**TNO Science and Industry**

**Public Sector**
De Rondom 1
P.O. Box 6235
5600 HE Eindhoven
The Netherlands

www.tno.nl

T +31 40 265 00 00
F +31 40 265 03 01
info-IenT@tno.nl

**TNO report**

# Impact of biofuels on air pollutant emissions from road vehicles

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Author(s)
Ir. R. Verbeek
Dr. Ir. R.T.M. Smokers (CE)
Ing. G. Kadijk

Drs. A. Hensema
Ir. G.L.M. Passier
Ir. E.L.M. Rabé
Ir. B. Kampman (CE)
Ir. I.J. Riemersma (Sidekick Projects)

Assignor

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# Summary

## Executive Summary

Industrialized nations such as the Netherlands face the dual challenge of reducing the emission of $CO_2$ as well as reducing concentrations of atmospheric pollutants. For reducing $CO_2$ emissions, the use of biofuels and other renewable fuels has received much attention recently. However, there is still much unclarity regarding the effect of the implementation of biofuels on polluting emissions. Is there a possible win-win scenario, where implementation of biofuels leads to lower concentrations of e.g. $NO_2$ or particulate matter? Or will there be adverse effects, for example due to an incompatibility of biofuels with modern emission control technology? Similar questions exist for CO2 reduction options in other sectors.

To investigate this issue, the Ministry of VROM has initiated the research programme BOLK[1]. In BOLK, different areas of renewable fuel production and use are investigated, including production, use in different situations, and capture/sequestration. The work reported here, carried out by TNO and CE, gives an overview of the expected effects of the use of biofuels on vehicle emissions up to 2020.

Three main questions have been the guideline in this work:

1) Which biofuels will be used in significant quantities up to 2020?
2) What engine development are expected, both for diesel and petrol engines?
3) How does engine technology interact with the use of biofuels, both on short and longer term, and what are the expected implications for exhaust emissions?

To answer these questions a survey was made of recent literature and international experts on engine technology and fuels were consulted. The current work is the first phase in the BOLK project, and is still rather exploratory in nature. Nevertheless, some important conclusions for policy makers already become clear.

## Biofuels mix in 2020

Although many different types of renewable fuels exist, it is expected that up to 2020 the renewable fuels mix will be dominated by (first generation) ethanol for petrol and FAME (biodiesel) for diesel engines. In addition to this a for the time being small but increasing quantity of synthetic diesel can be made by e.g. Biomass-to-Liquid (BTL) processes, if these are stimulated.

## Engine development and biofuels compatibility

For petrol engines, the main development lies in further increase of fuel economy. This is primarily done via engine downsizing and advanced injection technologies. To reach the coming emission legislation, further optimization of engine control in combination with 3-way or $NO_x$ absorption catalysts will be used.
For diesel engines, the development focus is in emission reduction (mainly $NO_x$ and particulate matter). Future emission limits will be met by advanced emission control systems which include the general applications of particulate filters and de$NO_x$ catalysts, the latter in particular for larger vehicles.

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[1] Beleidsgericht Onderzoeksprogramma Luchtkwaliteit en Klimaat 2008-2009

Most engines are already now compatible with low biofuel blends (below 10%), and this is not expected to change with coming engine technology. Moving up to higher blends is not recommended due to durability concerns and possibly high emissions.

**Effect of biofuels on emissions**

For the current vehicle fleet, the available emission data show large variation, both positive and negative. This is caused by variations in biofuel properties, vehicle technology, engine management and the driving cycle. It applies to both petrol and diesel engines and especially to light duty vehicles, i.e. passenger cars and delivery vans. Due to these many influencing factors and to relatively small amount of available emission data it is not possible to draw firm conclusions regarding the emission impact of biofuels on a national scale.

For future vehicles, the emission levels of petrol engines are expected to improve as biofuels will be implemented in Euro 5 (2010/2012), but petrol engine emissions are low anyhow. For diesel engines, the variability is likely to persist, due to the large sensitivity of the emission control technologies needed to meet the Euro 5/V legislation. In particular for $NO_x$, there appears a risk of a steep rise in emissions with the use of biodiesel. The extent to which this will pose problems with future engines depends strongly on the way biofuels are implemented in future emission legislation.
For synthetic diesel (BTL, GTL) the picture is brighter. Generally reductions of both $NO_x$ and particulate matter are seen, but at the expense of a slightly lower fuel economy and power. For future engines positive effects on emissions are expected to diminish.

**Main conclusions**

1) To reach the EU target for 2020, it is recommended to use low blends (E5-E10, B5-B7) in general fuel applications, combined with high blends for specific niche applications (public transportation, local freight transport).

2) There is no indication for a win-win situation on the short term, in the sense that the most probable biofuels mix for the coming years will not lead to a significant and consistent reduction in atmospheric pollutants. The picture shows a large variability. Only in the case of synthetic fuels (BTL, GTL) on the short term a consistent emission reduction is expected.

3) If mainstream use of biofuels is limited to low blends, emission effects will generally be limited, although large differences between vehicles may exist. The extent to which emissions will be influenced by biofuels on the longer term depends strongly on the way biofuels are implemented in the emissions legislation.

4) Problems may arise with EURO IV and V heavy duty vehicles with $deNO_x$ catalysts on high blend biodiesel (B20-B100). To prevent this, it is recommended to request special emission control software from the vehicle manufacturer in combination with extensive monitoring of the performance of these vehicles.

5) The current state of knowledge does not allow a reliable quantification of emission effects of biofuels. Therefore, a systematic emissions measurement

program is needed to fill the large knowledge gaps that have been identified. This program should focus on low blend biodiesel, low and high blend ethanol, and should also include non-regulated toxic components.

6) Further work, including literature surveys and interviews with experts from the automotive and fuel industry and from R&D institutes, is necessary to improve insight in the possible impacts of biofuels on future engine technologies.

## Technical Summary

### *Introduction and objective*

In Europe the national emission levels of $NO_x$, $SO_2$, VOC and $NH_3$ are regulated by means of National Emission Ceilings (NEC). As part of the process for preparing new National Emission Ceilings for the year 2020, the Ministry of VROM has initiated the BOLK programme[2]. The specific aim of the BOLK programme is to provide the Dutch government with knowledge and advice regarding the impact on NEC emissions in 2020 of a number of techniques aimed at the reduction of greenhouse gases.

For the transport sector, the use of biofuels is an important option to provide a reduction of $CO_2$ emissions. Air quality effects of biofuels, however, are still unclear. In the work described here TNO and CE Delft have evaluated the Tank-to-Wheel (= exhaust) emissions resulting from the use of biofuels in road transport[3]. The work was carried out by evaluation of available literature and information and by the consultation of technical experts within the automotive and fuels industry. The following questions have guided this study:

- Which biofuels will be used in significant quantity up to 2020?
- What engine developments are expected, both for diesel and petrol engines?
- How does engine and aftertreatment technology interact with the use of biofuels, both on short and longer term, and what are the expected implications for exhaust emissions?

The study provides an overview of available information and leads to a number of recommendations for governmental policies. Also, important knowledge gaps have been identified that require further study.

### *Which biofuels will be used up to 2020?*

The EU biofuels directive 2003/30/EC sets a European target of 10% substitution of fossil fuels with biofuels by 2020. The Dutch government investigates the possibilities of raising the national target to 20% in 2020. In these targets the percentages are by energy content, while e.g. the term B5 indicates a 5% blend of biodiesel by volume in conventional diesel. This means that the 10% biofuel target corresponds to a higher percentage by volume. Changing all diesel into B10 and all gasoline into E10 would not be enough. Both low blends and high blends are necessary.

A wide range of alternative fuels are considered for automotive use. However, looking at the time frame up to 2020 not so many fuels will be produced in substantial quantity. The renewable fuels up to 2020 are dominated by ethanol for petrol (Otto) engines and Fatty Acid Methyl Esters (FAME, biodiesel) for diesel engines.

In addition to this, significant quantities of synthetic diesel fuel can be made available. Synthetic diesel fuel can be produced from renewable or fossil feed stocks and can be used in pure form or blended into conventional petrol and diesel. Synthetic fuels are: Hydrotreated Vegetable Oil (HVO), Biomass To Liquid (BTL), Gas To Liquid (GTL) and Coal To Liquid (CTL). Fossil ETBE (Ethyl Tertiary Butyl Ether) is already used on

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[2] Beleidsgericht Onderzoeksprogramma Lucht en Klimaat 2008-2009, coordinated by Netherlands Environmental Assessment Agency MNP

[3] Well-to-tank emissions in the energy supply chain for biofuels are evaluated by Ecofys in a parallel study.

a large scale as octane improving blend for petrol. ETBE can also (partly) be produced from renewable feedstock.

Table 1 Biofuels used or considered, either as pure/neat fuel or as blend in standard fuel.

| Gasoline engines (spark ignition, Otto) | Diesel engines (compression ignition) |
|---|---|
| Ethanol | FAME or biodiesel |
| Bio ETBE | Hydrotreated Vegetable Oil (HVO) |
| Biopetrol | Biomass To Liquid (BTL) |
| Butanol | Ethanol with ignition improver |
| Methanol | Pure Plant Oil (PPO) |
| | Methanol with ignition improver |
| | Dimethyl-ether (DME) |

### *Petrol engines: engine developments and compatibility with biofuels*

Within the period from now to 2020, the development of petrol engines (Otto or “spark ignition”) is primarily focused on improvement of fuel consumption and reduction of $CO_2$ emissions. This will primarily be done via engine downsizing, which involves technologies like turbocharging, direct injection and variable valve timing. In addition to that some vehicle manufacturers might use the lean burn and spray guided combustion (stratified charge) engine technology. The coming emission limits will be met by further optimization of engine control in combination with three-way or $NO_x$ adsorption catalysts.

Looking at low blend ethanol in petrol, it is determined that 90%-95% of current vehicles can already run on E10 (10% ethanol blend in petrol) without any problems. For the remaining, primarily older vehicles, E5 should be kept available. Higher blends of ethanol (up to E85) can only be used in special Flexible Fuel Vehicles (FFV). It should also be noted that 8-9% (by volume) ethanol is required to meet the 5.75% biocomponents target on an energy basis (target 2010).

Other bio components considered for petrol are bio-ETBE, biopetrol and butanol. All three have a better compatibility with petrol than ethanol, but technical and economics aspects of large scale production still need to be demonstrated.

### *Otto engines: effects of biofuels on emissions towards 2020*

The effects of biofuels (blends) on emissions for both otto and diesel engines will mainly depend on the extent to which emission requirements for these biofuels are implemented in the emission legislation. This implementation is happening slowly. With the entering into force of Euro 5 (2010), the test fuels will contain 5% biofuels. With Euro 5 phase b (2012) Flexible Fuel Vehicles (FFV) need to fulfil the limits on both petrol and high blend ethanol (E85). This also means that vehicles sold before 2010 / 2012 will not have formal emission requirements for biofuels (blends). Also for the mainstream vehicles sold after 2010, the formal emission requirements are limited to 5% biofuel blend.

The most relevant emission components for otto engines are $NO_x$ and unburned hydrocarbons. The latter can contain toxic species such as aldehydes. For the influence on emissions of low and high blend ethanol in petrol, the majority of the information available is based on Euro2 and Euro 3 engines (up to 2005/2006). The data does show considerable variation in emission levels when ethanol is added. This is the case for both low blend in standard vehicles and high blends in FFVs. The variations are in the range of - 50% to +50% for hydrocarbon emission to -50% to +300% for $NO_x$. It should be noted that the $NO_x$ levels are low in comparison to diesel engines. For vehicles sold after 2010 / 2012 emissions with ethanol blends are expected to improve, due to the implementation of ethanol in the legislation. For ETBE blends, the limited data available show only a small influence on emissions. No information is yet available for biopetrol and biobutanol. Overall it is difficult to draw conclusions on the effect on emissions of ethanol blends, but emissions are expected to improve when formal emission requirements for biofuels are implemented

***Diesel engines: engine development and compatibility with biofuels***

The development of diesel or "compression ignition" engines up to 2020 will be focused on emission reduction. Future emission limits will be met by advanced emission control systems which include the general application of diesel particulate filters. $DeNO_x$ catalysts will be installed on most diesel engines with the exception of small passenger car engines.

B5 (5% FAME in diesel) will be formally required for the Euro 5 type approval testing for passenger cars (phase in 2009-2010). For heavy-duty legislation this still needs to be arranged. For passenger car diesel engines it is advised to limit the FAME content to 7% (B7). This is because of the technical choice to use "post injection" technology for DPF regeneration. For heavy-duty vehicles use of high blend FAME (B20-B100) is possible, but will require some engine and fuel system adaptations. It will also require more maintenance including more frequent oil drain intervals. It is expected that the availability of trucks suitable for B100 can be increased towards 2020 if desired. Instead of FAME, pure plant oil (PPO) can be used in somewhat modified diesel engines. It is however not recommended to do this on a significant scale, because of the work required to ensure durability and emissions of the vehicles.

In addition to or instead of FAME, synthetic diesel (HVO, BTL, GTL, CTL) can be added to diesel fuel. Of course only HVO and BTL are renewable fuels. The synthetic diesel fuels are characterised by a good compatibility with diesel fuel. They can be used in any blend percentages without any adverse effects on engine maintenance or durability.

Other biofuels considered for diesel engines are pure ethanol or methanol with ignition improver or dimethyl-ehter (DME). These fuels do require special engines and they are not very attractive to commercial vehicle owners because of the much lower energy content of the fuel (up to a factor of 2). Also a European fuel infrastructure would be required. Ethanol is currently used in niche applications (public transportation). Methanol and dimethyl-ether would require new engines and also consensus within industry and government, before this can be developed as an automotive fuel. Therefore it is unlikely that these fuels will be used in the foreseeable future.

### *Diesel engines: effects of biofuels on emissions towards 2020*

The most relevant emission components for diesel engines are $NO_x$ and particulates. In addition there can be some specific toxic components such as poly-aromatic hydrocarbons and derivatives.

For the influence of FAME (blends) on emissions, the majority of the available data is based on Euro2 and Euro 3 engines (up to 2005/2006). For truck engines the particulates emission show a decrease with increasing B100 percentage from 0% to -70% depending on the engine type. $NO_x$ showed an increase of between 0% and +30%. For passenger cars the variation was even larger with positive and negative effects for both $NO_x$ and particulates. The variations are caused by the variations in biofuel properties and engine technology. Because of the large emission variations and durability concerns for passenger car engines with diesel particulate filter, it is recommended to limit the biodiesel (FAME) content for passenger cars to 7%.

For Euro IV and V truck engines and also future passenger car engines equipped with $deNO_x$ catalysts, there appears a risk of a steep rise in NOx emissions due to the impact of biodiesel. To prevent this some truck manufacturers provide special calibration software for the $deNO_x$ catalyst when biodiesel is used. To prevent $NO_x$ emission problems, it is advised to monitor $NO_x$ emission of vehicles using biodiesel extensively. The problem might be solved when closed loop $NO_x$ control systems are implemented (expected phase-in between 2008 and 2014).

Synthetic diesel fuels (blends) show a more positive picture. Generally reductions for both $NO_x$ and particulates are seen for passenger car and truck engines in the range between 0% and about 30%. There is however a small reduction in fuel economy and power output due to the lower (energy) density of the fuel. Also for future engines no negative effects are expected. It should be noted that with the general application of particulate filters with future diesel engines, particulate emission reductions of the engine itself become less relevant.

Summarizing it can be stated that implementing low blend biodiesel can lead to both positive and negative effects on PM and $NO_x$ emissions, in particular for higher blends. Synthetic (bio)diesel fuels will generally lead to emission reductions.

### *Overview of emission effects of biofuels*

In the tables below, a schematic overview is given of the various emission effects of biofuels discussed above.

Table 2 Effect of ethanol blends on petrol engines. Euro 3 and older based on experimental data. Expert view for Euro 4 and later.

| | | Euro 3 and older | Euro 4 | Euro 5 | Euro 6 |
|---|---|---|---|---|---|
| | | 2000 - 2005 | 2005 - 2009 | 2009 - 2014 | > 2014 |
| NOx | E5 | NOx - 50% to + 50% | NOx variations possible | NOx variations within limits possible | |
| | E10 - E20 | NOx - 50% to + 100% | NOx large variations possible | | |
| | E40 - E85[1] | NOx - 50% to + 300% | NOx large variations possible | NOx variations within limits possible | |
| HC | E5 | HC - 40% to + 30% | HC variations possible | HC variations within limits possible | |
| | E10 - E20 | HC - 40% to + 40% | HC variations possible | | |
| | E40 - E85[1] | HC - 40% to + 30% | HC variations possible | HC variations within limits possible | |

[1] FFV vehicle

Table 3 Effect of biofuel (blends) and synthetic diesel on passenger car diesel engines. Euro 3 and older based on experimental data. Expert view for Euro 4 and later.

| | | Euro 3 and older | Euro 4 | Euro 5 | Euro 6 |
|---|---|---|---|---|---|
| | | 2000 - 2005 | 2005 - 2009 | 2009 - 2014 | > 2014 |
| PM | B5 - B10 | PM - 20% to + 20% | PM - 20% to + 20%, no effect for vehicles with DPF | PM no significant effect | |
| | B20 - B100 | PM - 80% to + 40% | PM - 80% to + 40%, no significant effect for vehicles with DPF | PM no significant effect | |
| | pure XTL, HVO | PM reduction 0 - 40% | PM reduction 0 - 40%, no significant effect for vehicles with DPF | PM no significant effect | |
| NOx | B5 - B10 | NOx reduction 0 - 20% | NOx some decrease or increase possible | NOx decrease or increase possible with B10, probably no significant effect with B5 | |
| | B20 - B100 | NOx - 10% to + 20% | NOx - 10% to + 20% | | Risks of larger NOx variations with certain vehicle types |
| | pure XTL, HVO | NOx reduction 0 - 20% | NOx reduction 0 - 20% | | |

Table 4 Effect of biofuel (blends) and synthetic diesel on heavy-duty diesel engines. Euro 3 and older based on experimental data. Expert view for Euro 4 and later.

| | | Euro 3 and older | Euro 4 | Euro 5 | Euro 6 |
|---|---|---|---|---|---|
| | | 2000 - 2005 | 2005 - 2009 | 2009 - 2014 | > 2014 |
| PM | B5 - B10 | no significant effect | no significant effect | | |
| | B20 - B100 | PM reduction 0 - 70% | PM constant to some reduction | | no significant effect |
| | XTL, HVO | PM reduction 0 - 30% | PM constant to some reduction | | no significant effect |
| NOx | B5 - B10 | no significant effect | no significant effect | | |
| | B20 - B100 | NOx increase 0 - 30% | NOx some increase | NOx some increase or stable with special software or closed loop NOx control | NOx probably stable |
| | XTL, HVO | NOx reduction 0 - 20% | NOx reduction 0 - 30% | | NOx stable |

### *Conclusions and recommendations for government policy*

Based on the findings of this BOLK study, Table 5 shows the recommended (bio)fuels mix up to 2020.

Table 5 Recommended fuel mix up to 2020

| | Otto engines | Diesel engines |
|---|---|---|
| Main stream | ▪ E5 for main stream and old vehicles. Optionally E10.<br>▪ E85 for Flexible Fuel Vehicles | ▪ B5 or B7<br>▪ B20 – B100 for dedicated heavy-duty vehicles |
| Niche | CNG / biogas | E95 with ignition improver |

**1) Biofuels mix up to 2020; low blends for mainstream, high blends for niche applications. The Dutch 20% target is not recommended.**
The desired share of biofuel components up to 2020 can best be made up of low blends for main stream in combination with high blends for specific (captive) fleets of vehicles. For petrol engines E5 and optionally E10 is recommended for main stream, in combination with up to E85 for flexible fuel vehicles. For diesel engines B5 or B7 is recommended for main stream in combination with B20 to B100 for dedicated heavy-duty vehicles. This means that the 20% biofuel target that the Dutch government will be very hard to achieve. Having a different standard fuel than the rest of Europe would lead to complicated infrastructural, legislative and practical issues. With the above mentioned B5-7 and E5 blends only a reduction of 3-5% on energy content is feasible, which means that for an overall 20% energy share of biofuels around 15% of the replacement should be achieved with high percentage blends. Potential niche fuels for petrol engines are CNG or biogas and for diesel engines it is E95 with ignition improver (see table 5).

**2) Short-term emission effects: in general no win-win situation, large variability**
Based on the data and findings of this study, it cannot be concluded that biofuels can both decrease $CO_2$ emissions and lead to a significant and consistent reduction of atmospheric pollutants when applied in currently available engines. In other words, in general there is no win-win situation. Emission data show a large variability. For specific diesel engines types (especially Euro III and older truck engines) engine particulate emissions can be reduced with no or a small NOx increase. For Euro IV and V truck engines, special engine software is needed to prevent a (steep) rise in NOx emissions.
In the case of synthetic fuels (BTL, GTL) a consistent emission reduction is expected.

**3) Emission effects up to 2020**
Given that future diesel engines will be equipped with particulate filters and closed-loop NOx control, the impacts are in general expected to become insignificant. Major concerns however are possible incompatibilities between biofuels and the operation of advanced emission control systems. This requires further research. With Otto engines possible negative emissions impacts will disappear due to the implementation of low and high blend (E85 in Flex Fuel Vehicles) ethanol in the European emissions legislation.

**4) Emission legislation is the main tool for avoiding excessive emissions**
In order to avoid undesirable effects on exhaust emissions with the use of biofuels (blends) in general, the most important point is to implement the desired biofuels (blends) into the European emission legislation. Due to the long lead time of development of legislation and the life time of the vehicles it is necessary to plan for 20 years ahead. Even though a lot of work is currently being done, much more is required to avoid problems in the period from 2020 to 2030. Future emission legislation should not only refer to the type approval test as such but also to OBD[4]-requirements, durability and in-use compliance.

**5) Risk of excessive $NO_x$ emissions can be avoided by regulation**
Clear communication and (national) regulations can avoid undesirable side effects such as NOx increase with high blends biodiesel (B20-B100). Regulations that should be considered are:

- Type approval, in particular for Euro IV and V heavy duty engines
- Avoid usage of high blend biodiesel in passenger cars
- Monitoring of flex fuel vehicles with high blend ethanol.

**6) Synthetic diesel is promising from an emissions and engine durability point of view, but available quantities up to 2020 are expected to remain limited**
Further increase in biocomponents share without any adverse effects on vehicle durability and exhaust emissions is possible with the stimulation of synthetic diesel fuels (hydrotreated vegetable oil and biomass-to-liquid diesel fuels).

**7) Pre-introduction of EEV[5] or EURO VI will help**
Stimulation of heavy duty EEV vehicles or pre introduction of Euro VI vehicles before 2015 can likely improve air quality. These vehicles can be equipped with engines running on (bio)diesel fuel, CNG or ethanol.

### *Recommendations for future research*

Emissions of vehicles running on biofuels blends appeared to be strongly dependent on the engine technology, fuel composition and also driving behaviour. Future engine technology can lead to an even increased sensitivity towards fuel variations, due to the applied emission control devices. It is therefore recommended to extensively monitor emissions performance of future vehicles on a variety of biofuels (blends). Especially important are the monitoring of heavy-duty diesel vehicles on high blend biodiesel (FAME) and passenger car Flex Fuel Vehicles on high blends ethanol. It is also recommended to investigate the toxicity of the exhaust gases, since very little data is currently available and some studies reported increased emissions of certain toxic components or increased mutagenity related to the use of biofuels.
The emission measurement programs can be performed in cooperation with international platforms such as DACHNLS, IEA or EC.

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[4] OBD stands for On Board Diagnostics
[5] EEV stands for Enhanced Environmentally friendly Vehicle

Table 2 Shortlist of possible consequences of the use of biofuels

| **Aspect of biofuels** | **Consequence** |
|---|---|
| Biofuels not (yet) implemented in emission legislation | Emission may vary and exceed limits |
| Energy density is generally lower | Reduced driving range or increased tank size |
| Biofuels can contain impurities | Possible catalyst deterioration and engine fouling |
| Biofuels are more aggressive | Metals corrosion and deterioration of elastomers and coatings |
| Different boiling range, viscosity and stability | Engine oil deterioration |

# Contents

**Appendices**

# 1 Introduction

## 1.1 Objectives and context

Biofuels are an important option for achieving $CO_2$ emission reductions in the transport sector. In response to the European Biofuels Directive the Dutch government has set targets for the share of biofuels in the total fuel consumption for road transport, ranging from 2% in 2007 up to 5.75% in 2010. For the year 2020 targets up to 10 or 20% are being considered.

For biofuels not only greenhouse gas reductions are claimed, but also benefits with respect to exhaust emissions that affect local air quality. The impacts, however, are generally different for different fuels and available measurement results show a large scatter, with the spread in results often larger than the average of the measured impacts (see e.g. [Smokers 2004]). A complicating factor is that establishing reliable emission factors (average emissions of average vehicles under average driving conditions) for conventional vehicles on conventional fuels already requires advanced statistical analysis of a large amount of measurement results due to the very different emission behaviour of the various vehicle models on the market. Furthermore effects of using pure biofuels in vehicle emissions can not be directly translated into effects of biofuels blended into conventional fuels.

Knowledge of the impacts of the use of biofuels in road vehicles on atmospheric pollutants is important from the point of view of local air quality problems[6] as well as of emissions at the national level. The latter are regulated by means of National Emission Ceilings (NEC). Possible exhaust emission benefits of biofuels can create a win-win situation between air quality and climate policy, but conflicting impacts, i.e. trade-offs between impacts on air quality and greenhouse gas emissions are also possible.

Beginning of 2007 new and more ambitious climate policy targets have been declared at the European as well as national level. Many of the measures foreseen under these climate policies may have side effects on emissions of air pollutants. Some of these side-effects are still uncertain. For the Dutch Ministry of VROM knowledge of these side-effects is important input for the determination of new National Emission Ceilings which are being prepared for the year 2020. This knowledge is also relevant for the local air quality policy that aims at meeting European standards in 2015.

For this reason the Ministry of VROM has initiated the BOLK programme[7], which is co-ordinated by the Netherlands Environmental Assessment Agency MNP. Besides biofuels for road transport the technologies evaluated in this programme include application of biomass in stationary energy generation systems and $CO_2$ capture and storage. In the BOLK programme TNO and CE Delft together evaluate the Tank-to-Wheel (= exhaust) emissions resulting from the use of biofuels in road transport. Well-to-tank emissions in the energy supply chain for biofuels are evaluated by Ecofys.

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[6] European Air Quality Directive, Nationaal Samenwerkingsprogramma Luchtkwaliteit - NSL

[7] Beleidsgericht Onderzoeksprogramma Lucht en Klimaat 2008-2009

Whereas the focus of the BOLK programme is on the longer term, i.e. emission impacts of biofuels applied in the 2015-2025 period, SenterNovem is interested in the short term emission impacts of biofuels and a range or other available alternative fuels. TNO has investigated these impacts on the basis of an extensive review of available literature.

This report combines the results of work carried out under the BOLK programme as well as the contract with SenterNovem. The biofuels project under the BOLK programme, as reported here, is to be considered as an inventory phase. Based on the results described in this report a more in depth assessment of remaining issues is expected to be carried out in a second phase of the programme between May 2008 and December of 2009.

## 1.2 Structure of this report

Chapter 2 of this report sketches the state-of-the-art and overall developments in the field of conventional, fossil fuels and biofuels. A similar picture for conventional engine and exhaust aftertreatment technology is sketched in chapter 3. Chapter 4 assesses dedicated fuel-engine combinations that are under development.

Based on conclusions from Chapters 2 to 4 one can draw conclusions concerning biofuels that are likely to be used in short and longer term future. This is especially relevant to narrow down the work for the assessment of longer term impacts on emissions from the use of biofuels as reported in chapter 6.

Results of the study for SenterNovem on impacts of biofuels and other alternative fuels on emission of vehicles with currently available engine and aftertreatment technology are presented and discussed in chapter 5. Possible impacts of biofuels when applied in vehicles that may be on the market in the 2015 – 2025 timeframe are assessed in chapter 6. Conclusions from both projects are summarised in chapter 7, while chapter 8 contains recommendations for future work, including the possible set-up of an international measurement programme to improve practical knowledge of the emission impacts of biofuels and to provide experimental data that can serve as input for emission factor modelling.

Note that abbreviations are listed in Appendix A.

## 1.3 Literature

| | |
|---|---|
| [Smokers 2004] | Smokers, R.T.M. and Smit, R. (2004), *Compatibility of pure and blended biofuels with respect to engine performance, durability and emissions*, SenterNovem report nr. 2GAVE04.01. |

# 2 Developments in conventional fuels and biofuels

## 2.1 Introduction

The current biofuel market in the Netherlands consists mainly of biodiesel (FAME), bio-ethanol and ETBE, with a small share of pure plant oil (PPO) in a number of niche applications. Biodiesel, bio-ethanol and ETBE are mainly sold as blends with conventional fuels; PPO is used as a pure fuel. However, in view of the R&D efforts currently ongoing that are aimed at developing better and cheaper biofuels for the future, it can be expected that other types of biofuel may enter the Dutch market in the next 10 to 15 years. Furthermore, due to the increasing biofuel targets set by both the EU and the Dutch government, it can be expected that the percentage of biofuels blended into conventional fuels will in-crease during that period, as will probably the market share of pure biofuels (100%) or high percentage blends (e.g., E85).

This chapter provides an overview of the state-or-the-art and expected future developments with respect to conventional and biofuels. It starts with an overview of the current types of biofuel available and of the various biofuels under development that might enter the market in the next 10 years. We will also try to assess the most likely types of biofuels and biofuel blends that will be for sale in 2020. This analysis is based both on literature, expert knowledge at CE Delft and TNO and on interviews with experts.

## 2.2 Characteristics of current conventional fuels

In the assessment of the suitability of biofuels for use in combustion engines and of their impacts on exhaust gas emissions the properties of these fuels, both as neat fuel and blended into conventional petrol and diesel, play an important role. Fuel properties are measurable physical and chemical characteristics of the fuel. An overview of the definition of some relevant fuel properties is given in Annex B. When looking at impacts of biofuels on engine operation and emission often fuel characteristics are compared to those of conventional petrol and diesel.

Specifications of existing conventional fuels are governed by international standards and European legislation. Tables with standard specifications of conventional fuels are included in Annex C. The actual properties of the conventional and alternative fuels, which are assessed in this report, are listed in Annex D.

## 2.3 Developments in conventional fuels

Important developments in conventional fuels for road vehicles over the last decade include a strong reduction in sulphur content as well as reductions in aromatics content. According to European legislation union[8] sulphur levels must be lower than 10 mg/kg (10 ppm) fuel for both diesel and petrol by 1 January 2009. A first reduction step was taken in 2000 (petrol S < 150 ppm, diesel S < 350 ppm), and a second step by 2005 (petrol and diesel S < 50 ppm). Due to government incentives the actual delivery of low sulphur fuel is generally a few years ahead of the formal requirement.

