TNO report

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Workshop: Dimethyl-ether as an automotive fuel

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The TNO Road-Vehicles Research Institute carries out research and provides services in the field of road vehicles and their components.
The primary areas of attention are Vehicle Dynamics, Crash Safety, Combustion Engines and Homologations.

Netherlands Organization for Applied Scientific Research (TNO)

Executive summary

The workshop "Dimethyl-ether as an automotive fuel" was organized by TNO-WT for the executive committee of the Implementing Agreement "Alternative Motor Fuels" of the International Energy Agency (IEA/AMF).

The objectives of the workshop were:
* To pool the knowledge within the IEA member countries,
* To formulate an expert view on the possibilities of DME as an automotive fuel,
* To possibly recommend the necessity of a new Annex on DME.

The "expert view" should be an overall view covering the subjects: DME production and distribution, engine development, comparison with other alternative fuels and position of DME in the future energy supply.

The two day workshop was attended by DME experts from the chemical industry, oil and gas companies, government, automobile industry and consultants. The first day of the workshop consisted of presentations (11 in total), while the second day was used for discussions/evaluations in task groups and definition of necessary developments.

Current developments/demonstration projects:

DME engine developments are currently taking place in Europe, USA and Canada. These developments concentrate on fuel injection system development. Although in principle the requirements of the DME fuel injection system are much lower than a direct-injection diesel fuel injection system (due the lower injection pressure) difficulties still arise because of the very low viscosity of DME in combination with the high vapour pressure.

The engine developments should lead to demonstrations with buses for public transportation in Scandinavia and medium-duty trucks in USA and Canada.

The Scandinavian public bus demonstration program is the most comprehensive one, since an oil and gas company (for DME distribution), public transportation companies and the bus manufacturer are strongly involved. The project is currently in the engine (fuel injection system) development and preparation phase. Actual demonstration with 3 to 6 buses in Denmark is planned to start in 1997. The total project budget is 2.7 million dollar.

TNO report: "Global assessment of DME as an automotive fuel":

The well to wheel comparison and the conclusions from this report are evaluated by the workshop participants. This lead to the following modifications:
- The engine efficiency of the heavy-duty diesel en DME is raised from 36% to 40%.
- The energy consumption for (fast-fill) refuelling of natural gas vehicles is increased from about 9% to 18%. There is however still some disagreement on this point. Some data indicate an energy consumption of only about 6%.
- For light-duty a (high efficiency) direct injection gasoline engine is added.
- Concerns expressed in the report about possible aldehyde emissions can be omitted, since measurements actually show very low aldehyde emissions.

It is clear that the well to wheel CO_2 emissions and energy efficiency comparison is considerably affected by the first two modifications. Regarding CO_2 emission DME is still comparable to diesel fuel, but (up to 40%) better than the other alternative fuels and gasoline. Regarding energy efficiency DME is now rated second after diesel fuel.

Recommendation of IEA/AMF Annex.

The positive scope of DME as an automotive fuel is confirmed during the workshop. The most important reasons to stimulate the development are:
- Energy security: DME can be produced from a variety of feedstock such as (remote) natural gas, coal, heavy crude oil, heavy residual oil, coal, waste and biomass.
- Clean and efficient transportation fuel: DME combines high (diesel cycle) engine efficiency with clean exhaust emissions.

Of course considerable engine development and durability testing still has to take place and has to be succesfull.

Because of the positive outlook of DME as an automotive fuel and the willingness of the companies which are carrying out R&D in this field to work together, it is recommended to the IEA/AMF to introduce an Annex for DME.

Joint research is very much desired for the following subjects:
- Fuel quality evaluation and fuel standard definition,
- fuel costs during market introduction,
- fuel characteristics (properties),
- materials compatibility,
- further live cycle analysis,
- general safety evaluation,
- setting up general design guidelines,

- exchange of test results.

Also exchange of know how via workshops and an information centre/newsletter is desired.

Companies which are suitable to carry out tasks for the subjects listed above are identified during the workshop. TNO is put forward as the potential operating agent if this would become an Annex under IEA/AMF.

Contents

1 Introduction/Workshop procedure

The decision to organize a DME workshop or expert meeting was made at the 20th IEA ExCo meeting of the Implementing Agreement on Alternative Motor Fuels (AMF) in Harwell, England. At that meeting TNO had presented the results of the study: "Global assessment of dimethyl-ether as an automotive fuel". Consequently the Executive Committee asked and TNO agreed to organize this workshop.

The objectives of the workshop were defined as follows:
* To pool the knowledge within the IEA member countries
* To formulate an expert view on the possibilities of DME as an automotive fuel.
* To possibly recommend to the ExCo the necessity of a new annex on DME. If this would be the case, to recommend necessary tasks to further investigate and/or develop the possibilities of DME as an automotive fuel.

The invitation for the two day workshop was first directed to the National Delegates of the Implementing Agreement Alternative Motor Fuels. This led to a first group of participants. Two additional participants were invited outside the IEA/AMF countries (one from Norway and one from Austria). This was done to get all experts in the DME field together and to possibly interest these countries for participation in the AMF Implementing Agreement. The list of participants is included in Appendix B.

The two day workshop can be divided into three parts:
1. Presentations of workshop participants.
2. Discussions in three task groups:
   - DME production, distribution and position in a world-wide energy supply,
   - Automotive application compared to other fuels,
   - Automotive market introduction.
3. Presentations of task group results and discussion about the possibilities of a DME Annex.

The (final) Agenda of the workshop and the list of presentations is presented in Appendix A. Mr van Spanje, chairman of the IEA/AMF Implementing Agreement was present on the second day of the workshop. He gave a short presentation about the possibilities within the IEA.

A summary of the presentations is presented in chapter 2, while the task group results are presented in chapter 3. A summary of the R&D needs is given in chapter 4. The recommendation for an IEA/AMF Annex and a proposal for continuation in IEA context is finally presented in chapter 5 respectively 6.

2 Presentations/Current R&D activities

Below follows a summary of the presentations (11 in total).

