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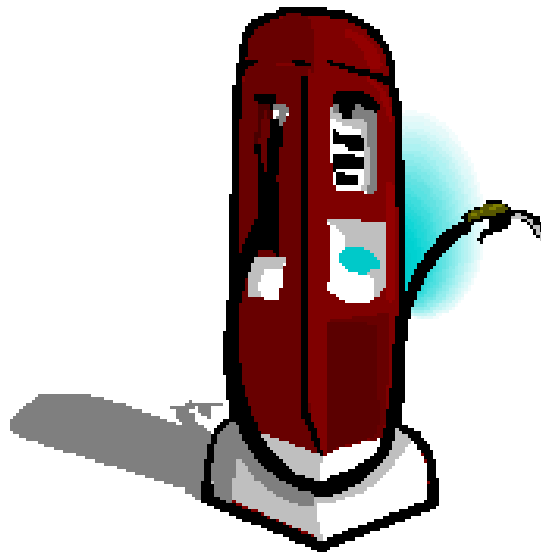
DISTRIBUTION STRATEGY FOR DME AND METHANOL ON THE SWEDISH FUEL MARKET

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EXECUTIVE SUMMARY

Introduction and background

Methanol and DME are two fuels that can be produced from biomass via the so-called synthesis gas route. In both cases, fuel production can be made at high energy efficiency, i.e. among the highest of all biofuels, as several well-to-wheel studies have shown. The energy-efficiency in the vehicles can also be high. However, none of these fuels are used in large quantities on the market today so there might be several issues to take into consideration and several options to investigate before an introduction strategy could be established. In addition, most of the industrial stakeholders in the oil and automotive industry prefer other fuel options.

Sub-project 3 (SP3) in the RENEW project has the objective to show the technical and commercial impact of DME/methanol production from black liquor at the pulp mills. One part of SP3 has been to assess potential distribution strategies on the Swedish and European market for these fuels. In the work reported here, contacts with oil companies and technology development companies, as well as the auto industry have been made to discuss the proposals presented.

There are a number of different options to use methanol as a motor fuel. Blending component in petrol, feedstock for MTBE and FAME production, M85 in fuel-flexible vehicles as well as in dedicated M100 vehicles are some of the options. In contrast, DME has fewer options besides the use in dedicated fleets. The scope of this project has been to investigate the various options and issues related to the introduction of those fuels on the market.

Safety

Safety due to, e.g. fire and explosion, is always an issue for new fuels on the market where there is little previous experience from the field. In the methanol case, there is indeed much experience from the use of M85 vehicles and similarly, many experiences can also be drawn from the use of E85. In general, methanol cannot be assessed to be more dangerous from a fire and explosion perspective than conventional hydrocarbon fuels. Recommendations from the oil industry in combination with the measures already implemented by the car industry are sufficient to handle this risk.

DME has a couple of safety issues but there are many similarities to the distribution of LPG, an established technology today.

Health and environmental impact

Methanol is more toxic than petrol when ingested. On the other hand, it is not toxic in low concentrations, since methanol is present in the human body due to metabolism of food and beverages. Few of the possible exposures to methanol will normally give high concentrations in the body. Methanol is handled in the USA in large quantities as windshield washer fluid without any apparent fatalities.

In a spill (land, water etc.) methanol has higher acute toxicity than petrol and diesel spill on a local level but due to its solubility in water, the concentrations rapidly decrease to a level where it is no longer toxic.

In contrast to methanol, DME has a very low toxicity and is environmentally benign from many other standpoints as well.

Potential barriers

Of all the potential barriers for an introduction of methanol investigated, engine wear is the only one that potentially could be a "show-stopper". However, data generated on old engines is not applicable on future engines so more investigations in this field would be necessary.

Introduction strategy

Initially, DME can be introduced on the market at the same pace as dedicated fleets are introduced. DME should be given a higher priority than methanol, whenever possible, due to a greater acceptance by the industry.

The use of methanol in FAME and MTBE are the most uncontroversial routes of utilising methanol in the transport sector. Blending in petrol is economically viable but not favoured by the oil and auto industry. The use in fuel-flexible (M85) and dedicated (M100) light-duty vehicles is an option on a somewhat longer term.

In order to distribute methanol in an efficient and cost-effective way, anhydrous M100 could be the only fuel quality that needs to be distributed. M85, and possibly M70 in the winter time, could be obtained by using a blending pump. Eventually, also heavy-duty vehicles could run on M100 when the fuel distribution network has been established. A potential distribution strategy is shown schematically in **Figure ES1**.
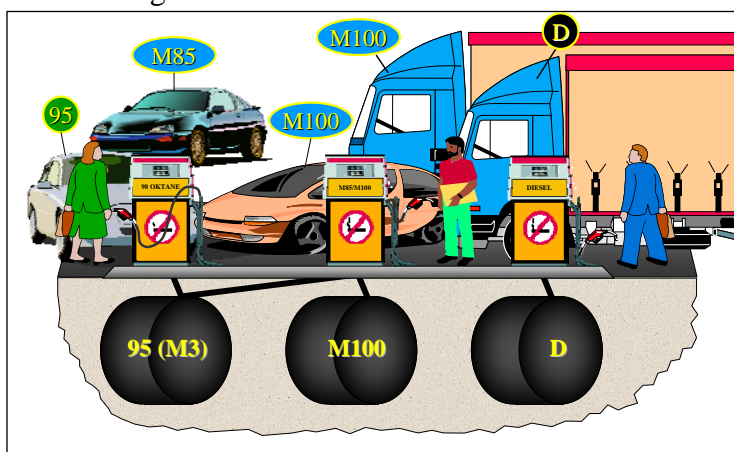
Figure ES1.   *Distribution strategy*

Conclusions

In short, the conclusions in this study are the following:

- Methanol was one of the first alternative fuels to be considered for a large scale introduction in the 1980's. However, since the 1990's, most stakeholders have lost interest in this option. In contrast, DME is a relatively "new" alternative fuel on the market.
- The fire and explosion safety hazards with methanol have been investigated. In general, methanol should be considered safer than or at least as safe as petrol in this respect. DME has some safety issues to be taken into consideration. DME distribution has many similarities to the distribution of LPG, an established technology today.
- Material compatibility must be addressed for methanol, since methanol is corrosive and degrades some polymers and elastomers. However, there are suitable materials

available on the market and test methods for material selection (e.g. SAE J1681) have been developed. Methanol is a chemical commodity today and is handled in large quantities on the world market without any apparent problems.

– DME, as a new fuel, has several material compatibility problems that must be overcome until DME could be introduced on a larger scale. Much development work is going on in this field.

– Phase separation with methanol/petrol blends is an issue to consider. In low-level blending a stabilising agent must be used. This stabiliser could be ethanol. Some options of fuel distribution must be avoided to prevent phase separation.

– The health effects of methanol exposure have been thoroughly investigated in the past. Methanol is more toxic than petrol when ingested. On the other hand, methanol is neither mutagenic nor carcinogenic, as in contrast to petrol. Normal exposures of methanol to humans give concentrations that are far below the level of health effects. Human body metabolism and ingestion of diet beverages and fruit generally cause higher concentrations.

– Methanol spill to land and water does generally have lower environmental impact than petrol and diesel fuel spills. Below a certain concentration, methanol is not toxic, is metabolised by micro-organisms and consequently, the impact is only local.

– Engine wear is the most severe of all potential show-stoppers for methanol that have been identified in this study. The increased engine wear was investigated in the 1980's and the mechanisms are fairly well-understood. However, these results are not directly applicable on modern engines. It is hypothesized by these authors that advanced engine technology such as, e.g. direct injection, might overcome those problems.

– DME cannot be used in fuel-flexible vehicles so it would have to be used in dedicated fleets during an introductory phase. In the first production plants, where both DME and methanol could be produced, the share of DME would have to scale with these fleets. Since DME seems to be favoured over methanol by oil and auto industry, DME should be given highest priority.

– On the short term horizon, the use of methanol in low-level blending would have the greatest potential. Cost calculations show that methanol would be cost-competitive with ethanol and it is not likely that ethanol could be produced in sufficient quantities in the EU to meet the demand. However, neither the oil nor the auto industries favour the blending option. Therefore, the "safest" and most conservative route of introducing methanol would initially be to use it as a substitute for fossil methanol in FAME and MTBE production.

– On a longer term horizon, the use of fuel-flexible and dedicated light-duty vehicles is the most favoured option. The use of direct injection would greatly enhance the cold start properties and enable a significant increase in engine efficiency. Furthermore, M100 could be used instead of M85. Dedicated heavy-duty M100 vehicles could be introduced at a later stage.

– An introduction strategy based on the distribution of anhydrous M100 and the use of blending pumps to make other fuel qualities (e.g. M85) available is proposed.

In the discussion with oil and auto industries it has been found that they are currently not particularly interested in methanol as a motor fuel. However, it has been very difficult to pinpoint any particular reason as to why these negative attitudes have been formed. Ecotraffic welcomes a debate of the pros and cons of methanol as a motor fuel of the future.

1   INTRODUCTION AND BACKGROUND

Methanol and DME are two fuels that can be produced from biomass via the synthesis gas route. In both cases, fuel production can be made with high energy efficiency, i.e. among the highest efficiency of all biofuels. The energy efficiency in the vehicles can also be high. The potential to high energy efficiency for DME and methanol has been shown in several well-to-wheel studies. However, none of these fuels are used in any large quantities on the market today.

Within the RENEW project, the production and use of methanol and dimethyl ether (DME) has been investigated in sub-project 3 (SP3). Part of the work carried out in this SP has been to assess potential distribution strategies for these fuels. The objective of this report has been to summarise the findings from this investigation.

The background for utilisation of methanol and DME are quite different. First of all, methanol was one of the first alternative fuels to be considered for a large scale introduction. Much work was conducted with this aim during the 1970's and 1980's, primarily in the USA. In spite of all the efforts, methanol never reached the stage of even being close to a large scale commercial introduction. Consequently, after this period, the interest in methanol as an alternative fuel was more or less lost by most industry stakeholders.

In contrast to methanol, DME is a relatively "new" alternative fuel on the market. A few publications in this field originate from the 1980's. However, the main interest in using DME as a motor fuel basically started at the SAE Congress in Detroit in 1995 when five SAE Papers on this subject were presented. During the following decade, much research and development work has been conducted to enable the use of DME as a motor fuel in diesel engines. In assessing the results so far, it has to be said that the commercial success has not been very fast. Perhaps needless to say in view of this modest progress, several technical problems related to the practical utilisation of DME have been encountered in the development. Thus, although more than 10 years have now passed on since the initial interest in 1995, no larger fleets of DME-fuelled vehicles have yet been introduced on the market. However, prospects today look somewhat brighter. In view of recent development related to the use of DME in vehicles, the phase when the first fleets of vehicles could be introduced on the market seems to be reached within the next couple of years. For example, Volvo Truck Co. is planning to perform a first customer field test with DME-fuelled trucks in 2009.

The overall objective of SP3 within the RENEW project has been to show the technical and commercial impact of DME/methanol production from black liquor at the pulp mills of Södra Cell in Mörrum, in southern Sweden. The project manager of SP3 is the Swedish development company Chemrec. Chemrec is a technology developer and licenser of high-temperature black liquor gasification (BLG). The role of Ecotraffic in SP3 has mostly been devoted to the distribution strategy of DME and methanol. Contacts with oil companies and technology development companies, as well as the auto industry, have been made in this process.

2   METHODOLOGY AND DELIMITATIONS

Two different methodologies were used in this study to collect information and to gain the knowledge needed as a basis for making the conclusions and recommendations presented in this report. First, some literature was collected in the specific areas of interest. The authors had already most of the necessary literature more or less readily available from previous work in this field. Second, discussions with some stakeholders in this field, e.g. oil companies, auto industry and suppliers of fuel dispensing systems, were brought up about the distribution strategy proposed and related problem areas regarding fuel distribution and end use.

The proposed strategy has also been discussed with other participants in SP3. Specific questions regarding future EU specifications for petrol have been discussed with Swedish participants in the stakeholder meetings in Brussels where these issues have been covered [1, 2][1]. Last but not least, a person responsible for this field within the European Commission has also been contacted for the EU opinion in this field [3].

Based on the collected information and the various viewpoints from the stakeholders, a distribution strategy was elaborated and discussed. Comments and remarks from the participants at the RENEW meeting in Stuttgart, where this work was presented, have also been considered in the final report.

2.1   Potential use of DME and methanol

First, it is of interest to discuss some various options to use DME and methanol as motor fuels. Each of the fuel has some specific advantages and disadvantages in various applications. Before going into detail, it is of interest to provide an overview of these issues.

2.1.1   Use of DME

Today, DME is mainly used as a chemical feedstock and as an aerosol propellant for spray cans. In the near future, DME could also be used as a substitute for LPG (e.g. for household cooking) and as a fuel for gas turbines. Such applications have already been initiated or else, work has started in some of these sectors. In all these applications DME has favourable properties and can be used with minor modifications of the equipment in distribution and end use phases.

DME could also be used as a "green" chemical (i.e. a feedstock for olefin production) provided that there is a market for such a product, i.e. that the market s willing to pay a premium price for the green DME. While a premium price in comparison to fossil DME would be of no particular problem for expensive products such as e.g. perfume, this is not the case in general. However, it is likely that there are still several sectors to be found where a premium price could be paid. It should also be realised that the global market for DME is relatively small today in comparison to the market for methanol. Therefore, it might be more difficult for DME than for methanol to find a market in a situation where there would be a surplus of DME on the market. For example, the market could easily become saturated after the first plant has been built unless new markets for DME could be developed at the same pace.

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[1] Numbers in bracket designate references listed at the end of this report.

In this project, the aim has been to assess the possibilities to use DME as a motor fuel. However, it has to be realised that as production capacity and size of vehicle fleets cannot develop at a similar pace, there must be situations where there will be a deficit or a surplus of DME. Since DME cannot be utilised for low-level blending in diesel fuel without significantly increasing the vapour pressure of the fuel, a similar possibility as the case of blending methanol in petrol (where the base petrol can be modified to accomplish this) is not a realistic alternative for DME. One the other hand, if a niche market is found, relatively high prices could be expected, which would be of great benefit for the first production plants.

As for methanol, DME could also be used in fuel cell vehicles. The reforming temperature is only slightly higher than for methanol and among the lowest of all potential fuel candidates for fuel processors in FC vehicles. Likewise, DME might be a suitable fuel for the use in direct DME fuel cells, in analogy with direct methanol fuel cells. For both options of using DME in fuel cells, it should be noted that very little R&D has been conducted in this field. Particularly for the direct DME fuel cell, it is far too early to say that this option could be viable at all in automotive applications. Eventually, a scientific breakthrough has to be made first.

2.1.2   Use of methanol

Methanol can be utilised in many different ways. Some of them are (in no particular priority order):

– Blending component in petrol up to the limitations in the fuel specification
– Feedstock for production of MTBE (i.e. bio-MTBE)
– Feedstock for transesterification of fatty oils to FAME
– Fuel-flexible M85 vehicles and, presumably on a longer term, utilisation of methanol in dedicated M100 vehicles as well.
– Blending in diesel fuel (emulsions and blendings using co-solvents)
– Use of methanol in fuel cell vehicles
– Methanol as a "green" chemical (e.g. for olefin production)
– Methanol is sold on the world market at the same price as fossil methanol

Blending component in petrol

Low-level blending is one of the most convenient ways of introducing a "new" fuel on the market provided that this solution is technically feasible. This has been the case for ethanol, where blending has been favoured by many companies in the auto industry and in some cases also by many oil companies. Today, 5 % ethanol is blended into all 95 octane petrol in Sweden[2]. Limited investments in the fuel infrastructure and small or no incremental investments in the vehicles are two of the major advantages or this strategy. The main disadvantage is that there is a practical limit for the blending level taking into account, among other things, that the "new" fuel must be utilised in the current vehicle fleet. This limit for ethanol might be at about 10 % or maybe even as high as 20 to 25 %, as the example from Brazil indicates. It is reasonable to presume that the limit for methanol would be lower than for ethanol; but potentially, it could be limited by the same oxygen content as for ethanol. Eventually, there is a limit for the blending unless the vehicles are modified to accept a higher blending level, which in practice would turn them into fuel-flexible vehicles, with a higher associated cost per vehicle than simpler modifications.

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[2] The market share of 98 octane petrol in Sweden is limited and no ethanol is currently blended into this fuel.

Given the practical limits discussed above, it can be realised that the momentum of introducing alcohols will be lost when the limit is approached. Thus, fuel-flexible and dedicated vehicles should be given higher priority on a longer term. The question is when this situation would occur. Even today, when the ethanol production in the EU cannot keep up with the current demand and certainly not if 5 % ethanol would have to be blended in all petrol in all member states, an increase in the limit for ethanol in petrol from 5 % to 10 % is under discussion[3]. Due to the great short-term potential, low-level blending is one of the main routes discussed in this report for the initial phase of the introduction of methanol on the market.

Feedstock for MTBE production

Biomass-based methanol could replace fossil methanol as a feedstock for MTBE production. In the USA, MTBE is being phased out due to environmental problems related to leaking fuel tanks. In case of a leakage, MTBE contaminates the ground water table. Avoiding tank leakage does not seem to be a solution considered in the USA. As a contrast, the discussion about MTBE in the EU has not led to a ban. The EU position on this issue was established in preparing for the new petrol and diesel fuel standards [4] along with accompanying studies in this field [5, 6]. In order to simplify the problem in a nutshell the authors of this report would summarise the findings as follows: if underground tanks are not leaking, there is no environmental problem with MTBE. The advantages over blending with alcohols (ethanol and methanol), such as lower evaporative emissions and reduced exhaust emissions, would then predominate.

Compared to many other fuel components in petrol, MTBE does not appear to have more adverse health effects due to fuel exposure. The possibility of MTBE being a carcinogen or mutagen has been discussed by some researchers but no such firm evidence has yet been presented. In contrast, benzene, a fuel component in petrol, has been found carcinogenic.