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[8] See: http://europa.eu/scadplus/leg/en/lvb/l28077.htm

According to EN590 the poly aromatic hydrocarbons content of fuels must be below 11 % (m/m) for all three sulphur content levels on the market (350, 50 and 10 ppm).

A more recent trend has been the introduction by various fuel producers of new premium petrol and diesel fuels, whereby some of the premium diesel fuels (e.g. Shell V-Power) contain GTL components.

## 2.4 Proposed changes in the Fuel Quality Directive

### 2.4.1 *Introduction*

The quality of the fuel distributed in Europe is currently regulated by EU Directive 98/70/EC. The community strategies on air quality and on climate change require that higher volumes of biofuels are used to replace fossil fuels, in order to reduce greenhouse gas emissions from transport. Since the current directive contains fuel quality demands that conflict with the use of certain biofuel types, a proposal for amendment was introduced to enable the use of biofuels. At the same time this proposal sets environmental and health requirements to prevent that the introduction of biofuels introduces other adverse effects. The proposal is also meant to reduce the emissions of particulate matter, mainly by reducing the maximum allowed sulphur content in the fuel. The main changes introduced by the proposal will be described in this paragraph.

### 2.4.2 *Reviewed documents*

The relevant documents that have been reviewed are the following:

- COM (2007) 18 final: Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and the introduction of a mechanism to monitor and reduce greenhouse gas emissions from the use of road transport fuels and amending Council Directive 1999/32/EC, as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC, 31-1-2007 [EC 2007a].
  - This document is not a fully revised directive. It only lists the amendments to the original text of Directive 98/70/EC. The objectives are clarified in the introduction.
- SEC(2007) 55: Commission Staff Working Document “Impact Assessment of a Proposal for a Directive of the European Parliament and of the Council modifying Directive 98/70/EC relating to the quality of petrol and diesel fuels”, 31-1-2007 [EC 2007b].
  - This document accompanies the proposal for changes to the FQD, and forms a basis for most of the proposed changes.
- Final rapporteur report, Committee on the Environment, Public Health and Food Safety, Rapporteur: Dorette Corbey, 6-12-2007 [Corbey 2007].
- Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on the type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and 6) and on access to vehicle repair and maintenance information, 20 June 2007 [EC 2007c].

### 2.4.3 *Directive structure*

Apart from Directive 98/70/EC, there are some other directives that involve fuel quality. For completeness, these are identified here:

- Directive 2003/17/EC is amending Directive 98/70/EC, however this mainly concerns some changes to the allowed sulphur content in the fuel.
- Before Directive 98/70/EC entered into force, the fuel quality was regulated by Directive 93/12/EEC. It was almost completely revised by Directive 98/70/EC, except for one article. With the new proposal this old directive will be fully replaced.
- Directive 1999/32/EC also specifies fuel quality, but this is restricted only to ships on inland waterways.

### 2.4.4 *Proposed changes to the fuel quality directive*

As an introduction to the document with the proposed amendments, the main changes are described together with the motivation. The most relevant changes for this study (in the wording of the proposal) are:

- The mandatory date for a maximum of 10ppm sulphur in diesel is confirmed as 2009. This will result in lower pollutant emissions, primarily particulate matter, as well as facilitating the introduction of other pollutant control equipment and provides certainty to industry.
- The maximum poly aromatic hydrocarbon content in diesel will be reduced to 8% from 2009. This might result in a reduction in particulate matter and poly aromatic hydrocarbon emissions; however the level and date have been chosen to ensure that there will be no cost from the change proposed.
- To enable a higher volume of biofuels to be used in petrol, a separate petrol blend is established with higher permitted oxygenate content (including up to 10% ethanol). For the same reason, the vapour pressure limit is increased for petrol blended with ethanol. All blends available on the market will be clearly labelled. These changes will facilitate development of the biofuel market while avoiding the possible risks of damage to existing vehicles. Higher emissions of volatile organic compounds will be controlled by collecting emissions in petrol stations for all fuels. The Commission will bring forward a proposal for mandatory introduction of filling station vapour recovery in 2007.
- A mandatory monitoring of lifecycle greenhouse gases is introduced from 2009. From 2011 these emissions must be reduced by 1% per year. This will ensure that the fuel sector contributes to achieving the Community's longer term greenhouse gas reduction goals and parallels efforts on improving vehicle efficiency. It will also stimulate further development of low carbon fuels and other measures to reduce emissions from the production chain.
- The permitted maximum vapour pressure for ethanol blends has been changed in order to allow the biofuels industry to develop in the early years. However, as base petrol could be manufactured to allow a higher content of biofuels and ethanol with a lower vapour pressure, oil companies have been invited to develop these blends also in Europe. When this lower vapour pressure base petrol is available in sufficient quantities, the vapour pressure limit might be reviewed.

More concretely, the following is proposed to achieve these objectives:

- The vapour pressure limit for ethanol blended fuel is increased from 60 to 70 kPa for those member states that experience arctic or severe winter conditions. For the summer period the vapour pressure may also exceed the 60 kPa limit, depending on the ethanol content (since the relation between ethanol content and vapour pressure is non-linear, see e.g. Annex D.4).
- As of January 2009 member states are obliged to report on the fuel use related emissions of greenhouse gases, taking into consideration the whole lifecycle of the

fuels. Between 2011 and 2020 an annual emission reduction of 1% has to be achieved. The reported greenhouse emissions (per unit of energy) in 2020 may not exceed 90% of the reported value for 2010.
- Demands to the fuel quality of so-called ‘high biofuel petrol’ are defined separately (refer to Annex V of the proposal). This fuel specification allows for a maximum ethanol content of 10% v/v (3.7% m/m as maximum oxygen content).
- Important pre-requisite for the allowance of biofuels to the market is that this may not lead in any way to an increase of negative health or environmental effects. To serve this obligation, the Commission shall by no later than 31-12-2012 deliver a report that will address a.o. this requirement. Every three years after that, an updated report will be published. If necessary, these reports may be accompanied by a proposal for amendment of the directive.

Draft regulation [EC 2007c][9] specifies the (proposal for a) revised fuel quality of reference fuels. In Annex IX the reference petrol fuel for type approval testing is specified to have a volumetric ethanol content of 5% (E5), while the diesel reference fuel needs to contain 5% FAME (B5). For flexible fuel vehicles also other reference fuels are specified (E85 and –provisionally– E75, NG/Bio-methane G20 and G25).

### 2.4.5 *Impact assessment*

An Inter Service Group was established in April 2006 to prepare the Impact Assessment that would accompany the proposal for changing the fuel quality directive. The Directorate generals AGRI, ECFIN, ENTR, JRC, SG, SJ, TREN participated in the group. Important recommendations of this assessment are the following:
- In contrast to the EN590, no limit on the maximum FAME content in biodiesel is set.
- There is no need to define quality specifications for hydrogen, emulsion fuels and DME.
- The PAH content can be lowered from 11% to 8%.
- The maximum allowed ethanol content is 10%. This is to limit car emissions and ensure fuel compatibility with the existing vehicle fleet. Ethanol is incompatible with some vehicle fuel systems, so a fuel that contains ethanol can only be permitted as a separate blend for compatible vehicles. Since $NO_x$ emissions may rise for vehicles on a high oxygenated fuel, the maximum ethanol level is limited to 10%.
- It is undesirable to make an exception for a higher vapour pressure to allow the blending of ethanol, since this is not technologically neutral. Since ethanol suppliers are in direct competition with both ether suppliers (e.g. ETBE) and other biofuels, this would de facto favour one production pathway over others.

These recommendations have largely been followed in the proposal. The only remarkable exception is the last point, on the higher allowed vapour pressure for ethanol blends. The consultants estimated that an ethanol blend that meets the 60kPa requirement by extracting the volatile components from the base fuel would increase the production costs by 0.14 €cents per litre. There are also indications that the total cost to fuel suppliers of using ETBE as a route for incorporating ethanol in petrol is lower than direct ethanol blending. A major factor in this may be because ETBE has a higher value as a blending component and creates fewer constraints in distribution.

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[9] See Annex IX of the document that can be downloaded from:
http://ec.europa.eu/enterprise/automotive/catp_meetings/agenda91/euro_5_and_6_comm_regulation.pdf
See also Annex C.6.

### 2.4.6 *Issues and positions*

There are questions concerning the claimed target of reducing 10% of the fuels' lifecycle greenhouse gases by this proposal, especially since there is also other existing or upcoming legislation to reduce $CO_2$ emissions or to encourage the use of biofuels and other renewables. Issues surrounding this 10% target are:

- How should efforts of fuel suppliers to cut greenhouse gases before 2011 be accounted for?
- The 1% per year target is seen as overly rigid. Alternatively this could be achieved in a more flexible way by two five year stages with an interim goal of 5%, or by a 2% reduction every 2 years.
- The fuel suppliers and oil producers fall under the EU Emissions Trading Scheme, which is already an incentive for them to cut greenhouse gases, so some argue that no further legislation would be needed. Furthermore, less than 15% of the fuel related greenhouse gases is associated with the fuel production, while the remainder is produced by using the fuel. On the other hand, this proposal sets an absolute target, while fuel suppliers can also decide to purchase emission rights in the ETS. Therefore, both obligations seem complementary, not contradictory, but there might be some overlap.
- There are also those that embrace the 10% target as an alternative for the requirement of 10% biofuels by 2020. They claim that this requirement gives too much weight to the biofuels path, while a $CO_2$ reduction may also be obtained by improving vehicle technology, or by employing other energy sources (e.g. green electricity). A $CO_2$-based target would therefore be more technology-neutral.

Various stakeholders have expressed the following concerns[10]:

- There are concerns that quantitative targets for the amount of biofuels alone could encourage fuel suppliers to invest in cheaper but environmentally harmful biofuels. Dutch Socialist MEP Dorette Corbey says legally-binding criteria on how biofuels must be made should be included in the directive. Others have questioned if the fuel quality directive is the right place for such criteria.
- On November 27th 2007, Parliament's environment committee approved a number of basic biodiversity and social criteria for this purpose, as well as the requirement that the life-cycle CO2 savings of biofuels would at least be 50% with respect to fossil fuels in order to be counted for the 10% target. However, these criteria are not yet into force, so separate criteria will be needed in the meantime to prevent the lifecycle reduction obligation causing unsustainable production of biofuels.
- The European Petroleum Industry Association Europia stressed the inconsistency between promoting higher quality fuels and biofuels on the one hand and the introduction of a lifecycle approach on the other, saying that such an approach would put highly-upgraded refineries, capable of more complex conversion techniques, at a disadvantage because they are often more energy-intensive, and that this would ultimately create a "perverse incentive" for the incomplete and inefficient conversion of crude oil.
- The European Bioethanol Fuel Association (eBIO) warned that this proposal may form a political barrier to the development of second generation biofuels. They explained: "Focusing solely on the greenhouse gas savings of biofuels leaves other sustainability concerns out of the equation. Biofuels with relatively high greenhouse gas savings, such as Brazilian bio-ethanol, are not necessarily produced in an environmentally sustainable manner." In order to address this situation, eBIO

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[10] see: http://www.euractiv.com/en/transport/review-eu-fuel-quality-directive/article-167990

believes the solution is to subject only fossil fuels, and not renewable fuels, to the 10% lifecycle greenhouse gas reduction goal. They also recommend including an obligation for the car manufacturers to raise the minimum capacity for biofuel consumption.

- The manufacturers association ACEA welcomed the lifecycle approach, since they feel that also the fuel suppliers should take their responsibility. They feel that until now the Commission has focused too much on the vehicle technology.

## 2.5 Presently available biofuels

### *2.5.1 Introduction*

The term biofuel covers a number of different fuels that may be produced from different types of biological feedstock (biomass). The biofuels currently on the market are often called “1st generation” biofuels, while a number of “2nd generation” biofuels are currently under development.

There is some confusion about the definition of these generations, but in most cases, 1st generation biofuels are considered biofuels that are produced from food crops, such as wheat grains, sugar beet, sugar cane, maize, rapeseed oil or sunflower oil. These biofuel products thus compete for their feedstock directly with the food industry, which has, in the past few years, caused price increases of several of these commodities.

The 2nd generation biofuels are generally produced from non-food biomass, such as woody biomass (straw, waste wood from forests, willow, miscanthus, etc.) and waste streams such as used frying fat or organic household waste. Especially the conversion of woody types of biomass into a high quality liquid fuel is technically more complex than conversion of plant oil or crops with high sugar or starch content. These biofuels are still in the R&D stage. The processes are currently being demonstrated, tested and improved in small scale production or test facilities. Biodiesel production from frying fat is already being done commercially. Contrary to what the terms 1st and 2nd generation biofuels may suggest, apart from ethanol, these new technologies are quite different from the current ones.

Biofuels are more expensive than their fossil counterparts, the current market is thus created and strongly determined by government policies. In response to the EU biofuels directive 2003/30/EC, the Netherlands started with large-scale biofuels policy in 2006. In that year, the fuel tax was reduced for biodiesel and ethanol/ETBE, and a number of PPO projects were granted tax exemption. This resulted in biofuel sales as shown in Table 3, replacing 0.3% of all petrol and diesel sales in 2006.

Table 3 Total biofuel sales in 2006 the Netherlands

| | million litres |
|---|---|
| biodiesel | 18.5 |
| bio-ethanol / ETBE | 30.1 |
| PPO | 2.3 |

Source: Rapportage over 2006 ingevolge artikel 4, eerste lid, van richtlijn 2003/30/EG ter bevordering van het gebruik van biobrandstoffen of andere hernieuwbare brandstoffen in het vervoer, VROM, 2007

From 2007 onwards, the tax exemption was replaced by a biofuels obligation, setting a minimum biofuels share for each year from 2007 (2%) to 2010 (5.75%). This will be discussed further in section 2.9. Actual sales data for 2007 are not yet available, but it is expected that the 2% biofuel obligation of that year has been met (for both biodiesel and bioethanol/ETBE) It is expected that these shares will increase further after 2010, up to 10 or 20% in 2020, though there is currently a lot of debate about the sustainability of current biofuels (mainly regarding greenhouse gas reduction and potential impact on biodiversity) and their effect on the global food market.

### 2.5.2 *Current biofuels*

The current biofuel obligation of 3.25% (in 2008) will most likely be met by bio-diesel (FAME) and bio-ethanol or ETBE, blended into conventional fuel (petrol and diesel) up to the limits the fuel specifications allow. These are currently the biofuels that can be produced and blended using well established processes. Biodiesel and bio-ethanol can be blended into diesel and petrol respectively, ETBE can replace the petrol additive MTBE. However, base fuel properties (i.e. the fossil components of the blends) need to be adapted to some extent when these fuels are blended, in order to keep the resulting blend within fuel specifications.

Current fuel specifications allow blending of up to 5% (by volume) biodiesel and bio-ethanol, and up to 15% ETBE in the standard petrol and diesel that is being sold. For 100% biodiesel separate specifications have been developed (see e.g. DIN EN 14214) In a recent proposal of the European Commission [EC 2008A], new fuel specifications are proposed for 7% and 10% biodiesel, in order to enable oil companies to meet the higher future biofuel targets. The 2007 proposal for changes to the Fuel Quality Directive, summarized in section 2.4, contains a proposal for specifications for the base fuel for a 10% ethanol blend.

These fuels can be produced from a wide range of biomass sources. Biodiesel requires plant oil as a feedstock, and is currently mainly produced from rapeseed oil in the EU, with some sunflower oil, soy oil and palm oil as well. The specifications of the final product depend on the plant oil used, and rapeseed has favourable characteristics to meet the standard.

In addition to these, a number of other biofuels can currently be produced that have not (yet) achieved a significant sales volume or market share, for various reasons. These biofuels are:

- pure plant oil (PPO) or virgin plant oil (VPO), mainly rapeseed oil in the Dutch situation. PPO can be used in adapted diesel vehicles. It can not be blended in diesel, and is thus only used as pure fuel. The Dutch government has awarded tax exemption for a limited number of PPO projects. These are now sold at a limited number of pumps, and used in dedicated (adapted) vehicles[11];
- biogas, from land fill sites, fermentation of manure or crops such as maize (the latter often in combination with manure);
- bio-methanol;
- ‘renewable diesel’, a diesel fuel produced with thermal hydrotreatment of either a mixture of diesel with plant oil, or of pure plant oil. Also referred to as HVO (hydro treated vegetable oil). As this option is not yet available in large quantities but does

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[11] For example, the road sweeping trucks of Venlo, Meppel and Leeuwarden have been adapted to use PPO (www.senternovem.nl/gave).

seem a promising candidate for the near and longer-term future, it is discussed in section 2.6 on “Future biofuels”.

In the following, a brief overview of the various biofuels is provided, describing the main feedstocks, conversion processes etc. More information on these processes can be found for example in [IEA 2004], [WI 2007] or [Refuel 2008].

### 2.5.3 *1st generation bio-ethanol*

Ethanol is currently produced from feedstock that contains sugar or starch. Currently, most ethanol is produced from sugar cane, sugar beet, wheat and corn. The ethanol is produced from the fermentation of sugar by enzymes produced from yeast. When sugar crops are used, the sugar first needs to be removed from the rest of the crop, after which it can be fermented. When cereals are used as feedstock, the starch first needs to be separated. After that it is converted to sugar (usually by enzymes), which is then fermented. The final step in both processes is purification of the ethanol, and removal of the water.

Bio-ethanol can be blended with gasoline. Most petrol cars in Europe can run on ethanol blends of up to 10%, but many car manufacturers withdraw the warranty if blends higher than 5% are used. An increasing number of car manufacturers now offer flex fuel vehicles (FFV) that can run on petrol with up to 85% ethanol. So far, only a very limited number of these FFVs have been sold in the Netherlands.

In the Netherlands, most of the ethanol consumed is produced from sugar beet and wheat. The price of ethanol from sugar cane from Brazil is lower than that of European ethanol, but import tariffs currently prevent large scale import of that ethanol here.

### 2.5.4 *Biodiesel / FAME*

Biodiesel, a term generally used for fatty methyl esters (FAME) is produced from oils or fats. The feedstock can be vegetable oils such as that of rapeseed, sunflower, soy, palm etc., used frying oil or animal fat. To produce biodiesel, the oil or fat needs to be filtered and pre-processed, after which it is mixed with an alcohol (usually methanol) and a catalyst, for transesterification. The characteristics of the biodiesel will depend to some extend on the type of oil or fat used as a feedstock.

The biodiesel can then be blended with diesel, or used as neat (100%) fuel in engines suitable (in many cases adapted) to run on neat biodiesel. Most conventional diesel engines can run on blends up to 10 or 20%, but not all car manufacturers provide warranty if blends higher than 5% are used. Blends above 20% often require modifications of the engine, since some rubber parts can be sensitive to the biodiesel.

In the Netherlands, most biodiesel is currently produced from rapeseed oil, but plans for a large palm oil biodiesel plant in the Rotterdam area are in an advanced stage[12].

### 2.5.5 *Biogas*

Biogas, upgraded to natural gas specifications, can be blended with natural gas, and used in CNG vehicles, as is currently done e.g. in Malmö, Sweden. In the Netherlands, biogas is not yet used in transport, mainly due to the very limited use of natural gas for transport and the costs involved. Biogas, however, is achieving more attention,

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[12] http://gave.novem.nl/gave/index.asp?id=25&detail=2020

especially in relation to the plans of several Dutch cities to apply natural gas in buses for public transport and to convert their municipal fleets to natural gas.

For application of biogas in CNG vehicles it is not necessary that the biogas is physically used in the vehicles. It is also possible to buy the biogas using green gas certificates, whereby the vehicles are fuelled with natural gas from the grid at the location of vehicle use, while the contracted biogas is mixed into the grid at the location of production.

### *2.5.6 Bio-methanol*

Bio-methanol can be produced through gasification, and has similar characteristics to ethanol. However, not much effort has been put in place to promote the production and use of bio-methanol, mainly because of its toxicity, aggressiveness to materials and low energy content. Car manufactures do not allow methanol in current vehicles.

It should be mentioned here that methanol might be a fuel for the longer term future, since it could be a suitable fuel for fuel cell vehicles. The methanol then needs to be reformed on-board to hydrogen.

## 2.6 Future biofuels

A number of different biofuels are currently under investigation or in the phase of pilot plants. Some of the R&D is directed at producing the current biofuels with different feedstocks, some R&D aims to develop new routes for use of the current feedstock, and other R&D efforts investigate new routes for the production of biofuels altogether:

- Probably the most well known R&D into existing processes but new feedstock is the development of ligno-cellulosic ethanol. This is ethanol produced from woody biomass, such as straw and grass, forest residues, etc.;
- For biodiesel, efforts are aimed at using algae as a feedstock, or plants such as Jatropha. R&D is mainly aimed at improving cultivation of the biomass, not at the production of the fuel itself (the technology is well known, also for these new feedstocks);
- BP is currently investing in the development of a process to produce bio-butanol, from feedstock such as wheat. Butanol is somewhat similar to ethanol, but has more favourable characteristics (closer to the properties of petrol), providing advantages both for the blending into petrol and for its use in the current car fleet;
- Fischer-Tropsch biofuel is another 2nd generation biofuel currently under investigation and testing. It can (in theory) convert a large range of bio-mass into a synthetic fuel (petrol, diesel, kerosene, etc). The technology of gasification and Fischer-Tropsch synthesis is proven technology for coal and gas (coal-to-liquid, CTL, and gas-to-liquid, GTL), but is still in the R&D stage (pilot plant) for biomass (BTL, biomass-to-liquid);
- One can argue that the ‘renewable diesel’, already mentioned in the previous paragraph, is also still in the R&D phase, since it is quite a new technology (although already in operation in a small number of refineries worldwide);
- In the Netherlands, efforts are also being directed at making the hydro-thermal upgrading process operational. The HTU process can use wet biomass as a feedstock, and produces a crude oil that can then be converted to diesel;
- Hydrous ethanol is ethanol with water content higher than the 1% seen as maximum in standard, anhydrous ethanol. It has the advantage that it does not require dehydration, saving cost and significantly reducing process energy use. In current

ethanol, the water is removed due to its immiscibility with gasoline – the water and gasoline separate. Research is currently ongoing to make blending possible, for example by the Dutch company HE Blends[13]. They report successful tests with ethanol/gasoline blends with up to 50% ethanol, where the ethanol has a water content of up to 10%.

Biofuels that can convert cellulosic biomass are often called 2nd generation biofuels. Cellulose based feedstock is much more resistant to being broken down than the feedstocks used today for biofuel production, but it has a number of advantages over the current types of feedstock: it can be cheaper, there is less competition with food, and the greenhouse gas emissions during cultivation of the feedstock are generally less due to lower fertiliser requirement. A number of companies throughout the world are therefore putting a lot of effort into investigating methods to convert this feedstock to a liquid biofuel. There are two primary pathways to pre process these cellulosic feedstocks: thermo-chemical and biochemical conversion (see for example [WI 2007] for a brief description of these routes). The first is typically used for the Fischer-Tropsch biofuel route, the latter for cellulosic ethanol production.

### 2.6.1 *Cellulose-based bio-ethanol*

Cellulose-based ethanol has exactly the same chemical composition and properties as current ethanol. The difference is in the feedstock, which may be any type of biomass with a high content of cellulose or hemicellulose, such as straw or other crop residues, grasses, trees, forestry waste, etc.

The cellulose first has to be converted to five- of six-carbon sugars via a process called saccharification. Various types of saccharification are currently being developed by different researcher institutions and companies: thermal, chemical and biological processes are being considered. The resulting sugars can then be fermented and distilled, with the use of specific organisms. In fact, research is also aimed at developing a combined process, “consolidated bioprocessing” (CBP) in which the saccharification and fermentation take place in one step, i.e. in one reactor. The lignin, the third major component of this type of biomass, can be used as an energy source, for example to power the production process.

There is currently no large scale commercial cellulosic ethanol production in operation, but various governments, most notably the US and Canada, attempt to speed up these developments with significant financial support.

### 2.6.2 *Bio-butanol*

Butanol can be produced from biomass by fermentation using the A.B.E. process[14]. The process uses the bacterium clostridium acetobutylicum. The process also creates a recoverable amount of $H_2$ and a number of other by-products such as acetic, lactic and propionic acids, acetone, isopropanol and ethanol. The difference from ethanol production is primarily in the fermentation of the feedstock and minor changes in distillation. The feedstocks for butanol are the same as for ethanol: energy crops such as sugar beets, sugar cane, corn grain and wheat as well as agricultural by-products such as straw and corn stalks. According to DuPont[15], existing bioethanol plants can cost-

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[13] http://www.heblends.com/

[14] See: http://en.wikipedia.org/wiki/Biobutanol

[15] See: http://www.dupont.com/ag/news/releases/BP_DuPont_Fact_Sheet_Biobutanol.pdf

effectively be retrofitted to biobutanol production. Currently also processes are under development to produce biobutanol using algae.

Butanol has significant advantages over ethanol:

- higher energy density
  - due to that higher blends possible in conventional engines
  - less impact on volumetric fuel consumption
- no segregation of water if blend falls below 10%
- lower vapour pressure
  - as a result no or less likely poisoning of carbon canister and thus less risk of increased evaporative emissions.

### 2.6.3 *"Renewable diesel" or hydrotreated vegetable oil*

"Renewable diesel" is a term mainly used in the US but production is increasing worldwide. It is currently being produced by ConocoPhillips in the US, by Petrobras in Brazil, and by Neste Oil, in Finland (see e.g. [WSDA 2007]). The first two use a process in which diesel is mixed with animal fat or plant oil, the latter uses pure plant oil as feed-stock and is known by the name of NExBTL[16].

NExBTL and other renewable diesels, also referred to as HVO (Hydro-treated Vegetable Oil), are produced in a vegetable oil refining process, which entails direct catalytic hydrogenation of plant oil. The plant oil triglyceride is converted into the corresponding alkane. As the glycerol chain of the triglyceride is hydrogenated to propane, there is no glycerol side stream. The process removes oxygen from the oil so that the resulting fuel is not an oxygenate. The resulting fuel has specifications very close to that of conventional diesel, so that it requires no modification or special precautions for the engine.

### 2.6.4 *Synthetic biofuel from the Fischer-Tropsch process*

Using the so-called Gas-To-Liquid (GTL) technology it is possible to produce liquid fuels from synthesis gas. This synthesis gas can be obtained by means of gasification from a variety of feedstocks including coal (coal-to-liquid, CTL), natural gas (GTL) and biomass (biomass-to-liquid, BTL). From the syngas diesel is produced using the Fischer-Tropsch (FT) process.

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[16] See e.g.: http://www.nesteoil.com/default.asp?path=1,41,539,7516,7522

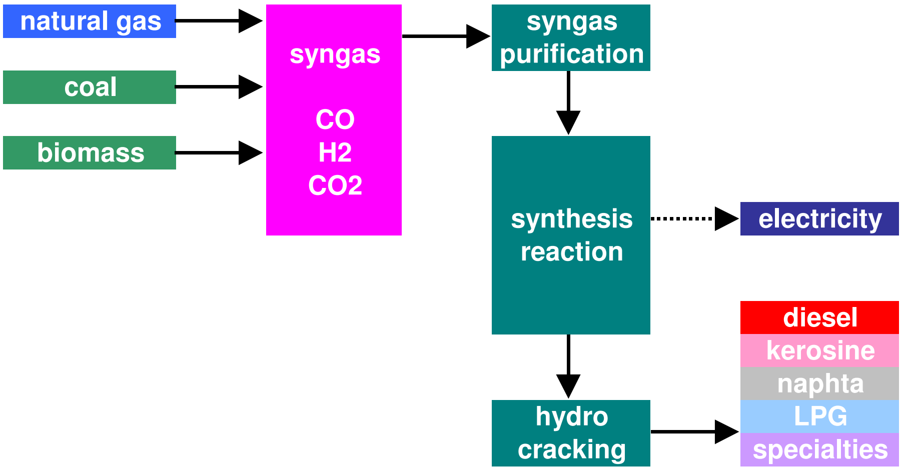

Figure 2.1 The Fischer-Tropsch process for production of synthetic fuels

The FT-process produces a mix of outputs with varying chain lengths. The composition of this mixture can be influenced by variation of process parameters. The maximum share of diesel in the output of the synthesis process is about 20%. A higher diesel share can be obtained by cracking of the higher alkanes in the mixture. The other outputs besides diesel, however, also have market value, e.g. as result of their high purity.

Synthetic diesel from the FT process is a premium fuel with zero sulphur and high purity.

### *2.6.5 DME*

Dimethyl ether (DME) is a gaseous fuel that can be produced from syngas from fossil sources, but also from a variety of biomass sources, including wood, waste and agricultural products[17]. It has been used for decades as a benign aerosol propellant, more recently its potential as an automotive fuel is being explored. Its vapour pressure is similar to LPG, and it can be contained as a liquid at relatively low pressure, but it requires special sealing materials in the engine (such as metal-to-metal sealing) since it dissolves most standard sealing materials used in the automotive industry.

DME can be used in both gasoline (30% DME/70% LPG) and compression ignition (diesel) engines. Research is mainly focussing on application in diesel engines, and optimisation of diesel engines to DME, because of their higher fuel efficiency and the emission benefits that the DME can provide. Road trials are ongoing to test its durability, performance and practicability [WI 2007].

DME production is not yet taking place at large scale, mainly due to the high cost (compared to CNG). Also vehicles with DME engine are not yet commercially available.

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[17] For more information on DME, see http://www.aboutdme.org

## 2.7 Chemical components and characteristics of biofuels

An overview of the characteristics of the biofuels discussed above is presented in Annex D. Recently proposed standards for higher percentage blends of ethanol in petrol and biodiesel in diesel are listed in Annexes C.4 and C.5.

## 2.8 Considerations regarding the impact of the production and distribution infrastructure on (bio)fuel characteristics

Not only the production but also various steps in the distribution and storage determine the properties of the fuel before it is used in the vehicle's engine [Kattenwinkel 2008].

In general the fuel industry is limited in the number of fuel grades it can handle. Offering multiple low-percentage blends (e.g. B10 next to B7 and E10 next to E5) is not preferred. Every additional grade introduces additional risks of contamination and resulting high damage costs. Niche fuels are also not preferred but generally easier to handle. These are often offered by smaller specialised companies.

Refinery products are made in batches. During transport and distribution these batches can not be fully separated. There will always be some level of mixing with other batches. ”Empty” fuel storage tanks usually still contain about 10% product so that transfer of a batch from one storage tank to another causes mixing. At a fuel producer's depot usually also “comingling” takes place with products supplied by third parties. Fuel producers make large efforts to properly manage and control distribution chains in order to guarantee that the product delivered to the customer meets the expected/required specifications.

