DME as a Transportation Fuel

A project carried out for
The Danish Road Safety & Transport Agency
The Danish Environmental Protection Agency

Reported by
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First Prototype DME-Fuelled Bus
Abstract

The aim of the project was to demonstrate and evaluate the feasibility of DME (Dimethyl Ether) as a clean diesel fuel for busses through laboratory and field tests.

The performance and emission targets of an HD DME bus engine (Euro IV) have been successfully demonstrated and a bus has been converted to accommodate a DME engine and a fuel tank system, making it the first DME bus in the world. Two DME filling stations have been built. Additives for DME lubrication and odour have been selected. A chassis dynamometer test on the demonstrator bus has verified the target emission value.

Due to remaining problems with especially elastomers, the engine manufacturer decided to cancel field tests mainly due to bus availability and safety aspects and with regard to the project time frame and internal resources.

Work sponsored by the project has been carried out within the IEA Alternative Motor Fuel Implementing Agreement Annex XIV “Investigation into the feasibility of Dimethyl Ether as a fuel in Diesel Engines”. The work has included a Life Cycle Analysis (LCA), specification of fuel standards, safety and design guidelines, and DME production from biomass.

Introduction

After the excellent properties of DME as a diesel fuel was made public at the SAE conference in March 1995, a strong interest was created for its potential as an alternative diesel fuel.

In Denmark it was decided to start a project sponsored by the Danish Road Safety & Transport Agency and the Danish Environmental Protection Agency.

Three major bus companies: Copenhagen Transport, Combus A/S and Odense Bytrafik agreed to participate and cover part of the additional costs of the DME busses.

Volvo Truck and Bus Corporation offered to develop the engine and bus technology for the DME application out of their own funds.

Statoil Denmark A/S would provide tank facilities, logistic support, and lubricant, and odorant know-how to the project free of charge.

A Steering Committee headed by the Danish Road Safety & Transport Agency was formed consisting of the project partners and the Technical University of Denmark. The project started officially with the first Steering Group meeting in October 1995. Throughout the project, six Steering Group meetings were held.

The aim of the project was to demonstrate and evaluate the feasibility of DME-fuelled busses, through laboratory and field tests. When it became evident that the full field test would not be feasible, it was decided to use a small portion of the leftover funds for the IEA work.
Project Goals

To reach these goals the project had the following main activities (the main responsible partner in parenthesis):

- Development of a DME-fuelled prototype version of the VOLVO DH10A engine (Volvo)
- Conversion of the VOLVO B10BLE bus to a prototype DME version (Volvo)
- Establishment of distribution, storage and filling facilities dedicated to DME (Statoil, DTI)
- Development of lubrication and odour additives for DME (Statoil)
- Verification of performance and exhaust emissions (DTI)
- Adaptation of bus garages and service facilities to accommodate DME busses. Cancelled. (Statoil, DTI)
- Field test of three DME busses for more than one year. Cancelled (Bus companies, DTI)
- Update on production costs (Haldor Topsøe A/S)
- Dissemination of results and overall project management (Haldor Topsøe A/S)

The targets for the DME bus engine included: unchanged performance compared to the baseline diesel engine (180 kW and 1050 Nm) and low noise emissions and acceptable reliability (> 75%) for a field test. The field test should fulfil uncompromising safety standards. The exhaust emission target was set at a conservative level (NOx ≤ 3 g/kWh and PM ≤ 0.05 g/kWh) compared with the potential of the concept as the focus of the project was on the feasibility of DME as a fuel for HD vehicles, not optimum emission data.

Engine Development

Due to the fact that DME is a gas at ambient pressure and temperature (like LPG), a fuel injection system for DME must be able to handle:

- High vapour pressure
- High compressibility
- Low viscosity

These fuel features can be handled by a common rail type FIE. With the time and cost limitations of this project, it was necessary to use as much existing hardware as possible, including components not optimised for vehicle use. The layout of the FIE is shown in Figure 1. The main components are:

- The fuel tanks with low-pressure feed pumps.
- The high-pressure pump, feeding fuel to the rail.
- The common rail with 3-way solenoid valves plus high-pressure fuel lines and injectors.
- The purge system, including purge tank and return fuel pump.
- The fuel cooler.
• The “control block” with valves to handle the different modes of the FIE.
• The control system, with sub-units handling the injection control, the fuel tank system, and the global control of the system.

