an existing diesel engine and the combustion is optimized for low emissions and fuel consumption. The development has to be completed with endurance testing on the engine dynamometer and with one or two vehicles.

Initial demonstration:

After the first phase engine development the first demonstration program(s) with 5 to 15 vehicles can take place.

Feasibility study:

During the first demonstration programs further feasibility of DME as an automotive fuel should be carried out. This should include further evaluation of the role of DME in the global energy supply (also Refer to Chapter 10), environmental effects, technical feasibility (OEM acceptance) and last but not least the investigation of barriers.

Engine development:

The second phase engine development includes (further) development of dedicated DME fuel injection system(s) and combustion optimization to further decrease exhaust emissions and fuel consumption. It could also include the development or conversion of a lighter weight (otto) engine block.

Demonstration:

The second phase demonstration would include field testing preferably at different places, with fleets with 50-100 vehicles.

During the demonstration programs exhaust emissions, fuel consumption, wear and maintenance should be monitored and reported.

Since the results in terms of technical feasibility and operational acceptance might work out quite differently, it would be desired to have different development and demonstration programs be carried out in parallel. These should include both light duty and heavy duty vehicles.

At this moment different development programs are carried out and demonstration programs are prepared:

- AVL powertrain is developing a common rail fuel injection system.
- A demonstration program with three buses for public transportation is prepared by Haldor Topsøe, Volvo and Statoil. After initial road testing in Sweden they will be put in service in three cities in Denmark. This is planned for mid 1997. The number of buses might be expanded to 6 in the course of the program.

For the companies that eventually will make the DME vehicles commercial available there are two options: Via OEM (original equipment manufacturer) channels or via the parts supply or retrofit industry.

OEM motivation to come with such products could include:

- local law enforcement; for example stringent city emission requirements for NO_x and particulates (for buses) which cannot be met with diesel engines,
- image / marketing reasons (to have a very clean engine in the product line),
- law enforcement; due to the emission requirements for HD diesel engines for the next decade, the diesel engine becomes much more complicated than it is today. A DME engine might be a lower priced alternative.

For heavy duty engines close OEM cooperation is almost mandatory, because of the high requirements with respect to reliability and maintenance. For light-duty also the retrofit route is certainly an option. In the Netherlands there is an infrastructure for production and distribution of retrofit packages for LPG/CNG systems. This same infrastructure can probably be used for DME.

9.3 Fuel costs during introduction

DME is currently only produced in small quantities in high chemical grade for the pharmaceutical industry. The production is, via dehydration of methanol, and not directly from natural gas. As a result the price is very high in relation to world energy prices. The current DME price is about \$ 50/GJ, which is about a factor 10 higher than the wholesale price for oil products (excluding tax).

It is clear that these fuel prices will have a considerable influence on the costs during the different phases of the introduction of DME as an automotive fuel. The approximate average energy consumption of a van and a city bus in the Netherlands are respectively 90 and 1000 GJ per year. This means that during demonstration programs, for a typical van about \$ 4000 per year is needed to compensate for the additional fuel costs. For a city bus this is \$ 45000 per year.

The price of DME will come down if a methanol plant can be converted to DME or if a DME plant can be build of that size. Such a DME plant would produce about 1500 to 1800 ton DME per day, which corresponds to about 13 to 15 million GJ per year. This means that 150,000 vans or 15,000 buses, or a combination of this would have to be in service to keep one plant operational. The DME production costs would in that case come down to about \$ 8/GJ.

The best option during the introduction phase will probably be the conversion of a methanol plant such that it can also produce DME in a variable quantity [2, 10].

A further price reduction to below the diesel price level is according to [10] possible with plants with a production capacity of 5000 ton per day, which uses cheap natural gas feedstock of \$ 0.75 per GJ. This cheap natural gas is readily available in countries like Venezuela, Australia, Nigeria and Indonesia. Refer to Appendix A.

10 Position DME in global energy supply

In the previous chapters it has been demonstrated that DME is an attractive alternative fuel. With a limited amount of research and development DME engines already demonstrated exhaust emission levels comparable to lean-burn LPG and natural gas engines (heavy-duty) and even comparable to vehicles with 3-way catalyst (light-duty). The exhaust emission levels are clearly better than diesel cycle engines running on methanol and ethanol. The well to wheel CO₂ emissions have been projected to be about equal to diesel fuel.

The strong point of DME as an automotive fuel is, that the overall performance with respect to environment, operational aspects and economics is good. It does not show serious disadvantages, which are sometimes seen with other alternative fuels. Examples are the storage (CNG, LNG) and the necessity of ignition improver (methanol & ethanol). The only other alternative fuel for which this is also the case is LPG.

For the energy supply for the next 30 years it is expected that natural gas will gradually play a more important role. The natural gas reserves are about the same as those of crude oil, but the consumption is only about half [18]. In this context it will become increasingly more important in the future to transport natural gas over longer distances. This can be done by pipelines, LNG and gas-to-liquid fuels conversion processes (such as methanol and DME) [36, 40, 18, 19].

For environmental reasons it is also necessary to find economic ways of using associated gas from crude production. The quantity of gas being flared-off equals to 8-10 million GigaJoule energy per day [19, 41]. This is 2 to 2.5% of the energy content of the crude oil.

With respect to the transport of natural gas from remote locations there is a trade-off between the distance of the sea transportation and the way of transport; pipeline, LNG or methanol (Refer to Appendix D and IEA [36]). The figure in Appendix D shows that up to a distance of 3000 miles a pipeline is the cheapest way of transport. LNG and methanol are cheaper above respectively 3000 and approximately 7000 miles. This does not include the energy efficiency of the vehicle.