In the distribution and storage of ethanol and ethanol/petrol blends the following aspects require attention:

- Ethanol and ethanol/petrol blends are hygroscopic. Water in the fuel can cause corrosion and may lead to segregation;
- Terminal blending of ethanol is considered best practice. This eliminates water sensitivity issues in the refinery and the primary distribution system. Pipeline shipment of ethanol/petrol blends is usually not practical because of the risk of water pickup. Terminal blending also allows better control of the blending ratio;
- To keep the vapour pressure within the allowed specifications a low vapour pressure base fuel is necessary;
- One must ensure that all materials in the distribution system are compatible with ethanol. It is recommended to add a corrosion inhibitor to the ethanol.

In the distribution and storage of biodiesel and biodiesel/diesel blends the following aspects require attention:

- The low temperature properties of biodiesel may cause segregation of the fuel and filter plugging.
- Ideally blending should be carried out at the refinery into warm product run-down to ensure thorough mixing and dissolution of cold flow additives. Terminal blending requires special precautions. The base diesel (DBOB) may need cold flow quality margin to ensure that the finished blend meets EN590 climatic requirements. Cold flow additives may need to be injected. Splash blending into ships, barges, etc. is not recommended due to difficulties in guaranteeing homogeneity across all tanks. Also temperature conditions and the presence of

water can cause haze problems. Splash blending furthermore has poor cold flow additive mixing conditions and limited opportunity for thorough testing of finished blend;
- The stability of biodiesel is worse than that of conventional diesel. This gives problems with long term storage. Fuel may furthermore oxidize in the vehicle's fuel tank.

## 2.9 Policy and legislation for biofuels

### *2.9.1 EU legislation and policy*

In 2003, the EU agreed on directive 2003/30/EC, on the promotion of the use of biofuels or other renewable fuels for transport. This directive states that Member States should ensure that a minimum proportion of biofuels is placed on their markets, and set indicative targets for 2005 and 2010, namely 2% and 5,75% respectively. This directive is the main driver for all recent biofuels activities in the EU.

In 2007, the European Council decided on a 10% biofuel target for transport in 2020 (subject to production being sustainable, second-generation biofuels becoming commercially available and the fuel specifications being amended accordingly to allow for adequate levels of blending (SEC(2008) 85/3 [EC 2008b]. The European Commission therefore recently published a proposal for a binding biofuel target of 10% in 2020, in the EU (COM (2008) 19 final [EC 2008a]). This proposal also sets out a route to enable the sales of higher percentages blends, by:
- defining diesel fuel specifications for 7% and 10% biodiesel/diesel blends
- obliging Member States to ensure that diesel fuel complying with the 7% specifications is made available by 31 December 2010, in filling stations with more than two pumps that sell diesel fuel
- obliging Member States to ensure that diesel fuel complying with the 10% specifications, or other diesel fuel with at least 5% biofuel content by volume, is made available by 31 December 2014, in filling stations with more than two pumps that sell diesel fuel

It also aims to promote second generation biofuels, by stating that biofuels produced from wastes, residues, non-food cellulosic material, and lignocellulosic material shall be considered to be twice that made by other biofuels. In the next months, this proposal will have to be discussed by the EP.

### *2.9.2 Biofuel strategy in the Netherlands*

In the Netherlands, specific biofuel targets have been set for the coming years, as shown in Table 4 (% by energy content). It is expected that these targets will be met mainly by blending biodiesel into diesel, up to the maximum currently allowed in the diesel fuel specifications (for both petrol and diesel, a maximum of 5% by weight is allowed), and by blending ETBE or ethanol into petrol. These routes require the least modifications to the current fuel infrastructure, and they do not require changes to the car park (i.e., dedicated vehicles).

Table 4	Required content (energy base) on macro scale of biofuel in petrol and diesel in The Netherlands

| | Minimum share | | |
|---|---|---|---|
| | in the total amount of fuels sold for road transport | in petrol | in diesel |
| 2007 | 2% | 2% | 2% |
| 2008 | 3,25% | 2,5% | 2,5% |
| 2009 | 4,5% | 3% | 3% |
| 2010 | 5,75% | 3,5% | 3,5% |

Source: Besluit Biobrandstoffen, Staatsblad, 2006

In the future, the biofuel targets are expected to rise further, which will lead to either higher biofuel blend percentages or dedicated biofuel vehicles. As mentioned above, the EC has recently proposed to set an obligatory minimum target of a 10% share of energy from renewable sources in transport, in 2020, for each Member State. The Dutch government may even go further than this, since it announced in 2007 that it will investigate whether a 20% share is feasible in 2020 (VROM, Schoon en Zuinig, 2007).

### 2.9.3 *Biofuel strategies in other EU member states*

Some European countries had implemented biofuels policies prior to the EU directive 2003/30/EC, but most EU Member States set their own biofuels targets, and implemented policies in the past few years. Policies vary strongly from country to country, ranging from subsidies for biofuels producers, to fuel tax exemptions, to biofuels obligations[18]. It is currently not expected that the target of 5.75% will be met in all EU Member States in 2010; Eurobserver predicts a biofuel share of about 4.2% in 2010 within the EU [Eurobserver 2007]. However, biofuel production and consumption have clearly increased strongly within the EU in the past years (the biofuels share was only about 1% in 2005), and the growth is expected to continue, as is shown in Figure 2.2.

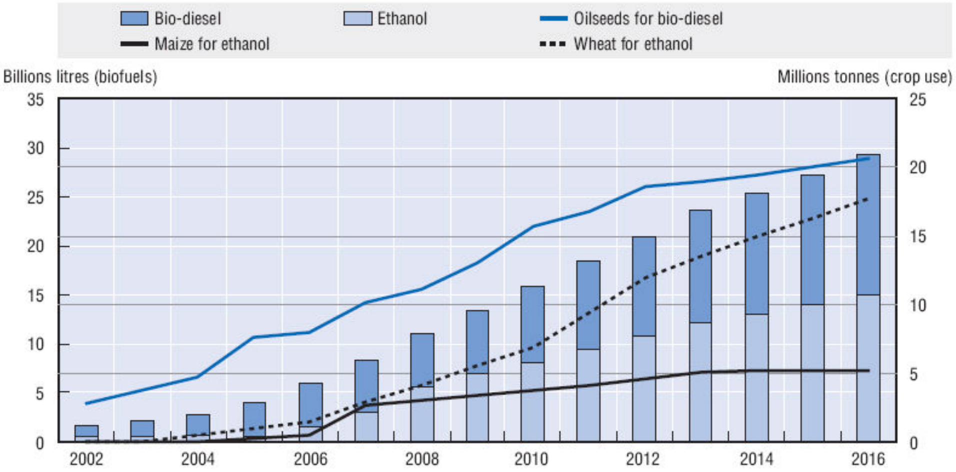

Figure 2.2	Ethanol and bio-diesel use in the EU – historic trends and future prognosis [OECD 2007]

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[18] Details about the policies and targets adopted in the various EU Member States can be found at http://ec.europa.eu/energy/res/legislation/biofuels_members_states_en.htm

*Note:* Ethanol and bio-diesel data before 2006 refer to production, from 2006 to 2016 to consumption.

### 2.9.4 *Biofuel strategies worldwide*

Brazil was the first country worldwide to adopt a biofuels strategy, with an ambitious bioethanol program that was started in the 1970s (using sugar cane as feedstock). This has resulted in Brazil being the world's main biofuel producer, and production is still increasing now that the global demand is growing.

More recently, ambitious biofuels targets and policies are also adopted in many other countries worldwide, in all continents [WI 2007]. In the US, for example, the Renewable Fuels Standard (RFS) was adopted as part of the Energy Policy Act of 2005. The RFS adjusts fuel standards in favour of ethanol and other biofuels, provides tax incentives for E85 refuelling stations, and sets increased mandated biofuel consumption quantities. Most biofuels currently produced and consumed in the US is ethanol from corn, although recent policies are also aimed at increasing the consumption of biodiesel. In addition, the research, production and consumption of new types of biofuel (mainly cellulosic ethanol) are explicitly promoted by the US policies. Many Asian countries, including China, India and Japan, have now also set biofuel targets and implemented biofuel policies such as tax exemptions.

### 2.9.5 *Pure versus blended biofuels*

There are a number of options to meet a future obligation of up to 10 or 20% biofuels:

- First of all, there is uncertainty about what types of biofuel will be available on the market in 2020, and at what cost. This will depend on issues such as supply and demand of the feedstock and technological developments of the various biofuels currently under development. But also on policies such as support for 2nd generation biofuels, import tariffs for non-EU biofuels, sustainability criteria, support for flex fuel vehicles or other types of policies to enable the sales of high percentage blends, etc.
- Secondly, it is as yet uncertain whether these higher shares will be achieved by large-scale blending of these percentages of biofuels in the general fuels sold, or if part of the fuel market will remain low blends or pure fossil, and a separate vehicle market develops that tanks very high percentages of biofuels, such as 100% biodiesel or E85. This depends on cost of blending vs. pure biofuel distribution, but also on the characteristics of the biofuels available in 2020 and the characteristics of the 2020 vehicle park. The latter two issues determine whether there are any technical limitations to use high percentage blends in the whole vehicle park, or whether separate fuel/vehicle systems need to be set up. Government policies may also be a strong determining factor in this, for example through promotion of E85 and/or B100 vehicles or vehicle regulation, or through promoting biofuels with properties similar to current fossil fuels.

### 2.9.6 *Sustainability criteria for biofuels*

Now that the global biofuels demand has grown significantly in a relatively short period of time, it is broadly recognised that there are several sustainability issues that need to be addressed. For example, some specific biofuels are found to emit more greenhouse gas emissions than the fossil fuel they replace (using a life cycle analysis approach). NGOs and scientists have draw attention to the destruction of rain forest to convert the area to oil palm plantations, and prices of commodities such as corn and cereals are found to increase significantly, creating serious problems for the poor that depend on these food products.

The Netherlands, the UK and Germany have therefore tried to develop sustainability criteria for biofuels. In the Netherlands, these efforts have led to a report by the commission Cramer, in which sustainability criteria for biomass were proposed (to be applied for both biofuels and bio-energy). As a follow up, $CO_2$-tools were developed with which the greenhouse gas emissions of specific feedstock-to-biofuel and bioenergy chains can be calculated. In line with these developments, the EU has recently included a number of sustainability criteria in the proposal on the promotion of renewable energy [EC 2008a].

Implementation of ambitious sustainability criteria can be expected to limit the biofuels supply, since some of the current feedstocks or biofuels on the market may be excluded. They may also increase the cost of the biofuels on the market, due to scarcity and perhaps also due to higher production cost of sustainable versus unsustainable biofuels. This may lead to the EU (or its Member States) setting lower targets.

Another effect may be that some types of biofuels are excluded. One of the main criteria in the proposal is the requirement that biofuels must achieve a minimum GHG reduction (well-to-wheel). In the proposal, this minimum is set at 35%, and one might expect that this minimum may increase in the future. If it is increased above about 60 or 70%, it may be very difficult for first generation (current) biofuels to meet this target. This will result in much higher shares of biofuels from waste or cellulosic feedstocks, compared to the situation without this criterion.

It is too early to draw any definite conclusions about the impact of these criteria (and the broader sustainability discussion currently ongoing) on the future biofuels volumes and types. The discussion on the exact definition of the criteria is still ongoing, and we would expect that biofuel producers may find ways to reduce the GHG emissions (and sustainability in general) of the current biofuels once these criteria have to be met. In more general terms we can conclude, however, that these developments will lead to increased efforts into R&D and market implementation of biofuels from waste and lignocellulosic biofuels (i.e. into Fischer-Tropsch and cellulosic ethanol). We would also expect that the proposed target of 10% biofuels in 2020 [EC 2008a] will not be exceeded, and may even be lowered in the coming years.

## 2.10 Economic viability of biofuels

Besides criteria with respect to e.g. applicability in various engine types and Well-to-Wheel greenhouse gas reductions the economics of various biofuels will be a decisive factor fir their future success. For users these economics are mainly related to impacts on fuel costs. For governments the economics of various options, together with their Well-to-Wheel greenhouse gas reductions, also determine the $CO_2$ abatement costs, i.e. cost effectiveness of biofuels with respect to greenhouse gas emission reduction.

Cost effectiveness of biofuels will strongly depends on the policies applied to promote biofuels, the scale of production and the associated cost developments and the price of oil.

If insight in the economic viability turns out to be crucial for the determination of the most likely fuels to be considered for the 2015 – 2025 period, this aspect may be studied in more detail in the follow up of this project. For the moment, however, the hypothesis is that not cost but policy will be the main determinant for the choice of specific biofuels.

## 2.11 Fuel industry perspective

From the perspective of the fuel producing industry the choice of biofuels is determined by yet different criteria. For this industry also considerations regarding system integration, system efficiency and value of by-products are important.

Transport fuels form about 50% of the end product output of a refinery [Kattenwinkel 2008]. This includes petrol, diesel, kerosene and heavy fuel oil for shipping. The shares of different fuel outputs can be varied by changing the refinery process design, by varying process parameters and by treatment of initial refinery products (e.g. cracking of heavier fractions into lighter fractions). Every refinery has its optimum fuel output mix and changing this mix goes at the expense of overall efficiency. Over the last decade, however, the demand for diesel has sharply increased in Europe due to the increased popularity of passenger cars with DI diesel engine. This has resulted in a diesel shortage in Europe. At the same time the US has a petrol shortage and diesel surplus, resulting in a vast amount of fuel trading and transport between Europe and the US. The diesel shortage in Europe makes that European fuel producers are more interested in biofuels that can be blended with or replace diesel then in alternatives for petrol.

From a system perspective it may furthermore become interesting to integrate biomass feedstocks into the conventional refinery process. At the moment this option would not yield biofuels that would be acknowledged as such in relation to the biofuel share obligations under the Biofuel Directive because in the output of a refinery that uses fossil and biomass feedstocks it is not possible to label which share of the various fuel outputs is biofuel. The objective for 1% p.a. reduction of lifecycle $CO_2$ emissions, as included in the recently proposed amendment of the fuel quality directive, would allow this option to be accounted for as a $CO_2$ reduction technology.

Further details of considerations that are relevant for the choice of biofuels from an industry perspective may be investigated in the follow-up of this inventory project.

## 2.12 Drivers for the fuel mix for the future

Some considerations on drivers that determine the future fuel mix are discussed below.

The fuels that will play a role for transportation in the future will depend on a number of market drivers. These drivers generally originate from the industry, who tries to negotiate favourable conditions for these fuels from the government. These favourable conditions can include (with existing examples):

| | |
|---|---|
| – fuel tax exemption | CNG, biogas, LPG |
| – financial support for infrastructure | CNG, biogas |
| – financial support for vehicles | CNG, biogas (LPG) |
| – direct support for R&D programs | $H_2$ |

The government (EU and/or national government) is giving this support because they believe that a fuel is important from e.g. an economic or environmental point of view. The car industry basically makes available those products of which they believe that they can be sold for a number of years and which might contribute to a positive brand image.

The drivers for a number of fuels are presented in Table 5. It can be concluded that government support or legislation plays a key role for many fuels. Without government support, there would not be many LPG and CNG vehicles and the quantity of FAME and ethanol used would only be a fraction of what it is now. The question is: is the government supporting the fuels, which can really play a significant role in the future? That means: will there be sufficient quantity, with good environmental impact and costs and will the costs of infrastructure and vehicles be competitive?

Table 5 Overview of drivers for several fuels

| **Fuel** | **Drivers** |
|---|---|
| FAME, ethanol, ETBE | It is available;<br>Push form agricultural sector;<br>Govern mandates min blend in standard fuel;<br>Pull from vehicle users / society. |
| Synthetic diesel: BTL, HVO (e.g. NExBTL) | Oil companies are positive, due to good compatibility with standard fuels;<br>Car industry is positive due to good compatibility with standard fuel. |
| Synthetic diesel: GTL | Push from oil companies;<br>Used as blend to upgrade standard fuel or as pure environmentally friendly fuel |
| Biogas, CNG (LNG), LPG | Government push: tax exempted, stimulation of infrastructure;<br>Push from (parts) supply industry;<br>Pull from vehicle users / society: low emissions image. |
| Butanol | Oil industry (BP). |
| Methanol | No strong drivers;<br>Proposed again by a few parties. |
| $H_2$ | Push from R&D industry;<br>Government financial support for R&D. |

Basically all possible fuels or energy carries should reviewed against a number of criteria. This is for example done by Volvo AB [Volvo 2008]. They proposed the following criteria:

| | |
|---|---|
| – climate impact: | well-to-wheel $CO_2$ reduction |
| – energy efficiency: | proportion of primary energy reaching the wheel |
| – land use efficiency: | driving distance per acre per year |
| – fuel potential: | availability of raw material |
| – vehicle adaptation: | complexity of adaptation of the vehicle to the fuel |
| – fuel costs: | costs of fuel including all distribution and handling costs |
| – fuel infrastructure: | impact and costs of a new fuel infrastructure |

Of course the criteria can be altered somewhat if desired, for example exhaust emissions can be included or combined with climate impact. Also safety can be added.

It can be concluded, however, that a multi criteria analysis would be necessary to decide on the best or most likely fuel options.

## 2.13 Conclusions

Assuming that the EU objective of 10% biofuels in 2020 will be upheld, there are a number of options regarding how these are then brought onto the market:
- The biofuels share will be increased further by gradually increasing the blend percentage in petrol and diesel up to an average 10% (by energy content). This requires further development of high-percentage blend specifications, in combination with large scale market introduction of vehicles that can run on these higher percentages biofuels
- The biofuel content of the ‘standard’ fuels sold will be kept low to prevent engine problems with the current car fleet. The remainder of the target is achieved by selling E85 and 100% biodiesel. This option requires that an increasing share of the car fleet can run on these neat or high-percentage blend fuels.
- New biofuels come onto the market that meet the current diesel and petrol specifications, and thus do not require any changes to vehicles or engines. Examples of these are the Fischer-Tropsch fuels from biomass, renewable diesel and butanol.

Very likely the future will be a mix of these 3 routes. For impact on emissions clearly the blending route is the most important option as this affects almost all vehicles in the fleet. Niche application of pure biofuels or high percentage blends can have significant impacts at the vehicle level but overall impacts on NEC emissions will only be significant if the amount of niche vehicles is large enough.

Clearly, both biofuels policies and technical R&D still leave quite some uncertainty regarding the types of biofuels one may expect to be on the Dutch market in 2020. Nevertheless, we can identify a number of possible biofuels on the market in 2020. A comprehensive overview of all potential biofuels currently known can be found in Table 6. Which biofuels will actually be on the Dutch market in 2020 depends on a number of developments:
- Government policies have created the biofuels market, and strongly determine its development. If, for example, stringent sustainability policies are put in place, and 2nd generation biofuels are strongly promoted, one can expect that 2nd generation biofuels (from waste streams and ligno-cellulosic biomass) will have a significant share in the biofuels market in 2020. Otherwise, 1st generation biofuels may still provide most of the biofuels on the market. If the government puts policies in place to promote biogas in transport, it could be possible that this gas may achieve a significant market share in the coming decade. The latter will also strongly depend on the development of the market for natural gas as a transport fuel.
- Government policies may also determine the way in which the biofuels are used. If fuel specifications are modified to enable large scale 10 of 15% blends on the market, the biofuel obligations will probably be met that way. Alternatively, if E85 and B100 vehicles are strongly promoted, the oil companies might rather meet their obligations by selling these high-percentage fuels to a part of the market.
- As there are a number of biofuels currently under development, technological developments may prove to be very important. If, for example, production of ligno-cellulosic ethanol becomes technically feasible, at reasonable cost, this fuel is expected to replace the current ethanol on the market. The same might hold for butanol or for biodiesel from algae. If the technological hurdles of BTL can be

solved, and costs can be brought down, BTL might achieve a significant share in total biofuel sales.

The share that various fuels may have in the biofuel market for 2020 is also determined by the rate at which production capacity can be realised. Especially GTL plants involve high capital costs. For the production of FT-fuels from biomass (BTL) also still some technical problems need to be resolved. As a result it is quite likely that 2nd generation biofuels will not be able to meet the demands set by e.g. a 10% biofuels target for 2020. Investments in 2nd generation biofuel production will only be made if fuel producing companies see a stable and promising development of the market for biofuels. For this the short term use of 1st generation biofuels is a necessity. Investments in plants for production of 1st generation biofuels will need to be earned back so that it is likely that production facilities built in the coming 5 to 10 years will still be in operation in the period from 2015 to 2025.

For a detailed comparison of biofuel options with respect to various criteria a draft multi-criteria matrix tool has been developed. For the moment, however, this tool is not yet used due to lack of time and inputs. In the follow-up of this project inputs from external experts and additional literature research may be used to fill the comparison matrix and to provide a more systematic selection of promising fuels for the short and longer term.

Table 6 Overview of biofuels and other alternatives available for the short and longer term

| **Type** | **Fuel** | **Production process** | **Feedstock** | **type of engine** | **available in short term** | **available in longer term** |
|---|---|---|---|---|---|---|
| alcohols | methanol | gasification and synthesis | variety of biomass | SI | x | |
| alcohols | ethanol | fermentation | sugar cane | SI | x | |
| alcohols | ethanol | fermentation | wheat | SI | x | |
| alcohols | ethanol | fermentation | sugar beet | SI | x | |
| alcohols | ethanol | cellulose hydrolysis and fermentation | woody biomass | SI | | x |
| alcohols | wet ethanol | fermentation | food crops | CI | x | |
| alcohols | wet ethanol | cellulose hydrolysis and fermentation | woody biomass | CI | | x |
| alcohols | butanol | fermentation | wheat, sugar beet, ... | SI | | x |
| alcohols | butanol | cellulose hydrolysis and fermentation | woody biomass | SI | | x |
| additives | MTBE | based on bio-methanol | all feedstocks for biomethanol | SI | x | |
| additives | ETBE | based on bio-ethanol | all feedstocks for bioethanol | SI | x | |
| plant oils | PPO | pressing of seeds | rapeseed | CI | x | |
| esterified oils | biodiesel (RME) | esterification of virgin vegetable oil | rapeseed oil / sunflower oil | CI | x | |
| esterified oils | biodiesel (SME) | esterification of virgin vegetable oil | soybean | CI | x | |
| esterified oils | biodiesel (PME) | esterification of virgin vegetable oil | palm oil | CI | x | |
| esterified oils | biodiesel (UVOME) | esterification of used vegetable oil | virgin rapeseed oil / sunflower oil | CI | x | |
| esterified oils | biodiesel (FAME) | esterification of animal fat and other residues | animal waste products | CI | x | |
| esterified oils | biodiesel (JME, algae) | esterification of virgin vegetable oil | Jatropha, algae | CI | x | x |
| synthetic fuels | FT petrol / BTL | BTL Fischer Tropsch synthesis | organic waste / woody biomass | SI | | x |
| synthetic fuels | FT diesel / BTL | BTL Fischer Tropsch synthesis | organic waste / woody biomass | CI | | x |
| synthetic fuels | FT designer fuel / BTL | BTL Fischer Tropsch synthesis | organic waste / woody biomass | | | x |
| ‘renewable diesel’ | renewable diesel | refinery based hydrotreatment | plant oil, animal waste products, ... | CI | x | x |
| hydrothermal upgrading | HTU diesel | hydrothermal upgrading | wet biomass | CI | | x |
| biogas | biogas (NG quality) | collection from landfills | waste | SI | x | |
| biogas | biogas (NG quality) | fermentation | dry or wet manure | SI | x | |
| biogas | biogas (NG quality) | fermentation | maize or other crops, often fermented in combination with manure | SI | x | |
| liquefied gas | DME | from biomethanol | all feedstocks for biomethanol | CI | | x |

## 2.14 Literature

| | |
|---|---|
| [Corbey 2007] | Dorette Corbey (2007), *Final rapporteur report*, Committee on the Environment, Public Health and Food Safety, Rapporteur: Dorette Corbey, 6-12-2007. |
| [EC 1998] | *Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC*, Official Journal L 350, 28/12/1998 |
| [EC 2007a] | COM(2007) 18 final, *Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and the introduction of a mechanism to monitor and reduce greenhouse gas emissions from the use of road transport fuels and amending Council Directive 1999/32/EC, as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC*, 31-1-2007. |
| [EC 2007b] | SEC(2007) 55, Commission Staff Working Document, *Accompanying document to the Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil that may be placed on the market and introducing a mechanism to monitor and reduce greenhouse gas emissions from the use of road transport fuels and amending Council Directive 1999/32/EC to remove the elements setting the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC*, 31-1-2007 (Executive Summary SEC(2007) 56/2). |
| [EC 2007c] | *Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on the type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and 6) and on access to vehicle repair and maintenance information*, 20 June 2007 |
| [EC 2008a] | *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*, COM(2008) 19 final, Brussels, 23.01.2008 |
| [EC 2008b] | SEC(2008) 85/3, *Commission Staff Working Document, Impact Assessment, Document accompanying the Package of Implementation measures for the EU's objectives on climate change and renewable energy for 2020* |
| [Eurobserver 2007] | EurObserv'ER (2007), *Biofuels Barometer 2006* |
| [IEA 2004] | International Energy Agency (2004), *Biofuels for Transport, An International Perspective* |

[Kattenwinkel 2008] Kattenwinkel, H. (2008), *Presentation on biofuels from an industry perspective*

[OECD 2007] OECD and FAO (2007), *OECD-FAO Agricultural Outlook 2007-2016*

[Refuel 2008] Refuel, EU project, http://www.refuel.eu/home/

[Volvo 2008] Volvo publication (2008), *Climate issues in focus*, http://www.volvo.com/group/global/en-gb/volvo+group/ourvalues/environment/renewable_fuels/

[WI 2007] Worldwatch Institute (2007), *Biofuels for Transport, Global potential and implications for sustainable energy and agriculture*

[WSDA 2007] WSDA (2007), *Renewable Diesel Technology*, by the Renewable Diesel Subcommittee of the WSDA Technical Work Group, July 2007.

# 3 Developments in engine technology

## 3.1 Introduction

In this chapter, the developments regarding future engine technology for 2020 will be described. The description focuses on the internal combustion engines (ICE) and emissions control technology. Other developments (such as hydrogen and electrification) are only described as far as relevant for using biofuel as a transport fuel.

Starting point of the analysis is a summary of the boundary conditions that present and foreseen emission legislation puts on the development of engines and aftertreatment systems. Besides compliance with future emissions legislation and the continuing strive for improvement of quality and performance, especially $CO_2$ emission reduction, as required by new European legislation that is currently being prepared, will be an important driver for engine development.

Relative to this legislative context, the on-going and expected developments in spark ignition engine technology (SI, Otto principle) and compression ignition engine technology (CI, Diesel principle) will be described separately. Besides general developments also a distinction will be made with respect specific developments for passenger cars and heavy duty vehicle, as well as for engines running on gaseous fuels.

## 3.2 European emission legislation

### *3.2.1 Exhaust emission legislation*

An overview of the emission legislation for passenger cars and light duty commercial vehicles is presented in Table 7. For passenger cars, the main developments are (euro 6 compared to euro 5):

- $NO_x$: 55% reduction (from 180 to 80 mg/km)
- $PM_{10}$: same value (4,5 mg/km measured by PMP measurement protocol; particulate number 6,0 * $10^{11}$)

An overview of the European emissions legislation for heavy-duty CI engines for trucks and buses is presented in Table 8. From the table it can be concluded that especially from Euro V to Euro VI a large emission reduction is required: $NO_x$ emissions needs to be reduced by a factor of 4 while PM needs to be reduced by a factor of 2 to 3.

Table 7 Overview European emission limits for passenger cars and light commercial vehicles (in g/km).

| Category | Date | Test cycle | Unit | CO | HC | HC+NO$_x$ | NMHC | NO$_x$ | PM 2) | PN |
|---|---|---|---|---|---|---|---|---|---|---|
| **Passenger car Otto (SI)** | | | | | | | | | | |
| M1 (≤ 8+1 seats) GVW ≤ 2500 kg 2) | Euro-4 – 2005 | MVEG-B | g/km | 1.0 | 0.10 | - | | 0.08 | - | |
| | Euro-5 – 2008 1) | MVEG-B | g/km | 1.0 | 0.10 | | 0.068 | 0.06 | 0.005 | |
| | Euro-6 – 2014 1) | MVEG-B | g/km | 1.0 | 0.10 | | 0.068 | 0.06 | 0.005 | |
| **Passenger car diesel (CI)** | | | | | | | | | | |
| M1 (≤ 8+1 seats) GVW ≤ 2500 kg 2) | Euro-4 – 2005 | MVEG-B | g/km | 0.50 | | 0.30 | - | 0.25 | 0.025 | |
| | Euro-5 – 2008 1) | MVEG-B | g/km | 0.50 | | 0.23 | - | 0.18 | 0.005<br>0.003? | 6x10$^{11}$ |
| | Euro-6 – 2014 1) | MVEG-B | g/km | 0.50 | | 0.17 | - | 0.07<br>0.08? | 0.005 | 6x10$^{11}$ |
| **Light commercial vehicles (CI)** | | | | | | | | | | |
| N1 class I GVW ≤ 1305 kg | Euro-4 – 2005 | MVEG-B | g/km | 0.50 | | 0.30 | - | 0.25 | 0.025 | |
| | Euro-5 – 2008 1) | MVEG-B | g/km | 0.50 | | 0.23 | - | 0.18 | 0.005 | 6x10$^{11}$ |
| | Euro-6 – 2014 1) | MVEG-B | g/km | 0.50 | | 0.17 | - | 0.08 | 0.005 | 6x10$^{11}$ |
| N1 class II 1350 < GVW ≤ 1760 kg | Euro-4 – 2006 | MVEG-B | g/km | 0.63 | | 0.39 | - | 0.33 | 0.04 | |
| | Euro-5 – 2008 1) | MVEG-B | g/km | 0.63 | | 0.295 | - | 0.235 | 0.005 | 6x10$^{11}$ |
| | Euro-6 – 2014 1) | MVEG-B | g/km | 0.63 | | 0.195 | - | 0.105 | 0.005 | 6x10$^{11}$ |
| N1 class III 1760 < GVW ≤ 3500 kg | Euro-4 – 2005 | MVEG-B | g/km | 0.74 | | 0.46 | - | 0.39 | 0.06 | |
| | Euro-5 – 2008 1) | MVEG-B | g/km | 0.74 | | 0.35 | - | 0.28 | 0.005 | 6x10$^{11}$ |
| | Euro-6 – 2014 1) | MVEG-B | g/km | .0.74 | | 0.215 | - | 0.125 | 0.005 | 6x10$^{11}$ |

1) Proposed values, for Euro-6 a PM number value may be proposed

2) For Euro 5 and 6 a revised measurement procedure shall be introduced before the application of a 4.5 mg/km limit value, substituting the 5.0 mg/km valid for the current measurement procedure

Table 8 Overview European emission limits for heavy duty CI truck and bus engines

| Category | Date | Test cycle | Unit | CO | NMHC | NO$_x$ | PM |
|---|---|---|---|---|---|---|---|
| **Europe** | | | | | | | |
| GVW > 3500 kg | Euro-IV – 2005 | ESC | g/kWh | 1.5 | 0.46 | 3.5 | 0.02 |
| | | ETC | g/kWh | 4.0 | 0.55 | 3.5 | 0.03 |
| | Euro-V – 2008 | ESC | g/kWh | 1.5 | 0.46 | 2.0 | 0.02 |
| | | ETC | g/kWh | 4.0 | 0.55 | 2.0 | 0.03 |
| | Euro-VI – 2014 1) | ESC / ETC | g/kWh | | | 0.4 | 0.01 |

1) Expected date. Values are based on ESC/ETC test cycles. Test cycle will probably change to World Harmonized Determination Cycle (WHDC)

Apart from lower emission levels, the future emissions legislation will include more requirements to secure the lowest possible emission in real world driving. These are:

- requirements for durability for the emissions performance;
- requirements for On-Board Diagnostics (OBD): this means that the engine diagnostics system detects possible malfunctioning of the emission control system and that the driver is warned;
- requirements for off-cycle emissions: this means that under all conditions; driving, ambient and altitude certain emission limits are met.