The high-pressure pump, the common rail and the “control block” are shown in Figure 1.

Figure 1. The main FIE components

The fuel system has three main modes:

• Purge mode, where the high-pressure parts of the injection system are at purge tank pressure level.
• Ready to start mode, where the high-pressure parts of the injection system are at fuel tank feed pump pressure level.
• Engine operation mode, where the engine is running and the different fuel system parts are working at optimised pressure levels to avoid cavitation.
**Engine Performance**

The engine performance data and the emission goals of the project are shown in the table below. These results were achieved with a minimum of combustion system optimisation, as the development work was focused on the basic design of the fuel system and on the necessary adaptation of different components to the specific features of DME.

Despite this development focus on the basic questions, the emission goals were accomplished. Compared to the emission potential of DME, however, these goals were conservatively set, even though the results are excellent compared to today's HD diesel standards. The poor efficiency is caused by the limitations in injection characteristics and the parasitic losses using the present injection system.

Some comments regarding the table below:

- For Euro4 only the ESC-cycle limits are shown, being most representative for comparison.
- The PM level has not been properly measured, but is probably well within the given value.
- The minimum BSFC value is given in diesel equivalents relative to the Euro 2 base-line engine.

<table>
<thead>
<tr>
<th></th>
<th>Project results ECE R49</th>
<th>Project goals ECE R49</th>
<th>Euro2 ECE R49</th>
<th>Euro3 ECE R49</th>
<th>Euro4 ESC</th>
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<tbody>
<tr>
<td>NOₓ</td>
<td>2.99</td>
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<td>7.0</td>
<td>5.0</td>
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<td>0.66</td>
<td>0.46</td>
</tr>
<tr>
<td>CO</td>
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<td>0.5</td>
<td>4.0</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>PM</td>
<td>&lt;0.02</td>
<td>0.05</td>
<td>0.15</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>BSFCₘIN</td>
<td>115%</td>
<td>100%</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Storage and Supply of DME in the Vehicle**

To enable the operation of a DME-engine in the bus, a new storage and supply system for fuel had to be designed. This was derived from existing LPG-technology with one exception, the purge system, see Figure 2.
**Functional Description**

The storage and supply system consists of the following main components:

- Fuel tanks with level indicators, integrated submerged fuel pumps for low-pressure supply of liquid DME
- Valves, connectors and fuel lines including safety enhancing devices such as pressure relief valves
- Electrical control unit and driver interface
- Wiring harness
- Purge tank for storage of gaseous DME
- Pneumatic control unit for the purge system
- Air-driven purge compressor

Refuelling takes place through a standard LPG-receptacle on one side of the bus. The filling is monitored by the tank system engine control unit (ECU) and the electrical filling valve in the tanks. One tank at a time is filled up to 80% except one which is filled to only 50%; this is the tank where the return fuel from the purge system is added. The filling level is regulated to avoid uncontrolled pressure increase caused by variations in temperature.

Distribution of DME to the engine is also monitored by the ECU. When the ignition is turned on, the system checks the fuel level in the tanks and chooses the one with the highest level. This tank will be emptied to 10% of the total tank volume. Another level check is performed and again the tank with the highest fuel level will be relieved of some of its content. This function assures an even distribution of the fuel in the tanks. The fuel is pumped from the tank at a working pressure of 10.5 bar above vapour pressure and a flow rate of approximately 93 litres per hour. It is circulated back to the tank passing a takeoff point where the fuel injection system is supplied with guaranteed liquid DME.