* John B. Hansen/ Haldor Topsoe: DME manufacturing and demonstration program:
Haldor Topsoe started the development of DME production from "syngas" (mixture of H2, CO and CO2) back in 1982 in connection with production of synthetic gasoline. A stable industrial catalyst has been developed.

The first phase of a demonstration program with 3 to 6 buses for public transportation in Denmark is now being carried out. Participants in this program are Haldor Topsoe (project management), Statoil (DME distribution), the Danish Technological Institute (emissions/environmental assessment) and Volvo Truck (DME buses). A European manufacturer will probably supply the DME.
The project costs are 2.7 million $, excluding the development of the bus engine. The project is financed by contributions of most of the participants, of which the Danish governement (ministeries of transport and environment) is a major contributer.

* Theo Fleisch/ Amoco corporation: Economics of DME:
Amoco has interests in both oil and natural gas. Amoco predicts that with large scale production the prices of diesel fuel and DME would be about the same. But this is without the costs of the DME infrastructure (DME distribution and filling stations) and the vehicle conversion (appr. $ 3,000/truck). If these costs would be added to the fuel costs DME would be about 35% higher than diesel fuel costs. The DME fuel costs are considerably lower than gasoline fuel costs (engine efficiency included).
DME can be transported with adapted LPG ships (adaption costs approximately $ 100.000,- per ship).

* Martin Hagen/ Gastec: Local production of DME
Gastec studies relatively small scale production of DME from natural gas. Size plants: 1 to 1000 m3 feedstock natural gas per hour (10kW to 10 MW). Gastec projects a DME production costs of Dfl 0.40 to 0.50 per litre.
The small plants should ideally be located near cities, such that the waste heat can be used for district heating. Hagen is the opinion that also small plants can be commercially attractive, because de lay-out of such a plant can be standardized.

* Hans Jaspers/ Akzo Nobel: Safety aspects:
Akzo Nobel has a DME plant in Rotterdam with a production capacity of 25 kiloton per year. This chemical grade DME is now sold to the cosmetics

industry as propellant for spray cans. With some investments Akzo can increase the production capacity with 10 kiloton per year, such that DME fuel comes available for vehicle demonstration programs.

Akzo Nobel has extensively researched the safety aspects of DME, both on production/distribution level and on spray can level. As a results of Akzo Nobel's safety investigation DME is put in the same safety class as LPG (European regulations).
As a propellant DME is very safe because it fully mixes with water. The mixture DME-water can be chosen such that it is virtually non-flammable.

* Per Age Soerum / Statoil: Future production and DME field trials in Scandinavia
The business interest of Statoil is to find alternative outlets for remote natural gas from the north of Norway. Because of location this gas cannot presently be fed economically into their current gas market. Production of DME from this gas might become a viable option to support off-shore field development.

Currently, a methanol plant based on associated gas from the Heidrun field is nearing completion at Tjeldbergodden, Norway. More gas than consumed by this plant can be made available, and hence a demo unit for new DME production technology can be built on this site. This will further ease the availability of DME through its market development phase. Statoil will welcome other interested partners to co-finance such a venture.

Having demonstrated the excellence of new production technology and the operability of DME fuelled vehicles, a large scale production facility might be considered. A likely solution could be a plant which could flex from methanol to DME production in order to minimise product outlet and sales risks.

Statoil are participating in the Danish demonstration programme for DME fuelled buses. Statoil envisage that Scandinavia might become a commonplace for further field trials with DME, including vehicles other than buses. However, before endeavouring into new large scale field trials, positive results from the Danish programme is considered a pre-requisite.

* Spencer Sorenson/ DTU Copenhagen: Summary engine test results
The Technical University has especially studied regulated and non-regulated exhaust emission components of a DME fuelled engine. The following is concluded:
- Organic materials are primarily DME and approximately 10% methane.
- Higher aldehydes are apparently not formed. Formaldehyde emission is very low (factor 2 lower than conventional diesel).

- CO emission of DTU engine may be due to "after injection" due to oscillation of DME in high pressure fuel lines.
- PAH have not been measured, but are expected to be very low.

* Jim McCandless/ AVL Powertrain Engineering: Engine test results and development

AVL Powertrain Engineering is developing a common rail DME fuel injection system under a NREL contract. The project consists of the following tasks:

- development common rail DME FIE (fuel injection system),
- demonstrate low exhaust emissions,
- field tests with medium-duty trucks.

Design targets of the FIE are: up to 250 bar rail pressure, 250 mm3 delivery per injection (300 HP engine), possibility of injection "rate-shaping" and it should be a bolt on system (no engine modifications).
Characteristics of the system are a swash-plate high pressure pump with bellows and a carbon/ceramic rotating face-seal, injector nozzles with variable lift and solenoid valves between a central rail and the injector nozzles.

Endurance testing of the high pressure pump showed wear problems of bronze plunger and bearing parts. These parts are now going to be replaced by hardened steel parts.

* Herwig Ofner/ AVL List: Fuel injection equipment development:

The DME fuel injection system has the same set-up as the AVL Powertrain system. Instead of the swash-plate pump a membrane type high pressure pump is used.
The system has an extensive "double" purging system to prevent leakage of DME to the cylinder after the engine is shut-off. It consists of 3-way solenoid valves which purge the DME from high pressure lines to the tank and secondly to a 1-2 bar gaseous buffer tank.
According to AVL one of the difficulties of DME is the temperature dependency of certain fuel characteristics, like the modulus of elasticity. Other point of attention is the chemical attack of elastomers.

* Gary Webster/ AET: Preliminary DME test experience on a small direct injection diesel engine and review of proposed research activity on a Cummins B light-duty diesel engine:

Gary Webster showed comparative measurement data of a small DI diesel engine running on DME and diesel fuel. It appeared that running on DME leads to an increased power output and a smoke emission is almost eliminated. The test engine showed poor starting behaviour due to "vapour lock" .

The AET report has been distributed among the workshop participants.

* Derek Beckman/ TNO: Fuel injection test rig:
TNO is currently assembling a test rig for DME fuel injection equipment. It consists of a standard Bosch fuel injection pump test stand completed by special DME sub-assemblies:
- DME feed system: feed pump to supply DME to high pressure pump.
- Flow meters to measure the DME flow in gaseous phase.
- Lubrications system.