Especially for HD vehicles the Euro V and VI legislation means more focus on real world emissions. The expectation is, that also for future emission legislation for passenger cars the focus will be more and more on real world emissions.

### 3.2.2 *Developments related to $CO_2$ emissions legislation*

In COM(2007) 19 and SEC(2007) 60 the European Commission has outlined its plans for a new Community Strategy for reaching the EU objective of reducing $CO_2$ emissions from new passenger cars to 120 g/km in 2012. The present average $CO_2$ emission of passenger cars, as measured on the type approval test, is around 160 g/km. As the main part of that strategy the European Commission has recently proposed in COM(2007) 856 and SEC(2007) 1723 new legislation setting a sales averaged $CO_2$ emission limit for passenger cars of 130 g/km in 2012. Targets for the sales averaged $CO_2$ emissions per manufacturer are set using a linear mass-based limit function. Similar legislation for light commercial vehicles is in preparation. This legislation will force manufacturers to develop and apply more efficient engine technology, advanced transmissions, hybrid powertrains as well as various measures reducing the energy requirements of the vehicle such as lightweight construction and improved aerodynamics.

Although proposals to this effect have not been made yet, it is assumed that between 2012 and 2020 the limit value for the sales weighted average $CO_2$ emission will be further tightened and that the target for vans will be lined up with that for passenger cars. The target for 2020 could be around 80 to 100 g/km. This will result in the need for further efficiency increase of SI engines in particular, probably closing the gap with CI engines by introducing technologies such as turbo-charging, direct injection and variable valve actuation, ultimately combined with full hybridisation.

## 3.3 Development of SI engine technology

### 3.3.1 *Engine downsizing*

The development of the spark ignition (Otto cycle) engine technology primarily takes place in the light of the demand for higher engine efficiency (lower $CO_2$) and improvement of driveability and performance. On top of that of course the engines need to meet the future exhaust gas emission legislation, but this can generally be achieved by further optimisation of the emission control devices including fuel injection systems and catalysts.

Measures to increase engine efficiency are generally focussed on reducing engine losses especially at part-load where most of time is spend in real world driving. In Table 9 an overview is given of measures to reduce these losses. The measures are often combined in one engine.

Table 9 Measures to reduce engine losses

| Reduction of losses | Measure |
|---|---|
| pumping losses | Downsizing (w/wo turbocharging), variable valve timing and lift, EGR, lean burn |
| engine mechanical friction | Downsizing, improved auxiliaries such as efficient water and oil pump, cam rollers instead of sliders, low viscosity lubricants |

The potential for fuel consumption reduction was summarized in [Smokers 2007]:

- direct fuel injection 10%
- engine downsizing in combination with turbocharging: 10-12%
- variable valve timing and/or lift: 3-7%
- improved cooling and/or lubricant system: 1,5%-3%

The most general technological direction is engine downsizing in combination with turbocharging and direct (in-cylinder) injection. As a result the same power and torque is achieved with a (much) smaller engine displacement. Engine efficiency then improves because the engine internal friction and pumping losses are reduced. The engines will generally run stoichiometric (lambda =1) across the engine map, because then the very efficient 3-way catalyst can be used. The pumping losses are further minimised by EGR and in few cases by variable valve actuation (VVA).

Variable valve actuation (without turbocharging) is also becoming more and more popular. Honda started in the nineties with a simple variant of VVA: “VTEC” which was tuned to reduce pumping losses and /or increase specific power output. After that, more advanced systems followed such as from Toyota and BMW.

In addition to or instead of downsizing, lean-burn engine concepts can be considered. Lean-burn is also a way of reducing the pumping losses of the engine. For examples this was done by Mitsubishi, Volkswagen and Renault a number of years ago. In later models the lean-burn operation was phased out again, presumably because the emissions control turned out to be too complex. The advantage of direct injection remains an improved driveability and also a possibility to increase the specific power output of the engine.

Mercedes and BMW are using the lean-burn operation in a number of engine types (respectively referred to as CGI and HPI). These have the so called “spray-guided combustion”, which is basically a form of stratified charge combustion where the injector takes care of a good ignitable mixture around the spark plug. These lean burn engines are using NOx adsorption catalysts for NOx reduction.

In Table 10 an overview is given of recently introduced or announced downsized spark ignition engines in the popular vehicle range. It is expected that these types of engines will become more and more common in the coming decade.

The trend of downsizing, started in recent years, will continue. Specific power output for SI engines in 2007 was up to 89 kW/litre. In the future, engine cylinder volume can be expected to drop below 1.0 litre (1000 cc), see e.g. announcements from Fiat (2 cylinder engine 900 cc turbo, 60kW, 69 g/km, production is scheduled for 2009) and Toyota (1/X concept car with 500 cc engine).

Table 10 Overview of new downsized SI engines

| **Brand** | **Type** | **Displ.** | **Power** | **Specific power** | **Technology** |
|---|---|---|---|---|---|
| | | dm3 | kW | kW/dm3 | |
| Audi | 1.8 T FSI | 1.8 | 125 | 69 | Turbocharging, VVA, DI |
| BMW (PSA) | 1.6 DI turbo | 1.6 | 90 | 56 | Turbocharging, DI |
| | 2.0 DI turbo | 2.0 | 125 | 63 | Turbocharging, DI |
| FIAT | 1.4 T | 1.4 | 110 | 79 | Turbocharging, DI |
| | 0,9 T | 0.9 | 60 | 67 | Turbocharging, DI * |
| VW | 1.4 | 1.4 | 125 | 89 | Turbocharging + supercharging, DI, no VVA |
| Nissan | 3.5 | 3.5 | 230 | 66 | Turbocharging, DI |

*Remarks regarding difference between diesel and petrol*

In [Smokers 2006], more available efficiency improvement options for SI (petrol) engines are listed than for CI (diesel) engines. When combining these options, attention was paid to combine only options that are compatible (such as strong downsizing, friction reduction and advanced cooling circuit). However, even compatible technologies have a reduced reduction potential when combined. This effect is much stronger for SI as there is more interaction (e.g. between variable valve control, DI lean burn & downsizing for SI engines). Currently diesel vehicles are more fuel efficient that petrol vehicles, but TNO expects that the difference in efficiency between SI and CI will diminish. When applying all $CO_2$ reduction measures known today, including hybrid technology, we expect that in 2020 petrol cars can on average achieve a $CO_2$ emission on the standard type approval test cycle of around 106 – 114 g/km, where as diesel cars in 2020 would achieve on average around 104 – 109 g/.

### 3.3.2 *New combustion concepts for petrol engines*

Controlled Auto Ignition (CAI) or partially pre-mix auto ignition is a new combustion concept that is under development for petrol engines. The concept is described by [Kalghatgi 2006], [Kalghatgi 2007] and [Sauter 2008]. Basically, the fuel is injected at a very early stage (earlier than normal and ends before the combustion starts). The fuel will ignite as in a diesel combustion. The advantage is a more homogeneous mix, which keeps the local combustion temperature low. As a result, diesel efficiency can be obtained with a gasoline engine. Due to the complex engine control, it is not expected that this technology will be introduced soon. Nevertheless Daimler-Chrysler is currently promoting this type of engine concept which is referred to as “diesotto” principle. According to DC, it is a downsized engine with a power of 175 kW from 1.8 litre engine displacement. Apart from de more usual turbo-charging and direct injection, it would have a variable compression ratio.

### 3.3.3 *SI engines for vehicles with hybrid powertrains*

Passenger cars with hybrid powertrains such as the Toyota Prius, the Honda Civic hybrid, and the Lexus GS450h, LS600h and RX400h have been introduced during the past 5 years in order to reduce the fuel consumption and $CO_2$ emissions of vehicles. In addition to this recently are also vehicles with so called micro hybrids (start-stop system) have been introduced on the market. These systems are for example supplied among others by PSA, BMW and Ford. All these vehicles are so-called charge sustaining hybrids, meaning that the battery is not charged from the grid but by electricity which is generated by the ICE.

A number of other vehicle manufacturers have announced to introduce mild or full hybrid vehicles in the coming years, such as VW (Golf hybrid) and PSA.

Another recent development is the so called plug-in hybrid. One extreme variant of the plug-in hybrid is basically a battery-electric vehicle in which a small engine is fitted which is only used as a range extender. The batteries are primarily charged from the grid, and the vehicle will run in pure electric mode most of the time. At the other end of the spectrum there are full hybrid plug-ins which are derived from charge sustaining concepts to which additional battery capacity and an external charger have been added to allow increased electric range and reduced fuel consumption (replaced by electricity consumption). Toyota is currently testing a plug-in version of their Prius.

In general hybrids are fitted with smaller engines than comparable vehicles with the same performance. When the engine is on, it is generally operated at higher loads. This leads to improved efficiency but generally also to higher engine-out $NO_x$ emissions. Due to the more stationary engine operation, however, the exhaust aftertreatment system can be better optimised to yield low tailpipe emissions. As the engine is operated in a start-stop mode care needs to be taken to keep start-up emissions at an acceptable level.

As the impact of biofuels on emissions can be different for part load than for peak load the impact of biofuels on emissions of hybrids can differ from the impacts on emissions from conventional vehicles.

### *3.3.4 Development of petrol emission control systems*

The mainstream emission control technology for spark ignition engines is the 3-way catalytic convertor in combination with stoichiometric engine operation (lambda = 1). Stoichiometric means that the amount of oxygen in the intake air is precisely in balance with the amount of fuel dosed. In that way the amount of HC and CO emitted can be balanced with the amount of $NO_x$ in the absence of oxygen in such a way that the HC and CO act as a reducing agent for $NO_x$ at the surface of the catalyst. Exhaust gas recirculation (EGR) at part load is sometimes added in order to reduce the pumping losses of the engine. In addition EGR will reduce the engine out $NO_x$ as well.

For engines operating in a lean burn combustion strategy, a NOx adsorption catalyst or Lean $NO_x$ Trap (LNT) catalyst can be used in combination with EGR. For the LNT two engine operating modes are necessary which is presented in Figure 3.1. Periodically (say every 30 – 60 s) the engine goes for a short period in a rich operating mode in order to release the adsorbed $NO_x$ molecules from the catalyst and convert them to $N_2$ and $H_2O$ according to the 3-way catalyst principle. At higher engine loads these engines operate in the stoichiometric combustion mode in which the catalyst operates in the 3-way conversion mode.

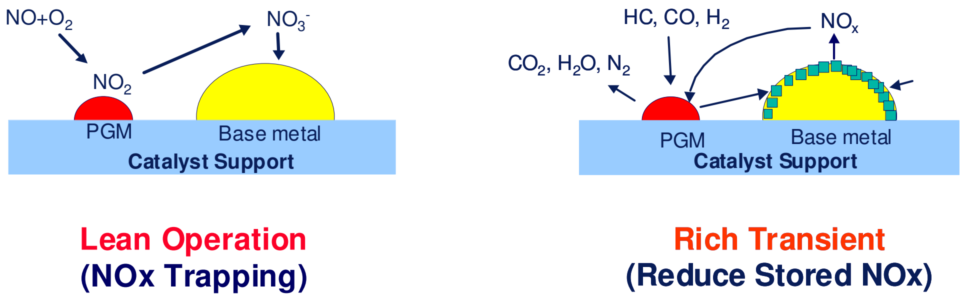


Figure 3.1 Operating principles of the Lean NOx Trap (LNT) or NOx adsorption catalyst

The 3-way catalytic convertor is a very powerful emission reduction device. For this reason, it will also be the mainstream emission control technology for Euro 5 and Euro 6 engines. Further developments to comply with the emission legislation include:

- Improvement of catalytic convertor technology both in improvement in catalyst-washcoat combination as well as more efficient substrates (catalyst carrier);
- Closed coupled and possibly electrically heated catalysts;
- Improved fuel dosage strategy and calibration.

Development of SI engines up to 2020 will be primarily focussed around downsizing, direct injection and variable valve actuation technology in combination with Lamba = 1 combustion with 3-way catalyst for emission control.

## 3.4 Development of CI engine technology

### *3.4.1 CI engine development in relation to emission legislation*

Historically the CI engines technology for trucks and passenger cars followed quite different paths. This was related to the emission legislation and the high requirements for truck engines on engine efficiency (fuel consumption) and durability.
With respect to emissions legislations the emphasis with trucks was on low particulates emission to be achieved in a test cycle with relative high engine loads and power. For passenger cars the emphasis was generally on low NO$_x$ to be achieved in a test cycle with relatively low engine load and speed. This steered to a large extent the development of the engine emission control technology. Passenger car CI engines were generally (from Euro 2 onwards) equipped with EGR (Exhaust Gas Recirculation) to control NO$_x$ emission. The EGR systems were quite simple because EGR was only necessary at low to medium engine load. The EGR was generally not cooled. For trucks up to Euro III most engines could do without special emission control devices such as EGR and exhaust aftertreatment. The emphasis was on high pressure fuel injection systems and combustion optimisation in order to achieve the required particulates and NO$_x$ levels, while maintaining optimal engine efficiency.

Looking at current legislation, Euro 4 and 5 resp. IV and V, there are still differences. While all passenger car engines use EGR, only a few truck manufacturers use this technology. The majority of the trucks producers use SCR deNOx aftertreatment for NO$_x$ control.

With SCR deNOx, a reagent is injected upstream of the SCR catalyst. The reagent is an aqueous urea solution called “AdBlue”. The main reactions upstream and within the SCR catalyst are:

Urea hydrolysis:
$NH_2\text{-}CO\text{-}NH_2 + H_2O \rightarrow NH_3 + CO_2$

Reaction of $NH_3$ with $NO_x$:
$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$ (1)
$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$ (2)

For passenger cars a general introduction of wall-flow diesel particulate filter takes place, while this is not seen for European trucks engines. For HD engines meeting EEV limits an open filter is used.

For Euro 6 and VI, it is expected that the technologies for truck and passenger car engines will further merge. All engines are basically expected to be equipped with EGR for $NO_x$ control and a wall-flow diesel particulates filter for particulates emission control. In addition to this all but the small passenger car engines will be equipped with a lean $NO_x$ catalyst, a lean $NO_x$ trap (LNT) or an SCR deNOx catalyst. The latter is also expected for the majority of the truck engines. For truck engines a continuous increase of injection pressures is seen, when going to newer engine generations. This is necessary to minimise the particulates emissions, even though wall-flow particulates filters are applied.

The $CO_2$ legislation for passenger cars (130 g/km fleet average by 2012) is likely to further trigger downsizing of the CI engines. This will result in an increased share of vehicles with advanced air systems such as variable geometry turbo (VGT), two-stage and sequential turbocharging.

### 3.4.2 *Development of CI engine technology for passenger cars*

Downsizing of CI engines by applying turbocharging was started more than a decade ago. Most CI engines these days are already turbocharged. Recently the trend towards higher specific power outputs is boosted by the application of sequential or in other words a special form of two-stage turbocharging. In this configuration a small turbocharger is combined with a somewhat bigger turbocharger. The small charger takes care of the boost pressure at low engine speeds, the bigger charger at medium speeds and the two chargers work together at high engine speeds. The specifications for several of these new engines are presented in Table 11. FIAT announced that with the introduction of the 1.9 JTD M, they are planning to phase out the 2.4 litre engine.

Downsizing works for CI engines in a similar way as for SI engines and will result in a fuel consumption reduction. This is due to two effects: 1) lower internal friction losses due to the smaller engine displacement and 2) lower weight of the engine which results in a lower vehicle weight.

Table 11 Overview of CI engines with high specific power output

| Brand | Type | Displ. | Power | Specific power | Technology |
|---|---|---|---|---|---|
| | | $dm^3$ | kW | $kW/dm^3$ | |
| BMW | 3.0 L | 3.0 | 210 | 70 | Dual turbo sequential |
| | 2.0 L | 2.0 | 150 | 75 | |
| FIAT | 1.9 JTD M | 1,9 | 140 | 74 | Dual turbo sequential |
| Volkswagen | 2.0 L | 2.0 | 147 | 74 | Dual turbo sequential |

### 3.4.3 *New combustion systems*

The objective of improved combustion processes under development for CI engines is to reduce the local flame temperature by dilution and homogenisation of the air-fuel mixture. In that way, the formation of $NO_x$ and particulates can be suppressed to a large extent. This combustion type is often referred to as HCCI combustion (Homogeneous Charge Compression Ignition), but also many other abbreviations are used, such as:

| | |
|---|---|
| PCCI: | Premix Charge Compression Ignition |
| CAI: | Controlled Auto Ignition |
| LTC: | Low Temperature Combustion |
| HPLI: | Highly Premixed Late Injection |
| HCLI: | Homogeneous Charge Late Injection |
| DCCS: | Dilution Controlled Combustion System |

These combustion systems can both be used for typical Diesel as well as typical Otto cycle fuels, although the objectives are different: for CI engines this is emissions reduction, while for SI engines the objective is improved engine efficiency.

A characteristic for homogeneous charge combustion is that the start of combustion is not directly after the injection or after the spark. [Hülser 2006] and [Gautam 2006] mention that in order to have good emissions the injection phase should be ended before the combustion starts. Process parameters such as the mixture temperature determine the start of the combustion. For petrol this temperature is much higher than for diesel fuel. With the very weak relation between moment of injection and start of combustion, the engine control (injection, EGR, air) becomes very important. For that reason closed-loop control using a combustion sensor (pressure, ion-sense) is probably necessary [Hülser 2006]. For CI engines with a practical engine lay out HCCI combustion is limited to light load and possibly medium load conditions [Duffy 2005]. For this reason and also because of the availability of flexible common rail fuel injection systems, HCCI is expected to be introduced first for passenger car CI engines. In that way costly deNOx aftertreatment systems can probably be avoided (for not too large vehicles).

### 3.4.4 *Development of diesel emission control systems for passenger cars*

Currently standard or frequently applied emission control systems for passenger car CI engines are:

- EGR: Exhaust gas recirculation: to control NOx emission
- DPF: diesel particulate filter: to control particulates emission

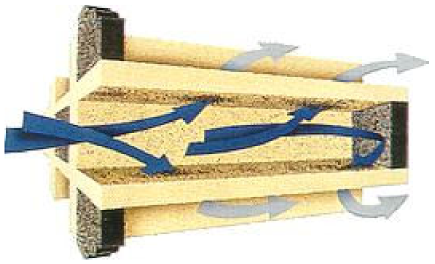


Figure 3.2 Diesel particulate wall flow filter (DPF)

Many Euro 4 vehicles are equipped with diesel particulates filter, but this is generally not necessary from technology point of view to meet the emission target. It is due to national stimulation programs or the preference of the car owner to have a clean diesel vehicle. The limits for Euro 5 have been set in such a way that from this Euro stage on diesel particulate filters will be necessary to meet the PM limits.

For future diesel vehicles additional $NO_x$ aftertreatment is required, especially for the heavier vehicles. The options are:

- DeNOx catalyst;
- Selective catalytic reduction of $NO_x$ (SCR) with AdBlue injection in the exhaust pipe.

The DeNOx catalyst can either be a “lean $NO_x$ catalyst” or a lean $NO_x$ trap (LNT). With the lean $NO_x$ catalyst, the HC content in the exhaust gases is increased by post injection or by injection in the exhaust manifold. The $NO_x$ reacts with the HC in the catalyst and is converted to $N_2$ and water. With the LNT, the CI engine has to go in a rich operating mode periodically in a similar way as explained for the SI engines (see section 3.3.4).

Emission control is more complex for heavier passenger cars and light duty trucks than for lighter vehicles. This is due to the fact that the emission limits are set in g/km and that $NO_x$ and PM limits are not or hardly vehicle mass dependent. For a heavier vehicle the engine work in order to drive the test cycle is larger which would result in extra emissions if not additional measures are taken. This is especially the case for NOx control. In Figure 3.3 it can be seen that with increasing vehicle size an increased share of vehicles with $NO_x$ adsorption catalyst (DeNOx-cat) or SCR catalyst with AdBlue injection (SCR) is to be expected. All engines will have EGR and from Euro 5 and later all vehicles will be equipped with a wall flow diesel particulate filter.

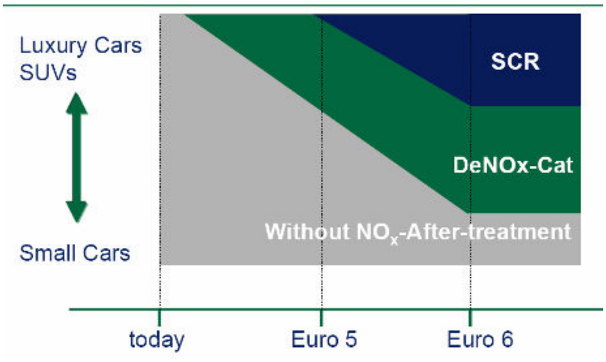


Figure 3.3 Exhaust aftertreatment technologies for passenger cars

### 3.4.5 *Development of diesel emission control systems for heavy duty vehicles*

An overview of emission control technology for heavy-duty CI engines is presented in Table 12.

Table 12 Emission control technologies for heavy-duty CI engines depending on emission legislation

| **Legislation** | **Emission control measures** |
|---|---|
| Euro II and III | high pressure fuel injection and injection timing control |
| Euro IV option 1<br>Euro IV option 2 | EGR and optional oxidation catalyst or flow through diesel particulates filter<br>SCR (with AdBlue injection in the exhaust) |
| Euro V option 1:<br>Euro V option 2: | SCR<br>High EGR and optional oxidation catalyst or flow through diesel high pressure fuel injection > 2200 bar |
| Euro VI | Medium EGR with SCR and wall-flow DPF, two-stage turbo-charging likely for higher ratings |

Many trucks sold during the last year in Europe are already Euro V, even though the introduction date of Euro V is formally between October 2008 (new engine types) and October 2009 (all engine types). This is primarily due to the German road pricing (Maut), which is lower for vehicles complying with Euro V and to a lesser extent Euro IV. For Euro VI the $NO_x$ limit will be a factor five lower and the PM limit will be a factor 2 lower. This really requires a stacking up of the emission control devices such as EGR + SCR + DPF. Also important is that the Euro VI legislation is setting additional emission control requirements, namely On Board Diagnostics and in service emission requirements (real world emissions).

The Euro VI strategy is graphically presented in Figure 3.4. The engine out $NO_x$ level is reduced to about 2 g/kWh with EGR. Consequently a DPF is applied to meet the particulate emission requirement and an SCR catalyst is added to meet the $NO_x$ emission requirement of 0.4 g/kWh. One positive point in this is that EGR and SCR are quite well complementary and compatible. Since the efficiency of SCR is good under high load high exhaust gas temperature conditions, the requirements on the EGR system can possibly be relaxed compared to the EGR systems of Euro V or US 2007 engines (without SCR).

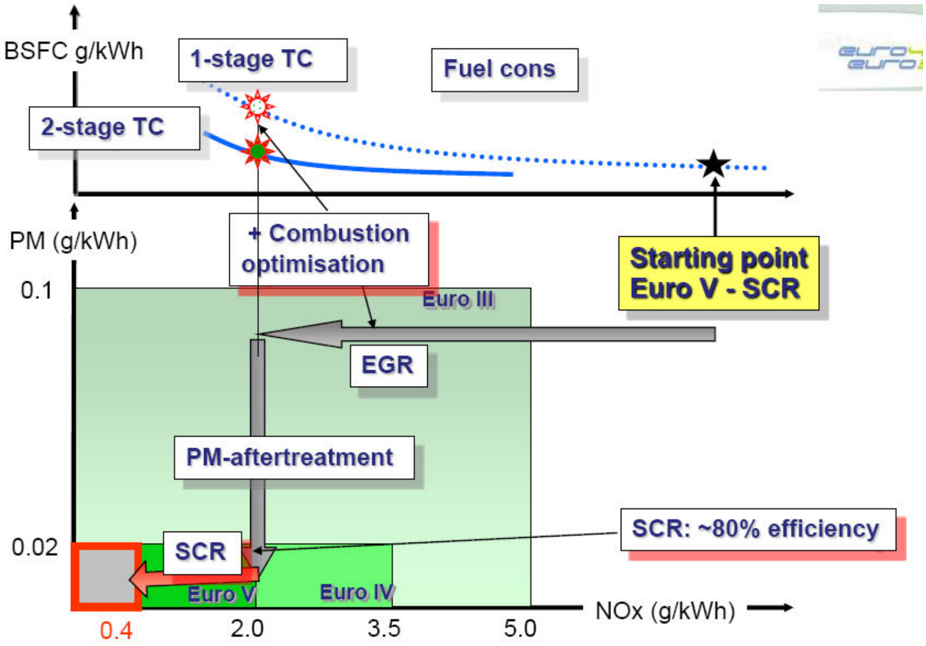


Figure 3.4 Emission control technology for Euro VI (Source: Iveco [Ellensohn, 2007])

## 3.5 Development of gaseous fuel engine technology

Main application of gaseous fuel engine technology will be for niche application and captive fleets (e.g. buses) due to absence of European wide infrastructure and packaging difficulties and limited range.

Stoichiometric SI engines on natural gas will be able to meet Euro 6 and Euro IV emission limits. Emission advantages compared to petrol and diesel will diminish. For LD vehicles CNG engines will undergo the same development as petrol engines.

## 3.6 Conclusions

For gasoline engine technology, the main trend until 2020 will be downsizing, due to the focus on improving engine efficiency. The increase of hybrid vehicles also results in smaller engines, as part of the peak power can be generated by the electric motor. To achieve stricter emission limits, the after-treatment systems will be further optimised, but no new devices are to be expected.

For diesel engine technology, the main trend until 2020 will be the completing of the emission control after-treatment system, as a result of the focus on emissions. Closed-loop diesel particulate filter and deNOx catalyst can be expected on almost all vehicles, both heavy duty and passenger cars. The efficiency of the diesel engine will also further improve due to downsizing and possibly diesel hybrid vehicles.

For both diesel and gasoline, there will be an increased focus on real world emissions of particles, nitrous oxides and real world fuel consumption.

Regarding developments in engine and aftertreatment technology which are relevant to the assessment of impacts of biofuels on emissions the following more detailed conclusions can be drawn:

- Euro 6 for LD vehicles and Euro VI for HD vehicles will enter into force in 2014. With Euro 6 the emission limits for petrol and diesel vehicles will be the same for $NO_x$ and PM and almost equivalent for CO and HC. Euro 6 limits for $NO_x$ and PM emissions from LD diesel vehicles are a factor of 3 resp. 5 lower than Euro 4. For HD vehicles Euro VI legislation involves emission limits for $NO_x$ and PM which are a factor of almost 9 resp. 3 lower than Euro IV.
- For petrol vehicles Euro 6 limits can be met by further optimisation of existing engine and aftertreatment technology. For meeting the Euro 6 / VI limits for diesel vehicles application of aftertreatment systems for $NO_x$ and PM is necessary.
- The absolute impact (i.e. in g/km) of the use of biofuels in Euro 6 / VI vehicles will be limited due to the already very low limits for Euro 6 / VI. The relative impact, however, can be large especially if the use of biofuels affects the conversion efficiency of the applied aftertreatment.
- Over the next decade development in LD engine technology will be largely driven by the requirements for efficiency improvement that result from the recently proposed European legislation on $CO_2$ emissions from LD vehicles. Where CI (diesel) engines are currently some 15 – 20% more fuel efficient than SI (petrol) engines, beyond 2012 the difference in efficiency between CI and SI will decrease. The technologies that are foreseen to be applied in order to improve engine efficiency (e.g. direct injection for petrol engines, downsizing with turbocharging and variable valve actuation) do not conflict with the effort to further lower exhaust gas emissions. As the impact of biofuels on emissions can be different for part load than for peak load the impact of biofuels on emissions of hybrids can differ from the impacts on emissions from conventional vehicles.
- Overall the expected development of engine and aftertreatment technology up to 2020 is as follows:
  - Application of direct injection to SI engines;
  - Further downsizing of engines (emphasis SI passenger car engines);
  - Further integration of both internal engine emission control and exhaust aftertreatment systems. Broad introduction of diesel particulate filters and deNOx catalysts on diesel engines;
  - Broad introduction of on board diagnostics and closed loop emission control leading to better real-world emissions;
  - Increase in market share of FFV vehicles;
- The blend percentage of FAME in diesel respectively ethanol in petrol (for non-FFV engines) will remain an issue. For that reason blend percentages will probably be limited for a large share of the vehicles. Nevertheless a number of diesel trucks are already released for higher blends up to B100 and the availability of trucks suitable for B100 is expected to increase towards 2020.
- New combustion concepts such as CAI and HCCI are currently under development, promising low emissions and good efficiency. Due to complex engine management issues these technologies are not expected to be applied on a large scale in vehicles sold around 2020.

## 3.7 Literature

[Boot 2007] Boot, M. et. al. (2007), *Oxygenated fuel composition impact on heavy-duty diesel engine emissions*, JSAE 20077293 / SAE 2007-01-2018

[Brezny 2007] Brezny, R. (2007), *Potential Particulate Trap Substrate and Catalyst Impact with Sodium and Potassium Contamination*, Manufacturers of Emission Controls Association (MECA), Biodiesel Technical Workshop October 17-18, 2007, www.meca.org

[Duffy 2005] Duffy, K. et al. (2005), *Heavy Duty HCCI development activities*, Presentation at DOE DEER conference, Chicago, August 2005

[EC 2007a] COM(2007) 19: *Results of the review of the Community Strategy to reduce $CO_2$ from passenger cars and light commercial vehicles*, 7.2.2007

[EC 2007b] SEC(2007) 60, *Impact Assessment*, accompanying document to COM(2007) 19, 7.2.2007

[EC 2007c] COM(2007) 856, *Proposal for a Regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce $CO_2$ emissions from light-duty vehicles*, 19.12.2007

[EC 2007d] SEC(2007) 1723, *Proposal from the Commission to the European Parliament and Council for a Regulation to reduce $CO_2$ emissions from passenger cars*, DRAFT Impact Assessment, 19.12.2007

[Ellensohn 2007] Ellensohn, R., (2007) *OEM Euro VI Strategy and Developments in Technology to meet the Emission Standards,* Diesel Emissions Conference 07 - Integer Research Frankfurt - 26/27 June 2007

[Gense 2005] Gense, N. et. al. (2005), *Euro 5 technologies and costs for Light-Duty vehicles, The expert panels summary of stakeholders responses,* TNO report nr. 05.OR.VM.032.1/NG, on behalf of the European Commission, DG Environment contract no. 070501/2004/381669/MAR/C1

[Gense 2006] Gense, N. et. al. (2006), *Euro VI technologies and costs for Heavy Duty vehicles, The expert panels summary of stakeholders responses,* TNO report nr. 06.OR.PT.023.1/NG, on behalf of the European Commission, DG Environment, contract no. 070501/2004/381669/MAR/C1

[Hass 2007] Hass, H. et al. (2007), *Optimum Diesel Fuel for Future Clean Diesel Engines,* SAE 2007-01-0035

[Hülser 2006] Hülser, H. (2006), EmIQ: Intelligent Combustion and Control for Tier2 Bin5 Diesel engines, SAE paper 2006-01-1146

[Junior 2002] Junior, H.J. (2002), *Vehicular Ethanol Fuel, Technical & Exhaust Emission Experience in Brazil*, Brazilian Automobile Manufacturers Association, ERDC Project No. 2511, 2002?