The main environmental *advantage* of MTBE is a reduction in exhaust emissions; compared to both base petrol and petrol blended with ethanol. Furthermore, it does not have a negative impact on fuel volatility as neat alcohols do have and thus, evaporative emissions are also reduced. In addition, using MTBE seems to be slightly more energy efficient than using methanol or ethanol due to that the base petrol does not have to be reformulated to handle the vapour pressure increase. As with low-level blending of methanol, there is a limit for the maximum blending level of MTBE in petrol.

A close competitor to MTBE is ETBE, where ethanol is replacing methanol. ETBE is already used in most EU member states as a blending component in petrol. The use of ETBE is considered a better way of using ethanol than direct blending by many oil companies. MTBE and ETBE have very similar properties and have also similar advantages regarding exhaust emissions. The impact on groundwater is a similar problem (although marginally less for ETBE) for both fuels but can be controlled if leakage is avoided.

The main advantage of using bio-ethanol instead of fossil methanol as a feedstock is, of course, that the ethanol is non-fossil and contributes to the EU goal of substituting fossil petrol and diesel fuel in the automotive sector. In a recent study by CONCAWE, EUCAR and EC/JRC, the production and use of ETBE has been assessed [7]. Somewhat surpris-

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[3] It could be noted that the E85 price in Sweden during the summer of 2006 has increased considerably; up to a level where the economic advantages for this option have diminished. This development has probably been a consequence of an increasing demand for ethanol in the EU.

ingly, bio-MTBE was not been investigated although methanol production has been studied as a hydrogen carrier for use in fuel cell cars. Since bio-methanol can be produced with higher efficiency and at a lower cost than bio-ethanol according to the mentioned joint study [7], bio-MTBE should be a very interesting alternative to bio-ETBE. An additional advantage for bio-MTBE over bio-ETBE is that no modification of existing MTBE plants has to be made.

A barrier for the introduction of methanol as a feedstock for MTBE is that the same tax reduction, or tax relief, must apply for the methanol part of MTBE. This is a common problem for all other biofuels, e.g. bio-ETBE, which are used in neat form or as blending components. To achieve this, the bio-origin of the methanol used has also to be controlled in some way. Currently, this is not the case in many member states. The implementation for bio-ETBE is less problematic, since very little fossil ethanol is available on the international market.

Feedstock for FAME production

Fatty acid methyl esters (FAME) are currently the mostly used biofuel in the EU. In fact, FAME is more or less synonymous with biofuel in many EU member states. Currently, relatively small quantities of FAME are used in Sweden (~0.6% of total transport fuel energy use) but use and production in Sweden is growing and will reach a production of close to 300 000 tons per year in 2008. In other EU-member states, the capacity is also increasing. On the longer term, there is of course a limit as to how much vegetable oil can be produced in the EU but this limit has not yet been reached. Import of feedstock from outside the EU could increase this potential.

Today, FAME or "biodiesel" is generally considered as a "neat" biofuel although part of the energy comes from fossil methanol used as a feedstock in the transesterification process. Bio-methanol could replace the fossil methanol. A barrier here is that a tax differentiation between bio and fossil methanol must be applied, since the fossil methanol will be less costly than bio-methanol in the foreseeable future. Today, FAME is often treated as a "neat" biofuel in those countries that have tax reductions for FAME. In the most recent tax reduction in Sweden, only the non-fossil part of FAME qualifies for a 100 % tax break. A limitation for the route of using methanol is, as indicated above, that there is a practical limit for the maximum FAME production in the EU.

- FAME can be used as a neat fuel in dedicated vehicles but a limited number of vehicle models accept FAME today. Under the current EU diesel specification, 5 % FAME can be used as a blending component. In Sweden, the limit for the 95 % boiling point of environmental class 1 diesel fuel in the previous standard provided a practical limit of the blending for FAME to about 2 %. However, after a proposal for modifying this specification was provided in an investigation by the Swedish Road Administration (SRA), a new specification has been adopted that limits the blending rate to 5 %. In the EU, an increase of the 5 % blending limit for FAME in diesel fuel to 10 % has been proposed.

A technical problem with FAME that was noted relatively recently is that neat FAME in combination with diesel particulate filters (DPF) in light-duty vehicles causes problems with dilution of the lubrication oil as the fuel is injected late in the combustion cycle in order to increase DPF-temperatures for filter regeneration purposes. Thus, no car with DPF has yet been released for the use of neat FAME. Most of the aftermarket DPFs used on heavy-duty vehicles have so far utilised passive regeneration, relying on the so-called

"NO$_2$-effect" for continuous regeneration of the DPFs[4]. However, with active or semi-active regeneration instead of relying on more or less passive regeneration, as could be expected for future systems, similar problems as on light-duty vehicles could be experienced here too.

M85 and M100 vehicles

M85 vehicles (fuel-flexible or monofuel) were produced in relatively large numbers in the USA during the 1990´s. However, most of these vehicles were running on petrol in in-use operation, since there were in total only about 100 refuelling stations for M85. Since then, both the vehicle and the oil industry have lost interest in the M85 option. Today, all fuel-flexible vehicles are dedicated for E85 and petrol, although it would be theoretically possible to make them M85 compatible as well. Discussions between representatives for the RENEW project and the two Swedish-based car manufacturers – of which both are currently producing E85 vehicles – about this issue has been carried out. The response has not been negative and SAAB has publicly declared that they are investigating a car that could run on both E100 and M100. However, no firm commitments have been made at this stage.

Blending in diesel fuel

Methanol cannot be directly blended into diesel fuel, as is the case with petrol. One option to use methanol in diesel engines (and thus, also in heavy-duty vehicles) is to create an emulsion or to use some kind of a co-solvent to make a more stable solution. However, none of these two options can provide a fuel that is stable and does not separate in two phases under all ambient conditions. At least, this is the current development status. To be able to provide a fuel that can be broadly used, a breakthrough regarding emulsifiers or co-solvents would have to be made. No such breakthrough has yet been reported although investigations in this field have been conducted from time to time for more than two decades. Thus, this option has been ruled out here and is not considered further.

Fuel cell vehicles

Methanol could be an ideal fuel for fuel cell vehicles, since the reforming temperature for methanol is lower than any other fuel candidate[5]. In addition to on-board reforming, off board reforming at the local fuel station is possible. These solutions might overcome the great hurdle of distributing (gaseous or liquid) hydrogen. However, the development of fuel cell vehicles have lost much of its momentum during the last couple of years and a large scale introduction seem to be very far away. Furthermore, the powertrain development carried out at the moment is mostly focussed on hydrogen as a fuel. Thus, there seem to be no market for methanol in this sector in the foreseeable future.

In contrast to fuel cells in vehicles, there is an option for a market for methanol in fuel cells for other applications, such as, e.g. laptop computers and fuel cells. Although the introduction of these fuel cells seem to be somewhat delayed, it is likely that there will be a market for some niche applications. However, the market for use of methanol will be very small in such applications for a foreseeable future.

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[4] The effect of using NO$_2$ for soot oxidation is also called the "CRT effect". This was first proposed by the catalyst manufacturer Johnson Matthey. Since their DPF is called CRT™ (Continuously Regenerating Trap), the denotation has been derived from this trade name.

[5] The reforming temperature for DME is, although not so thoroughly investigated as methanol, not much higher so this could also be a candidate. On the other hand, methanol, as a liquid under normal conditions, is easier to distribute.

Methanol as a green chemical

Methanol could be sold as a "green" chemical (with a price premium) or as a substitute for fossil methanol (at similar price). Although both these options could be viable in a situation where it would be difficult to introduce methanol on the motor fuel market, they are not considered further here. Whether methanol would have a higher – or lower – market value as a green chemical rather than as a motor fuel has not been investigated here.

2.2   Priorities

Very early on in this work, it was realised that, of the two fuel options considered here, i.e. DME and methanol, methanol was the fuel that was considered to be most problematic regarding its market opportunities. This might sound somewhat strange; bearing in mind that methanol is a chemical commodity on the international market, and as such, it is handled in very large quantities. Note, though, that this handling is performed by professionals and not by ordinary customers. The experience gained in the field of methanol handling and distribution is extensive and the information should be readily available for transfer to the distribution of methanol as a motor fuel. Furthermore, methanol is a liquid fuel that has been used in public refuelling stations in the USA mostly during the 1990's. Over 100 refuelling stations have been in operation in the USA.

In contrast to methanol, DME is a "new" fuel that is only produced in small quantities for the chemical market and for spray cans. Handling of DME is much more complicated than for liquid fuels, since DME has to be kept under pressure to remain in liquid state. However, many parallels to LPG can be made in this case. As with LPG, the risk of fire and explosion is greater for DME than for petrol and diesel fuel.

In spite of the apparent advantages for methanol regarding handling and use, *the perceptions from the auto and the oil industry towards methanol are moderately positive to sceptic*. In a recently finalised study [8], representatives for the Swedish auto industry and the Swedish Petroleum Institute (SPI) was interviewed regarding their interest and views in methanol as a motor fuel. For the auto industry, the general position may be described as positive to alcohols in general for liquid motor fuels, and for methanol the higher yield from production may be regarded as positive in respect to other alcohols. However, none of the interviewed was currently investing in the development of neat methanol cars. SPI, on the other hand was more sceptical to yet one additional alternative fuel besides that of ethanol, since relatively large investments have already been made in the ethanol infrastructure. Also in the case of M3, it is not clear if this is something that the oil industry would accept to handle but favoured the use of biomethanol in the production of FAME or MTBE. However, for the industry it has been difficult to pinpoint a particular problem area or areas where no technical solutions for the introduction of methanol as a motor fuel would be available. It may just be so that the sum of all potential problems might create a barrier big enough to prevent methanol from being successful on the market.

In the DME case, very little practical experience is available from use of this fuel in motor vehicle applications. This concerns both the use in dedicated fleets and in vehicles for public use. Many parallels can be drawn from the use of LPG in cars and heavy-duty vehicles. LPG is, together with ethanol, the most widespread and used alternative fuel on the world market today. There are some safety issues associated with the use of LPG – e.g. risk of fire and explosion – but the practical experience shows that these issues can be handled at

an acceptable level. It is likely that DME would behave roughly similar to LPG in this respect and many lessons learned from the use of LPG could be applied also on DME.

Due to the expressed perceptions regarding methanol from various industrial stakeholders and governmental authorities, and the relatively limited practical experience of DME as a motor fuel, it was decided to concentrate most of the efforts on methanol fuel rather than on DME.

3   HANDLING, STORING AND DISPENSING OF METHANOL FUELS AND METHANOL-CONTAINING FUEL BLENDS

Early on in the discussions with PREEM, but also other representatives from oil and automotive companies, it was clear that the hazards of using DME and methanol would have to be addressed. Some of these issues are fire and explosion, toxicity and other health effects, as well as environmental issues related to fuel storage, distribution and handling. These are of great concern for any "new" fuel on the market. Some of these issues are discussed in this chapter.

3.1   Fire and Safety

Here, risk assessments regarding fire and safety for the use of M85 and M100 are summarised. One such assessment on E85 and E100 is currently going on in Sweden. Ecotraffic has participated in this work and the company had the responsibility of compiling data and preparing the reports from this project. Some of the conclusions expressed below originate from this assessment but are the responsibility of the authors of this report unless otherwise stated.

3.1.1   Introduction

Recently, the use and availability of E85 as a motor fuel on the Swedish market has increased dramatically. One of the main driving forces behind this development was a Swedish law with an obligation for larger filling stations to distribute biofuels. Another factor has been the substantial increase in the number of E85 cars during the last year. Increasing environmental awareness and substantial economic incentives for biofuels and so called "clean cars" have speeded up this development. For example, the sales of clean cars increased in April 2006 by 500 % compared to April 2005. Similarly, the sale of E85 fuel has also increased considerably. This increase was due to both a significant increase in the sales of E85 cars as well as an increase in the use of 85 (in relation to petrol) for in-use cars. In addition, the fuel infrastructure for E85 has been further developed and, at the end of 2005, it amounted to more than 300 refuelling stations [9] and the 500 mark was passed in September 2006. Thus, 2005 it could be considered as the real breakthrough year for E85 in Sweden. In other member states in the EU, some fleets of E85 cars have recently been introduced but a similar breakthrough as in Sweden has not been experienced yet in any other member state.

Some of the economic incentives for clean cars[6] in Sweden that have spurred the development indicated above are the following: the value of fringe benefits for company cars in the tax assessment is decreased by 20% for alcohol-fuelled cars[7] (up to a maximum level of 8 000 SEK per year (approx. 800 €), parking is free for clean cars in several Swedish cities, and there is no charge for clean cars in the Stockholm congestion charging fee sys-

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[6] There are a number of definitions for clean cars in Sweden depending on the incentive. Some of them are local. No further details about these definitions are discussed here.

[7] The corresponding tax reduction for cars fuelled by methane (CNG and/or biogas) and for hybrid cars was 40 %, up to a maximum level of SEK 16 000 per year, although the fuels used in these cars in some cases (CNG and petrol for hybrids) are fossil fuels.

tem. From October 1, 2006, the yearly circulation tax in Sweden is differentiated in relation to the CO_2 emissions of the vehicle and not according to vehicle weight as it has previously been calculated. Consequently, the yearly circulation tax will be lower for cars that, for example, may use fuels mainly composed by alcohols in comparison to petrol and diesel-fuelled cars. An additional incentive for purchasing a new clean car in Sweden is the 10 000 SEK grant (approx. 1 000 €) paid to private persons only (no company cars) by the Swedish road administration for the period from April 2007 to the end of 2009. In addition to the incentives mentioned above, some municipalities have local incentives and/or additional funding available for clean cars.

The more widespread use of E85 during recent years has led to a debate about the fire hazards of this fuel. This could perhaps be anticipated since E85 is a relatively "new" fuel on the Swedish market[8]. The public perceptions in such cases cannot be ignored, in particular when daily newspapers and television have made it a big headline from time to time. It is likely that the same debate would occur also if M85, or any other "new" fuel, would be introduced on a large scale. The E85 fuel in Sweden is denatured in order to prevent attempts to extract ethanol for ingestion from E85. Although this is not likely to happen with M85, similar measures must be taken to avoid the risk of ingestion.

Combustible vapours of M85 fuel (and also E85) can occur at higher ambient temperatures – and in a broader interval – than for conventional petrol fuels. This fact constitutes the major reason for the safety concerns appearing regarding the possibility of increasing risks for fires and explosions when and if M85/E85 fuels (or A85 as a generic denotation for both fuels) are to substitute petrol. The possibility of electric spark ignition of the vapour phase above the liquid fuel surface in contained vehicle tanks has, accordingly, been recognized as being of particular importance for the risk assessments to be made. Such ignition could occur during filling of the tank at a filling station in case an electric tension had been built up, causing an electric spark to be released at the filling neck to the fuel tank. Such a spark could, conceivably, propagate down into the tank, thus causing ignition of the fuel vapour, especially at or near the stoichiometric point within the combustible range of temperatures.

Low-level blending of methanol is not considered to affect fire and explosion in any significant degree and is therefore treated as petrol. Today, the limits for petrol according to the EU specification are 5 % for ethanol and 3 % for methanol. However, the European Commission proposed in 2007 [EC, 2007] that the new standard for petrol will allow a maximum blending of ethanol of 10% by volume. The impact of this increase on fire and explosion hazard should still be insignificant. The safety issues discussed in this report are focussed on a methanol content ranging from 85 to 100 %[9].

Fire and Safety issues have previously been investigated for the whole distribution chain and the fuel storage in the vehicle. Here we have considered this as the chain from when the refuelling truck has been filled at the fuel depot and started its trip to the refuelling station to the stage when the fuel has been filled in the tank of the car. Potential security aspects from the stage when the fuel is being burned in the engine (after engine start) are not part of this assessment.

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[8] E85 was introduced in Sweden in 1995 for a test fleet of 50 cars. However, the public availability of E85 came a couple of years later.
[9] Note that 100 % methanol in this case should not be interpreted as absolute. It is likely that some additives would be used for M100, e.g. corrosion inhibitors, denaturants additives to increase flame visibility and so on.

3.1.2   Important Chemical and Physical properties

The physical properties of a fuel that affect fire hazards include its volatility, flashpoint, range of flammability, autoignition temperature and electrical conductivity. Other properties of fuels that affect the potential risk associated with a fuel fire include burn rate in liquid pool fires, the heating value of the fuel, flame temperature and thermal radiation emitted from the fire.

In **Table 1**, the most important physical and chemical properties have been summarised. The table below has been compiled using a number of different sources. Some of them are national standards (compatible to EU standards in the petrol case) [10, 11], a number of SAE papers [12, 13, 14] and a report by the Methanol Fuel Cell Alliance (MFCA) [15]. Since the sources are of different origin, minor differences in comparison to the case for variation of fuel properties on a local base might exist. Note that the diesel fuel in **Table 1** is Swedish Environmental Class 1 (EC1) diesel fuel and not a diesel fuel corresponding to the European standard EN 590. Anyway, the fuel properties of interest in this case are not decisively different between the two diesel fuel qualities.

***Table 1**.   Important physical and chemical properties for some fuels*

Fuel property	Unit	Ethanol E100	Ethanol E85[a]	Methanol M100	Methanol M85	Petrol	Diesel EC1
Density, liquid	Kg/m^3	794	765 - 785	795	780	720 – 775	800 – 820
Density (vapour)	rel. air	1.6	> 1			3-4	5-6
Boiling point	°C	78.5	25 - 205	64,7	25 - 215	25 – 205	180 – ca305
Conductivity	cu	140.000	as E100	30.000.000	30.000.000	3 - 10	50 – 100
Vapour pressure	kPa	17	40 – 50[b]			45 - 95	0.4
Flash point	°C	12	< - 30	11	- 36	< - 40	56 (60)[c]
Flammability range fuel vapour in air	%	3.3 - 19	1.4 - < 19	6.0 – 36.5	2 – 34	1 - 8	0.6 – 7.5
Flammability range, -summer[d] -winter[d]	°C	12 to 40	-35 to +5 -35 to -5[e]	10 to 40	- 40 to + 23	- 40 to -10 -45 to -20	50 -
Autoignition temperature	°C	425	360	465	385 - 480	250 – 280	220 – 316
Stoichiometric air/fuel ratio	Kg/kg	9,0	10			14,6	14,8
Heat of vaporisation	kJ/kg	910	850	1100	1044	335	251
Energy of combustion	kWh/lit	5.9	6.3			9.1	9.8
Energy of combustion, LHV	MJ/lit	21,2	22,7			32,8	35,3
CO$_2$-formation	g/MJ	71,6				75	72
Flame spread rate	m/s	2 - 4	3 - 5	2 - 4	3 – 5	4 - 6	0.02 – 0.08
Diffusion coefficient	cm^2/h	293		465	372	186	251
Pool burn rate	Mm/min			1.7		7.3	4.0
Energy of ignition[f]	mJ	0.14 - 0.24	~ petrol	0.14 – 0.22	0.14 – 0.24	0.20 – 0.24	0.20 – 0.24

[a]   A new standard for E85 has just recently been enforced in Sweden. The data for a fuel corresponding to this standard might slightly deviate from the data presented here.