* Ruud Verbeek/ TNO: Global assessment of DME as an automotive fuel
The presentation was based on the report written about this. The following was presented:
- Comparison exhaust emissions of DME and other fuels for light-duty and heavy-duty vehicles,
- Well to wheel comparison of energy efficiency and CO_2 emission,
- Comparison operational aspects with different fuels,
- Position DME in the future (world-wide) energy supply.

The global assessment report has been distributed among the workshop participants and the IEA/AMF national delegates.

3 Task group discussions

The workshop participants were divided into three task groups:

1. DME production, distribution and position in world-wide energy supply:
   Hansen, Soerum, Fouda, Naseman, Maeda, Hagen, Verbeek

2. Automotive application compared to other fuels:
   Sorenson, Ofner, Webster, Seko, Beckman

3. Automotive market introduction
   Mc Candless, Fleisch, Megas, van Spanje, van der Weide

In order to streamline the discussions TNO had put together a set of sheets with subjects to be assessed. Also tables about exhaust emissions and efficiencies and conclusions, both from the TNO global assessment report, were handed out to be critically evaluated.

The sheets of task group results are presented in Appendix C.

The updated conclusions and the updated well to wheel comparison of the TNO report: "Global assessment of DME as an automotive fuel", are presented in respectively Appendix D and E.

4 Summary R&D needs

The R&D needs defined by the three task groups were evaluated and summarized during the last part of the workshop. Below follows an overview of the R&D needs:

1. Fuel quality evaluation and fuel standard definition:
   The fuel costs become lower when a lower quality is accepted. Lower quality means that significant percentages of methanol and water are allowed. Haldor Topsoe has estimated that the investment in the production plant can be reduced by 4% when some 4% methanol en 4% water are allowed. The lower grade fuel has disadvantages with respect to corrosion, toxicity, exhaust emission and distribution costs.
   The trade-off between advantages and disadvantages should be investigated among production, distribution and engine specialists. Then a fuel quality can be recommended and a certain standard can be defined.
   This is especially important for phase 2 and 3 market introduction (1000 vehicles or more), because than significant investments need to be made and boundary conditions for fuel quality are needed.

2. Materials compatibility:
   Many plastics and rubbers tend to solve or swell when in contact with DME. DME resistant plastics (or sealing materials in general) need to be defined.

3. Fuels costs for phase 2 market introduction:
   The quantity of DME needed for phase 2 market introduction (thousands of vehicles) is too low for large scale production plants. For that reason solutions like "side stream production" (i.e. methanol plant which also produces DME) or the conversion of an (old) fertilizer or ammonia plant are needed.
   Possibilities and opportunities for the phase 2 DME production needs to be investigated.

4. Life cycle analyses:
   Life cycle analysis of DME have been carried out to a limited extend by Amoco and Haldor Topsoe (and others outside the workshop participants). TNO has done well to wheel analysis for CO2 emissions. The present data should be combined and summarized to obtain a clear view.

5. DME information centre / Newsletter:
   This is important to inform each other and also to know what is going on around the world. The information should provide safety information and

do's and do not's, such that unsafe experiments or conversions with DME are as much as possible prevented.

6. General safety investigation:
The safety evaluation should be focused on distribution and storage and the vehicle. A comparison with LPG should be made. The vehicle safety evaluation should include storage in garages, refuelling, failure mode analysis and vehicle fire (and possibly collision) tests.

7. Determination of fuel specifications:
Certain fuel characteristics such as viscosity and compressibility have a large influence on the fuel injection system design and dynamics. Collection or determination of these characteristics, which are temperature dependant, is important for the DME fuel injection system development.

8. General design guidelines:
Design guidelines of the DME fuel system in the vehicle (or on a test stand) are important to minimise safety risks. The design guidelines should include sealing in general and more specific the type of fittings or connectors to be used.

9. Exchange test results:
Test results and general experience from engine/vehicle testing and demonstration programs should be made available to assist and guide further developments.

10. DME workshops:
It was found that DME workshops are important to share R&D experience and define further R&D needs.
It was felt that there should be two workshops per year for the first couple of years.

11. Operating agent / secretary:
An operating agent is needed to coordinate the international activities, if this would be done in the context of an IEA/AMF annex.

Proposed additional R&D need after the workshop:
- Study of alternative process configurations such as cogeneration (to further improve overall efficiency).
- Investigation of necessity of purging the fuel system after engine shut down (especially for light duty vehicles).

5 Recommendation of IEA/AMF Annex

The workshop has confirmed the positive scope of DME as an automotive fuel:

* Energy security: DME can be produced from a variety of feedstock such as (remote) natural gas, coal, heavy crude oil, heavy residual oil, coal, waste and biomass.

* Clean and efficient transportation fuel: DME combines high (diesel cycle) engine efficiency with clean exhaust emissions.

It was felt by most if not all participants that continuation of DME R&D within an IEA context would be very desirable. This would be the best possibility to acquire international support for DME as an automotive (alternative) fuel. Most of the participants are willing to share their know-how to stimulate DME as alternative fuel in general.

Because of the positive outlook of DME as an automotive fuel and the willingness of the companies which are carrying out R&D in this field, it is recommended to the IEA/AMF to introduce an Annex for DME.

6 Proposal for continuation in IEA context

For continuation in an IEA context there are two possibilities to finance the activities of an Annex: cost-sharing or task-sharing. In the first case certain activities are paid by the countries who wish to participate. Only these countries will get the report. With task-sharing the activities are financed by the government (possibly in combination with industry) of the country in which the developments take place.
Mr van Spanje (chairman IEA/AMF Implementing Agreement) has suggested to carry out the majority of the DME work under the task-sharing option. Only some "overhead" tasks such as the information centre and the efforts of the "operating agent" including the organization of workshops should be financed under the cost-sharing option.

Of course, before any government financing can take place, the National Delegates of the Implementing Agreement Alternative Motor Fuels have to accept the study and R&D needs for DME as an Annex.