[Kadijk 2008] Kadijk G., et al. (2008), *Uitlaatgasemissies van PPO en biodiesel in Heavy Duty motoren*, TNO report number MON-RPT-DTS-2008-00153

[Kalghatgi 2006] Kalghatgi, G. et al. (2006), *Advantages of fuels with high resistance o auto-ignition in late-injection, low-temperature, compression ignition combustion*, SAE 2006-01-3385.

[Kalghatgi, 2007] Kalghatgi, G. et al. (2007), *Partially pre-mix auto-ignition of gasoline to attain low smoke and low NOx at high load in a compression ignition engine and comparison with diesel fuel*, SAE 2007-01-0006.

[Koyama 2007] Koyama, A. et al. (2007), *Vegetable Oil Hydrogenating process for automotive fuel*, SAE number 2007-01-2030, JSAE 20077163.

[Martini 2007] Martini, G. et al. (2007), Joint EUCAR/JRC/CONCAWE Programme on: *Effects of gasoline vapour pressure and ethanol content on evaporative emissions from modern cars*. EUR 22713 EN, ISBN 978-92-79-05249-1, ISSN 1018-5593

[Mitsuharu 2007] Mitsuharu, O. et al. (2007), *Evaluation of Medium Duty DME Truck Performances -Field Test Results and PM Characteristics,* SAE 2007-01-0032

[Rantanaen 2005] Rantanen, L. et al. (2005), *NExBTL – Biodiesel fuel of the second generation*, SAE 2005-01-3771.

[Rehnlund 2007] Rehnlund B. et al. (2007), *Heavy-duty ethanol engines: Final report for Lot 2 of the Bioscopes project*, February 2007, EC project TREN/D2/44-LOT 2/S07.54739

[Sauter 2008] Sauter, W. et. al. (2008), *Reduzierung der Motoremissionen durch kontrolierte Selbstzündung im Ottomotor*, MTZ January 2008.

[Serves de 2005] de Serves, C. (2005), *Emissions from Flexible Fuel Vehicles with different ethanol blends*, AVL MTC AB report 5509, date 2005/10.

[Smokers 2006] Smokers, R.T.M. et al. (2006), *Service Contract to review and analyse the reduction potential and costs of technological and other measures to reduce $CO_2$ emissions from passenger cars,* carried out by TNO, IEEP and LAT on behalf of the European Commission (DG Enterprise, contract nr. SI2.408212)

| | |
|---|---|
| [Verbeek 1997] | Verbeek, R. (1997), *Global assessment of Dimethyl-Ether: Comparison with other Fuels*, SAE 971607. |

# 4 Dedicated renewable fuel-engine combinations

## 4.1 Introduction

This chapter explores the compatibility of renewable fuels and engine and aftertreatment technology, and describes developments with respect to dedicated combinations of renewable fuels and engine technology. This includes both low-blends in standard engines as well as high blends or pure fuels in dedicated engines. For the first group the emphasis is on possible compatibility issues, while for the second group, the differences with standard engines are described. The influence of the application of biofuels on exhaust emissions is presented in chapter 5 and 6 for respectively existing and future engines.

## 4.2 Biofuels in Spark Ignition (SI) engines

In Table 13 an overview is given of the compatibility between the renewable petrol based fuels and the spark ignition (SI) engines. In a number of cases the engine needs to be adapted to accept the renewable fuel.

For SI engines the following fuels can be used in near conventional engines:
1. ethanol: low or high percentage blends
2. butanol: low or high percentage blends
3. neat hydrous ethanol
4. biopetrol

Table 13 Compatibility of petrol based renewable fuels with SI engine technology

| Fuel | Special engine/ vehicle | Engine – fuel compatibility |
|---|---|---|
| **Spark ignition** | | |
| ETBE | No | Good |
| Low % blend ethanol | No | water segregation possible |
| High % blend ethanol | Yes, FFV | water segregation possible |
| Neat hydrous ethanol | Yes, E100 SI engine | Cold start with petrol |
| Low % blend butanol | No | Good1) |
| High % blend butanol | Yes, FFV | Good1) |
| Biopetrol | No | Excellent1) |

1) Expected compatibility, needs to be confirmed by R&D

Below the fuel engine combinations are described in more detail.

### 4.2.1 *ETBE*

Fossil ETBE is currently blended on a large scale in gasoline as octane improver. In that respect it replaces MTBE which was used before. MTBE was phased out because of toxicity risks (ground water contamination). ETBE can also be produced via bioethanol and (fossil) isobutylene. In that way a 17% ETBE blend with petrol would count as 5.75% bio-component on an energy basis.

### 4.2.2 *Ethanol low percentage blends*

Petrol with a low percentage of ethanol blended is already a standard fuel. The addition of 5% ethanol to petrol (E5) is within the standard fuel specification and many standard petrol vehicles produced after 1990 can run on E10 (with formal approval of vehicle manufacturer). According to an assessment in Germany 90% to 95% of the vehicles can run on E10 without technical problems. This does however mean that 5-10% of the vehicles does have or may have technical problems. Problems in this context refer to driveability or durability problems. The exhaust emissions of vehicles will change with low blend ethanol in petrol (refer to paragraph 5.9).

Low blends do not require many vehicle or engine adaptations. The most important one is that the materials used (metals, elastomers and coatings) for the fuel system can withstand the ethanol blends. In addition to that, the engine control software needs to be able to adjust the fuel-air mixture to the right values (in most cases stoichiometric) such that the catalytic convertor remains fully operational. For Euro 5, E5 will be the standard test fuel for the type approval test (refer to paragraph 6.3.2). This means that engine is optimised and calibrated for emissions with E5 instead of currently standard reference petrol (E0).

### 4.2.3 *Ethanol high percentage blends (FFV)*

High percentage ethanol blends (up to 85% in petrol) can only be used in Flexible Fuel Vehicles (FFV). Vehicles and fuel are already on the market for many years. The additional costs to make the engine fuel flexible are low. The FFV engine has engine control software which can adjust the engine to the different air-fuel mixture requirements for petrol and ethanol. In addition the fuel injection parts and tank need to be resistant to ethanol which is more aggressive to elastomers and metal parts. In order to have the same driving range on E85 the fuel tank needs to be about 30% larger due to the lower energy density of ethanol. This would probably also lead to a larger carbon canister in order to fulfil evaporative emission requirements.

Ethanol has a higher octane number than petrol. The engine efficiency can benefit from this. From [Serves de 2005] it can be concluded that the engine efficiency increases with E85 resulting in a 3% lower fuel consumption on an energy basis. From a theoretical point of view, it is to be expected that HC emissions just after cold start are higher than with petrol. This is because it is more difficult to vaporize ethanol than petrol. In general, it is believed that with the right amount of optimisation and calibration of the emission control system similar regulated emissions can be achieved as with 100% petrol. In this respect it is important that the emission requirements with E85 and other blends should be well implemented in the future emissions legislation.

The currently available FFV vehicles have engines where the fuel is injected in the inlet manifold. Building an engine with direct injection that can accommodate different petrol-ethanol ratios is more difficult, due to the differences in fuel quantity and (in-cylinder) spray pattern. [Taniguchi 2007] describes a direct injection engine optimised for E100 (100% ethanol). The engine has injectors with a higher fuel flow rate in order not to increase the injection duration. To make use of the better octane number of ethanol the compression ratio could be increased from 11.5:1 to 13:1. The engine torque increased with about 10% over a large part of the engine torque range. This is due to a combination of increased engine efficiency and volumetric efficiency. The engine showed an improvement in injector deposits formation when running on E100, but also on E50 and E20.

In the period up to 2020, more and more direct injection fuel systems will be seen on vehicles. It is likely that also FFVs will come on the market with direct injections, since Tier 1 suppliers are likely to provide direct injection systems which can be calibrated for a range of ethanol blends.
For FFVs the Euro 6 legislation will almost certainly also involve type approval testing with E85 on the NEDC cycle with cold start. Furthermore a -7° C test is foreseen, probably using E75, with separate limits for HC and CO. A proposal for amending the test procedure is to be approved by the CATP (Committee for Adaptation and Technical Progress). After introduction of Euro 6 limits, current elevated cold start emissions from FFVs will thus no longer be a problem.

### 4.2.4 *Hydrous ethanol*

Pure hydrous ethanol, also referred to as E100, for SI engines is studied in Brazil [Junior 2002]. Hydrous E100 contains about 5% water. However, as the maximum water content is not defined, it may be double that amount. A potential problem is impurities solved in the water. It may contain inorganic salts that may cause significant increase wear and injector clogging. Also exhaust catalysts are sensitive and will in future become even more sensitive for these salts.

The advantage of hydrous ethanol compared to “dry” ethanol is that it is reduced costs and improves chain efficiency. Removing the water, which is formally necessary with the use of ethanol in petrol blends, requires energy which also translates into higher costs.

Starting on pure ethanol below 15°C can create problems. This can be solved with a small petrol tank such that during engine warm up the engine runs on petrol. It is expected that emissions and fuel consumption will be on a similar level as E85, provided the engine is correctly optimized.

New in this area is the proposal to use hydrous ethanol also for blends with petrol, because of the above mentioned energetic and economic advantages. A disadvantage could be the increased risk of separation of water in the fuel tank, especially at concentrations below 10%. R&D and field tests on the use of hydrous ethanol petrol blends are still ongoing and results still need to be summarised.

OEMs are currently not supporting hydrous ethanol. They prefer the very low ethanol water contents, max 0.24 % to prevent segregation and corrosion. From a logistics point of view, there are considerable advantages to have one ethanol specification for both low and high blend percentages and possibly also for pure ethanol with ignition improver (for diesel engines).

### 4.2.5 *Butanol: low or high percentage blends*

BP and DuPont are currently promoting the use of (bio)butanol as an alternative to ethanol. The production process of butanol is quite similar to that of ethanol. Only different enzymes are necessary for the fermentation process of butanol from sugars. If this can be sufficiently industrialised and if factories become operational, butanol can be a good alternative to ethanol. BP and DuPont have presented the following advantages compared to ethanol:

- more compatible to petrol: i.e. lower influence on fuel vapour pressure and lower risk of water separation;
- higher energy density: combustion value closer to that of petrol.

Butanol and ethanol both have a high octane number which can lead to somewhat higher engine efficiency. The lower vapour pressure of butanol reduces possible problems with evaporative emissions such as reported for petrol engines running on low blend ethanol.

From a fuels properties point of view, it is expected that FFV engines can also run on a butanol-petrol mixture with no or little modifications.

### 4.2.6 *Biopetrol*

Shell and Virent have announced the joint development of biopetrol components which have higher energy content than ethanol and butanol [Shell 2008]. The biopetrol components are fully compatible with gasoline and can be used in conventional petrol engines. The biopetrol would not require a separate distribution infrastructure as would be the case for ethanol and butanol.

## 4.3 Biofuels in Compression Ignition (CI) engines

In Table 14 an overview is given of the compatibility between various renewable fuels and compression ignition (CI) engines.

Table 14 Overview of compatibility between the renewable diesel fuels and compression ignition (CI) engines

| **Fuel** | **Special engine/ vehicle** | **Engine – fuel compatibility** |
|---|---|---|
| **Compression Ignition** | | |
| Low blend biodiesel or FAME | No | Good |
| High blend biodiesel or fame | Yes, fuel system modifications | Injector wear, engine lubricant deterioration |
| BTL, HVO, GTL low or high blends | No | good |
| Pure hydrous ethanol with ignition improver | Yes, E95, CI engine | Good |
| Pure methanol with ignition improver | Yes, CI engine | Good |
| Dimethyl-ether (DME) | Yes, DME engine | Still in R&D phase |
| Special oxygenates | No | Good |

The compatibility between the engine technology and the renewable fuel (components) is described below.

### 4.3.1 *Biodiesel or FAME*

Any diesel engine will run on a diesel fuel containing up to about 7% FAME, Fatty Acid Methyl Esters. Above this percentage technical problems are reported with engine oil dilution. For this reason there is a recommendation from ACEA to limit the FAME content in standard diesel to 7% m/m (B7). A number of truck types are released for higher blends up to B100. Oil change intervals for these vehicles are reduced and more corrosion resistant materials and compatible elastomers are chosen for the fuel system.

The following technical problems are reported related to the use of FAME (see e.g. [Nylund 2008]):

- possible fuel injection equipment problems such as deposits formation on injector tips;
- hygroscopic properties and risk of microbial growth, filter clogging;
- corrosion of metals, dissolve of paint coatings and swelling of elastomers (seals, hoses);
- engine lubricant deterioration, including polymer or wax formation (reduced drain interval necessary).
- Increased $NO_x$ emission.

Vehicle manufacturers generally prescribe a factor 2 or 3 shorter oil drain interval for trucks that are released and are running on biodiesel (B20 – B100). Oil drain interval can be increased again in some cases by installing a larger oil sump and increasing the lubricant quantity. Also elastomer materials in the fuel system are replaced by biodiesel resistant ones and water-separators are installed. Engine out $NO_x$ generally increases somewhat, reason why for some Euro IV or V vehicles with SCR deNOx aftertreatment new software can be installed in order to bring back the $NO_x$ tailpipe emission to its original level.

In addition to this there are some risks with respect to the durability of emission control components such as catalysts, diesel particulate filters and EGR systems. These issues are likely to become more relevant with future engines due to the general application of diesel particulate filters and catalysts and the decreased temperature level within the EGR coolers.

The durability issues of exhaust aftertreatment systems are related to the possible presence of sodium, potassium or phosphor in biofuel. The first two are related to the production process of FAME, while phosphor can be present in the feedstock. [Brezny 2007] reported that alkali and alkaline impurities have the following detrimental impact on catalyst performance and durability:

- Substrate thermo-mechanical properties
- Washcoat surface area stability
- SCR catalyst acid site neutralization
- Precious metal dispersion and active site blockage

[Sugiyama 2007] reported that FAME is relatively unstable and readily generates acids such as acetic acid and propionic acid. Because of that oxidation degradation is accelerated. In general, problems can be decreased by adding 1000 ppm antioxidant additives (BHT) to the fuel.

It is also imaginable that the regeneration characteristics of the diesel particulate filter are changed as a result of the use of biodiesel, leading to a possible shorter lifetime of the filter. FAME possibly leads to a different particulate composition with oxygen containing hydrocarbons attached, which might lead to higher temperature gradients during active regenerations. This might shorten the filter’s lifetime.

### 4.3.2 *Synthetic diesel: GTL, CTL, BTL, HVO*

The synthetic diesel fuels consist of paraffins and iso-paraffins and are very similar to the standard components within diesel fuel (see e.g. [Koyama 2007] and [Rantanaen 2005]). It is generally acknowledged that synthetic diesel has no adverse effects on CI engines and that it can be blended in any ratio with standard diesel. ACEA also recommends to increase the biocomponents share within diesel fuel above B7 with synthetic diesels BTL and HVO (Hydro treated Vegetable Oil) such as NExBTL.

Synthetic diesel is characterised by a high cetane number and low aromatics. The cetane number is an indicator for the auto-ignition temperature. The higher the cetane number the easier and quicker the fuel will combust. In most engines the combination of high cetane and low aromatics this will result in lower $NO_x$ and particulates emissions. Synthetic diesel can be used as blend in standard diesel fuel in order to upgrade the cetane number or as a pure fuel with high cetane number. The advantages of high cetane diesel components will slowly diminish with newer technology CI engines (i.e. Euro VI). This is because the CI engines will be equipped with closed loop $NO_x$ control and diesel particulate filters and will consequently show a relatively constant tailpipe emission level. When vehicles are equipped with SCR deNOx aftertreatment this can result in a somewhat lower AdBlue consumption.

### 4.3.3 *E95: Hydrous ethanol with ignition improver*

Compression ignition of ethanol is already used by Scania for more than a decade. The main application is public transportation in the city of Stockholm, where some 600 buses are running on ethanol. World wide there are about 700-800 vehicles from Scania on ethanol.

Since ethanol has a very low cetane number, about 5% ignition improver is blended and the compression ratio is increased compared to a standard CI engine. The ethanol fuel also contains about 5% water. Because of the lower combustion value compared to diesel, the injection quantity and flow rate during injection are quite different. Due to the oxygen in the fuel the emission control possibility with EGR is better. Scania can deliver these engines in EEV (Enhanced Environmentally friendly Vehicle) specification without SCR deNOx aftertreatment and without diesel particulate filter.

[Rehnlund 2007] gives a good overview of the technical issues and possibilities. Ethanol without ignition improver can be combusted with glow plug assistance. In that way a single (anhydrous) ethanol specification can be used for both E95 compression ignition and E85 spark ignition. The air-fuel mixture in the tank with pure ethanol is explosive in a much wide ambient temperature range than other fuels, but in 15 years no accidents have occurred. [Rehnlund 2007] recommends developing a European fuel standard for ethanol to be used as pure ethanol. Compression ignition ethanol is expected to remain a niche application up to 2020, among others because engines are not readily available.

### 4.3.4 *Methanol with ignition improver*

Methanol with ignition improver for compression ignition engines is recently proposed (again) by Volvo [Volvo 2008]. It would require similar engine adaptations similar to ethanol with ignition improver: a special (high flow rate) fuel injection system and special optimisation of combustion and emission control systems. Methanol can be produced via biomass gasification where ethanol is produced via fermentation.

Methanol was popular as alternative fuel for primarily SI / flex fuel engines in the eighties and nineties of last century. It, however, was replaced by ethanol because ethanol can be produced renewably in an easy way. Methanol also got a bad name because of risks of toxicity when consumed or when spoiled to the ground water and because of safety issues due to the invisible flame. If methanol would be considered again as an alternative fuel, these issued would need to be addressed.

General disadvantage of oxygenate fuels such as methanol, DME and ethanol is the low energy content per litre fuel. This means a reduced driving range and/or an increased fuel tank size (up to a factor of 2). Especially commercial vehicle owners see this as a large disadvantage, since space on a tractor or truck is limited and driving range is very important.

### 4.3.5 *Dimethyl-ether (DME)*

Dimethyl-ether (DME) as an alternative fuel for CI engines has been extensively investigated by Volvo, AVL, BP, Haldor Topsoe and also TNO. Currently the emphasis of the R&D is in South East Asia and Volvo is working on a third generation system. DME can be produced from natural gas or from renewable feedstock (same feedstock and similar process as GTL/BTL).

DME is basically a very nice “compression ignition” fuel, because it has a very low auto ignition temperature and it vaporizes to a gas almost instantaneous after injection. Because of these characteristics the $NO_x$ and PM emissions are intrinsically very low in a correctly optimized engine and without complex aftertreatment systems such as SCR deNOx system and diesel particulate filter.

Unfortunately DME has also some disadvantages:

- It is a liquid gas (similar to LPG) which requires a special fuel system both for the low and high pressure side;
- Even in liquid phase it is relatively compressible and characteristic are sensitive to temperature. This requires a special fuel injection system even though the fuel injection pressure is much lower than for diesel fuel;
- It is relatively aggressive to elastomers;
- It would require a new infrastructure for fuel distribution.

Volvo has built several demonstration vehicles within European or Swedish national programs. The Energy Technology Research Institute of Japan published a field test with a DME truck in which 13,000 km was accumulated [Mitsuharu, 2007]. The engine had a $NO_x$ level of about 2.5 g/kWh; 27% below the Japanese 2003 regulation. Particulates emission is practically absent due to the instantaneous evaporation of DME after injection. It is expected that with DME the Euro VI emission level can be achieved without $NO_x$ aftertreatment.

Series production of DME vehicles is uncertain at this stage. A prerequisite for that would be an agreement between government and industry to stimulate such a vehicle technology and the required fuel infrastructure. DME is a more practical fuel than for example hydrogen or natural gas because it is a liquid gas. Well to wheel efficiency might be among the best in comparison to other renewable fuels [Volvo 2008], [Verbeek 1997]. DME can also serve as a practical energy carrier for fuel cell vehicles. It can be concluded that up to 2020 DME will at best be a niche fuel for captive fleets or for fuel cell vehicles.

### 4.3.6 *Special oxygenate for diesel fuel*

FAME, PPO, ethanol and butanol are all oxygenate fuels. FAME, PPO and ethanol when blended with diesel fuel often have a positive effect on the particulate emissions of compression ignition engines: these tend to go down although this is very dependent on the engine type. In [Kadijk 2008] it was concluded that with FAME the PM emission reduction varies between 0% and 60%, while for PPO this is between 8% and 71%. This is of course a very positive effect although further research is needed with respect to possible toxicity of the exhaust gases. On the other hand $NO_x$ can increase somewhat.

Well known are fuels with ethanol blends, delivered under the names E-diesel and $O_2$-diesel. Ethanol contents are respectively 10% and 7% by volume. This does lead to reduced energy content per litre fuel of 3-4% and also to a similar power reduction of the engine. Effects found on particulate emission range from 0-30% reduction.

Research is ongoing into specially designed or chosen oxygenates which could be (much) more effective than standard oxygenate fuels or additives. These are for example complex species like: DiButylMaleate (DBM), Tripropylene Glycol Monomethyl Ether (TPGME), Tri-ethylene Glycol Dimethylether and Glycerol Tertiary Butyl Ethers (GTBE). In [Boot 2007] some of these species are investigated and compared with standard diesel, syndiesel and also ethanol-syndiesel blend using an engine with EGR. The blend percentages range from 6% to 15%. It appeared that under certain conditions the blends with TPGME and ethanol were very effective: PM emissions were 5 to 8 times lower than with standard diesel. Further research would be needed to demonstrate the performance across the engine map and with different engine types. Also compatibility with metals and elastomers should be checked or investigated. [Eijk 2008] diesel with low percentages GTBE and other bio-component blends with diesel fuel were investigated in a passenger car diesel engine. It was showed that 2% GTBE blend or 1% GTBE blend plus 4-5% biocomponents were effective in reduction of particulate emissions: 5-35% reduction depending on test cycle.

Oxygenate blends or additives can be considered as a method to clean up existing, relatively conventional engines (Euro 3 and older). In that case it should be checked whether the oxygenate is economically affordable and can be produced in sufficient quantities. Also fuel properties with respect to safety, such as the vapour pressure, should remain within the official fuel specification.

For future engines equipped with wall flow diesel particulate filters, the advantage of the lower particulates emissions resulting form oxygenate fuel disappears to a large extent: with wall flow filters the diesel particulate emissions will be very low anyhow. An advantage in that case might be a reduction of the number of active regenerations of the diesel particulate filter, which might lead to a fuel consumption saving of up to 1 or 2%. An oxygenate additive might also prevent plugging of a retrofit diesel particulate filter (for vehicles where regeneration is critical).

For the future engines the possible use of oxygenate fuels or blends actually has a large influence on the required development effort. This is because the performance and durability of engine and emission control systems have to be secured for the whole range of different fuels that are likely to be used. Increasing the spread in characteristics of available fuels by means of allowing varying degrees of oxygenate contents means a lot of (costly) engine dynamometer and field durability testing and possible product adaptations. For this reason the general introduction of oxygenate blends in diesel fuel is probably not feasible. The use of oxygenate blends can be considered for the use in captive fleets and should probably be limited to Euro 3 vehicles and older.

### 4.4 Conclusions

Regarding dedicated engine-fuel combinations the following conclusions can be drawn:

- Besides by blending into petrol and diesel for conventional vehicles, biofuels can also be used as high-percentage blends or neat fuels in dedicated vehicles. Likely candidates for application in the near and longer term future are:
  - Flex Fuel Vehicles with SI engines running on E85 (or possibly high percentage butanol/petrol blends);
  - HD engines running on B20 - B100 (100% FAME biodiesel);
  - Hydrous E100 ethanol with ignition improver used in CI engines (for niche markets);
- Use of synthetic petrol and diesel (GTL, BTL) as neat fuel is not expected as the premium fuel qualities makes these fuels ideally suitable for blending into conventional petrol and diesel. For use as neat fuel GTL does not require engine adaptations. But various engine modifications (e.g. changing compression ratio, injection rate and timing etc.) can be applied to make better use of the specific fuel properties, allowing for further reduction of emissions.
- It is highly unlikely that future mainstream engines will be designed to run on a wide variety of fuel specifications related to the application of various types and percentages of biofuels. Such flexibility will be too expensive due to advanced emission control systems (including OBD) and the need for high reliability and low maintenance.

Considerations on the application of biofuels in spark ignition engines leads to the following conclusions:

- The compatibility of ETBE with petrol is excellent but ETBE is only partially renewable.
- Up to 10% ethanol blend in petrol (E10) can be used in most vehicles without problems. It is probably sensible to keep E5 available for old vehicles.
- Additional complexity and costs of FFV vehicles for use of high percentage blend ethanol in petrol is limited. Development of Direct Injection FFV vehicle is more complex.
- Little information is available for butanol and biopetrol. Butanol in high blend percentage with petrol would also require a FFV vehicle. Biopetrol is expected to be fully compatible with standard petrol.

Concerning the application of biofuels in compression ignition engines the following conclusions can be drawn:

- Use of FAME for passenger cars will remain limited to low blend (B7) due to the post injection technology used for DPF regeneration.
- A number of diesel trucks are released for higher blends B20 to B100. It is expected that the availability of trucks suitable for B100 can be increase towards 2020 if desired. Use of high blend FAME will require some adaptations and affect oil drain intervals.
- BTL, HVO and GTL can be used in any blend percentages without any adverse effects on engine maintenance. Their high cetane number in combination with low aromatics leads to leads to lower emissions, especially in conventional diesel engines.
- Use of pure ethanol or methanol with ignition improver does require special CI engines. Within a reasonable period (5-10 years) more engines could be made available on a larger scale if desired. These fuels are not expected to be attractive to

commercial vehicle owners because of the much lower energy content of the fuel (up to a factor of 2). Also a European wide fuel infrastructure would be required. It is currently seen as suitable for niche application such as for captured fleets (i.e. city buses).

- Dimethyl-ether (DME) does require an all new engine and currently has limited support. Consensus would be needed within industry and government, before this can be developed as an automotive fuel.
- Oxygenate blends in diesel fuel (FAME, ethanol and special oxygenates) can be effective for particulate emission reduction, but primarily for Euro 3 and older engines. More R&D would be required to prove the effectiveness for a wide engine range. Compatibility with diesel engines with advanced emission control devices might be a problem.
- A special low cetane fuel for premix combustion or HCCI engines has substantial advantages and even is a prerequisite for application of the HCCI combustion concept over the full range of the engine map. It is however considered not likely that special engines will be developed and marketed for this type of fuel by 2020.

## 4.5 Literature

| | |
|---|---|
| [Boot 2007] | Boot, M. et. al. (2007), *Oxygenated fuel composition impact on heavy-duty diesel engine emissions*, JSAE 20077293 / SAE 2007-01-2018 |
| [Brezny 2007] | Brezny, R. (2007), *Potential Particulate Trap Substrate and Catalyst Impact with Sodium and Potassium Contamination*, Manufacturers of Emission Controls Association (MECA), Biodiesel Technical Workshop October 17-18, 2007, www.meca.org. |
| [Eijk 2008] | Eijk A. (20080, *The influence of GTBE on the emissions of a diesel passenger car,* TNO report MON-RPT-033-DTS-2008-00786, date March 7, 2008 |
| [Junior 2002] | Junior, H.J. (2002), *Vehicular Ethanol Fuel, Technical & Exhaust Emission Experience in Brazil*, Brazilian Automobile Manufacturers Association, ERDC Project No. 2511, 2002? |
| [Koyama 2007] | Koyama, A. et al. (2007), *Vegetable Oil Hydrogenating process for automotive fuel*, SAE number 2007-01-2030, JSAE 20077163. |
| [Nylund 2008] | Nils-Olof Nylund, Päivi Aakko-Saksa & Kai Sipilä (2008), *Status and outlook for biofuels, other alternative fuels and new vehicles*, VTT Tiedotteita research 2426, 2008, http://www.vtt.fi/inf/pdf/tiedotteet/2008/T2426.pdf |
| [Rantanaen 2005] | Rantanen, L. et al. (2005), *NExBTL – Biodiesel fuel of the second generation*, SAE paper 2005-01-3771. |
| [Rehnlund 2007] | Rehnlund B. et al. (2007), *Heavy-duty ethanol engines: Final report for Lot 2 of the Bioscopes project*, February 2007, EC project TREN/D2/44-LOT 2/S07.54739 |

[Serves de 2005] de Serves, C. (2005), *Emissions from Flexible Fuel Vehicles with different ethanol blends*, AVL MTC AB report 5509, date 2005/10.

[Sugiyama 2007] Sugiyama, G. et al. (2007), *Oxidation Degradation and Acid Generation in Diesel Fuel Containing 5% FAME*, SAE paper 2007-01-2027

[Taniguchi 2007] Taniguchi, S. et al. (2007), *Feasibility Study of Ethanol Applications to A Direct Injection Gasoline Engine*, SAE paper 2007-01-2037

[Verbeek 1997] Verbeek, R. (1997), *Global assessment of Dimethyl-Ether: Comparison with other Fuels*, SAE paper 971607

[Volvo 2008] Volvo publication (2008), *Climate issues in focus*, http://www.volvo.com/group/global/en-gb/volvo+group/ourvalues/environment/renewable_fuels/

# 5 Emissions of current biofuels in existing vehicles

## 5.1 Introduction

Biofuels have been launched on the current fuel market in order to realise a WTW-$CO_2$ reduction. Many biofuels have been introduced on the market and are offered in two concepts: Biofuel as low blend in regular petrol/diesel or biofuel as high blend/neat fuel. The latter require dedicated vehicle technology. Up to 2010 for road transportation purposes the biofuel share (on macro scale) will be increased to 5.75 % (energy content). However the effects of biofuels on vehicle emissions are not well known. Biofuels may positively or negatively influence exhaust emissions, evaporative emissions, driveability of a vehicle, maintenance schedules or sustainability of a fuel system.