As earlier mentioned, the need of a purge system is obvious due to the characteristics of DME. For reasons of safety, the purge function is autonomous. It is independent of electricity and signals from the other systems. It uses compressed air from the vehicle brake system for its operation. The purge tank is connected to the fuel injection system on the engine with a separate fuel line. Fuel purged from the engine will expand into the purge tank. Mounted on the purge tank is a level indicator like the ones on the supply tanks and a tank pressure control line connected to the pneumatic control unit. The level indicator measures the presence of liquid DME in the tank and if the amount is more than 15 litres, this is indicated on the driver interface. The signal is also relayed to the engine management system since this is an indication of fuel leakage in the engine. If the pressure in the purge tank is higher than a pre-set value, the pneumatic control unit will activate the purge compressor which will compress gaseous DME back into the predestined supply tank until the purge tank pressure reaches another pre-set value. The pressures corresponding to these pre-set values are chosen to avoid accumulation of liquid DME in the purge tank in the operational temperature range of the vehicle.

**Vehicle Installation**

The engine installation differs very little from the normal diesel one, however, the common rail adds on some weight. Fuel circulated in the injection system needs to be cooled. This was solved by the fact that the DH10A engine has water-to-air-charge air cooling in a separate circuit. The temperature of this water is suitable for cooling of DME. The fuel tanks of the first bus are fitted on a frame and into a recess in the bus roof in order to limit the total vehicle height and lower the centre of gravity. The dimensions of the frame are 2.8×2.2×0.5 measured in meters. The empty weight is 720 kg. There are 5 supply tanks with a volume of 138 litres and a purge tank with a volume of 180 litres. The total useful volume of the fuel tanks is 510 litres. The system is unnecessarily cumbersome due to the limited filling rate and the presence of a large purge tank. The operating range for the bus in city traffic would be approximately 600 km. The operating range for a CNG-bus using the same space for fuel would be 350 km.
Lubrication and Odor Additives

DME does not provide sufficient lubrication in the injection system and a lubrication additive must be added. Analysis of different lubrication additives was performed and Lubrizol LZ539N was found to have the best wear-reducing ability. In an earlier project some problems with keeping this product mixed with DME had been observed; there was a tendency to settlement when the mixture was left for some time [7]. Still, this product was selected and work concentrated on the blending problem.

For safety reasons, it is necessary to add an odour additive to DME as DME itself has no noticeable odour. Ethyl mercaptan, which is used as odour additive in LPG, was selected for DME as it is well suited based on positive experience with the blending ability and the fact that Ethyl mercaptan has a boiling point close to DME.

Initially 1000 ppm Lubrizol LZ539N and 20 ppm Ethyl mercaptan was added to DME. In order to minimise the potential negative impact on exhaust emissions, the ambition was to minimise the use of both lubrication and odour additives, but work in this area was not finalised.

Storage and Filling Facilities for the Busses

Based on earlier experience with DME and the fact that DME compares closely with LPG on a number of physical parameters, the installation instructions for LPG was a natural basis for development of DME storage and filling facilities.

However, DME differs significantly from LPG in that DME can dissolve most of the sealing materials normally used in oil and gas installations. When selecting components for the installations close evaluation of the component materials was therefore required.

In all valves the sealing material was replaced by Teflon where metal-to-metal sealing could not be achieved. For larger caps and assemblies without dynamic load, graphite and Kalrez sealing was used.

Based on the considerations mentioned above, a storage and filling facility was constructed. The facility consists of two tanks: a main storage tank containing raw DME and a consumption tank containing the DME and additive mixture. In addition there are two small storage tanks and dosage pumps for lubrication and odour additives. The consumption tank is suspended in a strain-gauge-based weight system, see Figure 3. To ensure a good mixing of DME and additives, a constant circulation of the mixture is provided by the circulation pump.
The installation was designed with an online computer-controlled mixing of DME, lubrication additive and odour additive which provided the opportunity to experiment with different dosages of lubrication and odour additives. The same computer controls and monitors the total contents of the consumption tank.

DME was delivered from AKZO Nobel Chemicals by Gerling Holz GmbH in Hamburg. DME was delivered in transport tanks containing 500 kg and pumped from the transport tanks to the main storage tank.