Below follows an overview of the study and R&D needs from chapter 4 and the companies which have a good background and are also willing to carry out this work:

1. Trade-off fuel quality versus fuel costs
   Haldor Topsoe

2. Materials compatibility:
   Akzo can supply a list with DME resistant elastomers. GASTEC has testfacilities for accelerated ageing simulation of elastomers.
   NRCan also expressed interest in participating.

3. Fuel costs phase 2:
   No one assigned during workshop.
   GASTEC expressed interest in studying side-stream production.

4. Life cycle analysis:
   Amoco, Statoil, Haldor Topsoe, Volvo, Innas and TNO

5. Information centre (cost sharing)
   US-NREL (AFC)
   Also Innas (Netherlands) is suggested.

6. Safety investigation and development of standards:
   TNO, Akzo Nobel for Europe
   NRCan, Amoco, AVL powertrain (?) for America

First investigation can be based on LPG documents (handling procedures, design guidelines, etc.)

7. Fuel specifications:
   Akzo Nobel can possibly make certain data available

8. General design guidelines:
   AVL Powertrain, AVL List, Volvo

9. Exchange test results:
   Via workshop presentations and visits (more specific appointments are not made).

10. DME workshops (cost sharing):
    TNO
    Two workshop per year would be desirable. The next workshop is planned for ~~June~~ May 1996 in Dearborn, USA.

11. Operating agent / secretary (cost sharing):
    TNO

It must be noted that for most tasks the now defined work is only a part of what needs to be done. Also most companies cannot carry out this work without external financial support.

Appendix A Agenda/list presentations

Agenda workshop "Dimethyl-ether as an automotive fuel"
Delft, November 14 & 15

Day 1: November 14

9:00	Opening / introduction Objectives of the working party Procedure Workshop
9:45	Presentations and discussions: - DME production, distribution and position in world-wide energy supply - Safety - Engine development - Automotive application compared to other fuels
12:15	Lunch
13:15	Presentations and discussions (continuation)
15:45	Coffee break
16:00	Discussion in task groups: - DME production, distribution and position in world-wide energy supply - Automotive application compared to other fuels - Automotive market introduction
18:00	End of session
18:30	Dinner

Day 2: November 15

8:30	Opening
9:00	Visit Motor Emissions Laboratory
9:30	Discussion in task groups Formulation conclusions
11:30	Presentations task group conclusions Discussion
12:15	Lunch

13:15	Presentations task group conclusions Discussion (continuation)
14:15	Discussion necessity IEA annex If yes: proposal IEA annex and activities
16:30	Closing remarks

Presentations at workshop:

John B. Hansen:	Manufacturing of DME
Theo Fleisch:	Economics of DME
Martin Hagen:	Local production of DME
Hans Jaspers:	Safety aspects
Per Age Soerum:	Future production and DME field trials in Scandinavia
Spencer Sorenson:	Summary engine test results
Jim McCandless:	Engine test results and development
Herwig Ofner:	Fuel injection equipment and general issues
Gary Webster:	Preliminary DME test experience on a small direct injection diesel engine
Derek Beckman:	Fuel injection testrig
Ruud Verbeek:	Global assessment of DME as an automotive fuel

Appendix B Names and addresses participants

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Appendix C Task group discussion results

Task Groups:

1. DME production, distribution and position in world-wide energy supply:
   Hansen, Soerum, Fouda, Naseman, Maeda, Hagen, Verbeek

2. Automotive application compared to other fuels:
   Sorenson, Ofner, Webster, Seko, Beckman

3. Automotive market introduction
   Mc Candless, Fleisch, Megas, van Spanje, van der Weide

Discussion points / questions are printed in italics.

C.1 DME production, distribution and position in world-wide energy supply

Hansen, Soerum, Fouda, Naseman, Maeda, Hagen, Verbeek

Position in future energy supply:

Fossil feedstock:

- *Natural gas:*
  Most European and US gas fields are connected to a pipeline grid, which leads to too high feedstock (natural gas) prices for DME production.

- *Remote natural gas:*
  * Many sources for example Australia, Canada, Indonesia, Nigeria, Norway, Venezuela.
  * DME is an opportunity to use this gas (transportation forms a new large outlet).
  * With gas prices below $1/GJ (approx. $1/MM-BTU), DME is competitive with diesel at a crude oil price of $22 per barrel.
    At $18 per barrel an incentive of 20% to 40% of the fuel costs (including new infrastructure costs) is needed.

- *Associated gas:*
  (size DME plant, production costs, efficiencies, comparison with methanol, LNG, introduction barriers)
  * Mixture of methane and heavier hydrocarbons. Better feedstock because of more favourable carbon to hydrogen ratio.
  * Gas is free or even has a negative value (because of prohibition to flare it off).
  * DME price is expected to be the same as from natural gas. Increased efforts to collect the gas compensates the lower feedstock costs.

- *Oil sands/other:*
  * For energy security DME production from coal, heavy crude oil, heavy oil residues and coal bed methane are of interest. DME costs are considerably higher.
  * Combination of DME and electricity production from a IGCC-plant might result in economically viable option (DME production instead of electricity at off-hours or off-season).

- *Comparison with CNG, LNG and methanol:*
  (transportation and other aspects)
  Not evaluated

Position in future energy supply:
Renewable feedstock:

- *Dedicated or waste feedstock ?*
  Which feedstock ?
  CO2 emission in gram/GJ fuel energy ?
  * Wood plus waste wood is best feedstock:
    a 140 kT unit with waste wood feedstock is being build in Vermont, USA. The unit produces syngas which is used for electricity production.
  * If supported by CO2 tax:
    - landfill methane (unit installed...)
    - plastics (combined with coal)
    - straw (difficult option due to composition and transport costs).

- *Feasibility in-expensive small scale production:*
  (Size plant in relation to feedstock supply)
  Gastec has studied DME production in relatively small plants to be located near urban areas. In that case waste heat of DME production can be used for district heating and the energy efficiency of DME production can increase from 71% to 90%.
  Economics have not been evaluated during workshop.

- *Comparison with methanol, ethanol.*
  Process scheme DME and methanol is far cheaper than ethanol.

- *Definition required research:*
  Research in the field of waste gasification (DME production from "syngas" is already developed).