Originally the current fleet is developed with a standard fuel specification (petrol: EN 228 and diesel: EN 590). These fuel standards allow a maximum of 5 vol% biofuel. During vehicle development the main focus has been put on compatibility of fuel and hardware (tank, fuel lines, pump, injectors and gaskets). In this way the fuel-fuel system compatibility is secured. However the vehicle emission type approval tests are carried out with fossil fuel, the effects of a biofuel share are unknown.

This chapter presents the results of a literature review, carried out by TNO on behalf of SenterNovem, on the possible impacts of the use of biofuels and alternative fuels in the short to medium term on emissions of existing vehicles. All biofuels are reported separately and the publications have been selected on their quality and applicability. The emission data are laboratory data and collected from different sources, all of which strongly influence emission levels. Despite the conditioning in these laboratories a lot of circumstances are different, the experiments are carried out with different vehicles (technologies), different (bio)fuels, different test equipment and different test cycles. As a consequence of this diversity the test results also show a large spread, and a similar spread is expected in real-world emissions. The relationship biofuels-emissions is very diffuse because vehicle technology and human behaviour are two primary factors which influence this relationship.

The results of this study can be used as an indicative only, because of the restricted available amount of emission data. Emission results per fuel are plotted in graphs, EN 228 petrol or EN 590 diesel are applied as reference fuels (100% emision levels).

Currently ethanol and FAME are major players in the biofuel market. Ethanol/FAME reduce WTW CO2 emissions but the results of this study show that regulated pollutants can increase or decrease, their effect on regulated emissions is not clear. Obviously application of biofuel does not result in a win-win effect.
Generally a captive fleet on biofuel offers the best conditions for possible emission benefits (CNG city buses with biogas or diesel city buses with biodiesel). In order to guarantee a local emission decrease every captive fleet must be analysed, a biofuel-vehicle technology/emission reduction assessment is required.

### 5.2 Fuel-engine combinations for the short term (now – 2020)

Table 15 presents the fuel-engine combinations for the short term as considered in this chapter. The list is not based on considerations regarding the likelihood of the various applications for the short term but rather on the Terms of Reference for the SenterNovem assignment. Information on the impacts of these engine-fuel combinations on exhaust gas emissions is relevant for short term R&D and taxation policies aiming at stimulating development and market entry of biofuels.

Table 15 Studied fuel-engine combinations for the short term

| SI engines | | | CI engines | | |
|---|---|---|---|---|---|
| **petrol low % blends** | **high % blends neat fuels** | **gaseous fuels** | **diesel low % blends** | **high % blends neat fuels** | **gaseous fuels** |
| E2 – E5 – E10 ethanol | E85 ethanol | LPG* | B2 – B5 FAME | PPO | bio-DME |
| ETBE | wet ethanol | CNG / LNG | | B100 FAME | |
| | E95 / E100 | CBG**** / LBG(biogas) | | E95 / E100*** | |
| | | | BTL/HVO | BTL/HVO | |

*) LPG in G3 and non-G3 engines

**) 95% ethanol / 4-6% water,

***) 95% ethanol / 5% ignition improver (AVOCET) / 4-6% water, mainly for application in HD engines

****) CBG Compressed Bio Gas is not directly used in vehicles, but upgraded to natural gas quality and distributed via de natural gas grid

## 5.3 General considerations

### 5.3.1 *Selection of literature for this study*

A number of recent review studies were identified and these studies have been used as a basis for this screening study. In addition, papers and reports that were published from 2004 onwards have been included in order to present the most up-to-date information and to capture ongoing developments in this area. Information from studies before 2004 has been included only if it presents added value to the most recent knowledge (e.g. unique study, relevance with respect to current or future vehicle technologies). Most references report test results of Euro 2 and 3 vehicles.

### 5.3.2 *Biofuels and exhaust emissions*

In response emission legislation large reductions in vehicle emissions have already been realised over the past two decades due to improved engine and aftertreatment technologies. As engine and aftertreatment technology on production vehicles have changed rapidly, the results of emission measurements in older studies have to be interpreted with care and may overestimate the potential for emission reductions by the use of alternative fuels in current and future vehicles. On the other hand, available emission data on the performance of biofuels are largely based on retro-fitted or bi-fuelled (flexible fuelled) vehicles. This may underestimate the potential emission reductions that can be achieved with alternative fuels in dedicated vehicles and through optimised engine design.

For petrol vehicles the use of a three-way catalyst with closed-loop lambda control has enabled emission reductions of a factor of 20 for most emission components. For the next ten years further emission reductions are foreseen with the introduction of Euro 6 emission limits. [TNO 2003a] shows that even further reductions are feasible and that petrol vehicles will be able to reach so-called zero-effect level emissions. Obviously, for these vehicles it will not be possible to gain large emission benefits in absolute terms for specific pollutants by switching to certain alternative fuels. As the closed-loop control of the engine and aftertreatment system is able to adapt to and compensate for changes in fuel quality, the impacts of fuel characteristics on emissions and performance are reduced and complex in nature. Nevertheless, some relative differences in emissions between conventional and alternative fuels should still exist.

For diesel vehicles the progress in emission reduction is considerable due to the introduction of Euro 4 and Euro 5 technologies. Emission legislation for diesel vehicles is more stringent and it is expected that Euro 6 emission levels for diesel and petrol passenger cars are equal.

Impacts of the use of biofuels are therefore expected to be more prominent in diesel engines without aftertreatment systems than in spark ignition engines as used in petrol vehicles. The impacts are particularly relevant as diesel vehicles (passenger cars and trucks) have a relatively high share in the $NO_x$ and PM emissions that pose problems with respect to national emission targets and local air quality. For the near future significant potential for emission reductions is generated by the development of engine EGR-technology, diesel particulate filters and effective $NO_x$ reduction technologies such as $NO_x$ storage catalysts and SCR-deNOx. These technologies will be applied on a large scale with the introduction of Euro 4, 5 and 6 emission limits for diesel vehicles. As with the case of petrol vehicles and Euro 6 diesel vehicles described above, the use of effective aftertreatment will reduce the possible emission benefits associated with the use of alternative fuels in diesel engines.

Several publications have directly averaged published emissions data to compare the emissions performance of (equivalent) vehicles using either alternative fuels or conventional petrol or diesel fuels. From a statistical point of view, this approach raises the question of significance of the results. For instance, it could be that, although emission results differ substantially, they are in fact not statistically significant due to e.g. a small sample size or large variation in emission results among test vehicles. Already for vehicles on conventional vehicles a large spread can be observed in the emissions of vehicles of the same type or of comparable vehicle types. Establishing statistically significant results in experimental emission studies therefore requires testing a large number of vehicles and proper statistical handling of the test results.

Due to the different test procedures for Light and Heavy Duty vehicles the LD and HD emission trends should be investigated separately. A LD vehicle test starts with a cold engine and a HD engine emission test starts with a hot engine. Cold and hot engine operation with biofuel may lead to different emission effects.

In this study emission results are collected and relatively plotted in graphs. If the base emission levels of a vehicle are low, the relative effects of the application of a biofuel

blend might be enormous. Especially NOx emissions in petrol cars are very sensitive and in some cases the biofuel emissions can increase 800 - 1200%. If a substantial amount of these cars run on biofuel they can be marked as "a very high emitting category" and their impact on the total fleet emission is also substantial.
The different studies/publications are carried out with different vehicles, fuels, laboratories and test cycles. The emission effects of biofuel to all these different circumstances must be taken into account.

### 5.3.3 *Biofuels and fuel consumption*

The density and heating value of the biofuels studied in this report is generally different from that of conventional petrol or diesel. With the same engine efficiency (expressed in MJ engine output divided by MJ fuel input) the fuel consumption expressed in l/100 km will therefore generally be different. From an overall energy point of view this is not a very relevant issue as vehicle efficiency should be measured in MJ/km. For the consumer, however, higher volumetric fuel consumption leads to reduced vehicle autonomy with the same tank size. For the distribution infrastructure lower energy content also has consequences as transporting and storing larger volumes generally induces higher costs.

### 5.3.4 *Biofuels and $CO_2$*

With respect to $CO_2$, this report only considers exhaust emissions of $CO_2$ for the different fuels. Well-to-wheel aspects are not taken into account. When comparing direct $CO_2$ emissions from the use of biofuels and conventional fuels the differences are caused by two factors:
- difference in the engine efficiency for the different fuels;
- difference in the C/H ratios of the fuels.

### 5.3.5 *Biodiesel and petrol as low blend in automotive fuel*

Since 2007 most European fuel suppliers are obliged to sell a certain percentage biofuel. In 2007 in The Netherlands 2% (on energy basis) of the total sold volume is biofuel. The required amount of biofuel can be sold pure or added to the petrol/diesel main stream. As a consequence of this standard every batch in a filling station may have a different content of biofuel. Nowadays it is a minor issue but in 2020 the biofuel content of automotive fuel may vary substantially (between 0 and 10%). Due to this possible biofuel content variation adaptive engine management control might be needed.

Table 16 Required content (energy base) on macro scale of biofuel in petrol and diesel in The Netherlands

| | Minimum share | | |
|---|---|---|---|
| | in the total amount of fuels sold for road transport | in petrol | in diesel |
| 2007 | 2% | 2% | 2% |
| 2008 | 3,25% | 2,5% | 2,5% |
| 2009 | 4,5% | 3% | 3% |
| 2010 | 5,75% | 3,5% | 3,5% |
| 2020 | 10%* | | |

* Proposed in EU 23.1.2008

Source: Besluit Biobrandstoffen, Staatsblad, 2006

### 5.3.6 *Biofuels and exhaust aftertreatment systems*

Most petrol LD cars are equipped with stoichiometric engines with closed loop adaptive emission control. The possible effects of biofuels mainly are eliminated by the lambda control system. If the lambda control system has sufficient adaptive performance it will be able to handle different fuel qualities in a specific range.

Diesel vehicles with Euro 4,5 and 6 technology mostly have aftertreatment systems with different conversion rates. An engine aftertreatment system with high conversion rate (80-95%) generally is less sensitive for biofuel. The absolute emission levels are relatively low and the effects of biodiesel (blends) are small. If aftertreatment systems are equipped with closed loop control ($NO_x$ sensor) the effects of biodiesel might even be compensated by the emission control system.

## 5.4 LPG (G3 and non-G3)

LPG (Liquified Petroleum Gas) is a propane/butane mixture and its origin is from crude oil, it is not produced from biomass.

LPG-vehicles mostly are bi-fuel vehicles and are equipped with uncontrolled (non-G3) fuel systems or controlled (G3) fuel systems. Simple LPG installations (non-G3) mix air and fuel with a carburettor, it is a system without air/fuel control device. The more advanced LPG installations (G3) have a lambda controller which will result in better catalyst performance. Due to the bi-fuel concept most LPG vehicles start on petrol and after 1-2 minutes engine operation is switched to LPG.
LPG vehicles are offered as OEM vehicle and as retrofit configuration. Generally the quality standard of OEM vehicles are higher than retrofit vehicles.

Nowadays LPG retrofit non-G3 systems are technically equal to G3 systems. Liquid or gaseous LPG is sequentially injected in the inlet ports of an engine. These systems can be implemented in nearly all petrol cars. The LPG-kit manufacturer is able to cover the whole market with one system. G3 as well as non-G3 LPG systems run with closed loop control. The G3 class is certified and vehicle emissions must comply with emission legislation. Exhaust emissions of the non-G3 class are not optimised and not certified, LPG tax of non-G3 vehicles is higher than G3 vehicles. Practically high volume series the LPG systems are certified, low volume series are not certified.

### 5.4.1 *Emission Impacts*

LPG is not produced from biomass so there is no bio-related emission benefit. Most bi-fuel vehicles start on petrol and after some warming up LPG operation is activated. Bi-fuel emission effects of LPG fuelled vehicles must be related to their petrol operation periods. The cold start and warming up effects of petrol are discussed in the accompanying chapters.

Data of non-G3 systems are not available. Practically exhaust emissions of non-G3 systems are expected to be good. The lambda controller is active but not optimised.

#### 5.4.1.1 *Regulated pollutants*

The emission benefits (CO, $NO_x$, PM) of LPG are reasonably well-established. Experimental studies [e.g. TNO 2003b] have shown that OEM-equipped Euro 3 passenger cars on LPG produce regulated tailpipe emissions equivalent to or lower than those of petrol vehicles.

In 2003 retrofit LPG vehicles were tested by TNO [TNO 2003c]

Table 17: Relative test results of retrofit LPG vehicles (100% = petrol) [TNO 2003c]

| **cycle name** | **CO [%]** | **HC [%]** | **NOx [%]** | **Average speed [km/h]** | **Driving dynamics [RPA]** |
|---|---|---|---|---|---|
| urban hot (UDC) | +857 | +588 | +82 | 18.7 | 0.14 |
| extra urban (EUDC) | +183 | -44 | +408 | 62.6 | 0.09 |
| CADC Urban | +754 | +87 | +113 | 17.5 | 0.30 |
| CADC Road | +61 | -23 | +69 | 60.3 | 0.16 |
| CADC Highway | -2 | -63 | +438 | 116.4 | 0.10 |

UDC: Urban driving Cycle (0 – 50 km/h), type approval test cycle
EUDC: Extra Urban Driving Cycle (0 – 120 km/h), type approval test cycle
CADC: Common Artemis Driving Cycle (0 – 130 km/h), real world driving cycle.

For detailed time-speed profiles see Appendix E.

During the cold start and warming up vehicles equipped with (non-)G3 LPG systems mostly have a similar emission behaviour as petrol vehicles, because a LPG vehicle is started and warmed up on petrol. Due to the high costs of the optimisation of a LPG cold start emission control strategy the petrol strategy is prefered. In case of an increased biofuel petrol content G3 and non-G3 LPG vehicles have a similar emission behaviour. No special effects are expected due to the increased biofuel content.

[TNO 2003b] investigated in 2003 the emission performance of petrol, diesel, LPG and CNG LD-vehicles.

Figure 5.1 Relative emissions LPG-G3 vehicles [TNO 2003b]

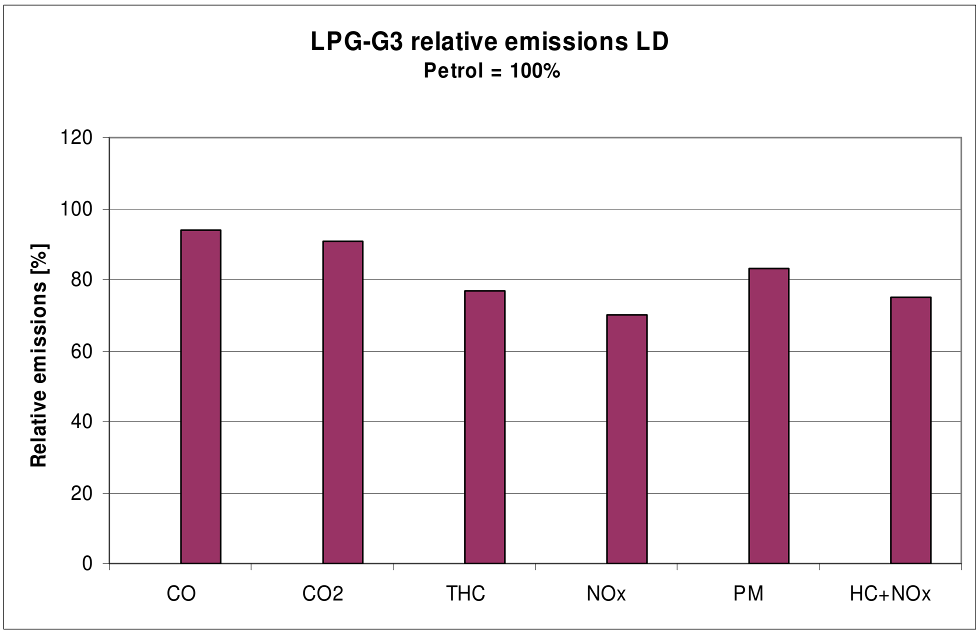


Table 18 Emissions different fuels Euro III LD vehicles [TNO 2003b]

| | | Average driver | | | | |
|---|---|---|---|---|---|---|
| | | Petrol | Diesel | LPG | Rel. LPG-petrol | Rel. Diesel-LPG |
| | | | | | [%] | [%] |
| $NH_3$ | [mg/km] | 17.3 | 0.9 | 50.6 | 292 | 2 |
| $SO_2$ | [mg/km] | 8.9 | 3.7 | 2.8 | 31 | 132 |
| $N_2O$ | [mg/km] | 3 | 7 | 3 | 100 | 233 |
| NO | [g/km] | 0.07 | 0.33 | 0.05 | 71 | 660 |
| $NO_2$ | [g/km] | 0.02 | 0.37 | 0.01 | 50 | 3700 |
| OC | [mg/km] | 1.1 | 11.5 | 0.4 | 37 | 2875 |
| EC | [mg/km] | 0.6 | 26.1 | 0.2 | 33 | 13050 |
| CO | [g/km] | 1.48 | 0.10 | 1.39 | 94 | 7 |
| HC | [g/km] | 0.13 | 0.02 | 0.10 | 77 | 20 |
| $NO_X$ | [g/km] | 0.10 | 0.80 | 0.07 | 70 | 1143 |
| $HC+NO_X$ | [g/km] | 0.24 | 0.83 | 0.18 | 75 | 461 |
| PM | [g/km] | 0.006 | 0.046 | 0.005 | 83 | 920 |
| $CO_2$ | [g/km] | 208.1 | 180.5 | 189.3 | 91 | 95 |
| FC | [l/100km] | 8.86 | 6.78 | 11.74 | - | - |

Except for ammonia emissions, LPG vehicles perform better then petrol vehicles.

There are considerable quality concerns with respect to retrofit systems which will lead to higher real world emissions. This was demonstrated with the evaluation of the Dutch LPG fleet in the period form 1999-2003. Although the quality seamed to go up for newer regeneration retrofit systems, these concerns remain. Due to the series size of retrofit system per vehicle type, the development and durability testing is very small in comparison to that was done for the original fuel by the engine manufacturer.

In table 5.4 the comparison for diesel and LPG vehicles is made for Euro 3 LD vehicles. For most emission components LPG vehicles perform better than diesel vehicles. Diesel vehicles only perform better for CO, HC, $NH_3$ and $CO_2$ emissions.

For Heavy Duty applications LPG is not often applied as automotive fuel. The relative low MON-number of LPG (89-93) only allows low engine compression ratios, engine efficiency is poor.

#### 5.4.1.2 *Unregulated components*

Figure 5.2 report an overall result of the emission performance of a LPG vehicle. Due to the fact that those vehicles are bi-fueled (petrol and LPG) a very good comparison can be made. In general LPG vehicles with current technology have equal or better emission performance then petrol vehicles.

The most outstanding points are:

- The overall evaluation shows that for a hot engine the human health effects are very low in the case of SI engines.
- In local situations (with cold start) LPG has a low impact potential.

- It is assumed that the additional cold start emissions from the LPG (and CNG) engines are primarily caused by their starting on petrol. If the content of biofuel is increased no significant increase of exhaust emissions is expected.
- In general the gaseous fuels show the lowest emissions for the average driver, and diesel the highest emissions.

Figure 5.2a Emissions and emission profiles: Average driver [TNO 2003b]

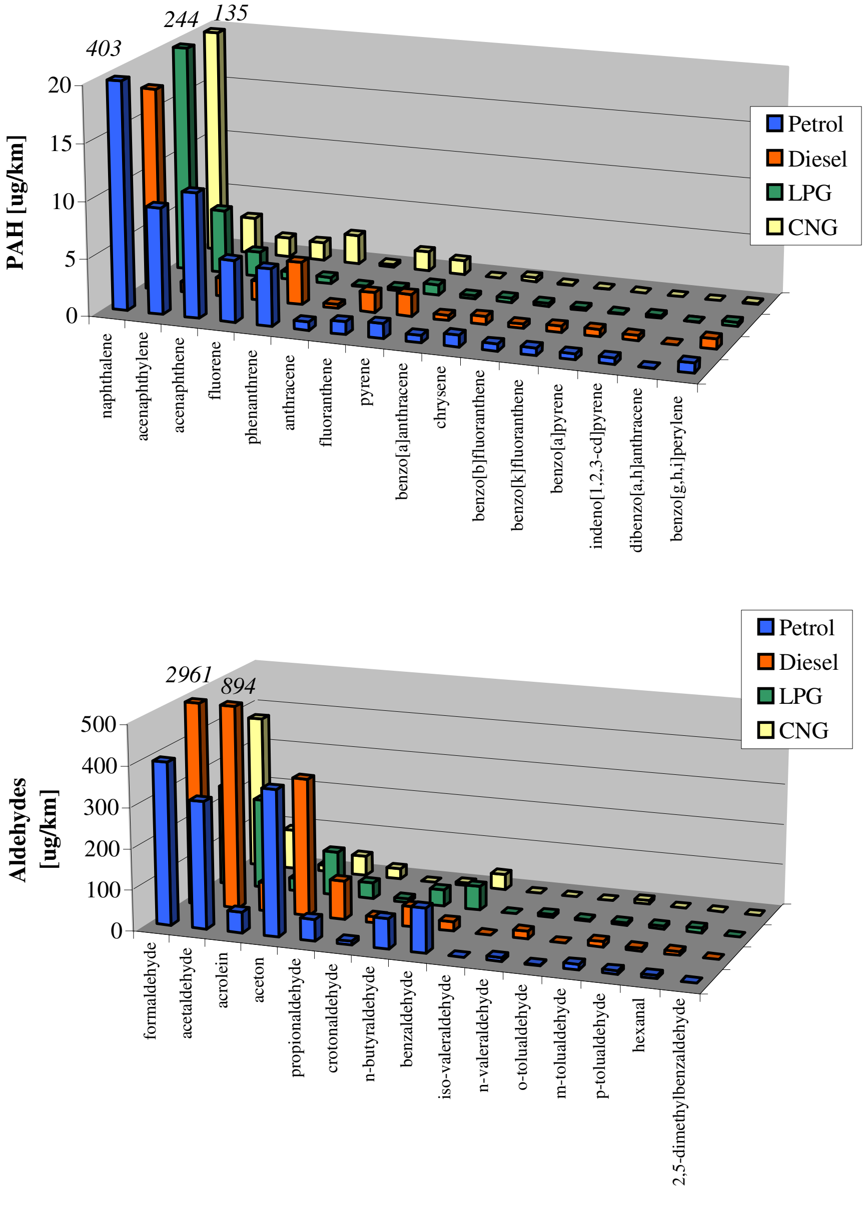
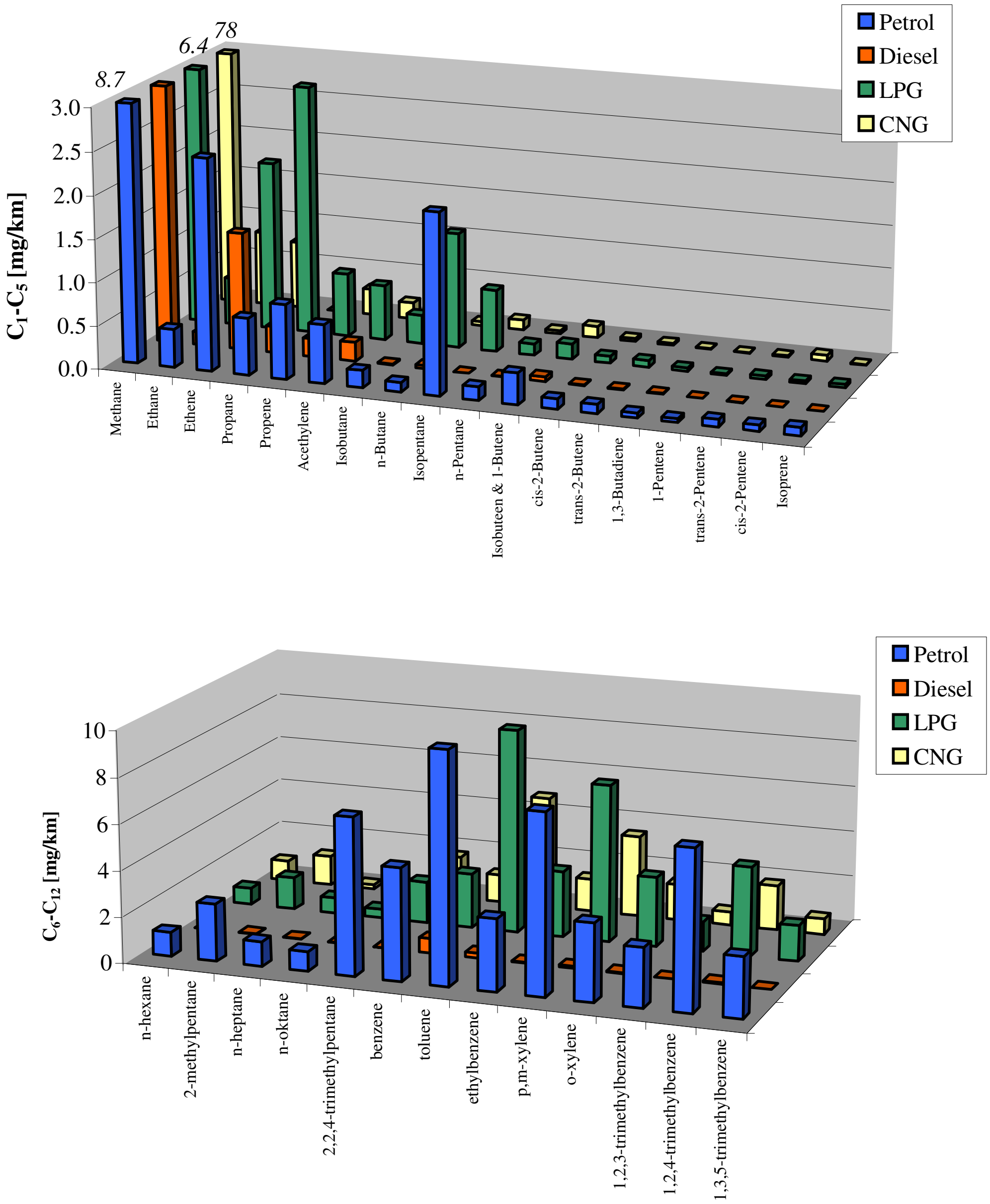


Figure 5.2b Emissions and emission profiles: Average driver [TNO 2003b]



### *5.4.2 Exhaust Gas Aftertreatment & Evaporative Emission Reduction*

Monofuel LPG vehicles have pressurised fuel systems. Normally hydrocarbon emissions due to leakage are negligible. If LPG is applied in a bi-fuel concept (petrol based) car evaporative emission behaviour aspects are also negligible. In case of increase of biofuel content in petrol no emission effects in the aftertreatment system are expected for LPG vehicles.

### *5.4.3 Fuel specifications*

LPG automotive fuel specification is described in EN589. Bio aspects are not applicable for LPG. No special attention is needed for the EN589 standard.

### 5.4.4 *In-use compliance emissions*

Most LPG vehicles are equipped with retrofit systems. In 2003 TNO investigated emission performance of Euro 2 and 3 LPG vehicles [TNO 2003c]. The most outstanding conclusions are:

- LPG-equipped retrofit vehicles exceed more often emission limits than petrol vehicles
- Practical emissions of LPG retrofit vehicles are far higher than petrol vehicles. NOx can be 3 times higher, HC and CO emission levels are 4-7 times higher. These statements are based on measurements in Poland and The Netherlands.
- Emissions of OEM LPG vehicles are below the limits [TNO 2003b].

### 5.4.5 *Conclusions*

LPG offers emission benefits to petrol if the LPG-installation has been installed by the vehicle manufacturer (OEM), retrofit LPG installations generally offer emission detereorations. LPG is a fossil fuel and applied in The Netherlands as a third possibility (after petrol and diesel). LPG vehicles which are built by car manufacturers (OEM) have a good quality standard and comply with emission standards. The emission levels of an OEM LPG vehicle are somewhat lower than petrol vehicles.
The emission behaviour of retrofit G3-LPG vehicles often exceed the legislative emission levels. Due to the type approval family approach of a group of vehicles, the restricted amount of required emission tests and the different installation companies some vehicles exceed their type approval emission limits.

For most emission components LPG Euro 3 vehicles perform better than Euro 3 diesel vehicles. Diesel vehicles only perform better for CO, HC, $NH_3$ and $CO_2$ emissions.

Biofuel effects of LPG-vehicles are not related to LPG but to their petrol operation periods. The cold start and warming up periods are relatively short and can be neglected.

## 5.5 CNG/Biogas

Biogas is derived from renewable materials such as sewage, landfills and agricultural waste by means of anaerobic fermentation. Depending on the source the composition of biogas differs greatly, with methane contents varying between 65 - 85% for biogas from agricultural waste, and 30 - 70% for landfill gas. Besides $CO_2$ the remainder may contains air ($O_2$ and $N_2$), water vapour and for some processes also hydrogen ($H_2$) and carbon monoxide (CO), and other impurities.

Raw biogas can be used in (stationary) combustion engines, but for use in modern vehicles upgrading to natural gas qualities is generally required.
For biogas upgraded to natural gas quality the regulated emissions may be expected to be similar to those of vehicles running on natural gas. The WTW $CO_2$ reduction of biogas (compared to natural gas) is about 75% [EU 2008].

Natural gas and biogas mostly are applied in spark ignition (otto) engines. For passenger cars stoichiometric engines ($\lambda = 1$) with a three-way catalyst are most commonly used. In heavy-duty applications both stoichiometric and lean burn ($\lambda > 1$)

engine concepts are used. Stoichiometric NG engines generally have emission advantages, while lean-burn NG engines generally have a better fuel efficiency. Natural gas and biogas can also be used in engines operating on the compression ignition principle. There a two options for doing this:

- diesel pilot injection: In this technology pilot injection of diesel is used to ignite the natural gas. These engines thus consume two fuels simultaneously. These are referred to in the industry as dual fuel engines (not to be confused with bi-fuel vehicles that can operate on either natural gas or gasoline);
- hot surface ignition: In this technology natural gas is ignited by means of a glow plug in the cylinder.

When sufficiently upgraded the fuel characteristics of biogas are comparable to natural gas, although natural gas also contains small portions of non-methane hydrocarbons such as ethane.

Although specific information with respect to biogas is very limited, there is increasing interest in using this alternative fuel in motor vehicles (e.g. [Landahl 2003]).

### 5.5.1 *Emission impacts*

The emission impacts are studied for mono-fuelled CNG vehicles.

#### 5.5.1.1 *Regulated pollutants*

The emission benefits (CO, $NO_x$, PM) of natural gas are reasonably well-established (e.g. [Nylund 2000][Umierski 2001][TNO 2003b]). Experimental studies [e.g. TNO 2003b] have shown that OEM-equipped Euro 3 passenger cars on natural gas produce regulated tailpipe emissions equivalent to or lower than those of petrol vehicles.