LNG can only economically be made in large production plants and is because of this less or not suitable for small natural gas sites or associated gas. Concluded can be that there can be a significant role for methanol and DME to transport energy to the market. If this energy would be used for transportation and the higher engine efficiency of DME would be included, DME is expected to be more cost effective than CNG when the energy has to be transported over distances of more than 5000-7000 miles.

Methanol is already being produced on a large scale from natural gas from remote locations. The methanol is however not used as a transportation fuel, but as feed-stock for the chemical industry. Methanol has also been proposed as the liquid fuel for automotive application and to transport associated gas from oil production.

DME could equally well fulfil this role. Because of the favourable characteristics of DME as an automotive fuel it may well increase the demand for natural gas from remote locations or associated gas. DME could be produced parallel to methanol both in combined and separate production plants, where the methanol is sold as feedstock for the chemical industry and DME as the automotive fuel.

Fuels from biomass:

Methanol, ethanol and RME (rape-seed methyl-ester) have generally been proposed as the renewable fuels for automotive application. DME can be added to this list. The production of (renewable) DME is similar to methanol via gasification of the feedstock.

The renewable feedstock and the conversion techniques for the different fuels are as follows:

- Methanol/DME: Via gasification:
Wood, straw, crop residues, miscanthus
- Ethanol: Via Fermentation (biological conversion):
- Sugar beet, wheat, potatoes, maize
Via fermentation & hydrolysis:
- Wood & crop residues
- RME: Press
- Rape seed

An important parameter for renewable fuels is the "net fossil energy consumption" (sometimes called primary energy ratio):

This can be kept low by using total energy and renewable fuels for the overall production process. For the best conversion techniques the net fossil energy input can be limited to about 10% of the energy content of the fuel [12].

The production costs of the renewable fuels vary widely depending on boundary conditions and production processes. The current costs are projected to be 100% to 250% higher than the costs of fossil fuels [12, 19, 37, 42]. This is without the ignition improving additives necessary for diesel cycle methanol and ethanol engines. Shell believes that by 2020 the costs of renewable fuels will be competitive with fossil fuels, provided that necessary developments take place and are successful [18].

As an automotive fuel DME has shown the potential of low exhaust emissions (refer to chapter 6). Unlike methanol and ethanol DME does not need an ignition improving additive. Up till now the costs of these additives have been very high. Methanol and ethanol can also be used in otto-cycle engines. In that case a 3-way catalyst can be installed and the regulated exhaust emissions are excellent and probably better than what can be achieved with DME. The otto cycle engine has however disadvantages with respect to engine efficiency and CO₂ emission.



11 Conclusions and recommendations

The following can be concluded with respect to exhaust emissions levels of DME fuelled engines:

- * Based on exhaust emission measurements with 3 different engines at AVL and 1 engine at the university of Denmark the following exhaust emissions results have been projected:
 - NO_x emissions for medium/heavy duty engines comparable to those of lean-burn LPG and natural gas engines (50% to 70% lower than commercially available EURO-2 diesel engines).
 - NO_x emissions for light-duty engines comparable to those of otto engines with three-way catalyst.
 - Particulate (soot) emissions approaching those of gas engines.
 - In general compliance with expected 2000-2004 emissions legislation for light and heavy-duty vehicles in Europe and the US, provided that an oxidation catalyst is used.
- * The DME test engines used EGR (exhaust gas recirculation) to reduce NO_x emissions. It is expected that further engine optimization (combustion, fuel injection and turbocharging) can further lower NO_x emissions with or without EGR.
- * A low emissions heavy duty DME engine is likely to be cheaper than future diesel engines with very low emissions.
- * Future diesel engine concepts using either EGR or DeNO_x catalytic aftertreatment have demonstrated compliance with HD emissions legislation of 2004/2-005. Disadvantages compared to DME fuelled engines are the complexity, the need of reagent injection (only with deNO_x catalyst) and the higher particulates emissions. Particulate traps have up till now not demonstrated reliable operation, although promising developments still take place.
- * Because of the simple molecular structure of DME it is expected that no significant emissions of PAH (polycyclic aromatic hydrocarbons) and Benzene, Xylene and Toluene take place (just like LPG, natural gas, methanol and ethanol).

- * Because of the oxygen atom in the DME molecule, there is a risk of emission of lower aldehydes (just like methanol and ethanol). For one engine a formaldehyde emission of 10% of the hydrocarbon emission has been measured.
- * SO₂ emission will be low, because of the absence of sulphur in DME (just like LPG, natural gas).

With respect to environmental and safety issues the following can be concluded:

- * The well to wheel CO₂ emission of DME is for light duty vehicles about equal to diesel fuel and CNG and about 25% lower than gasoline. For heavy-duty vehicles, CNG/LNG have a 5-10% lower CO₂ emission than DME and diesel.
- * For light duty application the well to wheel energy efficiencies of DME, gasoline and CNG are about equal (16%-17%). Considerable better is diesel fuel (22.5%).
For heavy duty application the energy efficiencies for the lean-burn gas engines are better than for DME. For urban bus application some numbers are: DME: 19%, CNG lean-burn 22%, LPG lean-burn: 24% and diesel 26.5%.
- * DME has a short-half live in the troposphere, and no release to the stratosphere.
- * DME is virtually non-toxic
- * With respect to fire and collision safety DME is very similar to LPG.