Economics:

- *Recommendation fuel quality:*
  More research is required. To start with a fairly high quality is recommended. Disadvantages of a low grade fuel (4% methanol & 4% water) are:
  - higher transportation costs,
  - possible corrosion problems due to methanol,
  - toxicity due to methanol,
  - possible aldehyde formation.

- *Relation fuel costs and quality:*
  Needs to be further investigated (figure fuel purity versus costs).

- *Fuel costs during market introduction:*

(refer to 9.3 Global Assessment)

* Phase 1: demo's up to about 10 vehicles:
Current fuel costs in relation to project costs are acceptable.

* Phase 2: 500 to 1000 buses or 5000 vans:
Price 1.5 to 2 times the diesel price is very costly.
Price is dependent on opportunity to produce DME in (old) fertilizer plant or as side stream production from a methanol or IGCC plant.

* Phase 3: 10.000 buses or 100,000 vans:
Large DME plants. More than one plant important for security.
Price is competitive with Diesel fuel at crude oil price of $22 per barrel.

DME distribution:

- from production plant to filling station

- comparison with LPG/CNG/LNG/methanol

* Similar to LPG, only seals need to be replaced by DME resistant seals.

* CNG/LNG more expensive due to high investment costs of compressor station or cryogenic equipment.

Safety:

Well to filling station

* DME in Europe in same safety class as LPG

* See global assessment report

* Further study recommended

- Accident safety:
production, transport, storage (optional: vehicle)

- Health safety with direct inhalation:

Well to Wheel analysis:

Energy efficiency and usage of other materials (water, etc.):

- Comparison with other fuels:
Refer table and appendix B of Global Assessment

The diesel engine efficiency (for both diesel and DME fuelled engines) was estimated 4% to low in the global assessment report. This leads to an increase in energy efficiencies of these engines compared to the otto-cycle engines. The new tables and figures are presented in Appendix E.

- *Possibilities higher efficiency processes to reduce well-wheel CO2 emission ? (such as proposed by DSM, refer to page 15 G)*
  Technically it is possible to increase the energy efficiency of DME production somewhat, but the increase in investment costs would be too high to make it economically feasible.

Well to Wheel analysis:
CO2 emission and other emissions:

- Comparison with other fuels:
  Refer to appendix B and C of Global Assessment
  Refer to "well to wheel analysis; energy efficiency". The CO2 emissions of the diesel cycle engines have been lowered due to a correction of the engine efficiency. Refer to appendix 1.

- *Optional: Global Warming Potential*
  (agreement necessary on CO_2, N_2O, CH_4, NO_x, CO, HC)
  When compared with the CO2-only emission of the TNO global assessment report, the positions of the "clean fuels" (among which DME) will relatively improve.
  Also refer to the Amoco/AVL publication at the "AVL Tagung Motor und Umwelt: DME - The diesel fuel for the 21st Century?"
  More extensive live cycle analysis are recommended.

Study and R&D needs / costs:

- *Subjects:*

Refer to chapter 4

- *Recommendation location (country):*
  (possibility task sharing between different countries)

se

C.2 Automotive application compared to other fuels

Sorenson, Ofner, Webster, Seko, Beckman

Engine concepts:

- *Heavy-Duty*
  * Direct Injection (DI) engines,
    common rail fuel injection,
    Dedicated DME, based on conventional diesel engines with only fuel system changes.

  * Main experience ==> Lighter engines due to lower pmax, dp/dt, lower friction, lower load factor and lower lambda

- *Light-Duty*
  * Limited experience
  * Need for engine/vehicle study

- *Engine costs*
  * Depends on safety, safety standards are required.
  * Costs savings due to:
    - simpler fuel injection equipment (but costs fuel handling uncertain)
    - smaller, lighter engine (bearing size, etc.) due to lower load factor and lambda.

- *Possibilities retrofit:*
  HD & LD
  * HD most likely, OEM support is important.
  * LD further study necessary, emphasis on conversion costs.

Comparison exhaust emissions and energy efficiency of DME engines with other engines:

- *Exhaust emissions:*
  Refer to tables Global Assessment
  * Tests are still very preliminary. There is a need for vehicle emissions test on a chassis dynamometer.
  * Direct Injection gasoline engine should be added.

- *Energy efficiency:*
  Refer to tables Global Assessment
  * Heavy-Duty: Engine efficiency of DME and diesel fuelled engines should be increased from 35% to about 40%.
  * Light Duty: (Direct Injection) DME engine efficiency should be about 10% higher than Indirect Injection diesel engine. 0.28 engine efficiency becomes 0.31. Refer to Appendix E.

Operational and practical aspects:
- Fuel tank size and weight:
  Refer to table GA report

Safety:
Collision and fire safety of DME in a vehicle:
* Minimum LPG standards
* Attention: Elastomers, static electricity
* Further study needed to define standards !!

Fuel quality:
- Influence fuel quality on emissions & energy consumption:
  * Engine tolerates methanol and water up to 3-4% each
  * Influence on materials (especially elastomers) and possible aldehyde emission should be investigated.
  * Assessment cetane number.

- Recommendation fuel quality:
  High quality for first stage recommended.

Optional
Environmental aspects:
Refer to table:

- Toxic effects: +
- Summersmog: +
- Wintersmog: +
- Acidification: +

- *Global Warming Potential*
  (agreement necessary on CO_2, N_2O, CH_4, NO_x, CO, HC)
  * CO2 comparable to CNG, LPG
  * N2O should not be a problem
  * HC/VOC (volatile organic components)
    Measurements on small Yanmar engine have shown:
    - HC/VOC are for 90% DME
    - CH4 < CH4 diesel

- formaldehyde < formaldehyde diesel
- aldehydes << aldehydes diesel

Study and R&D needs / costs:

- *Subjects:*

  * Safety requirements
  * Light-Duty vehicle engine
  * Optimize/Investigate DME engines
    - combustion / emissions
    - construction
  * Comparison with DI gasoline injection
  * Fuel injection system:
    - system optimization
    - fuel spray behaviour
    - alternatives

- *Recommendation location (country):*
  (possibility task sharing between different countries)