[b]   The interval is due to the difference between summer and winter qualities of E85 according to the Canadian study cited.

[c]   The demand for marine applications is 60°C

d)   The values of the end points are dependent on a variety of factors as, tank fill level, changing fuel composition due to "tank breathing", etc.

e)   The data for flammability range are taken from a Canadian study cited and might deviate slightly from Swedish and European E85 fuel.

f)   At the stoichiometric air/fuel ratio.

Fuel volatility is the vapour pressure exerted by a vapour over the liquid in a closed container. This is the key factor in determining a fire risk of a fuel, since it is (together with the latent heat of evaporation) a measure of the rate in which fuel vapour is produced from a container of fuel or a fuel spill. High vapour pressures tend to generate fuel vapour at a higher rate spreading the flammable vapour mixture through a wider area a therefore increasing the probability for ignition from an ignition source.

Temperatures above the flammability limit give a too "rich" vapour for flame propagation. This means that, in a closed space, only if the temperature is within the flammability interval, the vapour is capable to sustain flame propagation.

Also diffusion coefficients and vapour density can be significant factors in determining fire risks, particularly in poorly ventilated areas. A fuel with a low diffusion coefficient will lead to high concentrations within a limited space more readily. If the fuel has a high vapour density relative to air, then the vapour will accumulate in low areas increasing the fire hazard.

Ignition energy of both petrol and alcohol fuels are so low that potentially any ignition source will ignite either fuel.

Fuels that have low conductivity tend to accumulate static charge and release the charge through a spark. This has potential to become an ignition source for a fuel fire. The higher the conductivity of the fuel, the more quickly a static charge can dissipate and therefore it is less likely to cause ignition.

Flame spread rate is a factor of great importance for personal safety as it determines the time that a person has to move away from a spreading pool fire. It is also important for how fast a fire develops.

3.1.3   Fire risks

Petrol have generally been considered to have a much higher fire hazard risk than alcohol fuels due to its relatively high volatility, low diffusion coefficient and high vapour pressure. In two studies conducted by the US EPA, the fire safety risk associated with M100 was projected to be 90 % lower than for petrol [15, 13]. A smaller but still significant reduction of 40 % was projected for M85. However, it is worth noting that this study did consider all risks but the flammability risk in the fuel tank and other confined spaces. This issue has been most in focus in the risk assessment made in Sweden for E85.

In most cases, diesel fuel has a lower risk than petrol, but nevertheless, comparisons between diesel fuel and methanol is also relevant and is commented in some cases below.

In an open space, the key determining factor for assessing the probability of fire are the fuel volatility and the lower flammability limits, as well as the fuel vapour density, diffusion coefficient and source of ignition. Low volatility makes it difficult to generate sufficient vapour to achieve a combustible mixture. The lower density for methanol vapours (approximately the same as for air) in combination with a higher diffusion coefficient as compared to vapours from petrol reduces the risk for vapour accumulation and thus the fire

hazards for methanol vapours are considerably reduced as compared to those of petrol. Alcohol fuels are much less likely to ignite in open areas compared to petrol. Since diesel fuel has a low volatility, the risk for fire in open situations is very low. However, diesel fuel has a relatively low autoignition temperature makes and this property makes it more likely to achieve ignition if exposed to a hot surface. Under the hood, this might be the case, if the exhaust manifold or the turbine of the turbocharger is hot enough when a fuel leak is experienced.

In a closed space, the key factors for assessing the probability of fire are the fuel volatility, flammability limits and ignition properties. As examples of the flammability limits for petrol and M85, two diagrams below have been digitized from a previously mentioned SAE paper originating from a Canadian study [14]. The graphs for summer petrol (**Figure 1**) and summer M85 (*Figure 2*) are shown, since these two fuels have a flammability range closer to the normal temperature range in Northern Europe compared to winter qualities of the same fuels. The reason for choosing the summer qualities for the comparisons is also that these fuel qualities have a greater proportion of the flammable range in more frequently experienced ambient conditions. On the other hand, this would imply that summer fuel is left in the tank of the car in the autumn when the temperature is falling. When winter fuel is introduce, the flammable range is shifted towards lower temperatures and the risk is reduced. The graphs for summer petrol and summer M85 are presented in *Figure* 1 and *Figure 2* respectively.
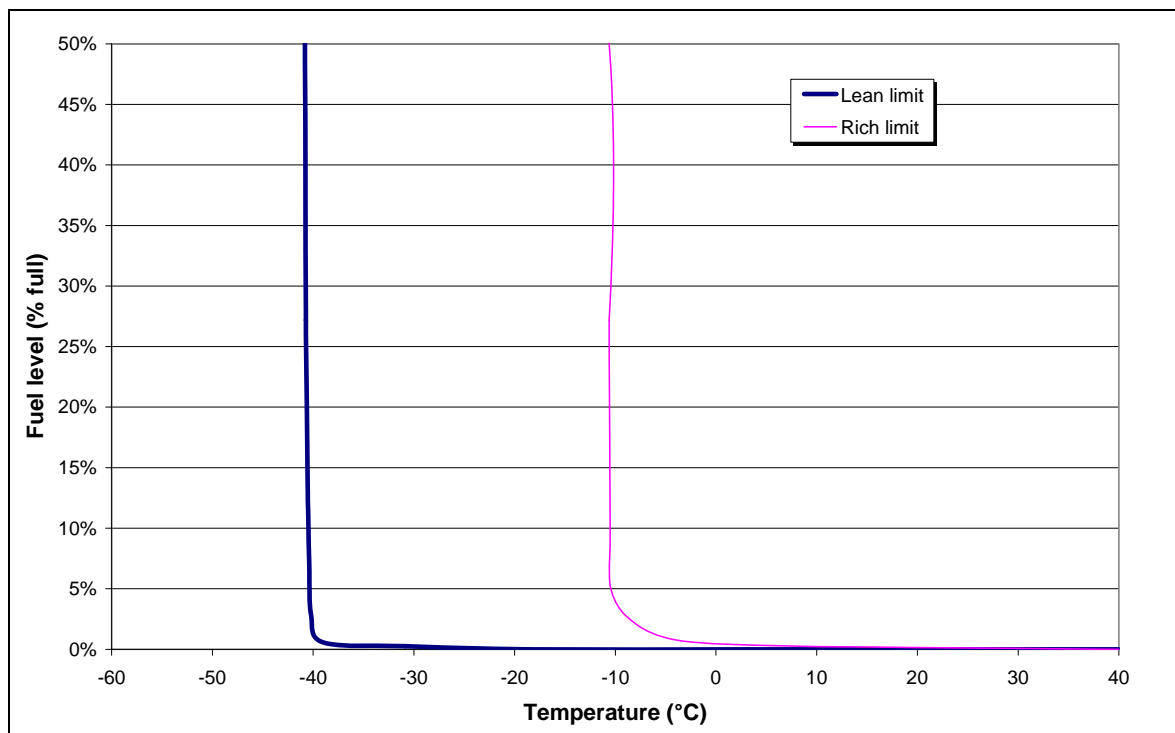

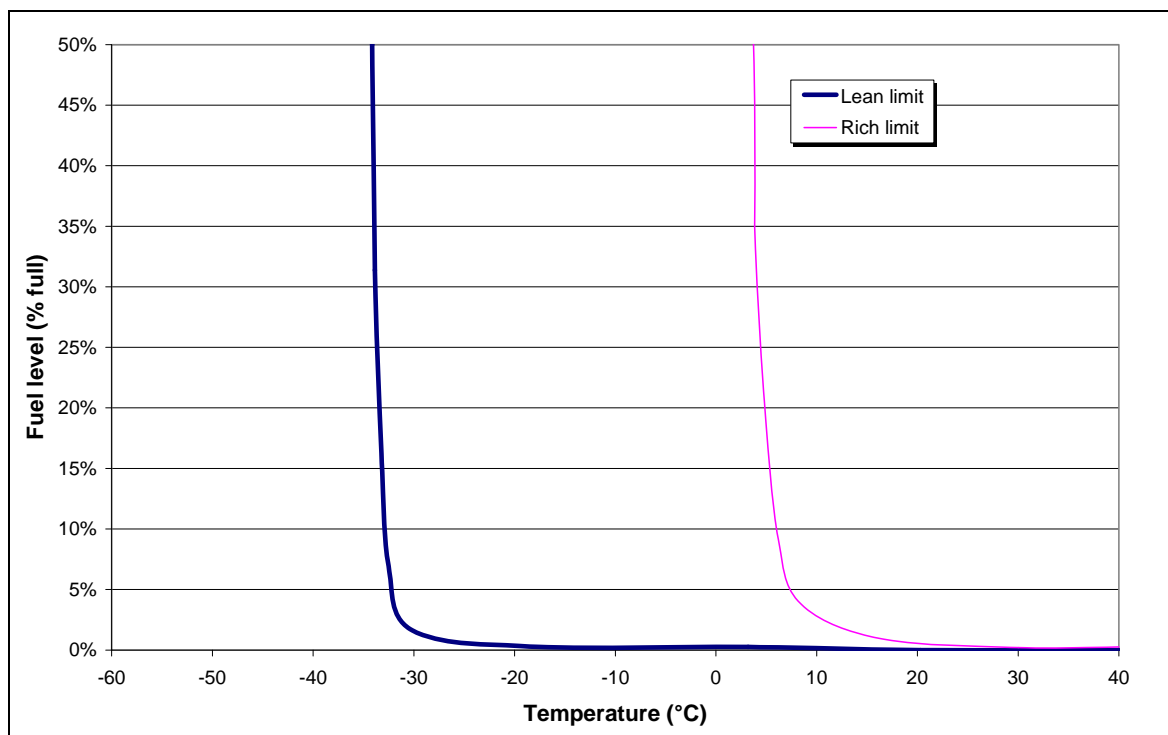*Figure 1.*   *Flammability range of summer petrol*

Figure 2. *Flammability range of summer M85*

From these figures is clearly observed that the flammability range is broader (approximately 40 degrees as compared to 30 degrees) for M85 as compared to petrol and that it is shifted towards higher temperature, i.e. a condition more often experienced under normal driving conditions. However, one should also note that there is actually no upper limit for the curves (i.e. they never completely reach the x-axis). Due to tank weathering, it is possible to get a tank vapour within the flammable limit also for petrol at higher temperatures, provided that the fuel level in the tank is very low. However, it is very unlikely that this condition would occur frequently in normal vehicle operation.

Sources of ignition within the closed space of a fuel tank may be a malfunctioning electric fuel pump or a fuel tank gauge. The latter source has such a low electric current level that it represents no significant probability of ignition but the fuel pump might pose such a risk [14]. External sources may be flames, cigarettes or static discharge entering from the fill neck. Alcohol fuels are more likely to ignite within an enclosed space than petrol and diesel fuels due to their different volatility and flammability limits.

The flammable range for fuels varies strongly with tank fuel level, as discussed by Vaivads et al. in a Canadian study [14]. There is a tendency that both the rich and lean flammability limits shift to warmer temperatures as the fill level decreases, especially the rich limits for the alcohols. The increased hazard of M85 is clear, particularly at low fill levels. It is worth noting, however, that petrol is also hazardous at temperatures common during the winter in Northern Europe. The use of summer petrol (lower volatility) during autumn cold snaps (or in the winter) is kind of a worst case. In practice, a fuel tank can have vapour pressure 15% or more below that of the initial fill if the time tank content drop to 10% of the full capacity. This can result in a flammable vapour at -10°C or higher.

The previously mentioned Canadian study shows that alcohol blends are clearly more hazardous than high volatility petrol (broader flammability limits and the limits are shifted to warmer temperatures); however, current low volatile petrol and weathered fuels in nearly empty tanks can have similar hazards [14]. Petrol may be somewhat more likely to exist in its flammable range inside fuel tank but measurements have shown that the temperature range for petrol often are roughly 10°C broader than listed values [13]. The suggestion is that the reduction in volatility may be due to evaporative loss of the higher volatility components of the fuel. This kind of weathering is likely to have an even greater effect on A85-fuels, since such a small fraction of the fuel is comprised of highly volatile components. Summer fuels, which are stored for several months, may easily exist in the flammable region if they are not used before the winter season.

Based on experiences from Brazil, where ethanol containing fuels (similar fire risks as methanol) are widely used, the occurrence of in-tank fires is rare [13, 15]. Even if ignition does occur, limited testing of methanol fuel tanks has shown that the "explosion" is relatively small and it is often contained by the fuel tank itself with no residual fire.

3.1.4 Fuel vapour

In stage II vapour recovery systems, either an on-board vapour canister or an off-board vapour recovery system at the retail pump is necessary. These kinds of devices result in a reduction of evaporative emissions during refuelling of a vehicle fuel tank. In Sweden, the stage II system is used for petrol but not for E85. The reasons for not implementing fuel vapour recovery on E85 are that the safety aspects have not been fully investigated yet. However, during introduction of new fuels, it is highly recommended to solve this issue. New fuels should not be associated with higher vapour emissions than petrol. The Saab 9[5] fuel-flexible cars are the only cars on Swedish market today that use an on-board vapour recovery system. A proposal regarding fuel recovery is currently under preparation by the Swedish Petroleum Institute (SPI).

3.1.5 Measures to increase safety

In the distribution chain, there are four areas of primary concern regarding fire safety, in-tank flammability, vapour releases, electrostatic charge accumulations and fuel spill. The amount of vapour generated during filling is directly related to the amount of turbulence generated as the fuels enter the tank. In-tank turbulence should be minimized. For alcohol fuels, charge build-up is not expected. However, the recommendation is still to make an electrical connection between the tank and the ground.

Fuel spill will always constitute a fire hazard. Several options are available to reduce the potential for in-tank flammability of alcohol fuels. These include eliminating contact between the fuel vapour and the electric fuel pump and incorporating flame arresters in the fuel neck. New tank designs including fuel filling from the bottom of the tank or tanks with bladders reduces the risk for flame propagation and limits the space of fuel vapours.

By following (and in necessary cases, changing materials for methanol use) the recommendations from the Swedish Petroleum Institute (SPI) for handling of E85, the conclusion by these authors is that the risk for fires will be minimized [16].

An ultimate solution for increasing safety and avoiding intended as well as unintended misuse of methanol would be to apply a dedicated refuelling dispenser along with modifications of the fuel neck in the car. Such a "spill free" dispensing system has been devel-

oped by the Swedish company Identic for the Methanol Fuel Cell Alliance (MFCA). A picture of the equipment highlighting some of its features is shown in **Figure 3**.

Spill-free dispensing could solve many issues regarding fire safety and risk of misuse of methanol. The disadvantage is that a new refuelling infrastructure is needed and that the fuel fill system in the car must be adapted to this solution. Ultimately, if no other solutions would be available to solve potential risks (e.g. fire, misuse, etc.) such solutions would have to be considered anyway. Although a spill-free solution might seem to be expensive and perhaps is considered "overkill", it should be noted that this solution is still significantly less expensive than a fuel infrastructure for gaseous fuels and fuels that are liquefied at moderate pressures (such as, e.g. LPG and DME). Already today, spill-free fuel dispensing is used for ethanol buses. A somewhat similar feature is employed in dispensers of the urea solution Adblue™ that is used as a reducing agent for SCR catalyst on heavy-duty vehicles.

Figure 3. *Spill-free dispensing of methanol in a fuel cell vehicle*

3.1.6   In case of fire

The fire hazard associated with a fuel is not only determined by the likelihood of that a fire occurs but also by the behaviour of the fire once it has occurred. Some important issues may be: how quickly the fire spreads, how easy it is possible to detect, heat release, toxic combustion products etc. Note that gaseous fuels can have very high heat release rates since the burn rate for these fuels is not limited by the need to first vaporise a liquid. However, no comparison to gaseous fuels is made here.

A high heat of combustion in combination with low heat of vaporisation results in a fire that will progress rapidly and burn violently (as is the case for petrol and to some extent for diesel fuel). The high volatility of petrol results in that a petrol fire will spread 100-fold faster than a diesel fire and progress very rapidly to an uncontrolled state. This in combination with a high heat release, flame temperature and smoke generation places petrol as one of the fuels that has the highest fire hazard of all liquid fuels on market.

Neat alcohols have the lowest fire hazard of the fuels discussed here (in comparison to diesel and petrol). They have low boiling point, low volatility, and low heat of combustion along with a high heat of vaporisation that gives a fire progress at a slow rate and a fire in a controlled manner. The heat of combustions for methanol is roughly half of that of petrol and it has a heat of vaporisation almost three times than that of petrol, resulting in a slow rate of fuel vaporisation. Alcohol fires emit much less heat through radiation and therefore spread more slowly to surrounding materials. In case of a great fire, the limited oxygen availability will, eventually, cause soot formation with ethanol – although lower than for petrol and diesel fuel – increasing the flame radiation. Methanol is better than ethanol in this respect due to vastly reduced tendency to soot formation under the conditions mentioned.

Methanol and ethanol flames have a low visibility during daylight conditions. In case of using neat alcohols as fuels, it may be necessary to use additives, which are increasing the flame visibility. In case of A85 blends, this is not necessary. However, the risk for these types of "clinical fires" must be very low. In practice, there are a lot of surrounding materials in and around a car, such as rubber, wood, textiles, plastic hoses, paint, concrete, asphalt etc." Also – in case of large fires – there will be suppression of oxygen availability, which will lead to a sooty flame [14].