The following position is proposed for DME in the future world-wide energy supply (also proposed and investigated for methanol):

- * Exploration of natural gas from remote locations; Australia, Indonesia, Nigeria, Venezuela
(transportation > 5000-7000 miles)
- * Exploration of associated gas from crude oil production
(up to 2.5% of energy content crude oil)
- * Production of renewable fuel, from waste or specially produced feedstock, like wood, straw and crop residues.

The fuel costs (corrected for engine efficiency) of DME made from natural gas is expected to be between 90% and 135% of the diesel fuel costs. This is only marginally higher than the range for LPG, CNG and LNG. When natural gas

needs to be transported over a long distance (> 5000-7000 miles) the DME fuel costs will be lower than pipeline natural gas costs.

The following subjects are recommended for further evaluation:

- * Investigation of barriers for market introduction of DME and alternative fuels in general.
- * Investigation of the technical and economical possibilities to produce DME from associated gas from crude oil production.
- * Feasibility of DME production from biomass. This should include costs analysis and a comparison with methanol and ethanol from biomass.
- * Evaluation of the DME role with respect to Enhanced Emissions Vehicles program (EEV: stringent exhaust emissions requirements for cities):
 - comparison with other alternative fuels,
 - comparison with clean diesel engine concepts.
- * Possibilities to make DME cost effective available for demonstration programs and the first phase market introduction.

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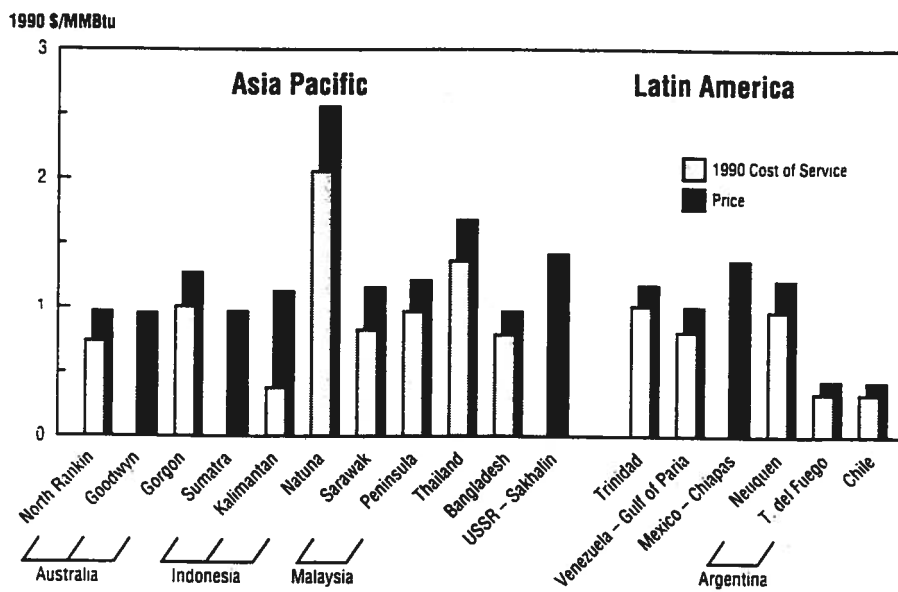
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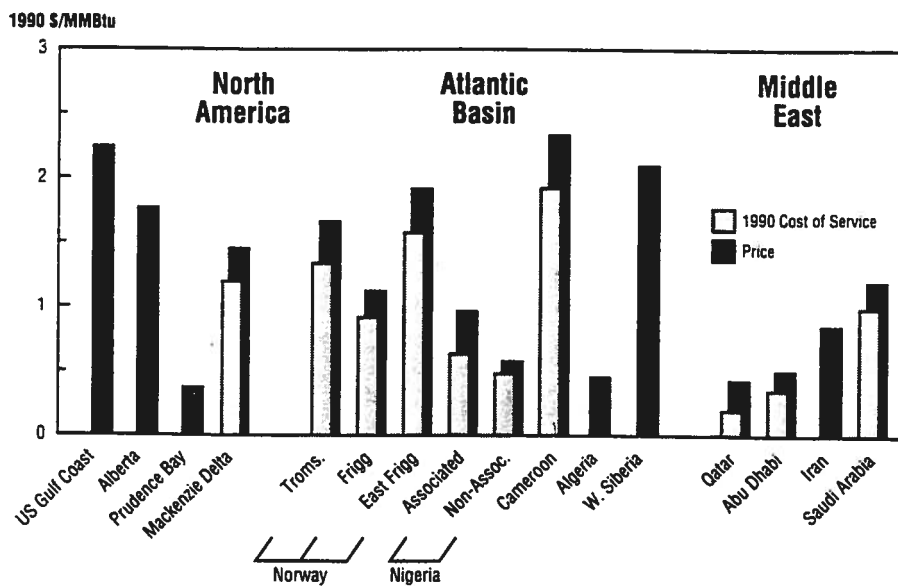
Appendix A Natural gas prices

Source IEA

ESTIMATED 1990 GAS COSTS AND PRICES



ESTIMATED 1990 GAS COSTS AND PRICES



Appendix B Energy consumption of fuel production

Appendix B

Energy consumption of fuel production

The energy consumption of fuel production can be calculated as the sum of two components:

- Feedstock recovery and transport to the production plant. Transportation may include sea transport in bulk vessels.
- Fuel production.

Three references present values for this energy consumption [B.1, B.2, B.3]. DeLuchi concentrates on the American situation, Ecotrafic considers the Swedish situation and TNO presents figures for the Dutch situation. Using these figures and taking into account that two out of three figures concern the European situation, a 'world average' value is chosen.