C.3 Automotive market introduction

Mc Candless, Fleisch, Megas, van Spanje, van der Weide

Market selection:
- *Heavy-Duty:*
- *Light-Duty:*

Driving forces DME as an automotive fuel:

* Very low emissions
* High performance
* Use existing diesel production technology (lowest capital needed)
* Cost effective fuel
* Energy security

Barriers against market introduction:
(costs, costs-uncertainty, operational aspects)

* High initial fuel cost
* Requires infrastructure
* Safety concerns/perceptions
* Engine technology not proved or fully developed

Market introduction strategy HD & LD:
possibilities in low emission programs (EEV, Auto-Oil program)

Heavy-Duty:

* Dedicated engines
* Small, centrally fuelled fleets - non attainment areas

* Urban and inter-urban operation

* Very low emissions (soot, NOx and aldehydes) with diesel cycle efficiency

* Low total cost of ownership
  - fuel

* Systems must be robust, durable, reliable and safe

* Need cost subsidies for initial introductions (fuel tax breaks, etc.)

Light-Duty:

Same as HD

Safety:

- Fuel storage at filling stations:

* Basic LPG procedures

* Automated filling/user friendly

* Need FMEA/FMEM

- DME vehicles in garages:

* Gas sensors

* Need FMEA/FMEM

Study and R&D needs / costs:

- Subjects:

* Conformable fuel tank technology (packaging)

* DME properties
  - Liquid viscosity
  - Elastomer compatibility
  - Quality of fuel

* Low cost flammable gas sensors

* DME handling & storage standards - like NFPA (National Fire Prevention Association):
  - World Standard
  - Appendix to LPG

* General design guidelines for DME engine and vehicle

* Financial support needed for field demo's

- *Recommendation location (country):*
  (possibility task sharing between different countries)

* International information exchange
  - test results
  - general technical info
  - safety information and information regarding fuel handling

Appendix D Update conclusions TNO report: "Global assessment of Dimethyl-ether as an automotive fuel"

The conclusion and recommendations of the TNO report: "Global assessment of Dimethyl-ether as an automotive fuel" have been updated by task group 1 (Hansen, Soerum, Fouda, Naseman, Maeda, Hagen, Verbeek).

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 DeNOx catalytic aftertreatment have demonstrated compliance with expected HD emissions legislation of 2004/2005. Disadvantages compared to DME fuelled engines are the complexity, the need of reagent injection (only with deNOx catalyst) and the

higher particulates emissions. Particulate traps have up till now not demonstrated reliable operation, although promising developments still take place.

* Emissions of DME engines can be further reduced by installing an oxidation catalyst or DeNOx catalytic aftertreatment. For the latter only a very small quantity of reagent injection would be required.

* 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).
  Measurements on a small Yanmar engine showed no detectable PAH emission.

* Measurements on a small DME fuelled Yanmar engine showed aldehyde emissions lower than the same engine on diesel fuel (methanol and ethanol engines generaly show much higher aldehyde emissions).

* SO2 emission will be extremely low (better than LPG, natural gas), because of the absence of sulphur in DME. Sulphure in the lubricant may couse some SO2 emission.

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

* The well to wheel CO_2 emission of DME is for light duty vehicles about equal to diesel (if directly injected). It is about 20% respectively 40% better than CNG and gasoline.
  For heavy-duty vehicles, DME has a 10% to 25% lower CO_2 emission than CNG/LPG.

* For light duty application the well to wheel energy efficiencies of DME (19%) is better than of gasoline, LPG and CNG (respectively 17%, 18% and 15%), but not as good as diesel (22%-26%).
  For heavy duty application the energy efficiency of DME is comparable to LPG, better than CNG and gasoline but not as good as diesel. For urban bus application some numbers are: DME: 22.5%, CNG lean-burn 20%, LPG lean-burn: 22% and diesel 30%.

* DME has a short-half live in the troposphere, and no release to the stratosphere.

* DME is virtually non-toxic

* No risk of ground water contamination because DME is a gas (it wil evaporate) and because it is 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 in for example Australia, Canada, Indonesia, Nigeria, Norway, Venezuela.

* Exploitation 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.

* Increased strategic energy security due to production of DME from coal, heavy crude oil and heavy oil 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 depending on the production plant size and the natural gas costs. This is about equal to the range for LPG, CNG and LNG. When natural gas needs to be transported over a long distance 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.

* Feasibility of DME production from biomass and waste materials. This should encompas costs analysis and include possible synergy with cogeneration.

* Evaluation of the DME role with respect to Enhanced Emissions Vehicles program (EEV: stringent exhaust emissions requirements for cities).

* Possibilities to make DME cost effective available for the first phase market introduction (about 1000 heavy-duty vehicles on DME).

* Investigation to the costs of large scale market introduction including the set-up of a DME distribution system.

* More extensive live cycle analysis.

* Definition of fuel quality standard, through analysis of fuel quality versus production costs and evaluation of engine requirements and corrosion, toxicity and materials aspects in relation to the fuel quality.

* General safety evaluation including failure mode anaylsis and tests and vehicle fire and crash tests.

* To set-up a (internet) information centre in combination with a news letter.

Appendix E Update well-wheel charts TNO report "Global assessment of Dimethyl-ether as an automotive fuel"

The modifications made by the workshop participants are the following:
- The energy consumption of the natural gas compression at the filling station is increased from 9.5% to 18% of the fuel energy. This is based on "fast-fill" refuelling and a natural gas supply pressure of 3 to 4 bar. There is however still some disagreement on this point. Data supplied by GASTEC indicates an energy consumption of only about 6%. This data comes from the manufacturer of natural gas compressors: Idro-meccanica (Italy).
- The engine efficiency of the diesel and DME fuelled heavy-duty engines is increased from 36% to 40% (the 36% was not based on a state of the art diesel engine.
- The light-duty diesel engine efficiency was based on primarily indirect injection (IDI) diesel engines. A direct injection (DI) diesel engine is added. This engine has a 4% higher engine efficiency. The DME fuelled engine is a DI engine and consequently also has the higher engine efficiency.
- For light-duty a (high efficiency) direct-injection gasoline engine is added. The data is based on publications of the new Mitsubishi DI gasoline engine.
- The CO_2 emission of the methanol production is slightly increased (it was to low in relation to the energy efficiency).