[TNO 2003b] investigated in 2003 the emission performance of petrol, diesel, LPG and CNG LD-vehicles.

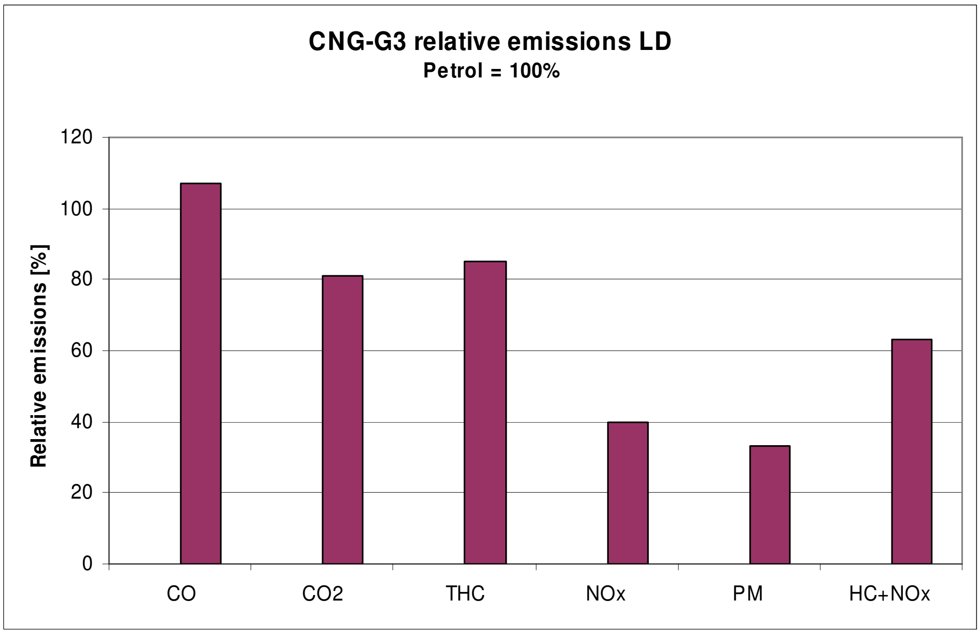


Figure 5.3 Relative emissions CNG Euro III LD-vehicle [TNO 2003b]

Table 19 Emissions different fuels Euro III LD vehicles [TNO 2003b]

| | | Average driver | | | |
|---|---|---|---|---|---|
| | | Petrol | Diesel | CNG | Rel. CNG |
| | | | | | [%] |
| $NH_3$ | [mg/km] | 17.3 | 0.9 | 34.5 | 199 |
| $SO_2$ | [mg/km] | 8.9 | 3.7 | 1.5 | 17 |
| $N_2O$ | [mg/km] | 3 | 7 | 1 | 33 |
| NO | [g/km] | 0.07 | 0.33 | 0.03 | 43 |
| $NO_2$ | [g/km] | 0.02 | 0.37 | 0.00 | 0 |
| OC | [mg/km] | 1.1 | 11.5 | 0.0 | 0 |
| EC | [mg/km] | 0.6 | 26.1 | 0.3 | 50 |
| CO | [g/km] | 1.48 | 0.10 | 1.58 | 107 |
| HC | [g/km] | 0.13 | 0.02 | 0.11 | 85 |
| $NO_X$ | [g/km] | 0.10 | 0.80 | 0.04 | 40 |
| $HC+NO_X$ | [g/km] | 0.24 | 0.83 | 0.15 | 63 |
| PM | [g/km] | 0.006 | 0.046 | 0.002 | 33 |
| $CO_2$ | [g/km] | 208.1 | 180.5 | 168.6 | 81 |
| FC | [l/100km] | 8.86 | 6.78 | 9.54 | |

Except ammonia emissions CNG vehicles perform better than petrol vehicles.

#### 5.5.1.2 *Unregulated Pollutants*

OEM-equipped Euro 3 passenger cars on natural gas tested in [TNO 2003b] showed that Euro 3 NGVs emit favourable levels of unregulated components. The emission behaviour of biogas is similar to that of natural gas, as compared to diesel fuel, emission benefits would apply with respect to several air toxics such as BTX and PAHs [e.g. Nylund 2000]. Since methane will account for the major part of HC emissions (> 90%), the proportion of NMHCs (e.g. photochemically reactive HCs) is small. On the other hand, exhaust emissions of methane, which is strong greenhouse gas, are relatively high.

Figure 5.4a Emissions and emission profiles: Average driver [TNO 2003b]

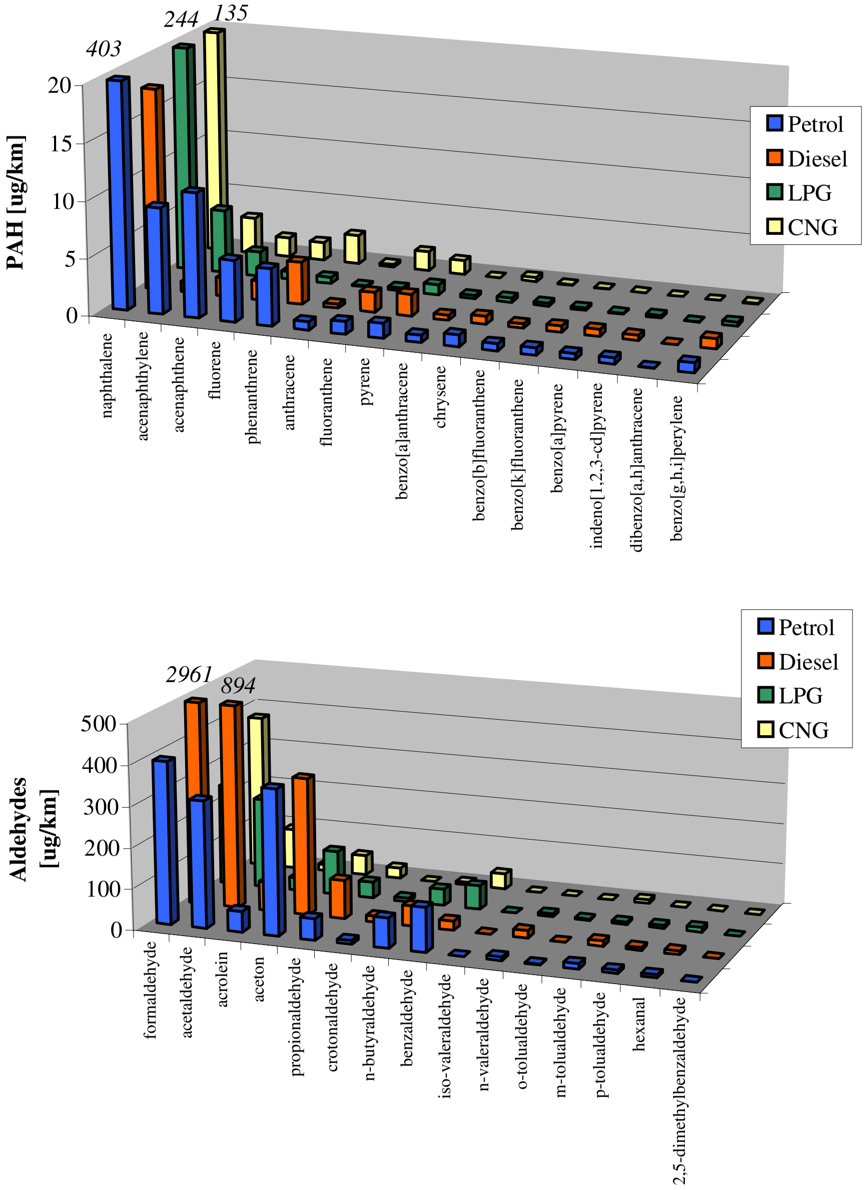
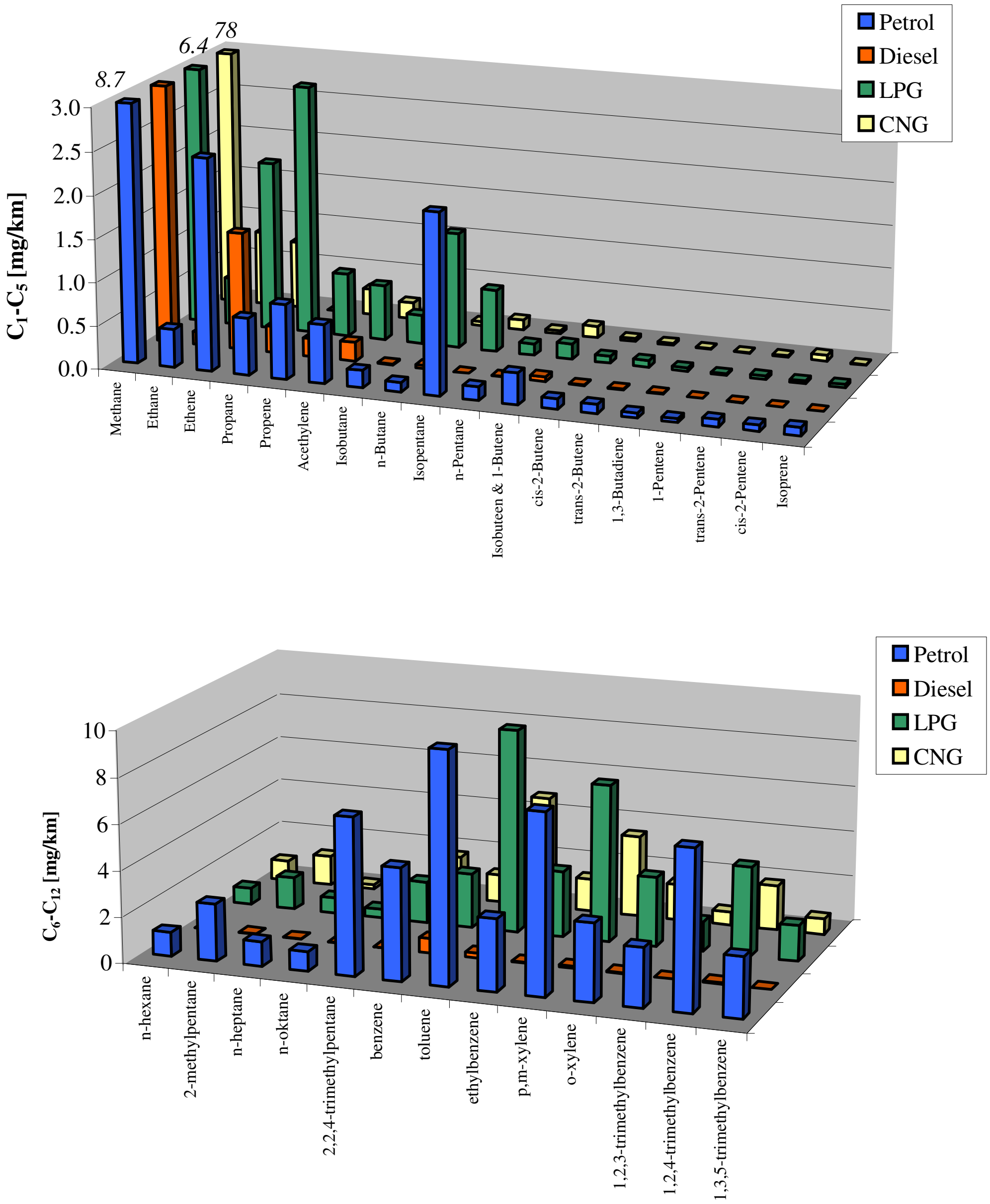


Figure 5.4b Emissions and emission profiles: Average driver [TNO 2003b]



### 5.5.2 *Exhaust gas aftertreatment and evaporative emission reduction*

Special palladium-based catalysts are required in order to achieve acceptable methane emissions. The long-term stability of the emission control system may be problematic [IEA 1999][Ahlvik 2002]. In addition, one researcher [Ahlvik 2001] anticipates some problems with future $NO_x$ storage catalyst technology as methane is one of the poorest HC reducing agents.

Euro 5 standards for passenger cars can be reached with natural gas vehicles using already available technologies. Euro 5 standards for HD vehicles and the Euro 6 limits as presently under discussion can be reached with natural gas vehicles using already available stoichiometric technologies. Alternatively, new to be developed technology based on diesel SCR might be applicable. CNG engines will not require particulate filters to meet stringent PM emissions limits. For lean-burn HD engines it is not yet certain whether Euro 6 limits can actually be achieved.

Monofuel CNG vehicles have pressurised fuel systems. Normally hydrocarbon emissions due to leakage are negligible. If CNG is applied in a bi-fuel concept (petrol based) car evaporative emission behaviour aspects are also negligible.

### 5.5.3 *Fuel specifications*

Depending on the source the composition of biogas or CNG differs greatly. Biogas from agricultural waste usually contains around 65 - 85% methane with the remainder mainly $CO_2$. Biogas may also contain water vapour and significant traces of other substances (e.g. up to 1%weight $H_2S$). The methane content of landfill gas may vary between 30 and 70%. Besides $CO_2$ the remainder contains air ($O_2$ and $N_2$), water vapour and for some processes also hydrogen ($H_2$) and carbon monoxide (CO).

Gas impurities may cause corrosion, deposits and wear. Substances requiring attention are:

- $H_2S$: causes corrosion (by formation of $SO_x$), but can be washed out;
- $H_2O$: causes corrosion and may accumulate in colder places of the fuel system. The latter can be solved by heating the gas supply system;
- Syloxanes: resulting from the presence of detergents in landfills, may form abrasive particles which cause damage to valves and valve seatings;
- Chlorine and fluorine (from refrigerators in landfills);
- Dust particles.

For stoichiometric ($\lambda = 1$) port-injected otto engines biogas must be upgraded to at least the quality of the G25 reference test fuel (85% methane, 14% $N_2$), as this is the minimum fuel quality for which these vehicles are type approved. The G25 specs are close to those of Dutch low-calorific “L-gas”. Impurities must be removed. Open loop lean burn engines can be calibrated to run on various gas qualities but are very sensitive to variations in gas quality. Closed-loop lean burn engines can to some extent adapt to variations in gas quality, but $NO_x$ emissions will generally suffer from incorrect $\lambda$-control and ignition timing.

Upgrading of biogas to natural gas quality is also necessary for mixing biogas in the natural gas distribution grid. A high percentage in biogas of other gases than methane also leads to higher energy requirements for compression per unit energy output and to a reduced range given a fixed tank size.

Compressed natural gas (200 bar) for automotive use is specified according to ISO Standard 15403. Safety regulations are according to ECE R 110. Natural gas has a varying composition through Europe. The engine must comply with the delivered fuel.

The knocking resistance of methane fuels is much higher than that of petrol. The octane number standard scale can not be applied for CNG and is replaced by the methane number scale.

### 5.5.4 *Emissions of future CNG engines*

Stoichiometric SI engines on natural gas will be able to comply with Euro 6 and Euro VI emission legislation. Differences in emissions between CNG on the one hand and petrol and diesel on the other hand are expected to decrease. Remaining differences by 2020 may be a small advantage of CNG in the area of unregulated emissions.

### 5.5.5 *Conclusions on CNG and biogas*

CNG/Biogas offers emission benefits if the CNG-installation has been installed by the vehicle manufacturer (OEM). CNG is a fossil fuel and nowadays most CNG vehicles are produced by car manufacturers. Retrofit CNG vehicles are rare. CNG-vehicles (OEM) have a lower emission level than petrol vehices. If biogas is upgraded to CNG quality it is expected that biogas vehicles have similar emissions to CNG-vehicles. Due to non-stable biogas quality variations raw biogas is not a favourable automotive fuel. If biogas is upgraded to CNG quality specifications (ISO 15403) vehicle emission behaviour will not deviate from standard CNG application.

## 5.6 Biodiesel low and high percentage blends

Nowadays pure biodiesel (EN 14214) often is a Fatty Acid Methyl Ester (FAME) and it is made from different feed stocks. In general it is only used as automotive fuel in pilot projects (public transport). More frequent engine maintenance and extra fuel handling are practical issues which must be solved. In combination with extra costs it is not attractive for commercial companies to switch to biodiesel.

The WTW $CO_2$ reduction of biodiesel (compared to regular diesel) in the EU is about 38% [EU 2008]. The main feedstock for biodiesel in the EU is rapeseed.

Within the next years the effective biodiesel content in diesel fuel will be increased to 5,75 % (energy based). All diesel vehicles will consume low blend biodiesel fuel, the possible (emission) effects will be caused by a total fleet.

ACEA has stated a maximum of 7 vol% (B7) biodiesel in Light Duty vehicles. Diesel engines with a closed DPF require an active regeneration strategy, fuel is injected during the expansion stroke. In most vehicles this causes extra dilution of engine oil and reduces the lubricity of the oil. In order to have sufficient lubrication in all circumstances ACEA prefers a maximum of 7 vol% biodiesel.

### 5.6.1 *Emission impacts*

For determination of the emission impacts of biodiesel a certain amount of publications has been studied. Light and heavy duty test results have been investigated separately as their test procedures and circumstances are different.

#### 5.6.1.1 *Regulated pollutants*

In Figure 5.5 to Figure 5.14 the emission results of FAME/biodiesel in LD and HD vehicles are reported. They scatter in a wide range. The effects of biodiesel in LD and HD engines differ.

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

Application of biodiesel blends in HD vehicles results in:

- increase of $NO_x$ emissions;
- decrease of CO and THC emissions;
- decrease of PM emissions;
- slight increase of $CO_2$ emissions.

Application of biodiesel blends in LD vehicles results in:

- increase of CO, THC and $NO_x$ emissions;
- increase of PM emissions for low blends and a decrease of PM emissions for high blends;
- no change of $CO_2$ emissions.

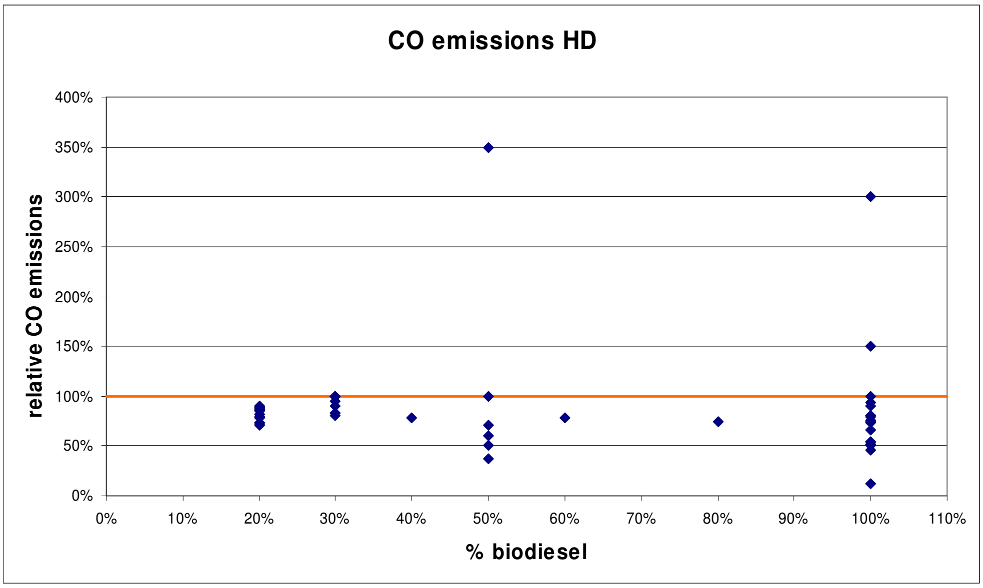


Figure 5.5 CO emissions from HD engines on biodiesel (blends)

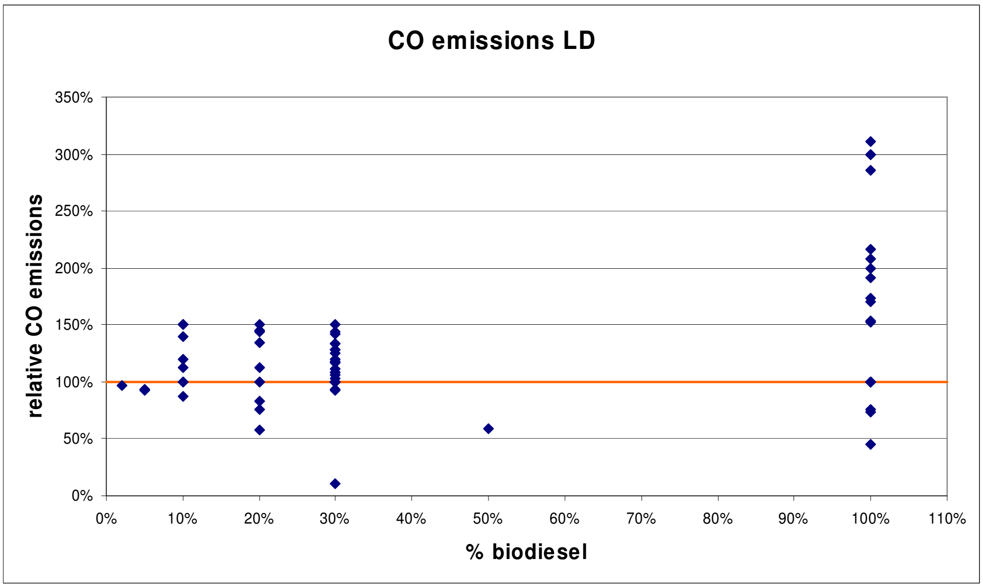


Figure 5.6 CO emissions from LD vehicles on biodiesel (blends)

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

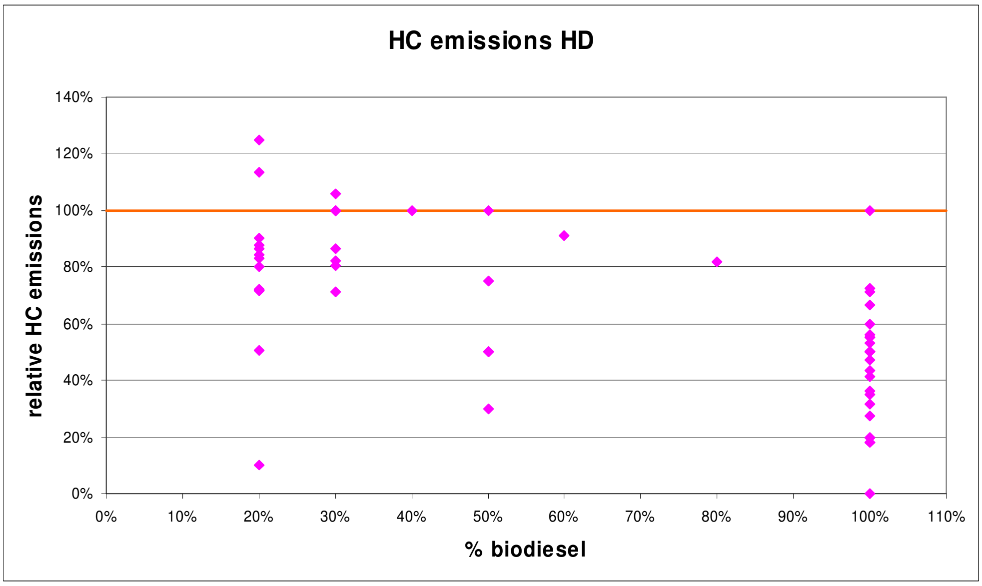


Figure 5.7 HC emissions from HD engines on biodiesel (blends)

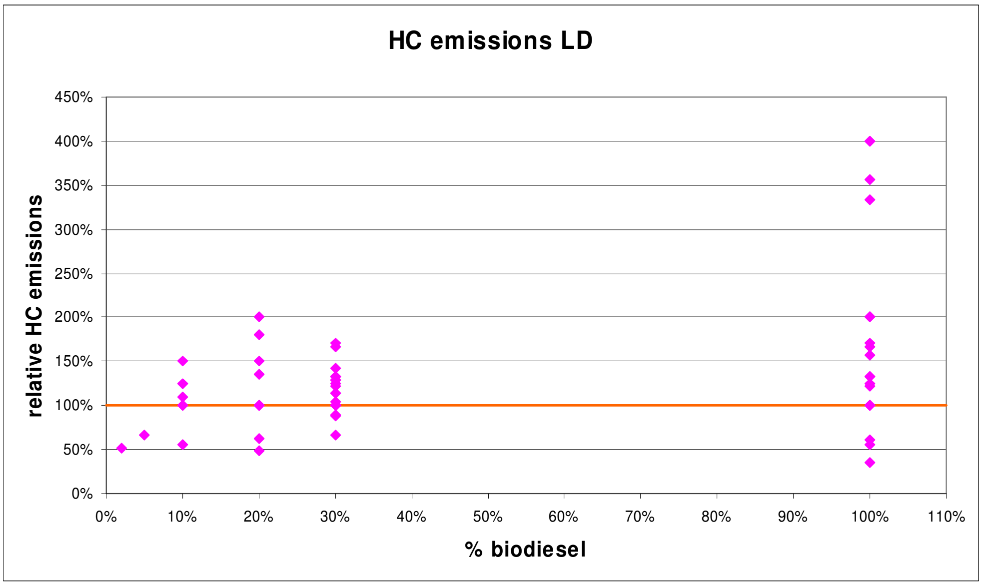


Figure 5.8 HC emissions from LD vehicles on biodiesel (blends)

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

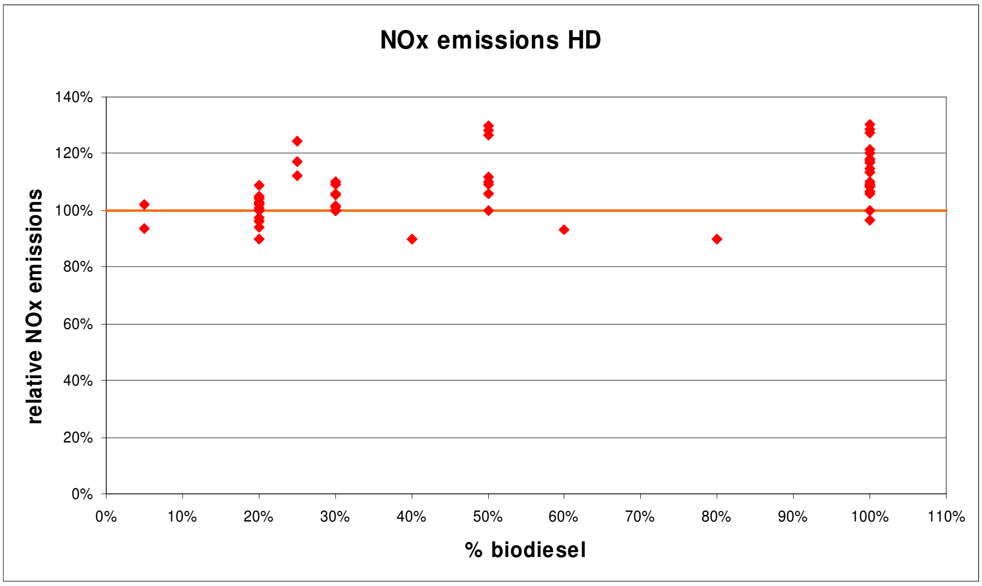


Figure 5.9 $NO_x$ emissions from HD engines on biodiesel (blends)

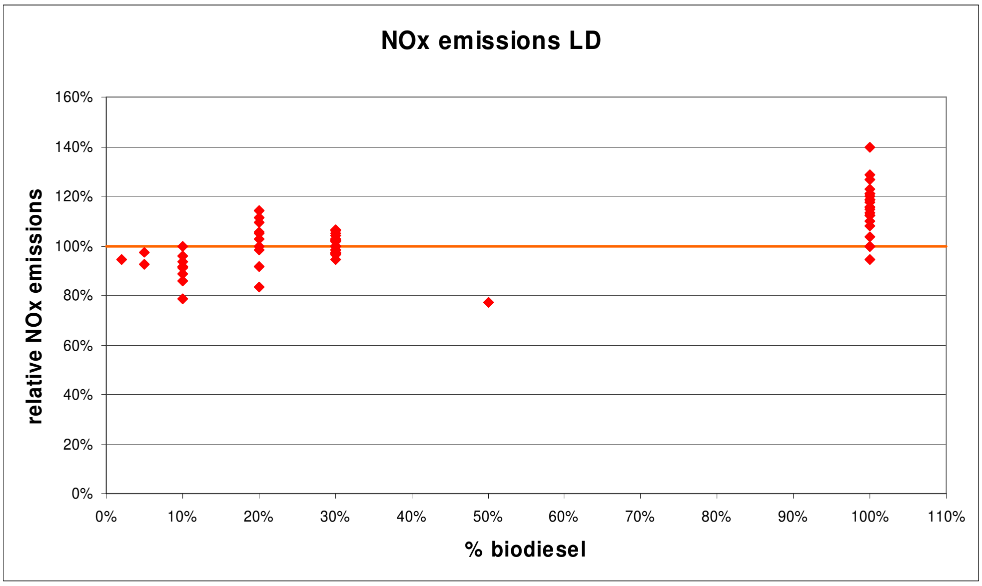


Figure 5.10 NO$_x$ emissions from LD vehicles on biodiesel (blends)

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

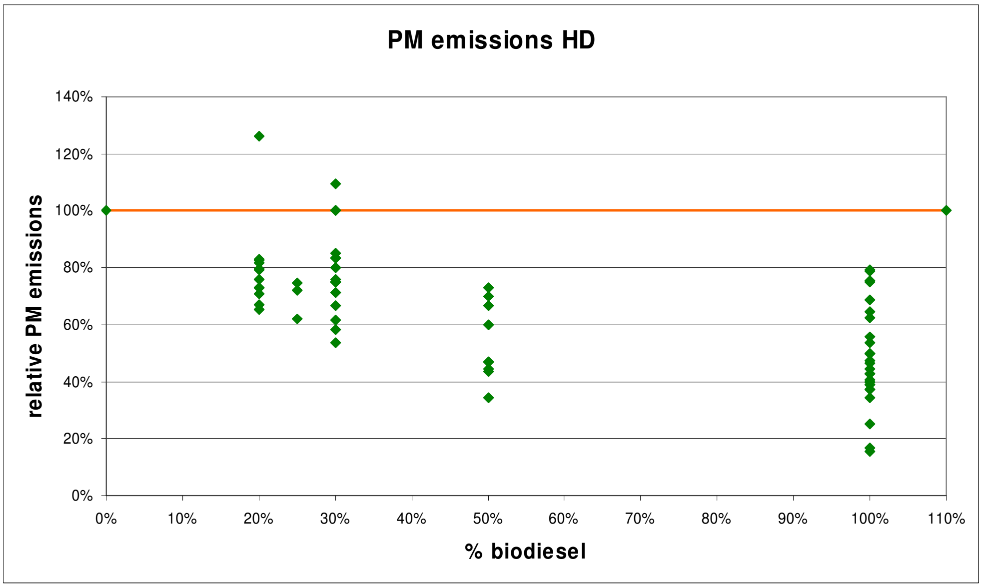


Figure 5.11 PM emissions from HD engines on biodiesel (blends)