The installation had a number of teething problems, which have been solved, but one problem concerning a fluid level sensor still remains. The level sensor is part of the safety monitoring system and the sensors tested so far have all had insufficient lifetime in connection with DME. Below a picture from the filling facilities is seen.
Approval by Local Authorities

Approval of the storage and filling installation was sought on the basis of existing rules for LPG installations. In Denmark technical requirements are issued by the Ministry of the Interior, the Emergency Management Agency and the LPG guidelines were followed in the construction of the installation. Approval by the local fire authority is also required in Denmark before the installation is put into use. All required approvals for the installation described above have been obtained.

Verification of Engine Test Bench Data

In order to demonstrate the DME prototype bus and verify the performance and emissions data obtained in the test bench, additional tests were performed on a chassis dynamometer.

Measurements were made using a simulated ECE R49 13-mode steady state test adopted for the chassis dynamometer. Based on the engine test bench measurements, a very low level of particulate emission was expected. Low levels of particulate are difficult to measure on a chassis dynamometer due to limited sampling time, and therefore particulate emissions measurements were ignored altogether.
It is well worth remembering that the DME-equipment is first generation technology and that a number of details were ready neither for production nor for everyday use. The results should therefore be seen as an indication of the potential for low emissions using DME and not as the end result.

Due to restrictions in the fuel supply system, the engine was not able to deliver the same performance on the chassis dynamometer as measured on the engine test bench. On the chassis dynamometer max. power was 109 kW at 2000 rpm (186 kW in test bench) and max. torque was 727 Nm at 1450 rpm (1050 Nm in test bench).

Still the emission measurements made at the chassis dynamometer and in the engine test bench are very similar:
The engine was equipped with an oxidation catalytic converter (from Haldor Topsøe A/S) which explains the very low HC and CO emissions. The very low NO\textsubscript{x} and particulate emissions, however, are engine-out operation and indicate the very favourable emissions obtainable with DME. Even lower emissions can be expected with optimisation of the combustion. Below the obtained figures are compared to Euro 2 values.

<table>
<thead>
<tr>
<th>Emission [g/kWh]</th>
<th>Chassis dynamometer</th>
<th>Engine Test Bench</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO\textsubscript{x}</td>
<td>3.30</td>
<td>2.99</td>
</tr>
<tr>
<td>HC</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>CO</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>PM</td>
<td>N/A.</td>
<td>&lt;0.02</td>
</tr>
</tbody>
</table>

**IEA Work**

Under the auspices of the IEA, DME annex work has been carried on fuel standard, safety and design aspects, life cycle analyses, DME from biomass and infrastructure aspects.

Trade-off studies have been undertaken by Haldor Topsøe A/S on product purity versus production costs [5]. An internationally accepted standard for DME fuel quality has thus been established, which is:
Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>Max. content by weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.01</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.05</td>
</tr>
<tr>
<td>Methyl Ethyl Ketone</td>
<td>0.20</td>
</tr>
<tr>
<td>Higher Alcohols</td>
<td>0.05</td>
</tr>
<tr>
<td>Higher Ethers</td>
<td>0.05</td>
</tr>
<tr>
<td>Ketones</td>
<td>0.05</td>
</tr>
</tbody>
</table>

It is believed that this fuel composition will not lead to additional compatibility problems with materials for fuel tanks, injection pumps etc compared to the use of pure DME.

The major by-product Methyl Ethyl Ether (MEE) has an auto-ignition temperature of 190°C, which is even lower than that of DME (237°C).

A complete well-to-wheel life cycle analysis on the following fuels: Diesel, Gasoline, LPG, CNG, DME, and Methanol has been carried out by the following: BP Amoco, Statoil A/S, Haldor Topsøe A/S, Natural Resources of Canada, Volvo Truck Corporation, Renault, TNO-Road Vehicles Research Institute, and INNAS.

The conclusions were that the total greenhouse gas emissions were in the same range for DME, diesel and the gaseous fuels, whereas they were higher for gasoline and especially methanol. With respect to NOx, particulate matter and SO2, DME was in the very low end.

Part of the Scandinavian bus project described in this paper was also to do an LCA analysis of DME used in heavy-duty busses.