Table B.1 Energy consumption of feedstock recovery and transportation, and fuel production. Figures are MJ per MJ of fuel produced.

[MJ/MJ]		DeLuchi ¹⁾ [B.1]	Ecotrafic ²⁾ [B.2]	TNO ³⁾ [B.3]	World average
Petrol	Rec. & tr.	0.0370	0.037	0.0463	--
	Fuel prod.	0.1847	0.155	0.123	--
	Sum	0.2217	0.192	0.1693	0.20
Diesel	Rec. & tr.	0.0467	0.037	0.0463	--
	Fuel prod.	0.0519	0.09	0.066	--
	Sum	0.0986	0.127	0.1123	0.10
LPG	Rec. & tr.	0.0387	0.037	0.0463	--
	Fuel prod.	0.0550	0.10	0.066	--
	Sum	0.0937	0.137	0.1123	0.11

1) These figures are based on the situation in North America and stand for:

- Reformulated petrol from crude oil.
- Low sulphur diesel from crude oil.
- LPG stems from crude oil.

2) These figures are based on the Swedish situation and stand for:

- Reformulated petrol.
- Swedish urban diesel, which is low in sulphur and aromatics.
- LPG stems from refineries.

3) These figures are based on the Dutch situation and stand for:

- The year 2000.
- Recovery and transport values are per MJ crude oil.
- The petrol production value is calculated from the TNO value and an energy content of 42 MJ/kg for petrol.
- The diesel production value is calculated from the TNO value and an energy content of 43 MJ/kg for diesel.
- The LPG production value is calculated from the TNO value and an energy content of 46 MJ/kg for LPG.

- [B.1] M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity*. Center for transportation research, Energy division, Argonne National Laboratory, Argonne, USA, November 1991.
- [B.2] *The life of fuels. Motor fuels from source to end use*. Ecotraffic AB. Stockholm, Sweden, March 1992.
- [B.3] R.C. Rijkeboer, P. van Sloten, M. Elderman, B. van den Haspel, P. Kroon. *Wijziging brandstofmix*. TNO report 92.OR.VM.001.0/RR. TNO, Delft, The Netherlands, October 1992.

Appendix C Emissions of fuel production

Appendix C1

CO₂ emissions of fuel production and distribution

The CO₂ emissions of fuel production and distribution can be calculated as the sum of three components:

- Feedstock recovery and transport to the production plant. Transportation may include sea transport in bulk vessels.
- Fuel production.
- Fuel distribution.

Three references present values for this energy consumption [C1.1, C1.2, C1.3]. DeLuchi concentrates on the American situation, Ecotraffic considers the Swedish situation and TNO presents figures for the Dutch situation. Table C1.1 (on the next page) gives an overview. A significant difference in American and European figures can be observed.

Table C1.1 CO₂ emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are grams CO₂ per MJ of fuel produced.

[g/MJ]		DeLuchi ¹⁾	Ecotraffic ²⁾	TNO ³⁾
		[C1.1]	[C1.2]	[C1.3]
Petrol	Rec. & tr.	--	2.4	3.1
	Fuel prod.	--	12	9.6
	Fuel distr.	--	1	0.01
	Sum	33	15.4	12.7
Diesel	Rec. & tr.	--	2.4	3.1
	Fuel prod.	--	7	5.0
	Fuel distr.	--	1	0.01
	Sum	--	10.4	8.1
LPG	Rec. & tr.	--	2.4	3.1
	Fuel prod.	--	8	5.0
	Fuel distr.	--	1	0.01
	Sum	22	11.4	8.1
Methanol	Rec. & tr.	--	1.8	--
	Fuel prod.	--	8	--
	Fuel distr.	--	2	--
	Sum	48	11.8	--

1) These figures are based on the situation in North America and stand for:

- Reformulated petrol from crude oil.
- Low sulphur diesel from crude oil.
- LPG stems from crude oil.

2) These figures are based on the Swedish situation and stand for:

- Reformulated petrol.
- Swedish urban diesel, which is low in sulphur and aromatics.
- LPG stems from refineries.

- 3) These figures are based on the Dutch situation and stand for:
- The year 2000. Only the fuel distribution figures are for the year 2010.
 - Recovery and transport values are per MJ crude oil.
 - The emission values are calculated with the TNO value of 76 kg CO₂ per GJ energy consumption of the refinery, and combustion values: petrol 41.2 MJ/kg, diesel 42.9 MJ/kg, LPG 45.8 MJ/kg.

[C1.1] M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity*. Center for transportation research, Energy division, Argonne National Laboratory, Argonne, USA, November 1991.

[C1.2] *The life of fuels. Motor fuels from source to end use*. Ecotraffic AB. Stockholm, Sweden, March 1992.

[C1.3] R.C. Rijkeboer, P. van Sloten, M. Elderman, B. van den Haspel, P. Kroon. *Wijziging brandstofmix*. TNO report 92.OR.VM.001.0/RR. TNO, Delft, The Netherlands, October 1992.

Appendix C2

Emissions of fuel production and distribution - regulated components

Figures on particulates are not available.

Table C2.1 CO emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are mg per MJ of fuel produced.