3.1.7 Experiences from use of E85 in Sweden and recommendations for handling

The question whether the use of E85 as a motor fuel would imply greater risks in terms of fire and explosion hazards has recently been raised in Sweden. The question has come up on the agenda because E85 is associated with a somewhat broader temperature range, within which the formation of a combustible mix of fuel and air is possible, as compared to conventional petrol. Furthermore, this temperature range is shifted towards higher temperatures for E85.

Combustion of fuel vapours requires that air is present within certain limits. When the fuel/air ratio corresponds to complete combustion of the fuel/air mixture, the tendency for ignition is at its maximum level. This point represents exact stoichiometry of the fuel/air ratio. Outside of the stoichiometric point, the combustibility decreases successively towards the two extreme temperature points, which define the combustible range of temperatures. Beyond these limits, the fuel/air ratio is either too lean or too rich for flame propagation to occur at all. In the case of petrol with a low volatility, i.e. "summer grade" petrol, the combustible temperature range extends from about -45°C, the lean limit, to about -10°C, the rich limit. On the other hand, the combustible range for E85 fuel is defined between about -35°C and up to about +5°C, what can be said to demonstrate the somewhat wider temperature range and its shift towards higher temperature levels for the latter fuel. It should also be noted, however, that the rich limit of the combustible range of temperatures is shifted towards a higher limiting value when the fuel tank is continuously being emptied. This phenomenon appears both for E85, M85 and petrol and indicates that none of these fuels are completely safe under all possible conditions. However, the probability of that the tank vapour will be within the mentioned limits will be less for petrol than for E85 and M85.

Referring to the discussion above, combustible vapours of A85 fuels can occur at higher ambient temperatures than is possible with conventional petrol qualities. This fact constitutes the major reason for the safety concerns appearing regarding the possibility of increasing risks for fires and explosions when and if M85 fuel is to be substituted by petrol. The possibility of electric spark ignition of the vapour phase above the liquid fuel surface in contained vehicle tanks has, accordingly, been recognized as being of particular importance for the risk assessments to be made. Such ignition could occur during filling of the tank at a filling station in case an electric tension had been built up, causing an electric spark to be released at the orifice of the fuel tank. Such a spark could, conceivably, be propagated down into the tank, thus causing ignition of the fuel vapour, especially at or near the stoichiometric point within the combustible range of temperatures.

Finally, it should be noted that the work in Sweden discussed above is still on-going or else might be revised and that the conclusions and recommendations expressed above might change in view of new knowledge.

3.1.8 Conclusions and recommendations

The conclusions and recommendations below are the responsibility of the authors of this report but are to a great extent supported by the literature cited above.

The risk for fires and explosions has been subject to quantification and comparisons between various fuels. Reports, which have been published regarding alcohols as motor fuels have focussed on both methanol and ethanol; in fact, there is more information available

for methanol. The properties of the two alcohols ethanol and methanol have been assessed to be similar enough to justify the assessment that the properties of E85 with regard to fire and explosion risks are about the same as those for M85 fuel. Our conclusions (with focus on M85) are as follows:

– Petrol and M85 have fire hazards. Petrol is classified as extremely fire hazardous (Class F+, R12). In Sweden, E85 has recently been re-classified from the same class as petrol to "only' very hazardous (Class F, R11). It seems likely that M85 could also be classified similarly. Anyway, the classification of the alcohol blends regarding fire safety is not much different from petrol.

– M85 is not being assessed as more hazardous than conventional petrol from a fire-safety perspective. The measures proposed to be undertaken by SPI (the Swedish Petroleum Institute), in combination with the design changes, which have already been implemented on Volvo, Saab and Ford's E85-cars, are aiming at an increased safety at the fuel filling stations.

– Spare tanks for M85 made from sheet metal are recommended to be equipped with flame arresters.

– Petrol fires have the feature of emitting much higher flame radiation in comparison with neat methanol fires. Therefore, an M85 fire is much less violent than a corresponding petrol fire.

– Extinction of M85 fires requires the use of alcohol-resistant foams. Such means of extinction are already included in the standard equipment for fighting fires caused by fuel leakages.

The risk assessment of the four different engine fuels studied in the present report is summarised in **Table 2** below. A '1' in the table means the lowest risk while the remaining numbers 2 - 10 are to be interpreted in terms of increasing risk with successively higher numbers. The table also includes assessments of the option to change the risk estimate by implementation of design improvements, the effects of which are provided, within parentheses, as a (lower) figure estimate.

The estimates as depicted in **Table 2** above do not represent any precise comparison between the various fuels in terms of their associated risk levels. Neither can these figures be added up to a "global estimate of risk" for the various individual fuels. It should also be mentioned that the risk assessment made for M85 should be better elucidated so as to increase the precision in assessing the risks for fires and explosions of that fuel. The fact that E85 has been accepted in spite of its associated risk seems to depend on its similarity with petrol, regardless its dominating content of methanol. It should also be mentioned here, that not even petrol has been subject to a comprehensive analysis of its "global safety level", as undertaken over the years and petrol's widespread use as an engine fuel. In case petrol would be a novel fuel to be introduced on today's fuel market, its acceptability as a motor fuel would conceivably be assessed and scrutinised, from a safety point of view, following other principles than have been applied in the past.

Table 2. *Risk assessment*

Risk type	Diesel fuel	petrol	Ethanol Methanol	E85 M85
Propensity of ignition Open situation	2	9	4	7
Propensity of ignition Closed situation	5	2	8 (2-4)*	3 (2)*
Risk for damage in case of fire Intensity of fire	8	10	3	4
Risk for damage in case of fire Difficulty of extinction	9	10	7	8
Risk for damage in case of fire Visibility of fire		1	7	3

(*) Following such design changes which have already been implemented by Saab, Volvo and Ford in their E85 cars. The recommendations as proposed by the Swedish Petroleum Institute (SPI) will also imply the same improvements as estimated with the lower figures within parentheses.

M85 fires can be considered to have less impact on humans as well as on property; they are also less difficult to extinguish compared to petrol and diesel fires. Risks that can be associated with static electricity in situations such as fuel filling at filling stations appear low both for neat ethanol (M100) and M85, resulting from the much higher electrical conductivity of these fuels in comparison with hydrocarbon fuels.

The impact of the higher electrical conductivity of alcohol fuels comes from the fact that there is a lower risk for build up of an electrical voltage due to e.g. friction between refill pipes and liquid fuel. This will offset the formation of igniting sparks. But, on the other hand, if a spark would, anyhow, arise in a fuel-refilling situation, and if this spark would appear inside or propagate into the fuel tank, the probability of ignition of the fuel vapour inside the tank is higher in the M85 and M100 cases compared to the pure petrol case, especially at "normal" outdoor temperatures. The risk associated with the petrol case is the increased supply of air at the orifice of the fill pipe, which would create an easily combustible fuel vapour/air mixture in the immediate vicinity of the orifice.

Fires from neat methanol have the disadvantage of having a low flame visibility, which implies an increased risk of injuries, especially for fire fighting personnel. The probability of a methanol fire without any surrounding material contributing to the visibility is low, neat methanol can be modified by using additives with particular chemical properties in order to increase flame visibility. M85 fires will, on the other hand, be visible, especially at the initial state of fire, due to the petrol component.

In consideration of what has been said previously, and taking into account what is being further presented in this report, M85 fuel cannot be assessed to be more dangerous from a fire and explosion perspective than conventional hydrocarbon fuels. The advices and recommendations given by the SPI can be assessed to be sufficient for improving safety in general for the fuel distribution system as a whole when combined with the safety measures, which have already been implemented by the pertinent car industry.

M85 fuel contains about half the energy compared petrol, on a volumetric basis. This fact implies that larger volumes of M85 fuel will be consumed compared to conventional petrol

for the same transportation work. However, the exact volumetric increase will depend on the potential development of fuel-flexible engines and vehicles to increase their fuel efficiency. The impact of this will also result in that the M85 infrastructure for supplying fuel to the market must be significantly larger than the infrastructure for the conventional fuels. Since the potential risks associated with methanol as a motor fuel is largely associated with the refilling of the vehicles, the higher frequency of refilling may, per se, constitute an increased risk as compared to petrol vehicles. The handling of larger fuel volumes would imply greater risk levels in general, if M85 were to substitute petrol completely, or to a significant degree, on the motor fuel market.

3.2 Fuel distribution and storage

Material compatibility, such as, e.g. corrosion and degradation of metals, polymers and elastomers, are issues often associated with the distribution and storage of methanol. This might seem somewhat striking, since methanol is a chemical commodity on the world market that is handled in large quantities without apparent problems. In general, the measures and experiences from this field could also be applied to fuel distribution of M85 and M100. However, it should be noted that there are a number of differences between these two applications that should be considered. First, methanol is handled by professionals today in the whole distribution chain and, as such, it is not intended for public use, as the case for distribution of a motor fuel. Second, there are also several differences also between the mentioned applications.

3.2.1 Material compatibility

The denotation "material compatibility" in this section is defined as corrosion of metals and impact on polymers and elastomers. In a later section (5.1.2, at page 30) engine wear is discussed. In many cases, engine wear is linked to material compatibility but nevertheless, it is discussed separately.

In order to give an overview of the resistance of elastomers to ethanol and methanol, as compared to petrol, an example from the DuPont Chemical Resistance Guide is provided in **Table 3** [17].

Although the picture provided in **Table 3** is only quantitative, it is evident that there are several elastomers that are not well-suited (marked red in the table, see rating legend) to alcohol fuels. On the other hand, this is also the case for petrol. In a situation where petrol is the norm for standard fuel in light-duty vehicle applications, it is likely that there would be some incremental cost associated with the use of different elastomers for alcohol fuels. According to the data from DuPont, there is no apparent difference between ethanol and methanol, although these data might be insufficient for such assessments. In the case of flex-fuel cars, it is apparent that the available material options are reduced since the overlap between "green rated" materials in **Table 3** is low between petrol and the alcohol fuels.

A standard for the testing of material compatibility has been prepared by SAE (SAE J1681) [18]. In its first version, the standard covered only methanol/petrol blends, but a later version from 2000 covers most liquid motor fuels. The standard has also been discussed by Harrigan [19]. According to the test method [18], various test fuels representing "worst case" scenarios have been specified. To represent low-level blending of alcohols in petrol, a mix of 85 % hydrocarbons and 15 % methanol has been selected. Methanol was chosen over ethanol since the former is considered more aggressive than ethanol.

In order to further increase the aggressiveness, additives of water, salt and formic acid have been formulated in carefully specified concentrations. In order to test materials for world-wide use in fuel systems for petrol and diesel engines, tests with four different test fuels are required. One is the fuel with 15 % methanol mentioned above, another fuel contains 15 % MTBE and the two remaining fuels are hydrocarbon based with corrosive additives. It could be added that materials in fuel systems for cars that are intended to be run on E85 and M85 must be subject to additional tests. Besides 85 % of the mentioned alcohol, blends with 15 % and 30 % must also be tested, as well as fuel combinations containing MTBE.

Table 3. *Elastomer resistance to alcohols and petrol*

Methanol resistance

Elastomer	Rating
Natural Rubber, Isoprene	1
Butadiene Styrene, Butadiene	1
Butyl	1
Ethylene Propylene	1
Nitrile	1
HNBR	1
Epichlorohydrin	2
Polychloroprene	1
Chlorosulfonated Polyethylene	1
Chlorinated Polyethylene	1
Urethane	4
Polyacrylate	4
Polysulfide	2
Silicone	1
Fluorosilicone	1
Tetrafluoroethylene/Propylene	1
Fluoroelastomer - Dipolymer	4
Fluoroelastomer - Terpolymer	1
Perfluoroelastomer	1

Ethanol resistance

Elastomer	Rating
Natural Rubber, Isoprene	1
Butadiene Styrene, Butadiene	1
Butyl	1
Ethylene Propylene	1
Nitrile	1
HNBR	1
Epichlorohydrin	2
Polychloroprene	1
Chlorosulfonated Polyethylene	1
Chlorinated Polyethylene	---
Urethane	4
Polyacrylate	4
Polysulfide	1
Silicone	1
Fluorosilicone	1
Tetrafluoroethylene/Propylene	1
Fluoroelastomer - Dipolymer	2
Fluoroelastomer - Terpolymer	1
Perfluoroelastomer	1

Gasoline resistance

Elastomer	Rating
Natural Rubber, Isoprene	4
Butadiene Styrene, Butadiene	4
Butyl	4
Ethylene Propylene	4
Nitrile	2
HNBR	1
Epichlorohydrin	1
Polychloroprene	3
Chlorosulfonated Polyethylene	3
Chlorinated Polyethylene	3
Urethane	2
Polyacrylate	4
Polysulfide	1
Silicone	4
Fluorosilicone	1
Tetrafluoroethylene/Propylene	2
Fluoroelastomer - Dipolymer	1
Fluoroelastomer - Terpolymer	1
Perfluoroelastomer	1

Rating Legend

1	Little to Minor Effect, 0 to 5% Volume Swell
2	Minor to Moderate Effect, 5 to 10% Volume Swell
3	Moderate to Severe Effect, 10 to 20% Volume Swell
4	Not Recommended
---	No Data Available

There are also recommendations and studies regarding fuel dispensing equipment that could be mentioned. In an SAE paper from 1992, a survey of material alternatives and design of refuelling stations for methanol was made [20]. A significant part of the study was devoted to material compatibility. A very comprehensive manual about methanol refuelling stations was compiled by the consultant company Acurex for the California Energy Commission (CEC) [21]. This manual covers all important details about methanol refuelling stations, including tanks and dispensers.

In view of the publications discussed above, and many other publications not cited here, it can be concluded that a considerable knowledge has been gained in this area. However, since most of this information was compiled a long time ago, it is not always readily available and may have to be "rediscovered" in case methanol would be re-introduced on the market. In general, it should be noted that problems have been reported from the field but most of the problems reported are in areas where these guidelines have not been fulfilled.

Once again, it should be noted that methanol handling is not a particularly new business – methanol is one of the largest chemical commodity on that market. Therefore, it has been demonstrated that distribution of methanol on that scale can be handled without apparent problems. It is very likely that this knowledge could easily be transferred to the field of motor fuel distribution.

An issue that has been put on the agenda during the last couple of years, due to the phase-out of MTBE in California is the increased fuel permeability through polymers and elastomers [22, 23]. This property is not directly covered by the SAE J1681 standard [18] discussed above. Tests on ethanol have shown a significant increase in permeability when ethanol is blended with petrol in comparison to the base petrol [24]. The result is a significant increase in evaporative emissions under real driving conditions (in California). Since the impact decreases with decreasing temperature, the impact should be of less concern in Northern Europe. Note that not only alcohols are permeating but also an increase in the permeation of light hydrocarbons occurs. The impact on permeation by MTBE, which is substituted by ethanol in California, is significantly lower. Methanol has not been investigated in the studies cited above but in several of the publications it is mentioned that methanol causes an even higher increase in permeability, which is conceivable taking into account the difference in molecule size between the alcohols. Of course there are materials available that reduce the permeability of the alcohol fuels and such materials are used in E85 and M85 cars. The practical problem here is though, that low-level blending is intended for the current fleet of petrol-fuelled cars that do not have those materials in the fuel system. Retrofitting of old cars is not realistic and therefore a certain limit of the blending level must be accepted. Maybe this is in the order of 10 % for ethanol and presumably, even lower for methanol.

Generally, methanol has been considered more corrosive on metals that ethanol. However, Norman Brinkman at GM showed in a study that E85 was more corrosive than M85 due to a higher solubility for corrosive compounds [25]. Corrosive compounds such as sulphates are known to initiate galvanic corrosion. An anode, a cathode electrolyte and an electrical connection are necessary for galvanic corrosion to occur. The electrolyte is the alcohol or the alcohol blend, in this case. The anodes and cathodes are the various metals in the fuel system. From **Table 1**, it is also apparent that the conductivity for alcohols are considerably higher as compared to that of petrol and diesel.

It should be conceivable to assume that the fuel systems in modern cars have materials that have been subjected to the tests specified in SAE J1681 [18]. Thus, a blending level of 3 % methanol, accepted according to the current EU fuel specification, should not present any particular problems. Although a certain safety margin in comparison to the test fuel used (i.e. 15 % methanol) it would be reasonable to assume that a higher content than 3 % could be tolerated. However, there is no guarantee that the materials used in all petrol-fuelled vehicles in the current vehicle fleet have been tested according to this method. Therefore, a prudent strategy would still be to set the limit at 3 %, unless experiments and field tests could reveal that a higher content could be tolerated by the current vehicle fleet.

3.2.2   Phase separation

First of all, it should be mentioned that there are several obvious applications where separation might occur and where petrol/methanol blends cannot be used at all or must be used with special care. For example, fuel storage on water beds in rock caverns, used to be common practice in Sweden in the past. This was previously used in Sweden for long-term

storage for military preparedness purpose. Today, this mandatory storage has been relaxed and thus, most rock carver storages have been abandoned. Storing alcohol-blended fuels on water bed is of course not possible with water containing fuels. Another difficult application is pipeline distribution where a water "plug" is often used to separate different fuels. Some differences in practice, or else that the blending is handled after the pipeline distribution, must be applied here. Distribution via pipeline is not used in Sweden but it is the case in some European countries and it is also frequently used in the USA.

Petrol and methanol are two fuels with different physical and chemical properties. Provided that the methanol used is water free, these fuels can be blended in any proportion. However, at a certain content of water, fuel separation will occur. The relative proportions of methanol and petrol, as well as temperature and petrol composition are some properties that determine the maximum allowable water content. The use of a stabilising agent (which could be e.g. ethanol or heavier alcohols) is mandatory for low-level blending of methanol in petrol. On the contrary to blended fuels, separation would not be an issue for neat methanol (M100), provided that this fuel is not used in fuel-flexible cars and thus, can be subject to mixing with petrol in the fuel tank. Since fuel-flexible cars are an obvious option during an introduction phase of a new fuel, it has to be considered that any proportion between petrol and methanol can be present in the fuel tank of such vehicles.