It is evident that the major part of the energy losses and thus CO2 occurs in the DME production plant and in the vehicle.

Even for an ideal process operating at standard conditions converting natural gas (here represented by methane) into DME, there would be losses associated with it, as illustrated in Figure 5.
Figure 5. Natural Gas conversion into DME

\[
\begin{aligned}
2 \times \text{LHV CH}_4 & \rightarrow \text{LHV DME} \\
1605.3 \text{ MJ} & \rightarrow 1328.7 \text{ MJ} \\
120.8\% & \rightarrow 100\%
\end{aligned}
\]

where LHV\textsubscript{CH4} and LHV\textsubscript{DME} are the molar, lower heating values of methane and DME, respectively.

The ideal energy conversion efficiency is thus 82.8%. The energy consumption for DME calculated in the case studies discussed above is about 40.5 MJ/MT DME, which is equivalent to 1.40 GJ of energy input for each 1 GJ of DME produced. The extra energy input is due to non-idealities in the process (loss to cooling water and flue gases, loss in compressors, pump etc.). The real conversion efficiency (71.2%) divided by the ideal is thus 86%, which in fact is quite high and demonstrates how highly optimised the process is. With a typical natural gas composition, the CO\textsubscript{2} emissions from the production are 355 kg/MT DME or 12.3 g/MJ fuel. DME can also be produced from biomass, which would obviously lower the CO\textsubscript{2} emissions considerably.

The fact that DME can be converted with Compression Ignition engine efficiencies and that it is based on natural gas with a higher energy content per kg carbon than crude oil explains why the well-to-wheel emissions of greenhouse gases are similar for DME and diesel.

All other emissions from the production step are very low in the order of:

\[
\begin{align*}
\text{NO}_x &= 4 \text{ mg/MJ} \\
\text{CO} &= 40 \text{ mg/MJ} \\
\text{CH}_4 &= 3.5 \text{ mg/MJ} \\
\text{PM} &= \text{below 1-2 mg/MJ} \\
\text{SO}_2 &= 0 \text{ mg/MJ}
\end{align*}
\]
Production Technology and Cost

Already in 1995, when the properties of DME as a clean diesel fuel was announced, an energy- and cost efficient process for its manufacture from natural gas had been developed by Haldor Topsøe A/S [1].

A simplified block diagram of the process is shown in Figure 6.

The process consisted of the following main steps:

- Desulphurisation
- Autothermal reforming (ATR)
- CO$_2$ adjustment
- Combined methanol and DME synthesis
- Final purification unit

The natural gas is first desulphurised to protect the catalysts in the downstream units. Recycle hydrogen is added to the natural gas to convert heavy, refractory sulphur compounds into hydrogen sulphide which is subsequently absorbed by activated ZnO.

The autothermal reformer is a key element in the production technology. It is described in detail in [1,5]. It consists of a refractory lined pressure vessel with a burner, a combustion chamber and a catalyst bed. It has a compact design which enables single line design up to 7000 MTPD DME capacities. There are no open flames, which means very low overall NO$_x$ emissions from the plant.
Basically the following takes place. Desulphurised natural gas is reacted with oxygen and steam according to:

\[
\begin{align*}
\text{CH}_4 + 1.5 \text{ O}_2 &= \text{CO} + 2 \text{ H}_2\text{O} \\
\text{CH}_4 + \text{H}_2\text{O} &= 3 \text{ H}_2 + \text{CO} \\
\text{CO} + \text{H}_2\text{O} &= \text{CO}_2 + \text{H}_2
\end{align*}
\]

Subsequently, some CO\(_2\) is removed in order to adjust the synthesis gas composition to an optimum value of the so-called module \((\text{H}_2 - \text{CO}_2)/(\text{CO} + \text{CO}_2)\) of slightly above two.