[mg/MJ]		DeLuchi ¹⁾ [C2.1]	Ecotraffic ²⁾ [C2.2]
Petrol	Rec. & tr.	--	5-6
	Fuel prod.	--	<<1
	Fuel distr.	--	<1
	Sum	50	5-8
Diesel	Rec. & tr.	--	5-6
	Fuel prod.	--	<<1
	Fuel distr.	--	<1
	Sum	--	5-8
LPG	Rec. & tr.	--	5-7
	Fuel prod.	--	<<1
	Fuel distr.	--	1
	Sum	27	7-9

1) Calculated using: 1 US gallon = 3.785 litre; lower calorific value of reformulated petrol 31.9 MJ/l. These figures are based on the situation in North America and stand for:

- Reformulated petrol from crude oil.
- Low sulphur diesel from crude oil.
- LPG stems from crude oil and from natural gas liquids plants.
- Emissions from all sources except vehicles. Includes emissions from materials manufacture and vehicle assembly.

2) These figures are based on the Swedish situation and stand for:

- Reformulated petrol.
- Swedish urban diesel, which is low in sulphur and aromatics.
- LPG stems from refineries.

Table C2.2 CH₄ emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are mg per MJ of fuel produced.

[mg/MJ]		DeLuchi ¹⁾	Ecotraffic ²⁾
		[C2.1]	[C2.2]
Petrol	Rec. & tr.	--	26-27
	Fuel prod.	--	n.d.
	Fuel distr.	--	<<1
	Sum	66	26-28
Diesel	Rec. & tr.	--	26-27
	Fuel prod.	--	n.d.
	Fuel distr.	--	<<1
	Sum	--	26-28
LPG	Rec. & tr.	--	26-27
	Fuel prod.	--	n.d.
	Fuel distr.	--	<<1
	Sum	64	26-28

- 1) Calculated using: 1 US gallon = 3.785 litre; lower calorific value of reformulated petrol 31.9 MJ/l. These figures are based on the situation in North America and stand for:
- Reformulated petrol from crude oil.
 - Low sulphur diesel from crude oil.
 - LPG stems from crude oil and from natural gas liquids plants.
 - Emissions from all sources except vehicles. Includes emissions from materials manufacture and vehicle assembly.
- 2) These figures are based on the Swedish situation and stand for:
- Reformulated petrol.
 - Swedish urban diesel, which is low in sulphur and aromatics.
 - LPG stems from refineries.
 - n.d. = no data

Table C2.3 NMHC emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are mg per MJ of fuel produced.

[mg/MJ]		DeLuchi ¹⁾	Ecotraffic ²⁾
		[C2.1]	[C2.2]
Petrol	Rec. & tr.	--	3
	Fuel prod.	--	17
	Fuel distr.	--	30
	Sum	23	50
Diesel	Rec. & tr.	--	3
	Fuel prod.	--	10
	Fuel distr.	--	<1
	Sum	--	13-14
LPG	Rec. & tr.	--	3
	Fuel prod.	--	11
	Fuel distr.	--	<1
	Sum	13	14-15

1) Calculated using: 1 US gallon = 3.785 litre; lower calorific value of reformulated petrol 31.9 MJ/l. These figures are based on the situation in North America and stand for:

- Reformulated petrol from crude oil.
- Low sulphur diesel from crude oil.
- LPG stems from crude oil and from natural gas liquids plants.
- Emissions from all sources except vehicles. Includes emissions from materials manufacture and vehicle assembly.

2) These figures are based on the Swedish situation and stand for:

- Reformulated petrol.
- Swedish urban diesel, which is low in sulphur and aromatics.
- LPG stems from refineries.

Table C2.4 NO_x emissions of feedstock recovery and transportation, fuel production and fuel distribution. Figures are mg per MJ of fuel produced.

[mg/MJ]		DeLuchi ¹⁾	Ecotraffic ²⁾
		[C2.1]	[C2.2]
Petrol	Rec. & tr.	--	28
	Fuel prod.	--	10
	Fuel distr.	--	10
	Sum	86	48
Diesel	Rec. & tr.	--	28
	Fuel prod.	--	6
	Fuel distr.	--	10
	Sum	--	44
LPG	Rec. & tr.	--	28
	Fuel prod.	--	6
	Fuel distr.	--	15
	Sum	53	49

1) Calculated using: 1 US gallon = 3.785 litre; lower calorific value of reformulated petrol 31.9 MJ/l. These figures are based on the situation in North America and stand for:

- Reformulated petrol from crude oil.
- Low sulphur diesel from crude oil.
- LPG stems from crude oil and from natural gas liquids plants.
- Emissions from all sources except vehicles. Includes emissions from materials manufacture and vehicle assembly.

2) These figures are based on the Swedish situation and stand for:

- Reformulated petrol.
- Swedish urban diesel, which is low in sulphur and aromatics.
- LPG stems from refineries.