Cold climate aggravates the fuel separation problem. Obviously, the Nordic countries have a considerable disadvantage in this respect compared to many other countries in the EU. This implies that particular care must be taken to avoid this problem in the Nordic countries.

The phase separation problem was thoroughly investigated early on when methanol was of interest as a motor fuel and several studies about this problem have been published, e.g. [26, 27, 28]. Since the interest for methanol use in low-level blending has decreased substantially after the 1980´s, relatively few new publications are available. A study published in the Journal of Automotive Engineering in 2005 is, however, worth mentioning [29]. In this study, the impact of using ethanol as co-solvent for methanol was investigated. For M10, a formulation comprising 8,5 %$_{vol}$ of methanol and 1,5 %$_{vol}$ of ethanol was used. For M25, the corresponding composition was 19 % and 6 % respectively. Through the use of ethanol as an additive, the phase separation problem was solved. It should be noted that phase separation is also mentioned in a couple of other publications cited in this report, although no further comments about them are made here. Finally, it should also be mentioned that no problems with phase separation have been reported from the Swedish "M15" project that comprised in total 1 000 cars and 19 filling stations [30].

3.3 Environmental considerations

The environmental considerations discussed here are mostly linked to methanol distribution. Exhaust emissions and evaporative emissions are not considered here. It is likely to assume that the combined impact on health and environment from these sources would be lower from methanol than from petrol, at least for most of these effects.

Today, considerable information about the toxicity and risk of exposure to humans and to the environment from the use of methanol has been compiled. Two such examples are a report compiled by Statoil [31] and the previously mentioned MFCA report [15]. In a previous EU project "BLGMF" in which some of the participants in SP3 participated [32],

these findings were already summarised so there is little point in repeating all of this in the present report. Anyway, a shorter overview might still be of interest.

3.3.1 Human exposure

Since methanol is toxic, the issues concerning handling and distribution require a specific analysis. Although both petrol and diesel fuel are toxic when ingested, as well, there is a long experience from handling and use of these fuels. Consequently, the number of fatalities is low regarding such effects. In general, the public is only confronted with the problem of the toxicity of methanol when fatal ingestion of methanol has been the case. In several cases, people that have been subjected to methanol have thought that they have been drinking ethanol. This could be easily avoided by using a bitter tasting additive.

Since methanol is a commodity chemical and it is traded worldwide in large quantities, the regulations for this type of handling are well developed. Therefore, it has not been considered necessary to summarise the regulations that govern this handling. Instead, the issues that might arise when methanol is distributed to the public are of main interest in this study. A similar approach has been used for methanol production. As always with technical processes, there might be issues concerning the working environment, but these issues are relatively limited and they are well taken care of today anyway.

Methanol is readily distributed more or less uniformly in the human body regardless of the type of exposure. Since methanol is fully soluble in water, the distribution in the organs is directly proportional to their water content. Methanol is also formed in the body by natural metabolic processes and it is present in low concentration in the diet, as well. Consequently, there is a natural "background" level of methanol in the human body. An exposure to methanol − or other substances that can be metabolised to methanol − will increase the methanol content in the body. Methanol is metabolised in the liver to CO_2 via formaldehyde, formic acid and its dissociate, methyl formate, and is thus eliminated from the body. The toxicity of methanol is due to formic acid. Since the metabolism of formic acid to CO_2 is the limiting process, the accumulation of formic acid will be the case when exposure levels are high. Formic acid can lead to ocular toxicity and metabolic acidosis might be lethal if left untreated. It should be noted that there are several possible treatments available but these methods are not referred to here. In general, it can be concluded that the mechanisms of the toxicity of methanol and its metabolism are well understood.

Minor exposures of methanol seldom lead to any significant increase of methanol concentration in the body. As a comparison, it can be concluded that ingestion of diet beverages that contains the aspartame sweetener also increases the methanol content in the body. A lethal dose of methanol is some 500 times higher than most probable exposures associated with inhalation, skin penetration and through diet (e.g. aspartame).

Some unintended and intended exposure (i.e. ingestion) of methanol could result in lethal doses. Statistic information from the USA shows that of the approximately 10 cases of lethal exposure that are registered every year [33]. About 50 % of them are related to suicide. However, in many of the other cases, the reason is unknown, which could render an even higher percentage of suicide. Whether these fatal cases could be influenced (increased or decreased) by a widespread use of methanol is pure speculation.

Both petrol and methanol penetrate through the skin but the absorption is faster in the methanol case since the methanol molecule is smaller than the (average) petrol molecule. On the other hand, methanol evaporates faster from the skin, which reduces the total expo-

sure, since the contribution from inhalation will be far less than from skin penetration. Methanol is not considered to be mutagenic or carcinogenic. Petrol, on the other hand is considered as carcinogenic, primarily due to its content of benzene[10], a known carcinogen. It should be pointed out that high exposure to petrol poses a risk of almost similar magnitude as methanol (considering both short and long-term exposure) but in this case, common practice has been well developed. Although the risk of "normal" exposure due to skin penetration is small, exposure for liquid methanol for a long period of time, e.g. through the use of gloves or boots soaked with methanol, might lead to high concentrations. It is not likely that the exposed people (e.g. mechanics and technicians) would tolerate such exposure to petrol without taking countermeasures, but in the methanol case, proper information might be necessary to avoid such incidents.

Inhalation of methanol is the most common exposure. Exhaust emissions from vehicles, evaporation from the tank and from spill and open containers are examples of exposures due to inhalation. A worst-case calculated exposure of 150 ppm methanol during 15 minutes would only slightly increase the dose by 0,6 mg per kg of body weight (42 mg for a 70-kg person). This dose is on a similar level as normal ingestion of fruit, vegetables and alcoholic beverages (0,3 to 1,1 mg/kg). Most exposures to methanol vapour in the air would result in far lower doses than in the mentioned case.

In **Table 4**, below, body concentrations resulting from different forms of exposure are presented.

***Table 4**.   Exposures of methanol and resulting body concentrations [15]*

Exposure / dose	Methanol, added body concentration (mg)
Background concentration	35[+]
Hand in methanol (2 min)	170
Inhalation (40 ppm, 8 h)	170
Inhalation (150 ppm, 15 min)	42[*]
Consumption of 0.8 L aspartame sweeten soda	42
Consumption of 0.21 mL methanol	170
Consumption of 90 mL methanol	70000
Lethal body concentration	21000-71000[**]

+   Estimated from 0.73 mg/L blood concentration and 70 kg body weight
*   100% methanol adsorption assumed (60-85% is however more likely [34])
** IPCS, 1997 [35]

Methanol is used as a windshield washer fluid in North America usually in concentrations lower than 50 % [36]. In Sweden and Europe, isopropanol, or in some cases ethanol, is normally used in this application. In Sweden, methanol is not allowed in concentrations higher than 5 % but then only in combination with ethanol. The use of alcohols in windshield washer fluids is to avoid freezing. There are few alternatives to alcohols if the requirements of primary importance in this application have to be fulfilled. The nature and purpose of the use of windshield fluid may be considered as a controlled alcohol "spill", and in North America, a spill of methanol.

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[10] It should be noted that the benzene content of petrol has been continuously decreased during the past years. However, petrol corresponding to the EU regulation for 2005 still contains benzene.

The use of methanol in windshield washer fluid is an example of widespread use of methanol by the public. The fluid is handled in a similar way as windshield washer fluid in Europe. It may appear obvious that windshield washer fluid should not be ingested; regardless of which alcohol is used as anti-freeze, as the fluid contain other substances than methanol and water. It is evident that methanol used in this application can be handled without significant fatalities in North America. In addition, it seems as the handling, storage, etc. of this fluid does not pose particular problems regarding the risk of fire or explosion. Health effects of methanol from windshield washer fluid could be expected due to evaporation and inhalation. However, it appears as the concentration of methanol in urban air is very low and therefore, the exposure to methanol from this use seems to be well below a safe level.

3.3.2   Methanol spill

The distribution of methanol in general could include various different transportation modes. In general, methanol of fossil origin is produced at remote sites. Thus, the distribution could include sea, rail and truck transport. Pipeline distribution is not likely other than in rare occasions. During distribution methanol could be spilled to surface water, ground water, soil and evaporate into the atmosphere. Spill of methanol to land, water and the air must occur from time to time, since methanol is one of the mostly traded chemicals in the world.

In a spill to land and water, the evaporation will be less and in this case, the distribution of the release is shifted. An increased use of methanol would of course increase the releases of methanol. On the other hand, the release of conventional fuels of fossil origin would decrease if these products were substituted by methanol. As will be shown below, the health- and environmental impact would presumably decrease if this substitution was carried through. The removal of methanol through biodegradation is generally faster than for fuels of crude oil origin, as these substances are not naturally present in the nature (as in contrast to methanol that is naturally occurring in the environment).

The release of crude oil or oil products (such as petrol and diesel fuel) to water and soil generally cause great impact on the environment (at least on a local scale). Catastrophic oil spills are regularly occurring on a smaller or greater scale and the environmental impact is sometimes great, as for a spill in a sensitive area (e.g. Exxon Valdez in Alaska). Accidents with tank trucks and rail cars can happen and in such cases, spill to soil and water is often the case. The question is what the consequences of a methanol spill would be in similar cases, as described previously.

Spill of methanol to surface water will result in a fast dispersion due to the infinite solubility in water which is in contrast to oil products that have a very limited solubility in water. Therefore, the acute toxicity of methanol will be noted only in direct association to the spill area since at concentration levels of less than 1 %, methanol is no longer toxic. Some life forms will even metabolise methanol, i.e. use the methanol as nutrition. Such an example is that methanol is used today as nutrition for the micro organisms used in wastewater treatment (denitrification, i.e. removal of nitrates).

Estimations by AMI (American Methanol Institute) [37] of a spill of 10 000 tons of methanol in the sea shows that the concentration would be less than 0,36 % within less than one hour. A similar release from a coastal pier would result in a concentration less than 1 % after 2 hours and 0,13 % after 3 hours. Thus, the impact of such a spill is rela-

tively small and local in both cases. One can easily envision the ecological consequences if similar spills of oil products would occur.

Methanol dissolve very fast in the ground water after *a spill on land*, and this might be a drawback in comparison to petrol and diesel fuel, where the diffusion is not as fast. In a worst-case situation, this could lead to a faster contamination of water supplies. However, it is not likely that the diffusion would be so fast that precautionary measures could not be taken to avoid the distribution of contaminated drinking water. Again, the advantage of faster biodegradation limits the damage to a local scale. Similar situation might occur for spill in surface water but in this case methanol is dissolved and diluted even faster.

There is always some *release (evaporation) of methanol to the air* from spill to water and soil. The question is whether this could pose any risk for health and environment. Since the equilibrium between air and water is shifted towards the water, vaporisation is minimal in this case. The vaporisation from spill to (dry) soil tends to be significantly greater than from water and in this case, this is a faster release than for petrol. The vapour pressure is lower than for petrol and likewise, the vapour density is lower for methanol vapour than for petrol vapour. Consequently, methanol vapour is dispersed faster in the atmosphere than petrol vapour. Although methanol vapour most likely has a greater acute toxicity than petrol vapour at the same concentration, this is compensated by the faster diffusion of methanol in the ambient air.

In summary, methanol should have significant advantages compared to petrol regarding releases to soil, water and air (and compared to diesel fuel in the two first cases).

3.3.3 Concluding remarks

In the discussion above, several issues of widespread use of methanol have been discussed. Although many of the properties (toxicity, corrosiveness, etc.) of methanol could be considered as barriers, solutions also exist, or else the problems sometimes tend to be somewhat exaggerated. In a recent study about biomass-to-liquid fuels by JRC, many of the negative attitudes towards methanol cited by several representatives of the auto and oil industries are expressed [38]. In the report, a CONCAWE study is referred to as the source of this information [39]. Further, the JRC report cites that "…methanol has shown 25 times higher fatalities than petrol". The source of this is a statement said to originate from a study by the US National Capital Poison Centre. However, no evidence of this study is found in the reference list. At least, in a brief search with the US organisation, we could not find this reference, although this does not prove that such a study does not exist. However, since much of the future for methanol in the EU seems to rely heavily on such statements, it might be of interest to further investigate if these statements are well-founded, if there is a general consensus about it, and if there are any scientific and statistical evidences to support such statements.

4 HANDLING, STORING AND DISPENSING OF DME

An overview of issues concerning DME can be found among the publications at the IDA (International DME Association) website [40].

4.1 Fire and safety considerations

As mentioned previously, DME has approximately similar properties as LPG regarding fire and safety. Much of the experience from fuel distribution and use of LPG could also be applied on DME. Today, no experience of the fire and other safety aspects from a wide-spread use of DME exists.

In a parallel work by Volvo within the RENEW project, a much more thorough investigation of health, fire, and safety aspects of DME is carried out. Thus, this potential problem is not discussed further here.

4.2 Environmental considerations

Today, the lion's share of the use of DME is as propellant for aerosol cans. This substitution of the previously used propellants was made to reduce ozone depleting impact on the stratospheric ozone layer. The use of DME as in aerosols often result in human exposure to the gases, and due to this, the health effects of DME has been thoroughly investigated. The results of these studies are not referred to here but in summary, it can be noted that the health effects of DME are very small. Neither does DME pose any environmental threat in case of a spill to the ground and to water.

In a report by DuPont, presented to the US EPA, tests referred to showed the impact of DME on humans and lab animals [41]. In general, DME exhibits low acute toxicity. Likewise, long-term exposure did not show an impact at doses much higher than what could be expected in normal exposure to humans.

Many of the issues concerning spill of fuel that are of high importance for many other liquid fuels (discussed above for methanol), are not applicable to DME, which is in gas-phase at normal atmospheric pressures and thus evaporates quickly in case of a spill.

All in all, it can be concluded that DME is one of the most benign of all the alternative fuels regarding its impact on humans and on the environment.

5 END USE

In this chapter, some of the most important issues regarding the end use of the fuels in the vehicle are discussed.

5.1 Methanol

5.1.1 Material compatibility

In the discussion above, material compatibility of methanol was concluded to be a major issue of concern. Since M85-fuelled cars have been in widespread use in the USA, it is of interest to show which systems in the car that are affected by a conversion to M85. In **Figure 4**, an overview of methanol-compatible or modified components is shown.
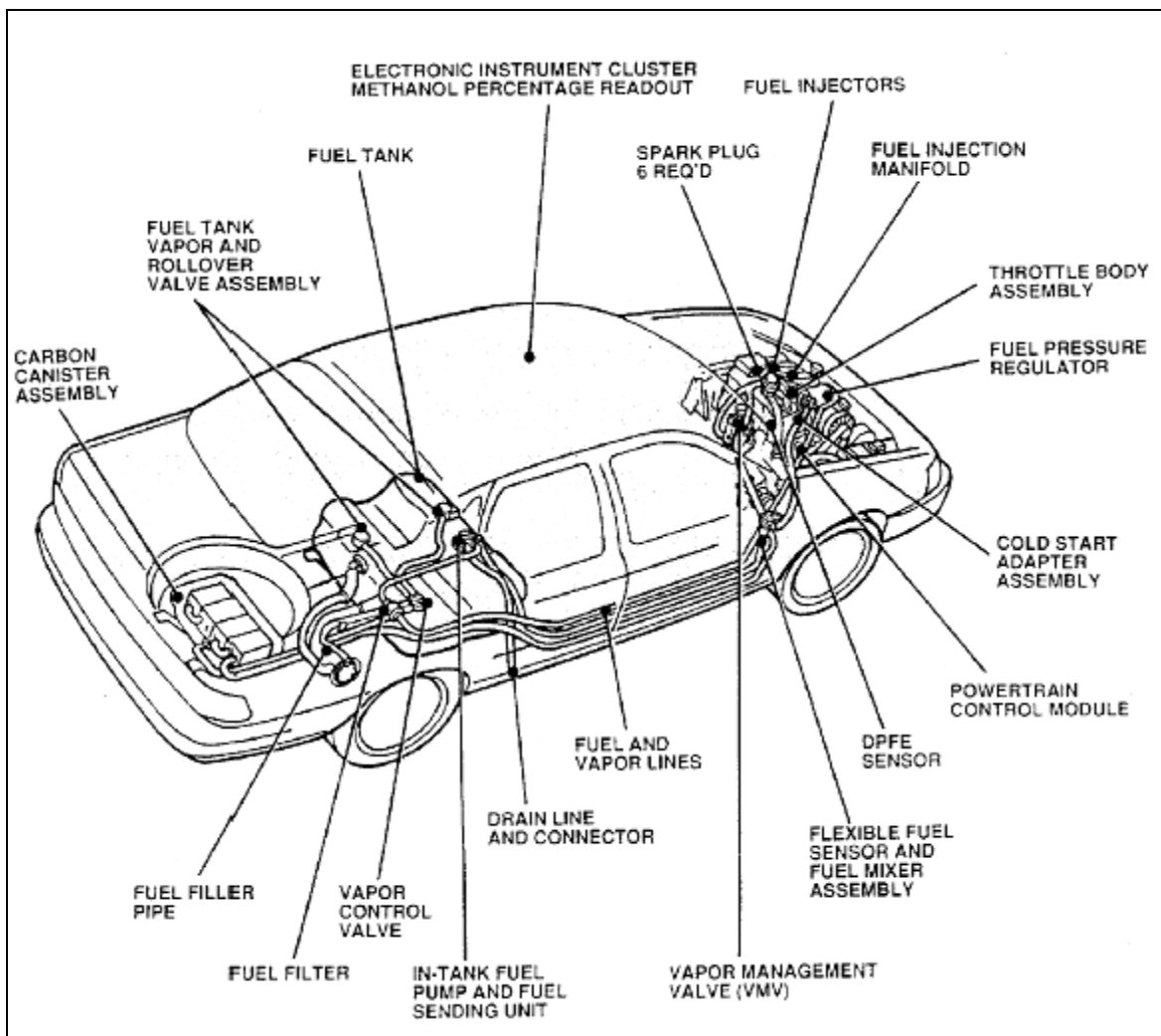
Figure 4. Modified (methanol compatible) components in the MY´93 Ford Taurus FFV.