Especially the first three modifications listed above have considerable influence on the energy efficiency and CO_2 emissions comparison for the different standard and alternative fuels.
The relevant tables and figures of the TNO report: "Global assessment of Dimethyl-ether as an automotive fuel" have been corrected and are presented on the following pages:
- Table 1,2 and 3: well to wheel energy efficiency (from Appendix F, Global Assessment report)
- Table 4 and 5: well to wheel CO_2 emission (from Appendix G, GA report)
- Figures 1 through 4: well to wheel energy efficiency and CO_2 emission (from chapter 7, GA report).

The numbers in the tables which have been modified compared to the global assessment report are printed in italics.

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	*0.980*	*67.5%*
LPG	0.964	0.93	0.90	0.985	88.7%
CNG	0.970	0.98	0.95	*0.820*	*77.9%*
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 well-station	Engine	transm. & auxiliaries	weight correction	Total vehicle eff.	Total well-wheel
Bus engines						
Diesel	0.901	*40%*	0.84	1.00	*33.6%*	*30.3%*
DME	*0.675*	*40%*	0.84	0.99	*33.3%*	*22.5%*
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	*0.779*	32%	0.84	0.97	26.1%	*20.3%*
CNG stoich., low calorific f	*0.779*	30%	0.84	0.95	23.9%	*18.6%*
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)		40%	0.84	0.99	33.3%	

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

	Total well-station	Engine	transm. & auxiliaries	weight correction	Total Vehicle eff.	Total well-wheel
Passenger cars & vans						
Diesel	0.901	0.28	0.89	1	25%	22.5%
Diesel DI	*0.901*	*0.32*	*0.89*	*1*	*28%*	*25.7%*
DME (DI)	*0.675*	*0.32*	*0.89*	*0.99*	*28%*	*19.0%*
Gasoline	0.817	0.23	0.89	1.01	21%	16.9%
Gasoline (DI)	*0.817*	*0.28*	*0.89*	*1.01*	*25%*	*20.6%*
LPG	0.887	0.23	0.89	1	20%	18.2%
CNG	*0.779*	0.23	0.89	0.95	19%	*15.1%*
Methanol	0.617	0.23	0.89	0.99	20%	12.5%

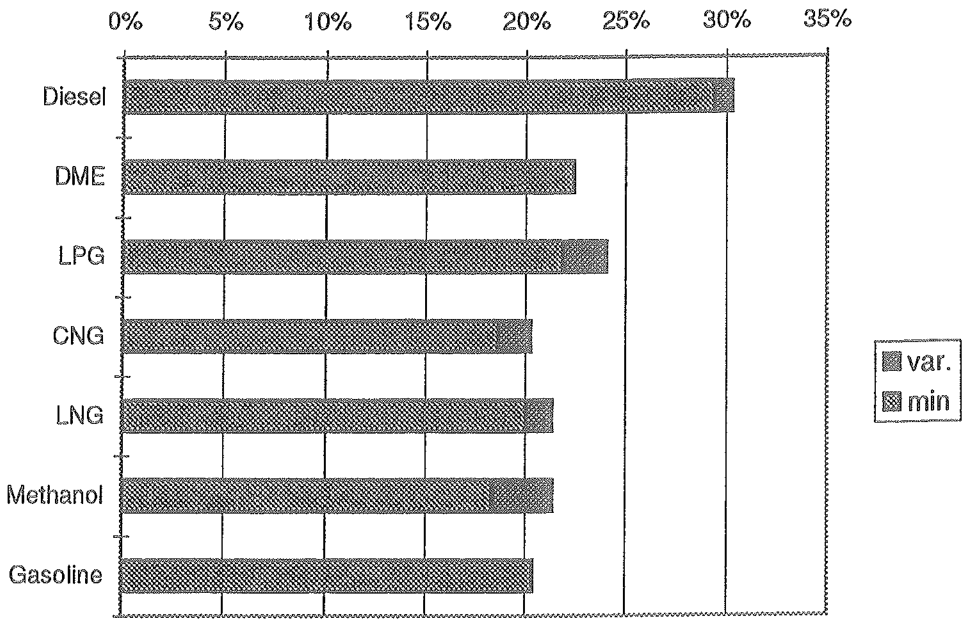
Table 4: Well to wheel (net) CO2 emissions heavy duty vehicles, urban bus application

	Vehicle efficiency	CO2 prod. kg/GJ fuel	CO2 vehicle kg/GJ fuel	Relative to diesel Production	Vehicle	Well-wheel
Urban bus applic.						
Diesel	*33.6%*	9.1	*73*	*0.11*	*0.89*	1.00
DME	*33.3%*	16.3	*66.4*	*0.20*	*0.82*	1.02
LPG lean-burn	26.9%	9.1	67	0.14	1.02	1.16
LPG stoich.	24.4%	9.1	67	0.15	1.13	1.28
CNG lean-burn	26.1%	*15.5*	55.2	*0.24*	0.87	*1.11*
CNG stoich.	23.9%	*15.5*	55.2	*0.26*	0.94	*1.21*
LNG lean-burn	26.9%	13.4	55.2	0.20	0.84	1.04
Methanol (diesel)	29.1%	*17.9*	70.7	*0.25*	0.99	*1.25*
Gasoline	24.6%	13.4	74.2	0.22	1.23	1.46
DME renewable	33.3%	13.9	0	0.17	0.00	0.17
Bio-ethanol, fr. sugar,	33.3%	13	0	0.16	0.00	0.16
Bio-ethanol, fr. wheat,	33.3%	32	0	0.39	0.00	0.39

Table 5: Well to wheel (net) CO2 emissions light duty vehicles, average of urban, sub-urban and motorway