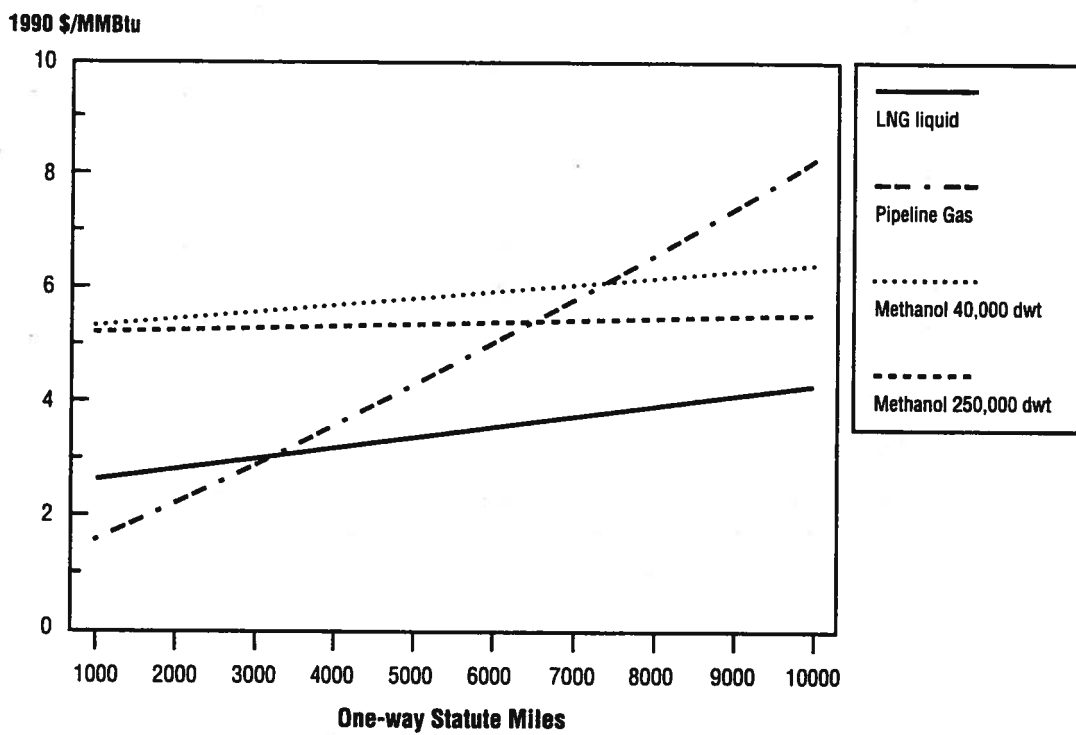
[C2.1] M.A. DeLuchi. *Emissions of greenhouse gases from the use of transportation fuels and electricity*. Center for transportation research, Energy division, Argonne National Laboratory, Argonne, USA, November 1991.

[C2.2] *The life of fuels. Motor fuels from source to end use*. Ecotraffic AB. Stockholm, Sweden, March 1992.