As can be seen in **Figure 4**, many of the materials in direct contact with methanol are substituted by methanol-compatible materials. Furthermore, one of the most important modifications is that a fuel sensor is incorporated in the fuel system. This car was also fuel-

flexible, i.e. it could tolerate any methanol content between 85 % and zero. Compared to a modification of a gaseous-fuelled vehicle, the modifications to the M85 car were relatively simple, straightforward and inexpensive.

Methanol is, as discussed before, a commodity on the international market. Thus, the experiences regarding material compatibility from methanol handling and distribution should also be applicable to methanol-fuelled cars. However, one important issue is different; i.e. the fuel temperature is often considerably higher in the vehicle application. This is due to heating of the fuel by the engine. There is one countermeasure that could be applied, i.e. a fuel cooler. Fuel coolers are used anyway on engines that have high injection pressure systems, such as diesel engines. Consequently, fuel coolers might be utilised also on direct injected alcohol-fuelled petrol and diesel engines.

5.1.2   Engine wear

The risk of corrosion described in the previous chapter is, presumably, linked to the increased wear in methanol-fuelled Otto engines described in many publications. M85 has been mostly investigated but in some cases M100 has also been examined. Little information on engine wear with low-level blending of methanol in petrol has been published in the open literature.

The impact on engine wear using methanol fuel was documented in an SAE paper from SwRI on a Ford 2,3 litre engine [42]. In spite of reduced build-up of deposits with methanol, the engine wear was significantly increased compared to petrol. The wear problem was later discussed in several publications from the same period [44]. For example, Ryan et al. showed that combustion products, such as formic acid, reacted with the iron in the cylinder walls [43]. Liquid methanol in the combustion chamber (i.e. at cold starts) has also a decisive role.

Naegeli showed in a study that a film of liquid methanol ignited on a polished steel surface produce distinct rust [45]. When methanol is burned, smaller amounts of formic acid, formaldehyde and dioxy-methylene-peroxide are formed as oxidation products. Some of these compounds solve in the liquid film. Formic acid was identified as the main cause of the initialization of the corrosion.

In a study by Toyota, the results from several other studies that had shown the influence of temperature on corrosion were confirmed [46]. At higher coolant and oil temperatures than 70°C, the wear with methanol was similar to unleaded petrol. The authors of the paper also conclude that the wear can be reduced by more frequent oil change intervals, through the use of special oils and by surface treatment of engine parts.

Another important factor that was concluded by Baisley and Edwards was that the corrosion speed was strongly influenced by how the air-fuel preparation is carried out [44]. A good atomisation and evaporation reduces corrosion. In contrast, the use of a carburettor increased the wear extremely.

In a field test conducted by the New York State, the engine wear was documented on four M85-fuelled Ford Taurus FFV and four petrol-fuelled cars of the same type (FFV) from a control group [47]. The results are shown in **Figure 5**.
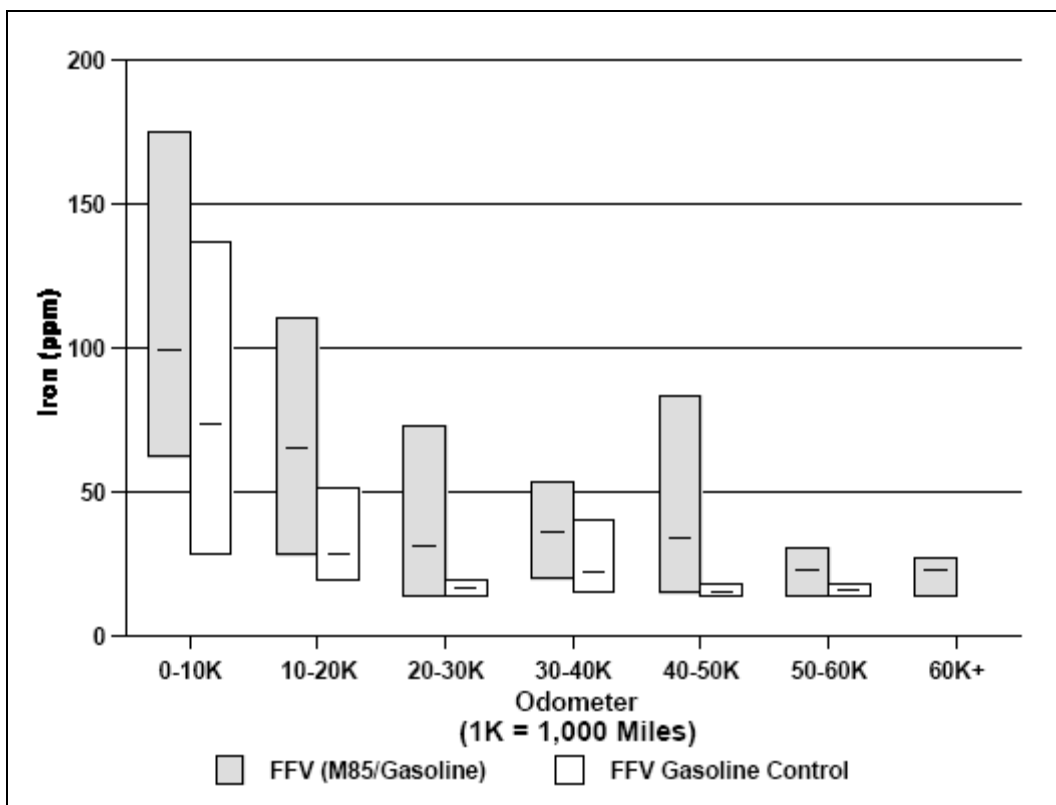
Figure 5. *Used iron oil content of four MY 1993 M85-fuelled Ford Taurus FFV and four gasoline-fuelled Ford Taurus FFV*

The oil analyses of iron showed an initially high wear for all cars when they were new, which consequently decreased when the engines were broken in (**Figure 5**). However, the iron wear was consistently somewhat higher for the M85-fuelled cars. The reason was believed to be that methanol washes away the oil film at the top of cylinder walls, resulting in higher wear rates. Also for aluminium somewhat higher levels for M85 were seen but these were not considered as a major concern regarding engine life.

The impacts of different engine oils and alternative oil formulations have been studied in a couple of projects. Some of the earliest studies originate from the 1980's [48, 49, 50]. In a study from a later date (1993), a laboratory test has been used to evaluate engine oils for FFV cars [51]. The wear increased with longer oil change intervals.

Potential lubrication issues associated with low level blending of alcohol in petrol have been studied by Black [52] as such blends allows a greater metal to metal contact than for petrol. The author states that low-level ethanol blends provides less lubrication as compared to low-level methanol blends. Test work has shown that M6.5 does not show an increase in engine wear and thus it has been concluded [53] that specially formulated lubricants are not necessary up to M6,5 %.

As mentioned previously, there are not many publications about the engine wear with M15 or E15. One exception though, is a study from Finland that describes the results from four Talbot Horizon cars that were using E15 for over 20 000 km [54]. A considerable increase in engine wear was noted, especially in so-called "stop and go" traffic. The necessity of matching fuels and oils was also pointed out in the study.

Above, it has been concluded that the combustion products of methanol are one important factor that contributes to the increase in engine wear, as seen in experiments and field tests. However, also the air/fuel preparation and the composition of the engine oil are important factors to consider. For example, carburetted engines have much higher wear than port-injected engines. Then the question arises as to which extent these data still are relevant for current and future alcohol-fuelled Otto engines.

Some considerations about future engines must be made before the relevance of engine wear data from the past can be discussed. Future engines using M85 and/or M100 must have a much better air-fuel preparation than current engines, especially during cold starts at low ambient temperatures. Partly this is due to customer acceptance, partly to stricter emission limits. Cold starts are also problematic for petrol-fuelled cars but the physical properties of the alcohol fuels aggravate these problems. One way of overcoming the cold start problems would be to use direct injection. The merits of direct injection were documented already in the late 1980's by e.g. Siewert et al. at GM [55]. Unassisted cold starts down to -29°C could be achieved by using direct injection of ethanol (98 % pure) and methanol (99 % pure). This was the lowest temperature that the test cell could achieve, indicating that the real cold start limit could have been even lower. Although direct injection was pioneered in modern time[11] already in 1996 by Mitsubishi, the opinion of these authors is that the second generation would have much better prospects to achieve low emissions and unassisted cold starts. Such injection systems have now been introduced by, e.g. BMW and Mercedes, and should provide opportunities to its use also on alcohol-fuelled engines. The Swedish manufacturer SAAB has developed such a concept for the use of E100. An additional advantage of direct injection would be that there is a potential to vastly reduce the fuel consumption in comparison to conventional systems. This has been showed by MIT in two theoretical studies [56, 57]. The reduction in fuel consumption is enabled through the use of turbocharging and direct injection combined with considerable downsizing. However, the potential of reducing the fuel consumption by some 25 % (in litre per 100 km) has yet to be confirmed in experiments. The prospects of using direct injection in combination with alcohol fuels have been advocated for almost a decade now by Ecotraffic. The MIT studies also advocate the use of double fuel injection systems to realise the potential to lower fuel consumption with a lower average percentage of ethanol used. Thus, the relative utilisation of alcohols could be even further enhanced. However, although very interesting, this route is more speculative and has not been further discussed here.

As the authors have now concluded that direct injection will, most likely, be a major feature on future alcohol-fuelled cars, the potential increase in engine wear must also be assessed against this conclusion. Direct injection was used on a relatively large scale (500 vehicles) in the 1990's by Detroit Diesel Co. on their M100 transit buses. However, these engines were 2-stroke diesel-cycle engines and thus, not very representative of modern 4-stroke Otto-cycle engines. Experiments were also conducted in the 1980's and 1990's on 4-stroke diesel engines running on methanol fuel with direct injection. Only in one of these cases, the authors have found a publication where the engine wear was investigated on such an engine. In an SAE paper from 1986, Kroeger describes the development of the Caterpillar 10.5 litre 3306 methanol-fuelled diesel engine [58]. This engine had many features not further discussed here and was, among other things, able to start without assist at very low ambient temperaturs. A 1 000-hour durability test was conducted in the engine laboratory on this engine. Component wear rates based on piston ring and liner

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[11] Here we do not consider for example, WW II aircraft engines and racing engines of a later date.

measurements indicated no wear life degradation attributable to the use of the methanol fuel. So, at least there is evidence that one engine with the interistic features of good air/fuel preparation that has exhibited low engine wear. Based on these relatively limited data, it can be concluded that there are prospects to reduce the engine wear provided that the air/fuel preparation is improved to a state where very little wall impingement occur. However, it must also be concluded that this field must be investigated further in much more detail before it can be concluded that the engine wear can be reduced to the same level as for conventional fuels.

5.2 DME

As pointed out before, there is no practical experience available yet about the use of DME for in-use vehicles. However, from published laboratory data, some hints can be derived anyway.

DME has very poor lubrication properties compared to diesel fuel. Even diesel fuel has to use additives today to improve its lubrication properties. The reduction of the sulphur content also reduces polar compounds in the fuel that deteriorates its lubricating properties. In engine tests with DME, many problems with the fuel injection systems have been found. Some additives that improve lubrication have been found and coatings on many components might also help but so far, it does not seem as this problem has been completely solved.

DME is very aggressive to many polymers and elastomers (as is methanol). Some metals also suffer from corrosion. It has been difficult to find materials suitable for, e.g., gaskets in the fuel system and fuel filters. After extensive material testing during the last decade, polymers and elastomers with much better properties in this respect have now been identified.

As pointed out before, DME has being investigated by Volvo within the RENEW project and thus, a much better overview of the problems in using DME will be covered in reports from that work.

6   DISTRIBUTION STRATEGY

In this chapter, a somewhat more in-depth discussion about the economic conditions for introducing DME and methanol on the market is carried out.

Low-level blending is one of the fastest and most cost-effective routes for utilising new fuels, provided that they can be blended in petrol or diesel fuel. It was also the initial assumption when this project started that this would be the primary recommendation. Therefore, much of the discussion below is concentrated on this option. Due to the negative attitude by many oil and automotive companies towards blending, this option has been somewhat reconsidered during the course of this study. Still, the legislative and technical limitations, as well as the economic conditions are of interest to discuss.

6.1   Impact of blending limits

There are two limits of interest when blending of alcohols is considered. First, the maximum oxygen content in petrol is limited. Second, there is a limit for each oxygenate listed in the fuel specification. Limiting both the oxygen content and the blending level of each oxygenate might be considered as a redundant limit in the latter case. However, there are no indications that this approach might be changed in the future.

6.1.1   Current EU petrol specification

Today, the maximum blending levels in petrol fuel corresponding to EU specification is limited to 3 % for methanol and 5% for ethanol. Blending by 3 % methanol gives an oxygen content of 1,6%, and a blending of 5% ethanol gives an oxygen content of 1,8 % [12]. The limit for oxygen content in the current EU petrol specification is 2,7 %. If both oxygenates would be added at the maximised limit respectively, the resulting oxygen content would amount to about 3,4 %. Thus, a certain percentage of ethanol and methanol can be blended in petrol but the percentage of one or both oxygenates must be reduced below the maximum limit. As a consequence: if 5 % ethanol is blended into petrol, only an additional percentage of 1,6 % of methanol can be blended into the petrol.

It may even be so that the need for increasing tolerances when additional components are blended may result in somewhat lower practical limits for the two alcohols. The most practical way of handling the blending of two alcohols on a fuel depot would, according to the oil companies, be to blend both alcohols in their right proportions and store this new blending component in a separate tank. After that, blending with petrol could be carried out when the fuel is distributed, as is current practice for ethanol blending today.

In **Figure 6**, the options for blending methanol and ethanol into petrol under the contemporary EU petrol specification is depicted. At the extreme ends, we have a maximum methanol scenario and, vice versa, a maximum ethanol scenario. The blending level for methanol ranges between 1,6 and 3 %. As noted before, a stabilising agent must be added when methanol is used as a blending component in petrol. Since this agent could be ethanol, the M3E3 specification could be an appalling option.

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[12] Note that the numbers for oxygen content, blending limits etc. may vary somewhat depending on the actual petrol fuel composition. This is due to that several of the limits (e.g. fuel density) can vary between quite great limits. The calculations discussed here are primarily based on the properties for a representative quality of Swedish petrol.
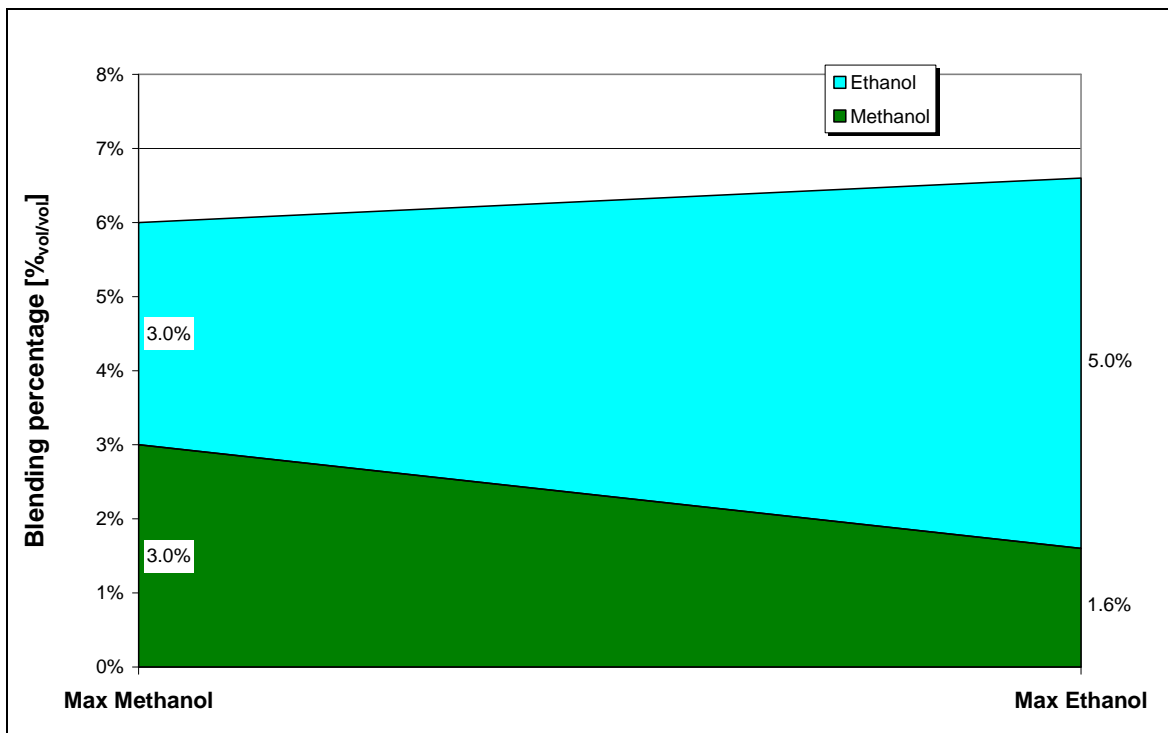
Figure 6.   *Methanol/ethanol percentage when methanol blending is limited to 3 %, etha-*
                   nol to 5 % and oxygen to 2,7 %

Since the oxygen content is the limiting factor for all combinations of methanol and etha-
nol in **Figure 6** and the energy content (on volume base) of each fuel is roughly inversely
proportional to the oxygen content, the energy content of the fuel is approximately similar
for all shown combinations of ethanol and methanol. Note though, that the energy content
on volume base of, for example, M1,6E5 petrol is about 1 % lower than for E5 petrol. Ac-
cordingly, the energy content of E5 petrol is about 1,75 % lower than for conventional pet-
rol. This is on the condition, though, that the base petrol would remain unchanged in all
cases. Eventually, this is not the case since the increase in vapour pressure caused by
blending alcohols in petrol necessitates a lower volatility for the base petrol when alcohols
are blended into it. This is often accomplished by reducing the butane content of the petrol,
thus increasing both density and energy content on volume base somewhat. So, in practice,
this compensates somewhat for the decrease in energy content due to alcohol blending.