In the synthesis section the following reactions take place over a proprietary, multifunction catalyst in three adiabatic reactors in series:

\[
\begin{align*}
3 \text{ H}_2 + \text{CO}_2 &= \text{CH}_3\text{OH} + \text{H}_2\text{O} \\
\text{H}_2\text{O} + \text{CO} &= \text{H}_2 + \text{CO}_2 \\
2 \text{ CH}_3\text{OH} &= \text{CH}_3\text{OCH}_3
\end{align*}
\]

The major part of the produced DME/methanol/water mixture is then condensed and separated. The unconverted synthesis gas is split into a recycle stream and a purge stream, which is used as fuel and as hydrogen recycle. Finally, the DME is purified by distillation.

Since 1995 advances in the DME manufacturing technology have been taking place, most notably for ATR. A new generation of burner technology (CTS burners) has been demonstrated in pilot unit as well as industrial plants. The burner design allows sootfree operation at lower steam injection ratios (down to S/C of 0.6).

The new developments in DME plants layout are shown in Figure 7.
The developments include:

- Prereforming
- CTS burners
- Reduced steam consumption
- Increased reforming temperature
- New principle for adjustment of synthesis gas composition.
- Recycle synthesis layout with lower recycle

In the prereformer all the higher hydrocarbons in the natural gas are converted to synthesis gas, which allows for a higher ATR preheat temperature and lower oxygen consumption.

Instead of removing some CO₂ before the synthesis loop, hydrogen is removed by inexpensive membranes from the purge gas and added upstream the synthesis section. This ensures high loop efficiency at a low recycle flow and low inert level.

All these advances led to significant savings on the plant investment (the most important element for the cost of DME) and thus a lower cost.

Case studies on very large DME plants (7000 MTPD DME) from cheap natural gas have been carried out. In Figure 8 the delivered Rotterdam diesel equivalent cost of DME is shown as a function of the cost of the natural gas feedstock. The two curves illustrate the situation in 1995 and 1999 demonstrating the savings obtained by the advances described above. Of course, the cost of diesel is normally almost proportional to the cost of crude oil, so the second Y-axis shows the crude oil price equivalent to the shown diesel price.
As remote natural gas is available at a price below 1 USD/GJ in many locations, it can be seen that DME is competitive when the crude oil price is above approx. 20 USD/barrel.

**Development Status and Potential for Improvement**

The durability and safety targets set by the project were not fulfilled due to the following circumstances.

As mentioned earlier, the purge system uses compressed air for its operation. The supply of compressed air from the brake system of the vehicle is limited and was in some cases not adequate to empty the purge tank. It is possible to overcome this problem by reducing the volumes of the parts necessary to purge. There are also alternative ways to power an independent purge system.

Limited durability of the system due to problems with sealing materials represented a major problem. DME compatible soft sealing materials should be developed.

During the development work, the supply pressure required by the fuel injection system increased. Since the low-pressure supply system uses existing LPG-equipment, this had a limiting effect on the flow rate of fuel and thus on the engine output. Using two pumps at a time to feed the engine is a potential for improved flow rate.

Looking ahead, it should be remembered that it was not within the scope of this project to develop a dedicated and optimised DME engine from scratch. DME has many unexplored possibilities. The absence of particulate emissions makes a high degree of exhaust gas recycle possible thus making way for even further NOx reduction. Alternatively, the engines could be optimised with respect to fuel consumption and equipped with a very simple Selective Catalytic Reduction unit, making a close to zero emission diesel vehicle possible.
Conclusion

The performance and emission targets of the HD DME engine has been successfully demonstrated and a bus has been converted to accommodate the DME engine and the fuel tank system. Two DME filling stations have been built. Additives for DME lubrication and odour have been selected. A Life Cycle Analysis (LCA) made under the International Energy Agency (IEA) auspices by some of the project participants has shown that greenhouse gas emissions from DME, diesel, LPG, and CNG are similar and lower than gasoline or methanol.

However, the field-test part of the project was excluded due to difficulties reaching the reliability goal within the cost and time frame of the project. The DME bus is now used for demonstration tours and internal company evaluation.

The project has added valuable information to the overall development of DME fuelled vehicles.

The strong arguments for DME as a major future fuel are still: production cost, flexible feedstock selection, low emissions, and high well-to-wheel efficiency.

References