Appendix D Natural gas transport & flare-off sites

Source IEA

DELIVERED FUEL VALUE REQUIRED TO YIELD \$1.00/MMBtu Netback Gas Value



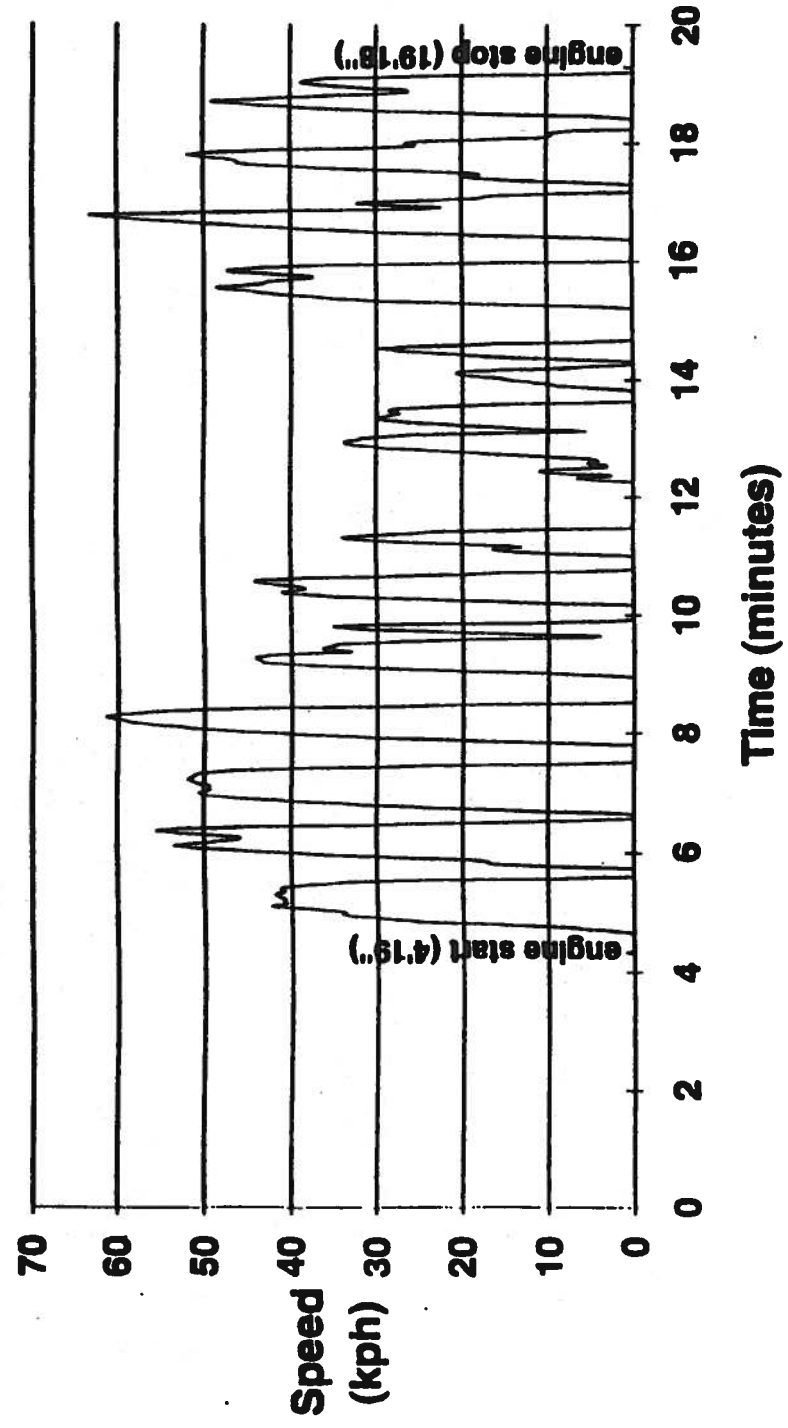
**WORLDWIDE GAS FLARING
1988**

	BCFD	Methanol Complex Equivalents ¹
U.S.S.R.	1.93	6.4
Nigeria	1.18	3.9
Algeria	0.58	1.9
Iraq	0.44	1.5
Indonesia	0.42	1.4
U.S.	0.39	1.3
Iran	0.39	1.3
India	0.38	1.3
Venezuela	0.35	1.2
Trinidad	0.34	1.1
Saudi Arabia	0.32	1.1
Canada	0.26	0.9
Libya	0.25	0.8
U.K.	0.22	0.7
Argentina	0.19	0.6
All Other	1.30	4.3
WORLD TOTAL	8.94	29.8

¹Methanol Complex Equivalents at 300 MMcfd feedstock requirements.

Appendix E Test cycles and g/km results

Urban Bus Driving Cycle



V_(km_h)

Fig cycle (version 4)

urban: 0-586 [sec]
rural: 587-1185 [sec]
Motorway: 1186-1800 [sec]

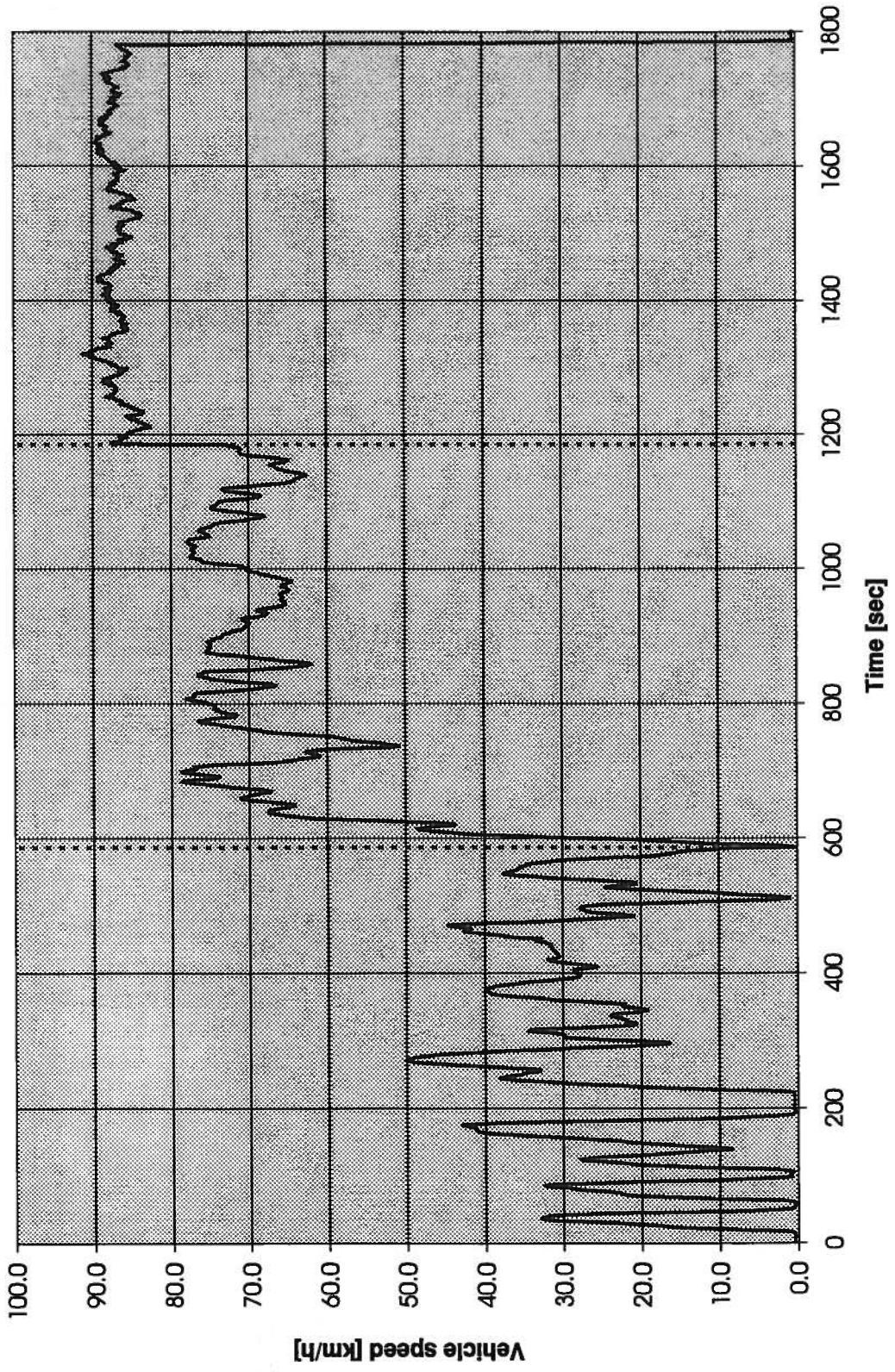


Table 1: Exhaust emissions and fuel consumption per vehicle category in g/km, urban use