6.1.2   Potential future EU petrol specification

Currently, a new specification for petrol and diesel fuels in EU is under discussion. A driv-
ing force is that the current limitations of 5 % ethanol in petrol and 5 % FAME in diesel
fuel results in that meeting the proposed indicative target for biofuel substitute of petrol
and diesel by 5,75 % on energy base according to the "biofuels" directive would be very
difficult. New specifications have been proposed by the European Commission [59] sug-
gesting an increase of the ethanol limit up to 10 % by volume and a corresponding increase
in the maximum oxygen content to 3,7% by mass. These new standards are suggested to be
enforced from 2011 and will retain the current maximum content of 3 % methanol. Under
the assumed conditions above regarding the future specification for petrol, the correspond-
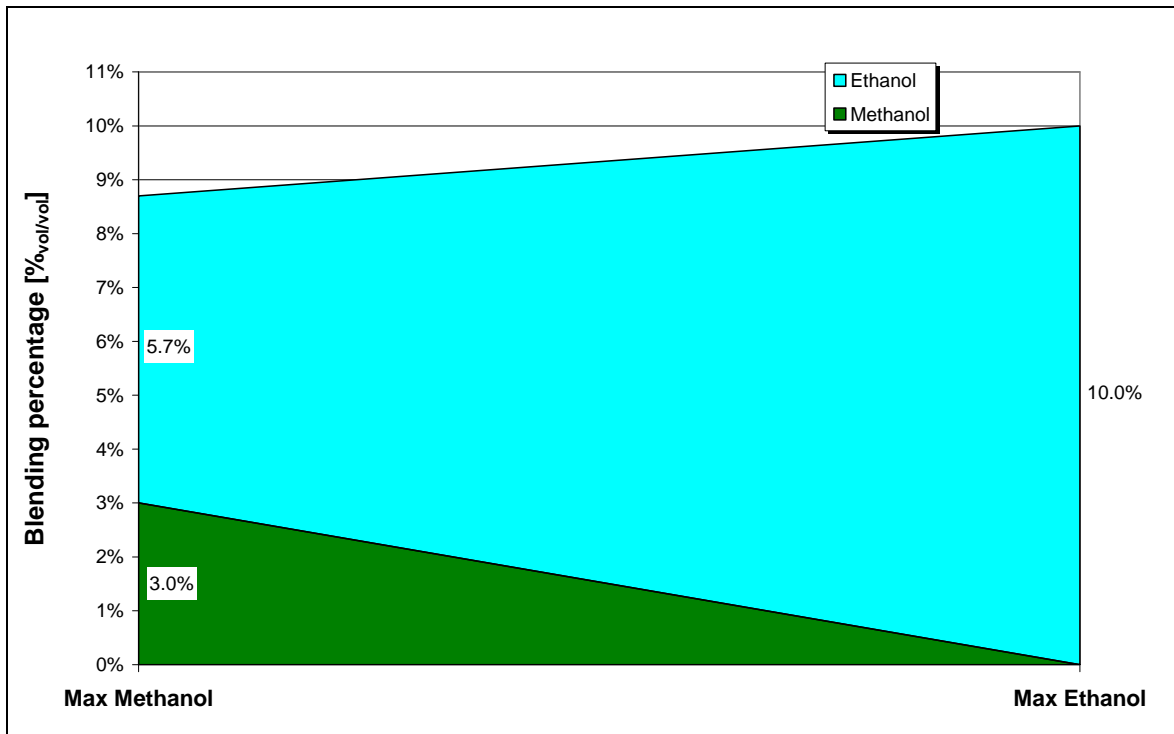ing methanol and ethanol limits would give the scenarios depicted in **Figure 7**.

Figure 7. *Methanol/ethanol percentage when methanol blending is limited to 3 %, etha-nol to 10 % and oxygen to 3,7 %*

For the sake of completing the picture by assuming that only the oxygen content in petrol would be limited, the scenario in **Figure 8** is shown. In this case, the maximum methanol content could be increased up to 6,9 % (**Figure 8**). However, it should be recalled that this scenario is not very likely, as discussed already above.

In both the two last cases (**Figure 7** and **Figure 8**), the energy content on volume basis is approximately constant when the share between the two alcohols is changed.
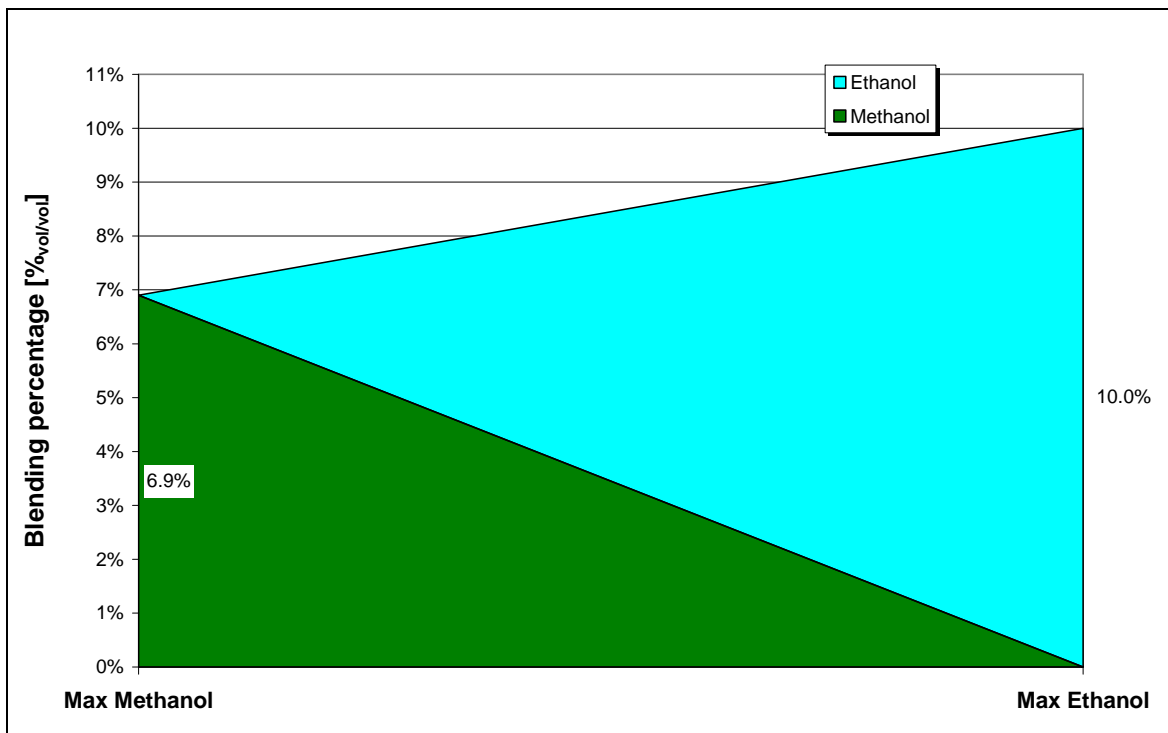
Figure 8.   *Oxygen limit is 3,7 % with no limits for methanol and ethanol*

6.2   Economical considerations

Today, the use of ethanol for low-level blending seems to be a much more interesting alternative for the oil companies than using the ethanol in E85. Conceivably, the distribution cost will be lower for the blending option, at least during an introduction phase. A similar situation as for ethanol could be foreseen also for methanol. This statement needs some more elaboration.

It can be anticipated that E85 and M85 users are aware of the fuel economy of their vehicles, i.e. the volumetric fuel consumption increases in comparison to petrol when E85 and M85 are used. There are only a few per cent (e.g. generally less than 10 %) improvement of the energy efficiency for contemporary fuel flexible vehicles implying that the volumetric fuel consumption increase in proportion to the decrease in heat value of the fuel. As an example, the increase in volumetric fuel consumption when comparing E85 and E5 would be close to 40 %. In order to provide the car user with at least a small economic incentive, the price for E85, and likewise for M85, must be lower or at least similar on an energy basis as for petrol.

When the alcohols are blended in petrol, the energy content on a volumetric basis is reduced compared to conventional petrol. For example, blending of 5 % ethanol in petrol reduces the energy content by 1,75 % if the petrol would have the same specification in both cases. In a practical situation, the base petrol must be modified for blending use to maintain a similar vapour pressure in both cases, which reduces the difference somewhat.

Generally, a lower energy content of the fuel would increase the volumetric fuel consumption, unless the engine efficiency would increase correspondingly. Some oil companies have stated that the volumetric fuel consumption would not increase for low level blend-

ing, although no solid evidence for this thesis has yet been presented. Determining the difference in fuel consumption is extremely difficult, since the differences often are of the same order of magnitude as the normal measurement scatter. One Swedish publication worthwhile looking at due to the low level of scatter in the measurements is a study carried out by AVL MTC (formerly MTC) in Sweden for SSEU, the predecessor to the Swedish BioAlcohol Fuel Foundation (BAFF) [60]. In an evaluation of the data from this report by these authors, we found that there seems to be some improvement of energy efficiency but not to the extent that it would fully compensate for the decrease in energy content. About 20 to 25 % of the energy loss on volume basis seems to be recovered by increased energy efficiency in the engine. This is roughly equivalent to the improvement in energy efficiency for fuel-flexible cars, i.e. there is no apparent benefit of using ethanol for either low-level blending or as E85. For methanol, some results have been generated in the Swedish project "INTROMET" coordinated by Ecotraffic. Measurements were carried out both on a chassis dynamometer at AVL MTC and on an engine dynamometer at the Technical University of Chalmers [61]. Although the measurement scatter was greater in relative terms than in the previously mentioned project, increased energy efficiency is observed for increasing concentrations of methanol in petrol (five fuels from M3 to M20). However, for the two passenger cars examined, one port injected and one direct injected, this improvement was considerably higher for the direct injected car.

Since the improvement of energy efficiency seems to be small for both low-level blending and M85 in contemporary vehicles (the proportion of direct injected cars of the vehicle fleet is low), no corrections to take the energy efficiency into account have been made in the economic calculations presented below. In the future, it is likely that vehicles running on E85/M85 or E100/M100 will use technology that significantly improves the fuel economy but this improvement needs to be quantified to be used in more advanced calculations.

In order to show the economic impact of different strategies, some simple calculations have been carried out. The base case has been that ethanol is blended into petrol at 5 or 10 % and the price on methanol is compared to ethanol on these conditions. The results are summarised in **Figure 9**.

In low-level blending, the blending level is maximised either by the limit for each alcohol, or in case more than one alcohol is used, by the limit for the maximum oxygen content. If the oxygen content would be the limiting factor, methanol has a disadvantage in comparison to ethanol. For a certain oxygen limit, roughly 30 % less methanol on a volume basis can be blended into petrol. Therefore, the price on methanol must be 30 % lower on a volume basis. However, on an energy basis, the difference would be "only" 7 %. This is shown in **Figure 9**, where the ethanol price is the reference in both cases. According to calculations in the RENEW project, but also in the CONCAWE/EUCAR/JRC WTW project [7], it should be possible to produce bio-methanol at a considerably lower cost than ethanol from wheat, sugar beet or cellulosic feedstocks. Thus, methanol should be fairly competitive in this comparison. A change in the duty on ethanol imported to the EU, as well as the demand for ethanol on the international market, might alter this picture.

As mentioned above, blending allows a reduction of the energy content. This is not directly to the benefit of the customer, who gets higher volumetric fuel consumption than with conventional petrol. A comparison of some of the alternative ways of using alcohols and their economic impact is shown in **Figure 10**. For the sake of comparison, the petrol price and taxation in January 2006 has been chosen as the base case.
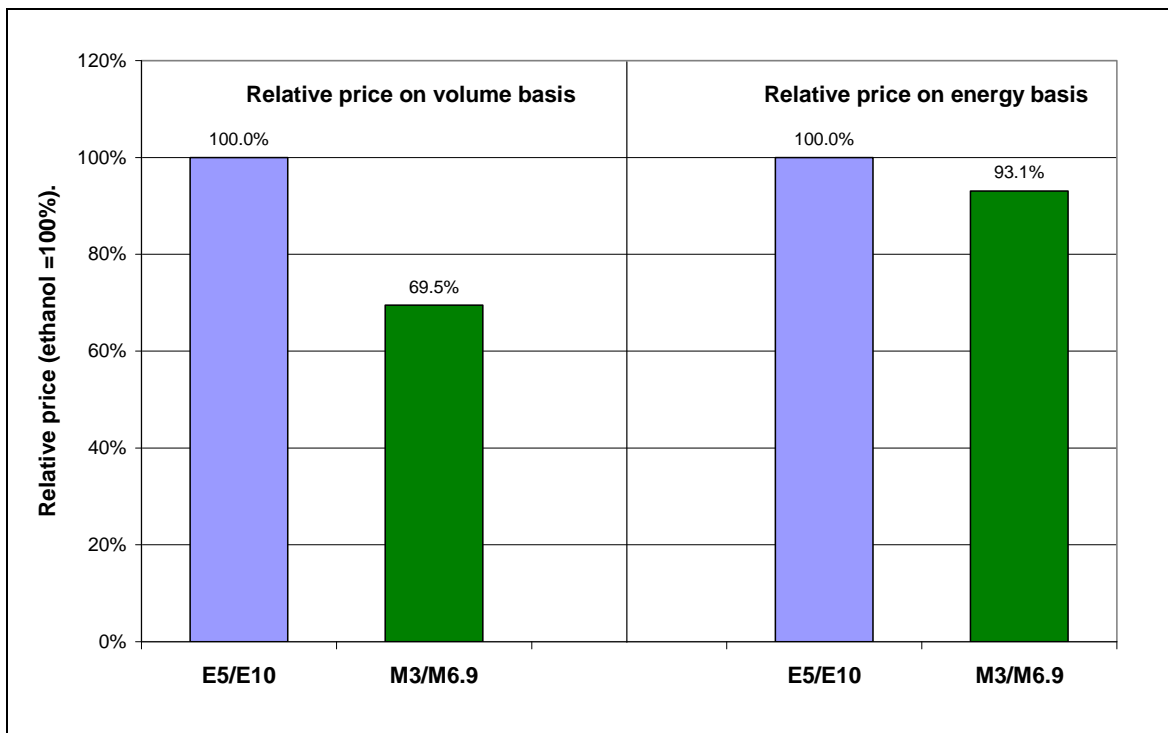
Figure 9. *Relative prices as blend stock components, ethanol as reference*
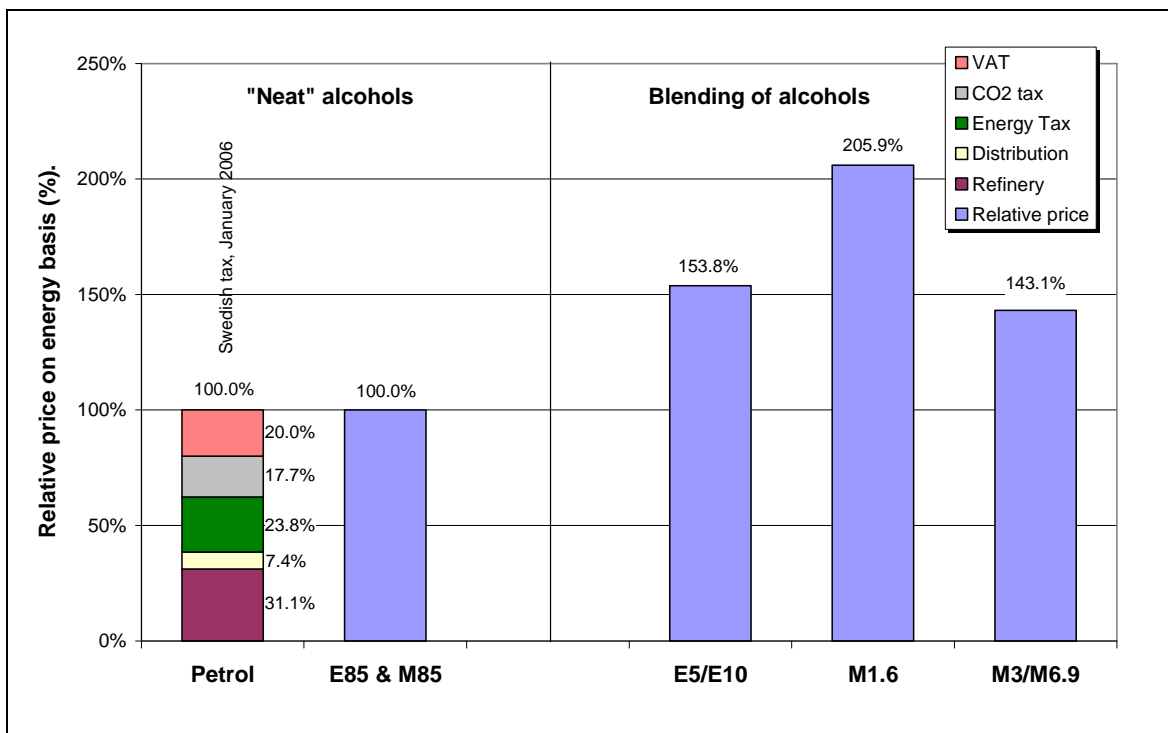

Figure 10. *Relative prices, petrol as reference*

On the condition that E85 and M85 do not provide an improved efficiency compared to petrol, the price at the refuelling station must be similar on energy basis. The economic conditions are vastly improved if low-level blending is used instead since petrol is substituted on volume basis and not on energy basis. The use of methanol as M1,6 is the most

favourable option. M3 and M6,9 up to the two limits for oxygen content is slightly less favourable than the price of ethanol at the two blending levels of 5 and 10 % respectively.

6.3 Introduction strategy

The timeframe for the introduction strategy has been divided into two stages: a short term timeframe, which is about 5 years from now, and a long term timeframe, which aim at the period after 5 years and ending at about 2025. A longer period than that is very difficult to foresee.