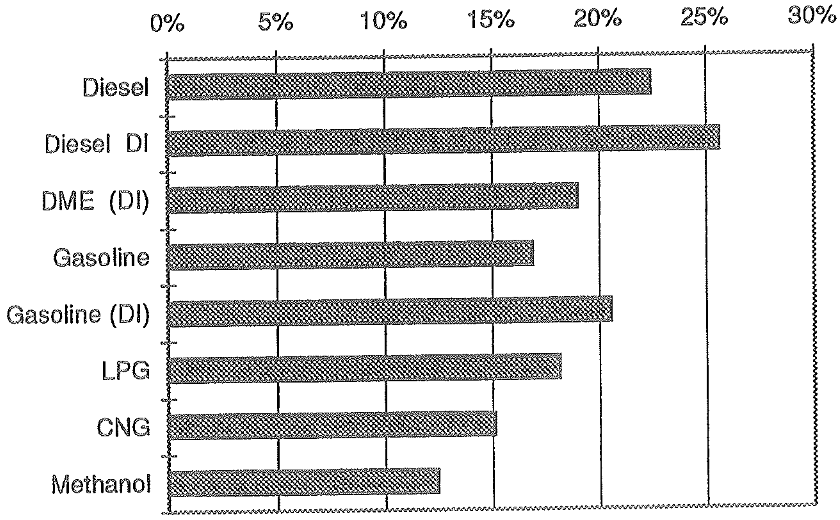
	Vehicle efficiency	CO2 prod. kg/GJ fuel	CO2 vehicle kg/GJ fuel	Relative to diesel Production	Vehicle	Well-wheel
Light duty vehicles						
Diesel	0.249	9.1	73	0.11	0.89	1.00
Diesel DI	*0.285*	*9.1*	*73*	*0.10*	*0.78*	*0.88*
DME (DI)	*0.282*	16.3	*66.4*	*0.18*	*0.71*	*0.89*
Gasoline	0.207	13.4	74.2	0.20	1.09	1.29
Gasoline DI	*0.252*	*13.4*	*74.2*	*0.16*	*0.89*	*1.06*
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	*17.9*	70.7	*0.27*	1.06	*1.33*
DME renewable	0.282	13.9	0	0.15	0.00	0.15

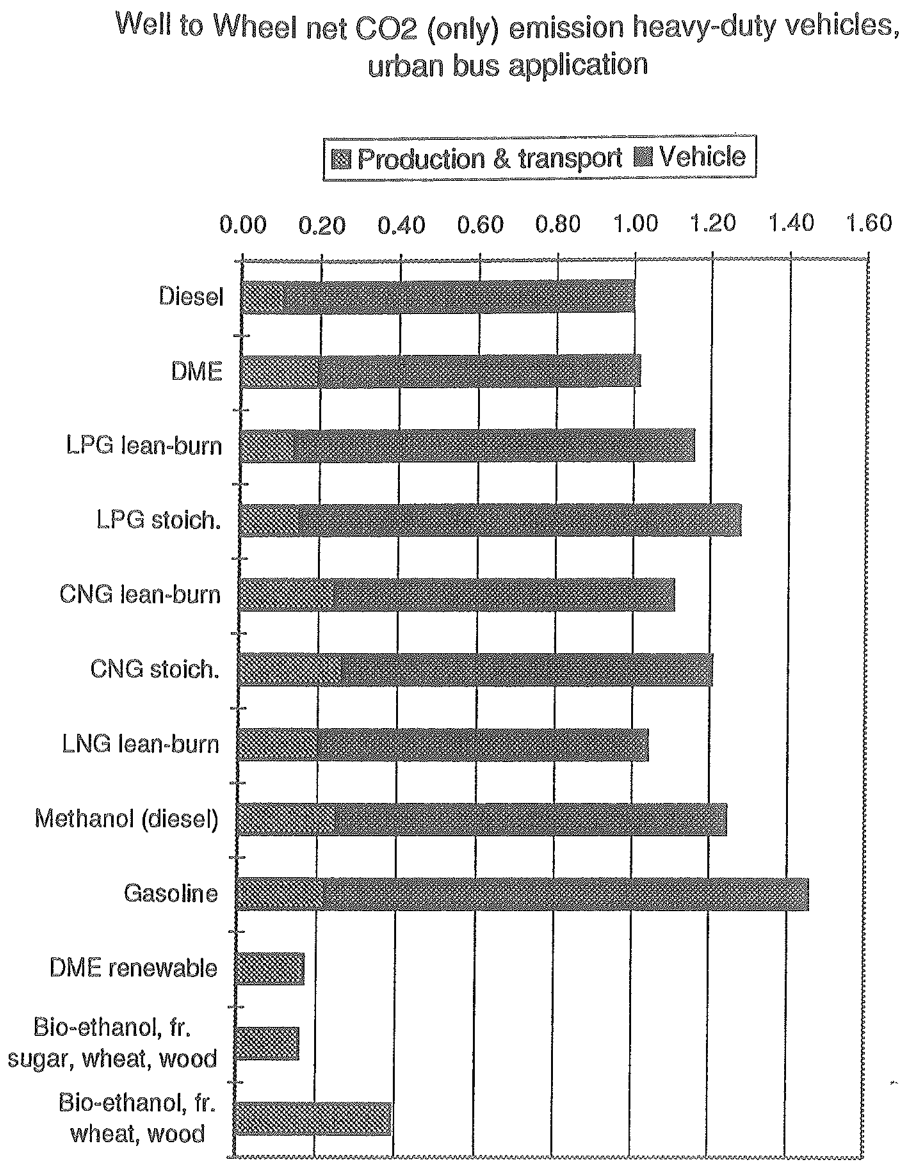
Well to Wheel energy efficiency heavy-duty vehicles, urban bus application



Range indicates differences in engine type

Well to wheel energy efficiency of light-duty vehicles
(mix of urban, sub-urban and motorway)




Well to Wheel net CO2 (only) emission heavy-duty vehicles, urban bus application
Production & transport
Vehicle
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
Diesel
DME
LPG lean-burn
LPG stoich.
CNG lean-burn
CNG stoich.
LNG lean-burn
Methanol (diesel)
Gasoline
DME renewable
Bio-ethanol, fr. sugar, wheat, wood
Bio-ethanol, fr. wheat, wood

Well to Wheel net CO_2 (only) emission, light duty vehicles
(mix of urban, sub-urban and motorway)