Category	Vehicle	Fuel	FC g/km	NOx g/km	PM g/km	HC g/km	CO g/km	SO2 g/km	CO2 g/km
1	Cars	Gasoline	65	0.320	0.005	0.029	0.300	0.016	208
2		Diesel	65	0.861	0.065	0.096	0.657	0.062	209
3		LPG	68	0.350	0.003	0.041	0.391	0.001	206
4	Vans	Gasoline	91	0.309	0.006	0.120	1.811	0.022	290
5		Diesel	85	1.414	0.083	0.116	0.400	0.081	271
6		LPG	83	0.108	0.004	0.062	0.438	0.002	252
7	Trucks < 16 tons GVW	Diesel	136	3.843	0.102	0.820	1.676	0.129	434
8	Trucks > 16 tons GVW	Diesel	239	7.001	0.129	0.811	2.813	0.227	762
9	Articulated trailers	Diesel	351	10.555	0.123	0.818	2.487	0.333	1121
10	Buses + Coaches	Diesel	411	11.565	0.260	0.516	2.035	0.390	1313



Appendix F Well to wheel energy efficiency



Table 1: Energy efficiency from well to filling station

	Rec.&transp.	Fuel prod.	Total	Distribution	Total well-station
Diesel	0.960	0.95	0.91	0.990	90.3%
Gasoline	0.965	0.86	0.83	0.984	81.7%
DME	0.970	0.71	0.69	0.966	66.5%
LPG	0.964	0.93	0.90	0.985	88.7%
CNG	0.970	0.98	0.95	0.905	86.0%
LNG	0.970	0.85	0.82	0.980	80.3%
Methanol	0.970	0.65	0.63	0.978	61.7%

Table 2: Well to wheel energy efficiency heavy duty vehicles, urban bus application

	Total		transm. &	weight	Total	Total
	well-station	Engine	auxiliaries	correction	vehicle eff.	well-wheel
Bus engines						
Diesel	0.901	35%	0.84	1.00	29.4%	26.5%
DME	0.665	35%	0.84	0.99	29.1%	19.4%
LPG lean-burn	0.887	32%	0.84	1.00	26.9%	23.8%
LPG stoich.	0.887	29%	0.84	1.00	24.4%	21.6%
CNG lean-burn, high calor	0.86	32%	0.84	0.97	26.1%	22.4%
CNG stoich., low calorific 1	0.86	30%	0.84	0.95	23.9%	20.6%
LNG lean-burn	0.804	32%	0.84	1.00	26.9%	21.6%
Methanol (diesel cycle)	0.617	35%	0.84	0.99	29.1%	18.0%
Methanol (otto cycle)	0.617	30%	0.84	0.99	24.9%	15.4%
Gasoline	0.817	29%	0.84	1.01	24.6%	20.1%
Bio-ethanol (diesel cycle)		35%	0.84	0.99	29.1%	

Table 3: Well to wheel energy efficiency light duty vehicles, mix of urban, sub-urban and motorway

	Total		transm. &	weight	Total	Total
	well-station	Engine	auxiliaries	correction	Vehicle eff.	well-wheel
Passenger cars & vans						
Diesel	0.901	0.28	0.89	1	25%	22.5%
DME	0.665	0.28	0.89	0.99	25%	16.4%
Gasoline	0.817	0.23	0.89	1.01	21%	16.9%
LPG	0.887	0.23	0.89	1	20%	18.2%
CNG	0.86	0.23	0.89	0.95	19%	16.7%
Methanol	0.617	0.23	0.89	0.99	20%	12.5%

Appendix G Well to wheel CO₂ emissions



Table 1: Well to wheel (net) CO2 emissions heavy duty vehicles, urban bus application

	Vehicle efficiency	CO2 prod.	CO2 vehicle	Relative to diesel		
		kg/GJ fuel	kg/GJ fuel	Production	Vehicle	Well-wheel
Urban bus applic.						
Diesel	29.4%	9.1	73	0.11	0.89	1.00
DME	29.1%	16.3	66.4	0.20	0.82	1.02
LPG lean-burn	26.9%	9.1	67	0.12	0.89	1.01
LPG stoich.	24.4%	9.1	67	0.13	0.98	1.12
CNG lean-burn	26.1%	9	55.2	0.12	0.76	0.88
CNG stoich.	23.9%	9	55.2	0.13	0.83	0.96
LNG lean-burn	26.9%	13.4	55.2	0.18	0.74	0.91
Methanol (diesel)	29.1%	11.8	70.7	0.15	0.87	1.02
Gasoline	24.6%	13.4	74.2	0.20	1.08	1.27
DME renewable	29.1%	13.9	0	0.17	0.00	0.17
Bio-ethanol, fr. sugar,	29.1%	13	0	0.16	0.00	0.16
Bio-ethanol, fr. wheat,	29.1%	32	0	0.39	0.00	0.39

Table 2: Well to wheel (net) CO2 emissions light duty vehicles, average of urban, sub-urban and motorway

	Vehicle efficiency	CO2 prod.	CO2 vehicle	Relative to diesel		
		kg/GJ fuel	kg/GJ fuel	Production	Vehicle	Well-wheel
Light duty vehicles						
Diesel	0.249	9.1	73	0.11	0.89	1.00
DME	0.247	16.3	66.4	0.20	0.82	1.02
Gasoline	0.207	13.4	74.2	0.20	1.09	1.29
LPG	0.205	9.1	67	0.13	0.99	1.13
CNG	0.194	9	55.2	0.14	0.86	1.00
Methanol	0.203	11.8	70.7	0.18	1.06	1.24
DME renewable	24.7%	13.9	0	0.17	0.00	0.17