6.3.1 Short-term horizon

By taking all the discussions and considerations above into account, a distribution strategy can be outlined on the short-term horizon. Our recommendations are the following regarding distribution of DME and methanol:

1. DME in dedicated fleets
2. Methanol as feedstock for transesterification of fatty oils to FAME
3. Methanol as Feedstock for production of MTBE (i.e. bio-MTBE)
4. Methanol as blending component in petrol up to the limitations in the current (and future) petrol specification

The rationale for recommending the use of DME in dedicated fleets as the highest priority is that the first commercial vehicle fleets will be available within the timeframe that the first production plant could be in operation, i.e. about 2010. DME has not been used at a larger scale in vehicle fleets before implying that it has to be used in a limited number of vehicles. However, it has so many environmental advantages over diesel fuel that it should be of interest for the environmentally oriented customer. Such advantages are also good for public relations, an issue of significant importance for a first plant and in an introductory phase for a new motor fuel. On the other hand – as has already been pointed out several times before – the attitude towards methanol is not at all that positive.

It is not likely that the number of DME vehicles would be sufficient to consume all the fuel produced in a first plant because these vehicles are in an early phase of development and consequently the number of introduced vehicles should be low.

FAME is currently the biofuel in the EU that is used in largest quantities. Using bio-methanol instead of fossil methanol for the transesterification of the fuel would be quite uncontroversial and straightforward. Thus, most of the negative perceptions about methanol as a motor fuel might also be avoided. The only barrier for the use of bio-methanol instead of fossil methanol is that there must be an economic incentive or obligation to overcome the higher cost of the bio-methanol compared to fossil methanol. Such an incentive already exists in some EU countries. One example is that the tax break for biodiesel in Sweden does include only the biofuel part of the fuel. Thus, this incentive is already in place. Under the presumption that at least some $200\,000\ m^3$ of FAME will be used in Sweden in the near future, this could motivate a production of some $30\,000\ m^3$ of methanol. This would, for example, be equal to the whole production volume (excluding any production of DME) for a plant size similar to the plant discussed at Södra Cell in Mörrum. The potential in the EU-25 is far greater, since a growth of biodiesel production up to some $5\ Mm^3$ could be foreseen for the not too far distant future. Thus, even though the present

production volumes of FAME are not particularly large they are certainly large enough to motivate the construction of a number of methanol plants.

Although MTBE has been under debate for some years now it does not seem likely that there would be a ban on MTBE in the EU. However, the competition with low-level blending of ethanol in petrol is serious. This is under the assumption that the future limit for ethanol would be 10 % and that the oxygen limit would be increased to facilitate this. Thus, no additional MTBE could be blended in the petrol, if the oil industry would choose the maximum level of ethanol. Again, this scenario is not very likely for all EU member states, since there is not enough surplus of ethanol on the international market to supply such high volumes. Likewise, new production capacity, either in the EU or abroad, could not be created within a few years. As discussed before, the production cost per unit energy for methanol would be lower than the production cost for ethanol (from agricultural or cellulosic feedstock) produced in the EU. It is also likely that the production cost for MTBE on oxygen content base would be lower than for ethanol. However, it is likely to believe that the maximum limit for MTBE would not be raised from the current level, implying that there would still be some margin for blending of ethanol and/or methanol before the oxygen limit is reached. As mentioned before, ETBE would be more costly than MTBE based on bio-methanol. All in all, it does not seem as using methanol as a feedstock for MTBE production would not be a risky business. This is on the condition though, that the economic incentives must also apply to the bio-methanol used as a feedstock for MTBE. Based on projections by some oil companies, the total market for MTBE might decrease in the EU. However, there will still be enough to motivate the erection of a number of methanol plants in the EU.

The use of methanol as a blending component in petrol is only ranked as number four on our list. This is although there are favourable economic conditions for this option in comparison to ethanol blending. Our concern is still that there are so many negative perceptions against methanol in the oil and auto industry that this option might not be considered in spite of its many advantages. Again, there will be competition with ethanol and other oxygenates about the same "volume" of oxygen allowed in the fuel. The risk that blending of methanol in petrol might be banned in the long-term future must also be taken into consideration. All-in-all, the negative aspects for low-level blending contributes to the relatively low ranking of this option.

It would be nice if there was an opportunity to introduce methanol as a fuel on the market on the short-term horizon. The Swedish car manufacturer SAAB has indicated to the press that they are working on a concept that should facilitate the use of E100 and M100, in addition to petrol and E85/M85. However, it is not yet clear when such a concept could reach production status. On the other hand, we have previously already concluded that the interest in using M85 and/or M100 from the automotive industry is very low. Thus, it would be bold at this state to anticipate that this would be a route that could be utilised on a short-term horizon. Therefore, this option is not recommended as one of the primary options in the near future.

Presumably, the options of selling DME and/or methanol as green chemicals or as substitutes for fossil DME and methanol at world market prices does not have to be considered on the short-time horizon.

6.3.2 Long-term horizon

In the previous section we have established that there are several options available for introducing DME and methanol on a short-term horizon. Some of these options will of course also be available on the long-term horizon. However, the quantities that can be introduced are, after all, relatively small in comparison to the total market of petrol and diesel fuel in the EU. In order for DME and methanol to reach a greater share of the market, a different strategy has to be proposed. The option of blending methanol in petrol (as methanol or MTBE) and as a feedstock for biodiesel production can enable a quick introduction of a certain volume on the market but whenever this level is reached, no further increase can be achieved. Therefore, a strategy that facilitates the possibilities for a continuous increase in market share is favoured.

An increase in the use of DME to dedicated fleets would be a strategy to increase the use of this fuel. Today, there is no realistic technical option available that would allow a fuel-flexibility great enough or a dual-fuel system to facilitate the use of *both* DME and diesel fuel in an engine. Modern DI diesel engines simply do not have room in the cylinder head for dual injectors. Using the same injector is more or less impossible since the difference in flow is so great. Finally, blending DME in conventional diesel fuel increases the vapour pressure too much to be a realistic option.

Once the number of DME-fuelled fleets is great enough and the number of (preferably public) refuelling stations is increasing accordingly, it would be possible to introduce DME-fuelled vehicles on a larger scale. It has to be said, though, that introducing a completely new fuel on the market will be a difficult task, in particular when this fuel is not in liquid state at normal conditions. Previously, fuels such as CNG and LPG have been introduced on some markets. Both of these fuels are used in other applications, and in the CNG case, there is often a pipeline network in place in most EU member states (excluding much of the Nordic countries and rural areas in some other countries). The use of DME in other applications is much lower in comparison to CNG and LPG. This could, however, change if DME were to be used for other purposes, e.g. cooking and in gas turbines. Thus, it would be an advantage if the introduction of DME as a motor fuel could go hand in hand with the use in other applications. Building the infrastructure for using urea solution as a NO_X reducing agent in heavy-duty vehicles is still a proof of that a new fuel infrastructure could be build if the driving forces are great enough. Anyway, starting with dedicated fleets and identifying such fleet one by one during the introduction phase, is the only viable option for introducing DME on the market.

On the short-term timeframe, the use of M85 and/or M100 vehicles can be avoided but this is not the case on a longer term timeframe, in particular if the market penetration should be high. The use of fuel-flexible cars is an excellent means of overcoming the catch 22 problem during the introduction phase. Examples in the USA, Brazil and Sweden have showed this. The incremental cost of fuel-flexible cars is also low in comparison to dedicated vehicles where, in particular for gaseous-fuelled vehicles, the incremental cost is almost prohibitive. In the methanol case, M85 would be the obvious choice of fuel quality initially. The drawback of fuel-flexible and dual fuel options is that a compromise must be made between both fuels that limit the possible improvement of energy efficiency and exhaust emissions. Thus, dedicated vehicles would be the better solution once the market has developed and the fuel is available.

One alternative of distributing M85 would be if the pump also could be flexible. If the blending level would be very low, e.g. 3 to 5 % (as for M3 or E5), there could be problems with tolerances, although some manufacturers of fuel dispensers claim that even E5 could be distributed this way. For practical reasons, we still anticipate that blending alcohols at the fuel depot would still be the best option for petrol corresponding to current (and future) EU petrol specifications. For M85, however, there could be another option. The petrol percentage in M85 is so high that tolerance issues would be avoided if this fuel was blended from M100 and petrol at the dispenser. A practical advantage could be that it would be possible to increase the petrol content during winter (e.g. M70) to improve the cold start capabilities. In this scenario, only M100 would be the methanol fuel quality that needs to be distributed. Potential additives to methanol would have to be selected that can operate in all applications. Eventually, also heavy-duty vehicles could run on M100 when the fuel distribution network has been established. A schematic illustration of a fuel distribution system according to these principles is presented in **Figure 11**.

If methanol is to be used in petrol up to the limit of 3 %, it would almost certainly be blended into petrol at the fuel depot. This is indicated as M3 petrol in **Figure 11**, although any other oxygenate allowed or a mix of them (e.g. E3/M3) could be anticipated instead. Today, the number of petrol qualities is quite limited in many EU countries. For example, 95-octane petrol is totally dominating over 98-octane petrol in Sweden. If neat methanol is to be introduced on the market, one tank might even be omitted at some refuelling stations. Today, most of the new tanks and pumps installed in Sweden tolerate both ethanol and methanol, which would further simplify a future fuel switch. In **Figure 11**, M85 vehicles are using the "fuel-flexible" dispenser that blend 15 % petrol with 85 % M100. Dedicated M100 vehicles (having otto or diesel engines) are refuelled directly. In addition, diesel fuel will of course be distributed.
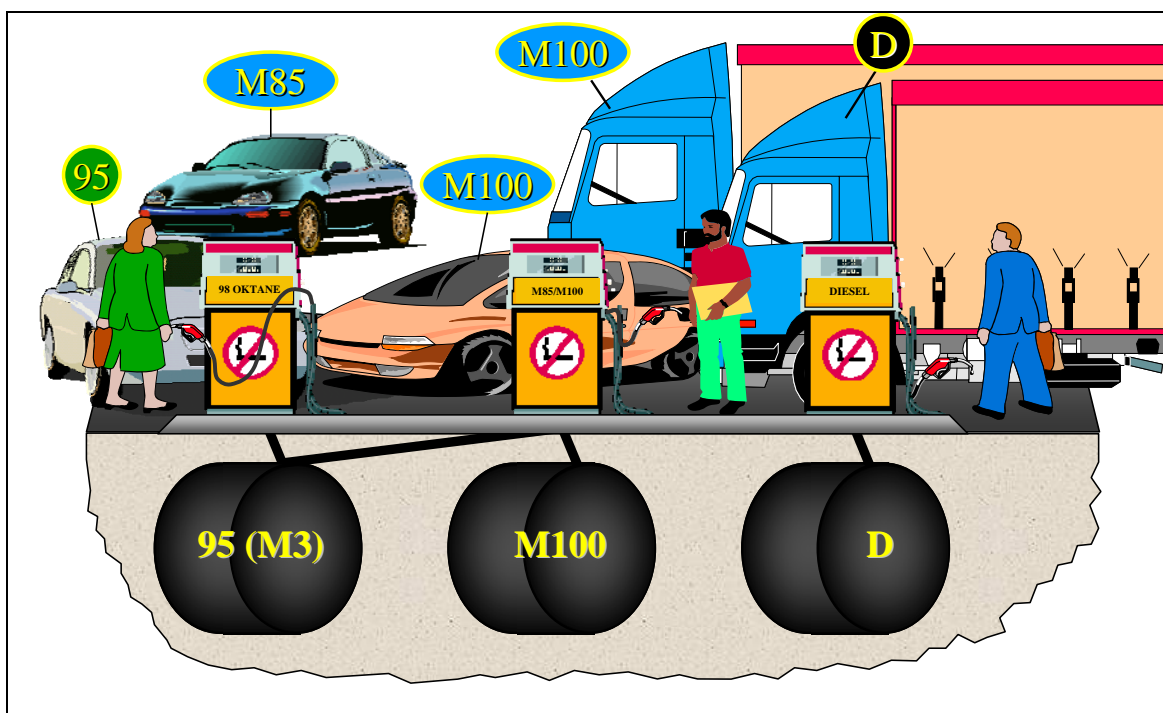

Figure 11. Distribution strategy

7 DISCUSSION AND CONCLUSIONS

7.1 General conditions to be taken into account

In the discussion above, it has been concluded that the oil and auto industries are currently not particularly interested in methanol as a motor fuel. This is with one exception, i.e. SAAB, where the interest in this option emerged at the end of the project work. Although many contacts have been made with representatives from the oil and auto industries during the course of the work, it has been very difficult to pinpoint any particular reason as to why these negative attitudes have been formed. One possible cause could be that the number of drawbacks combined is great enough to cause this position.

Regarding DME, there is little support from other vehicle manufacturers than the Volvo Group. Likewise, very few oil companies are advocates for DME as a motor fuel. Mostly, the oil and auto industry are quite indifferent towards DME. Outside the EU, as in e.g. Japan, more support for DME is found.

7.2 Introduction strategy

When this work was initiated, the use of low-level blending of methanol in petrol was assumed to be the fastest and most convenient route of utilising methanol in the fuel sector. Due to the many negative perceptions experienced, this initial conclusion has been somewhat reconsidered during the course of the study. In other applications of methanol these standpoints also apply.

Since DME is not plagued by the not so successful pre-history of methanol, the use of DME should be considered a priority over methanol, whenever possible. This is of particular importance for a first commercial-scale plant, when both fuels could be produced simultaneously at a percentage that could vary somewhat from time to time. These are some of the considerations that have led to our suggestion to give production of DME the highest priority.

In FAME and MTBE, bio-methanol could directly substitute fossil methanol as a feedstock. Provided that FAME and MTBE are accepted as fuels and/or fuel components on the market, the substitution of fossil methanol by bio-methanol is uncontroversial. Therefore, the two routes mentioned, are proposed as the next step in the introduction strategy. As a blending component in FAME, bio-methanol would have favourable economic conditions compared to ethanol in FAEE on the condition that production cost in the EU is considered. For the use of methanol in FAME and MTBE, as for all other biofuels today, a tax reduction or tax exception for the non-fossil fuel component would be necessary, or else a biofuel quota duty would have to be enforced. Until now, this has not been the case in most EU countries. A fair treatment of bio-methanol on similar conditions as other biofuels in this respect would, of course, be necessary.

Blending on methanol in petrol is permitted today in the EU, provided that a stabilising agent is added. This fuel additive could be ethanol. The current limitation of methanol blending rate in petrol is 3 % and the limit is suggested to be maintained at this level [59].

7.3 Conclusions

In short, the conclusions in this study are the following:

- Methanol was one of the first alternative fuels to be considered for a large scale introduction in the 1980's. However, since the 1990's, most stakeholders have lost interest in this option. In contrast, DME is a relatively "new" alternative fuel on the market.
- The fire and explosion safety hazards with methanol have been investigated. In general, methanol should be considered safer than or at least as safe as petrol in this respect. DME has some safety issues to be taken into consideration. DME distribution has many similarities to the distribution of LPG, an established technology today.
- Material compatibility must be addressed for methanol, since methanol is corrosive and degrades some polymers and elastomers. However, there are suitable materials available on the market and test methods for material selection (e.g. SAE J1681 [18]) have been developed. Methanol is a chemical commodity today and is handled in large quantities on the world market without any apparent problems.
- DME, as a new fuel, has several material compatibility problems that must be overcome until DME could be introduced on a larger scale. Much development work is going on in this field.
- Phase separation with methanol/petrol blends is an issue to consider. In low-level blending a stabilising agent must be used. This stabiliser could be ethanol. Some options of fuel distribution must be avoided to prevent phase separation.
- The health effects of methanol exposure have been thoroughly investigated in the past. Methanol is more toxic than petrol when ingested. On the other hand, methanol is neither mutagenic nor carcinogenic, as in contrast to petrol. Normal exposures of methanol to humans give concentrations that are far below the level of health effects. Human body metabolism and ingestion of diet beverages and fruit generally cause higher methanol concentrations.
- Methanol spill to land and water does generally have lower environmental impact than petrol and diesel fuel spills. Below a certain concentration, methanol is not toxic, is metabolised by micro-organisms and consequently, the impact is only local.
- Engine wear is the most severe of all potential show-stoppers for methanol that have been identified in this study. The increased engine wear was investigated in the 1980's and the mechanisms are fairly well-understood. However, these results are not directly applicable on modern engines. It is hypothesized by these authors that advanced engine technology such as, e.g. direct injection, might overcome those problems.
- DME cannot be used in fuel-flexible vehicles so it would have to be used in dedicated fleets during an introductory phase. In the first production plants, where both DME and methanol could be produced, the share of DME would have to scale with these fleets. Since DME seems to be favoured over methanol by oil and auto industry, DME should be given highest priority.
- On the short term horizon, the use of methanol in low-level blending would have the greatest potential. Cost calculations show that methanol would be cost-competitive with ethanol and it is not likely that ethanol could be produced in sufficient quantities in the EU to meet the demand. However, neither the oil nor the auto

industries favour the blending option. Therefore, the "safest" and most conservative route of introducing methanol would initially be to use it as a substitute for fossil methanol in FAME and MTBE production.

–   On a longer term horizon, the use of fuel-flexible and dedicated light-duty vehicles is the most favoured option. The use of direct injection would greatly enhance the cold start properties and enable a significant increase in engine efficiency. Furthermore, M100 could be used instead of M85. Dedicated heavy-duty M100 vehicles could be introduced at a later stage.

–   An introduction strategy based on the distribution of anhydrous M100 and the use of blending pumps to make other fuel qualities (e.g. M85) available is proposed.

7.4   Final comments

During the timeframe of this project, it has become clear that there are many negative attitudes regarding the use of methanol in the automotive sector. In these discussions, Ecotraffic has noted that those stakeholders have considered Ecotraffic as an advocate of this fuel, which is not correct. In contrast, we have had to assume this role in order to carry out the work in this project. For a company that is officially "fuel-neutral", this association is not directly in line with the company policy. Yet, our "neutral" opinion is that all fuels should be judged on an equal basis, and in this case, it can be concluded that there is some injustice that needs to be taken care of if methanol is to gain any larger market share in the EU in the foreseeable future. Therefore, we welcome a debate of the pros and cons of methanol as a motor fuel. If there is a significant show-stopper, methanol should not be used as a motor fuel. If not, methanol should be equally treated as other biofuels, and it could compete on the market on its own merits. Last but not least, the use of methanol should be taken into consideration when the future EU policy regarding biofuels is established.

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