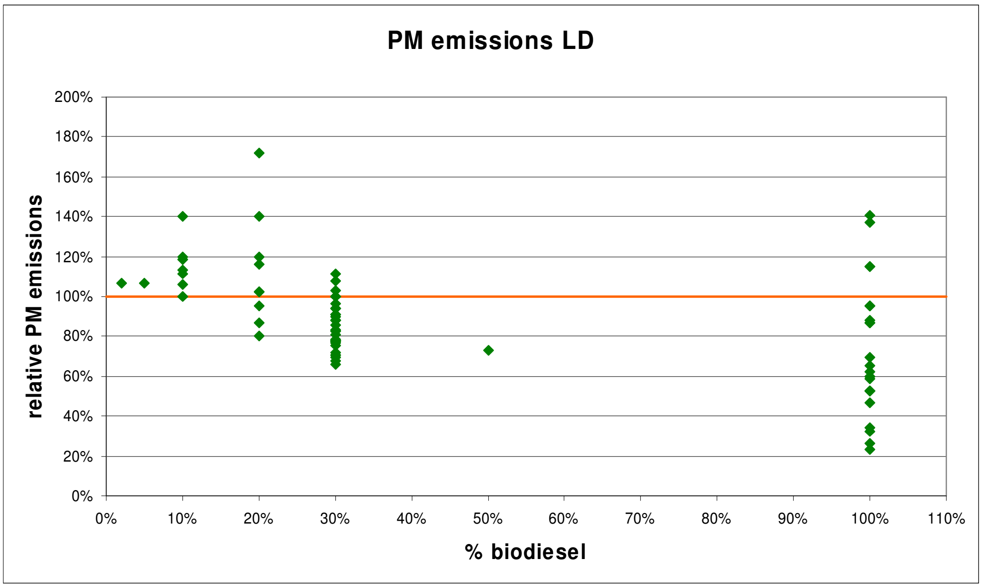


Figure 5.12 PM emissions from LD vehicles on biodiesel (blends)

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

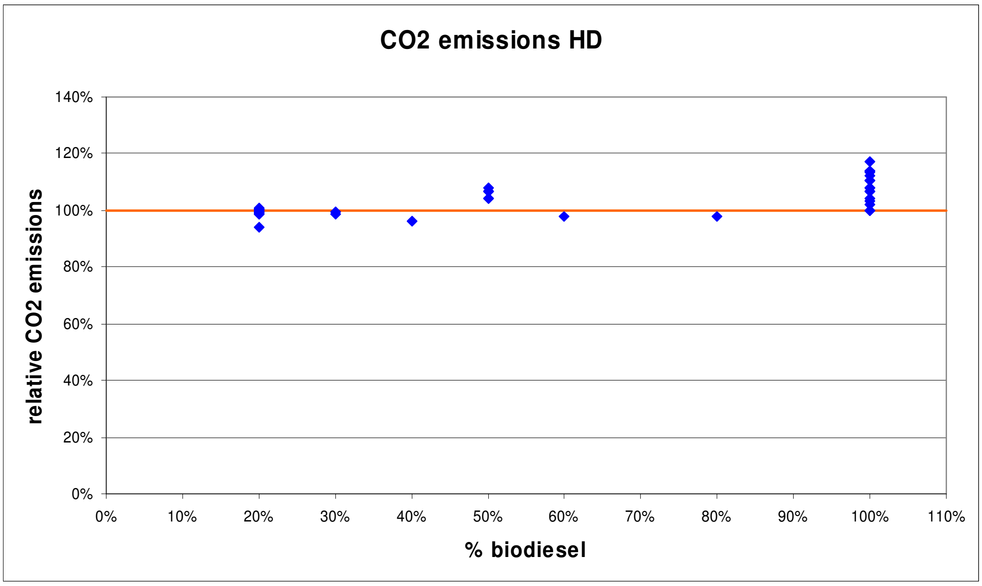


Figure 5.13 $CO_2$ emissions from HD engines on biodiesel (blends)

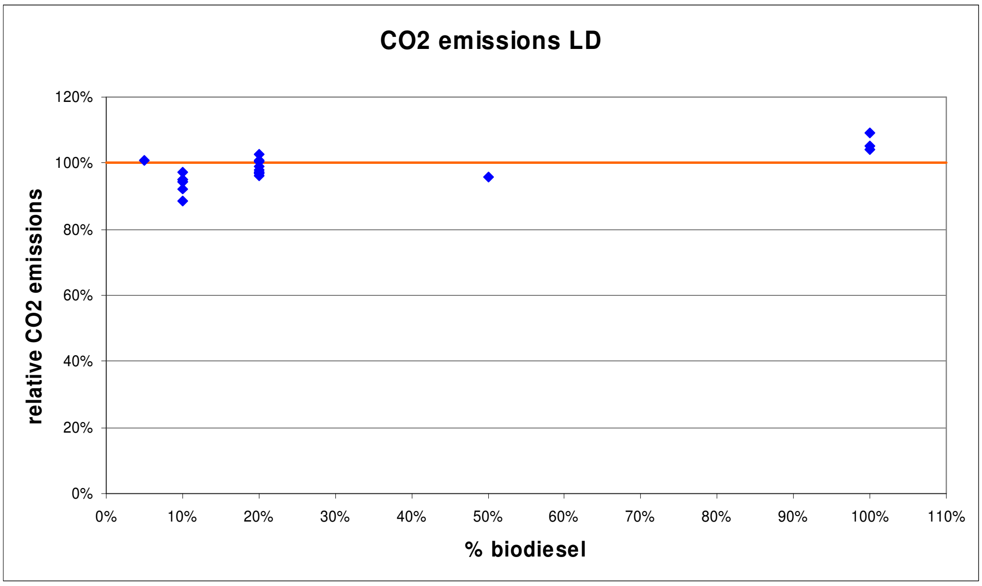


Figure 5.14 $CO_2$ emissions from LD vehicles on biodiesel (blends)

The test data are based on [Chuepeng 2007], [Tzirakis 2007], [Hu Li 2007], [Arapaki 2007], [Williams 2006], [Fontaras 2006], [McCormick 2006], [Krahl 2006], [Blassnegger 2005], [Verhaeven 2005], [Tibbet 2005], [Aakko 2000], [Aakko 2002], [Montero 2006].

The effects of biodiesel in LD and HD engines are different. The different requirements and the specific performance of LD and HD vehicles result in different engine operation (speed and load). In general injection systems of LD diesel engines have less performance than injection system of HD-vehicles. The injection pressures are lower because LD emission tests are not covering full load operation, combustion is optimised at part load and not at full load. For LD-vehicles most publications report NEDC test results. The NEDC test start with a cold phase and during testing the engine reaches a nominal hot status. Heavy duty engines only are tested in hot condition. Their fuel injection systems and combustion chambers are very well developed and should least for at least 1 million kilometres.

Biodiesel can result in different effects in one engine. [Czerwinski 2007] measured different fuels in a HD-engine. EN 590 diesel fuel and biodiesel as well as VPO are compared in steady state operation points. The results are reported in Table 20. They show for application of RME/VPO (compared to regular diesel fuel) a PM increase at low load and a PM decrease at high load. At high loads the penetration of the fuel in the combustion chamber is good and the fuel related oxygen contributes to a low PM-emission. At low loads due to increased viscosity the fuel injection is relatively poor, the fuel is not well mixed with air and the engine PM emissions increase. The integrated nanoparticles measurements (SMPS) give a similar result.
This experiment shows the complex mechanisms of fuel-engine-combustion combinations. Depending on engine speed and load an other fuel can result in better or worse emission results.

Table 20 PM emissions of a HD engine at 1500 rpm [Czerwinski 2007]

| | PM [g/kWh] | Rel. PM [%] | PM [g/kWh] | Rel. PM [%] |
|---|---|---|---|---|
| | Load 10% | Load 10% | Load 80% | Load 80% |
| Diesel | 0.28 | 100 | 0.36 | 100 |
| RME | 0.32 | 114 | 0.09 | 25 |
| VPO | 0.44 | 157 | 0.08 | 22 |

#### 5.6.1.2 *Unregulated pollutants*

Most biodiesel fuels have an ester structure, this is a different structure as the structure of diesel hydrocarbons (parrafins, aromatics). There are some concerns about the toxic emissions of biodiesel. The principal structure of biodiesel (ester) is quite different from regular diesel fuel (hydrocarbon) and this may cause specific toxic components. Due to the penetrant odour of this exhaust gas it makes much sense to investigate the possible health effects. Toxic components mostly are found in hydrocarbons and particles.

### 5.6.2 *Exhaust gas aftertreatment and evaporative emission reduction*

The low sulphur content of biodiesel reduces sulphate particle emissions and reduces poisoning of diesel oxidation catalysts and hence improves conversion efficiency. A general finding in the literature [e.g. Sharp 2000] is the shift towards less soot (IOF) and more volatile organic compounds (SOF) in particulate emissions. This would create a more favourable environment for exhaust treatment by a diesel oxidation catalyst. Diesel oxidation catalysts may prove to be adequate to reduce PM (SOF), making the use of DPFs unnecessary due to low IOF. However, high levels of (cooled) EGR will probably be necessary to control $NO_x$. It has been observed that potassium methoxide [Yamane 2004], which is a biodiesel fuel component, acts as a soot oxidation catalyst which causes DPF self-regeneration.

### 5.6.3 *Fuel specifications*

Defined fuel specifications are required to realise proper vehicle operation. Biofuel quality is influenced by the production of the feedstock, storage, production, transport and handling. Especially the very different sources of the feedstock, the different production sites and the big demand do not contribute to a stable biodiesel quality. The main parameters which may have impact on biodiesel quality are: Acid number, impurities, oxidation stability, content of sulphur, phosphorous, magnesium, calcium, water and ash. [Schuemann 2005] show in a field test from 2001 – 2005 by several biodiesel producers/traders that biodiesel fuel quality often does not meet the DIN 51605 specifications.

Table 21 Samples which do not comply with fuel specification DIN 51605 [Schuemann 2005]

| | Amount of samples | [%] | Reference |
|---|---|---|---|
| Acid number | 105 | 11.9 | EN 14104 |
| Impurities | 287 | 32.5 | EN 12662 |
| Oxidation stability | 152 | 17.2 | EN 14112 |
| Sulphur content | 42 | 4.8 | |
| Phosporous content | 112 | 12.7 | EN 14107 |
| Water content | 140 | 15.9 | EN ISO 12937 |
| | | | |

| | | | |
|---|---|---|---|
| Total amount samples | 882 | 100 | |

An underestimated item of a fuel functional life cycle is the infrastructure. All tanks, vessels, lines, pumps, trucks and vehicle systems must be clean and closed. Water and/or impurities may have big impact on vehicle/engine functionality. Due to production and storage failures biodiesels often are out of their fuel specifications.

An ester-biodiesel normally contains 10-12% oxygen and this will have negative impact on the stability of the fuel. In some cases fuel is stored for years and it is required to monitor the fuel quality.

Due to the different fuel molecule structure (and viscosity) of biodiesel the fuel injection spray is different. Some publications report about a fuel spray that may be spread against the cilinder walls (wall wetting). The condensated biofuel dilutes engine lubricant and lubricant stand times will decrease. Most vehicle manufacturers require a double amount of oil changes (compared to normal diesel operation).

### 5.6.4 *Conclusions on biodiesel*

Application of biodiesel results in positive as well as negative emission effects The chemical structure and the source of biodiesel differs from regular EN-590 diesel and this results in a different combustion behaviour. Emission impacts of biodiesel are substantial and scatter more dominant in LD vehicles than in HD vehicles. Fuel injection systems and combustion chamber configurations mainly determine the result of combustion quality and emission levels. In most cases oil drain intervals should be shortened. For low blends (0-10%) only a few data are available.

## 5.7 Virgin Plant oil (VPO)

Apart from past experimental studies on plant oils in older technology diesel engines [Fort 1982] and reactors or one-cylinder engines [Barsic 1981], there is recent information with respect to the effects on virgin plant oils (VPOs) in current (on-road) diesel vehicles. VPOs are unmodified oils that may be filtered, alkali-refined, water-degummed and/or ozone purified. The majority of studies with regard to plant oils have been undertaken on esterified products.

VPO can be used in pure form but can also be blended into diesel up to 25%vol. [McDonnell 1999]. These blends can in principle be used in unmodified DI engines. Also higher percentages blends and blends with different oils and e.g. ethanol are possible [IEA/AFIS 1996].

For use on 100% VPO vehicle engines are generally converted using a retrofit system [e.g. Elsbett 2008]. Conversion kits are available for all IDI diesel engines and for some types of DI diesel engines, and contain new injectors, fuel hoses, dedicated glow plugs, temperature sensors, electric filter heating, heat exchangers and other components . Some engines can be started on VPO so that a one-tank system can be used. For many engines start-up on conventional diesel is required. In that case a dual tank system is used.

It is demonstrated in several pilot projects that VPO can be applied as an automotive fuel. There are some items which need special attention. Lubricant is diluted with VPO (instead of diesel fuel), the viscosity of lubricant will be affected negatively. This will have a big impact on lubricant stand times. In some engines the formation of deposits in the combustion chamber and near the piston rings will block the piston ring movements and this may harm the engine.

### 5.7.1 *Emission Impacts*

Recently emission effects of VPO in Heavy Duty engines have been studied and investigated [TNO (2007-1)]. Most of the studied publications [Bünger 2007], [Hausberger 2007], [Lenaers 2008], [TNO 2007a] and [TNO 2007b] relate VPO emissions to diesel emissions (Euro 2 and 3). These engines mostly run without aftertreatment systems and thus the results give insight in the combustion behaviour of VPO. VPO has no boiling point or boiling range. After injection in a combustion chamber the VPO fuel molecules collapse, boil and react with oxygen. The cetane number is appr. 38 and relatively low to diesel fuel (50-55), this will have a negative impact on the $NO_x$ emission and noise production. In most engines no adjustments are made for VPO and this will result in a greater air/fuel-ratio, this has a positive effect on CO and HC emissions. [Lance 2004] from Ricardo have published emission test results of two VPO Euro 2 LD-vehicles.

#### 5.7.1.1 *Regulated pollutants*

The VPO emissions of HD-engines have a solid trend and are reported in Figure 5.15. In Figure 5.16 VPO LD emissions are plotted and they deviate extremely from diesel emissions. Due to the LD test procedure with cold start of the engine the VPO exhaust emissions are measured with a relative cold engine. LD diesel vehicle emissions also are very dependant on fuel quality. The very different VPO fuel quality will result in very different vehicle emissions.

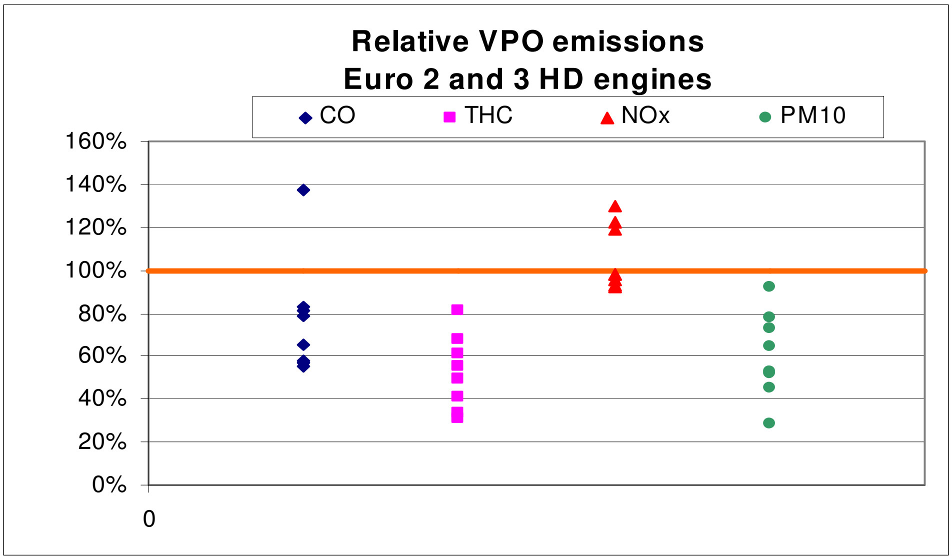


Figure 5.15 Exhaust emissions of HD engines on VPO [Bünger 2007], [Hausberger 2007], [TNO2007b], [Lenaers 2008]

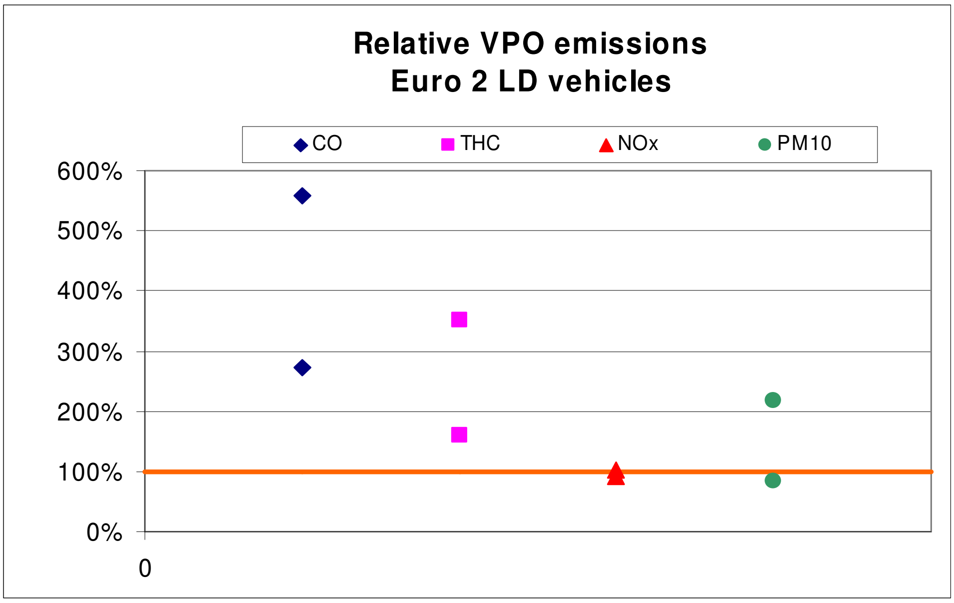


Figure 5.16 Exhaust emissions of LD vehicles on VPO [Lance 2004]

### 5.7.1.2 *Unregulated Pollutants*

[Krahl 2007] reports on emissions with diesel, RME, straight vegetable oil, modified straight vegetable oil and GTL in a Euro 3 certified HD engine. Compared with standard diesel, RME reduces particle emissions significantly, but increases $NO_x$ emissions. GTL, on the other hand, reduces both NOx and PM emissions, but is less efficient than RME for PM reduction. The unmodified straight rapeseed oil increases both $NO_x$ and PM emissions. [Krahl 2007] also carried out biological testing. The results are alarming for straight vegetable oil as mutagenicity increases significantly. [Krahl 2007] summarize the results: “Compared with the reference diesel fuel the two RSO qualities significantly increased the mutagenic effects of the particle extracts by factors of 10 up to 60. RME extracts had a moderate but significant higher mutagenic response. GTL samples did not differ significantly from diesel fuel. Concerning the regulated emissions, the results remained below the margins except a up to 15% increase of $NO_x$ for the tested bio fuels.” Straight vegetable oil has entered the transport fuel market in Germany, and the experts are very concerned about this phenomenon. This is also summarised in [Kadijk 2008].

VPO and diesel engine emissions are also investigated by [Krist 2007]. Their results are contradictory to [Krahl 2007]. [Bünger 2007] has measured an increased mutagenity for VPO use, [Krist 2007] has measured a decreased mutagenity. After detailed investigation of the experiments it was clear that the sampling procedures of both parties are different. Additional thorough research is needed to clarify the relationship of fuel properties and mutagenity.

The application of VPO as an automotive fuel in vehicles without aftertreatment systems results in a penetrant odour in exhaust gas.

### 5.7.2 *Exhaust gas aftertreatment and evaporative emission reduction*

Oxidation catalysts in aftertreatment systems could convert the hydrocarbon emissions and the toxicity of the exhaust gas. Additional thorough research is needed to clarify the relationship of aftertreatment systems and toxicity of exhaust gas. A relationship of an SCR system and toxicity of exhaust gas is not expected, this must be verified in an experiment.

### 5.7.3 *Fuel specifications*

VPO is produced from various natural feed stocks. These products are relatively viscous and must be heated (to 70 °C) to have an acceptable viscosity for injection into the combustion chamber. The base requirements for rapeseed oil are specified in DIN 51605. Impurities, chemical properties (acid number) and molecule structures can vary in a wide range and may effect engine emissions.

### 5.7.4 *Conclusions VPO*

Application of VPO as automotive fuel requires modifications of fuel systems and sometimes fuel injectors. The cold start of the engine should be done on regular diesel fuel. VPO is applied as a niche fuel and has substantial effects on engine emissions. HC and PM10 emissions decrease and NOx emission increases. Additional thorough research is needed to clarify the relationship of fuel properties and mutagenity.
There are durability concerns with respect to fuel systems and combustion chamber. Due to oil dilution oil drain intervals are shortened.

## 5.8 BTL/GTL/XTL

Fischer-Tropsch (FT) fuels have been used to some degree since the 1920s, and are more and more put on the market as a future fuel. In South Africa neat Fischer-Tropsch fuels, derived from domestic coal, have powered all of South Africa’s vehicles for the past 50 years. The majority of publications that report on FT fuel aspects have used synthetic FT diesel that is derived from natural gas (“GTL” or gas-to-liquid). Hence no information was found with respect to bio-FT-diesel. Nevertheless, it may be assumed that bio-FT-diesel (BTL) has a similar behaviour as GTL fuels.

FT diesel fuel mainly consists of paraffins. Properties can vary substantially depending on the process technology and product streams being blended. Generally, FT diesel fuels have favourable characteristics for use in CI engines. For instance, FT diesel is mixable with petroleum diesel, it has good auto-ignition characteristics, low sulphur content and low aromatics and it is suitable for use in unmodified diesel engines. Similar to conventional diesel fuel, FT fuel represents a generic type of fuel, rather than a fixed fuel specification. As a result, there are potentially an infinite number of FT fuels that each could have their own unique fuel specification (i.e. density, cetane number, etc.), which may lead to variation in emission test results.

NExBTL is a non-oxygenated hydrocarbon biodiesel and has similar chemistry and properties to the present synthetic GTL and BTL fuels. It is a mixture of n- and iso-paraffins.

### 5.8.1 *Emission Impacts*

#### 5.8.1.1 *Regulated pollutants*

Examination of Figure 5.17 and Figure 5.18 shows that FT-diesel shows rather consistent results with respect to regulated emissions, i.e. CO, HC and PM emissions are reduced in nearly all cases. Here the actual effect depended on the test cycle used or engine tested. The effect of FT-diesel on $NO_x$ emissions varies from “no effect” to an improved performance. [Myburgh 2003] reported that FT-diesel appears to provide further enhanced emission benefits in congested driving conditions. FT-diesel has a simple straight chemical structure which will result in a good combustion behaviour (also at low engine loads). Reduction of CO and HC emissions can be attributed to the high cetane number of FT-diesel (74 compared to 54 for EU2005 diesel), while lower PM and smoke emissions are the result of the absence of aromatic compounds in FT-diesel [Friess 2003].

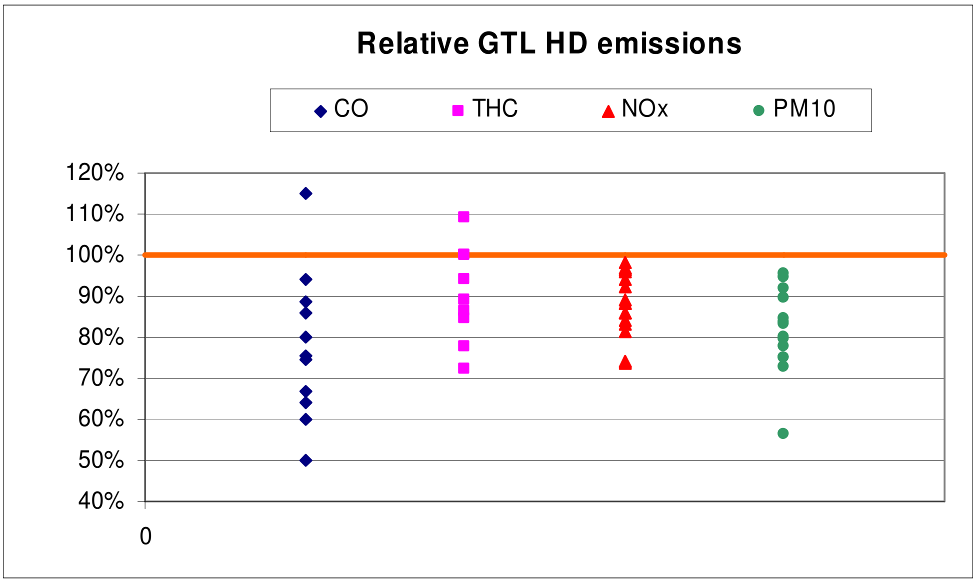


Figure 5.17 Exhaust emissions from HD engines on GTL [Alleman 2003], [Clark 2005], [Krahl 2005], [Thompson 2004],

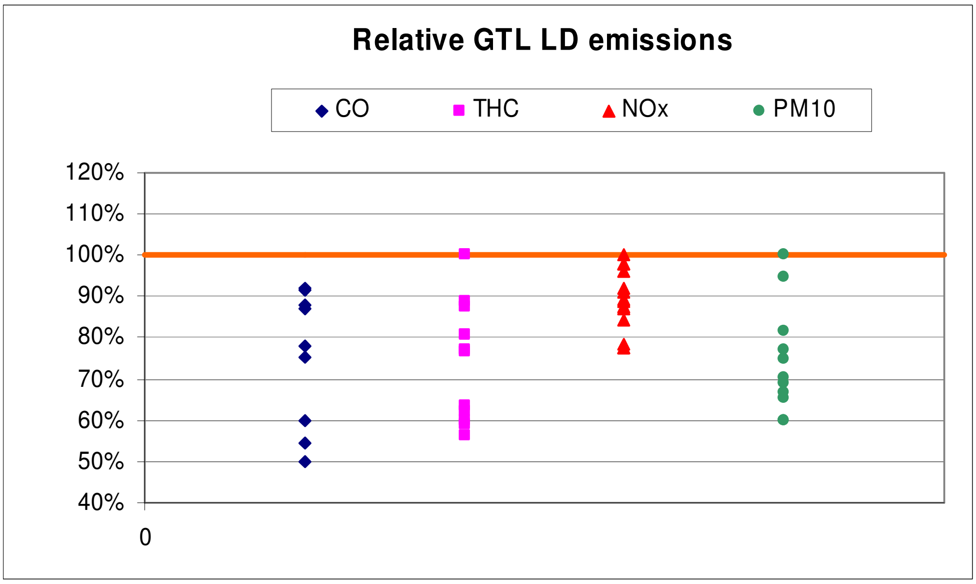


Figure 5.18 Exhaust emissions from LD vehicles on GTL [Alleman 2003], [Kitano 2007], [Schaberg 2005]

### 5.8.1.2 *Unregulated pollutants*

Application of GTL and diesel fuel has been measured by [Krahl et. Al. (2005)]. GTL doesn't increase toxic and mutagenic emissions. Due to the simple chemical fuel structure it is not expected that GTL/BTL result in toxic/mutagenic emissions.

### 5.8.2 *Exhaust gas aftertreatment and evaporative emission reduction*

Since sulphur content in FT-fuels is practically zero, synthetic fuels are compatible with a range of sulphur sensitive exhaust gas aftertreatment technologies such as $NO_x$ adsorbers or the CRT filter. Furthermore, this is a definite advantage when using EGR in diesels (i.e. less corrosion potential). However, since conventional diesel fuel is improving on this aspect, in response to EU legislation (e.g. ultra low sulphur diesel), this advantage of FT-diesel is diminishing [Ahlvik 2002].

### 5.8.3 *Fuel specifications*

Fischer-Tropsch diesel has good combustion properties for a diesel engine. The cetane number is 75. FT diesel can be produced with high purity and is inherently free of sulphur and aromatics. The chemical structure is paraffinic and the fuel density is relatively low (0,77 kg/dm$^3$).

A FT diesel has a low lubricity, special fuel additives are needed to comply with lubricity demands. The low density and high cloud point may also cause some problems [e.g. IEA/AFIS 1999].

FT-fuel may have problems (flow, atomisation) in cold weather, especially during cold start operation. This must be corrected by further refining, blending with other components or use of additives [Stavinoha 2000].

### 5.8.4 *Conclusions BTL/GTL/XTL*

BTL is very good applicable as automotive fuel (blend) and (after engine optimisation) the expected emission advantages are substantial. Nowadays no substantial quantities of BTL are available, the production facilities still are under development.
The chemical structure (parafine) of BTL is equal to GTL. GTL is a fossil fuel and in larger quantities available. BTL/GTL is very compatible with standard diesel and is applied as a blend. It also can be used as a neat fuel, a dedicated engine calibration is recommended. Emission data of low blend GTL/BTL fuel are not available.

## 5.9 Bioethanol (low and high percentage blend in gasoline)

Ethanol-fuelled vehicles date back to the 1880s when Henry Ford designed a car that ran solely on ethanol. Nowadays, ethanol is probably the most widely used alternative automotive fuel in the world. For instance, Brazil uses petrol with a 22% alcohol content [Amaral 2001] and a substantial part of the Brazilian fleet runs on neat alcohol [Kremer 1996]. Since 2004 all petrol sold in Sweden contains 5% ethanol. In response to the EU biofuels directive many oil companies add ethanol as an octane improver blend into regular petrol. The EU petrol specification (EN 228) allows a 5% ethanol blend.

Ethanol is usually produced from biomass and as a blend is primary used as an octane number improver. It can be produced with high purity and consequently a very low sulphur and aromatics content. Due to the chemical properties of an alcohol it is needed to apply alcohol resistant rubber hoses and alcohol resistant fuel system parts.

The European petrol Standard EN 228 allows 5 vol.% ethanol. In Table 22 the primary petrol and ethanol parameters for vehicle use are reported.

Table 22 Petrol, ethanol and ETBE properties

| | | Petrol | Ethanol | ETBE |
|---|---|---|---|---|
| Density | [kg/dm^3] | 0.75 | 0.79 | 0.75 |
| LCV | [MJ/kg] | 44 | 27 | 36 |
| RON | [-] | 95 | 108 | 118 |
| RVP min. | [kPa] | 45-70 | * | 28 |
| RVP max. | [kPa] | 60-100 | * | 28 |
| Boiling curve | [°C] | 35-210 | 77.8 | 73 |
| Stoich. Air-Fuel ratio | [-/-] | 14.5 | 9.0 | 12.2 |

* RVP pressure in petrol/ethanol mixtures is very sensitive to ethanol content

A graph showing the relation between ethanol vol.% and RVP can be found in Annex D.4.

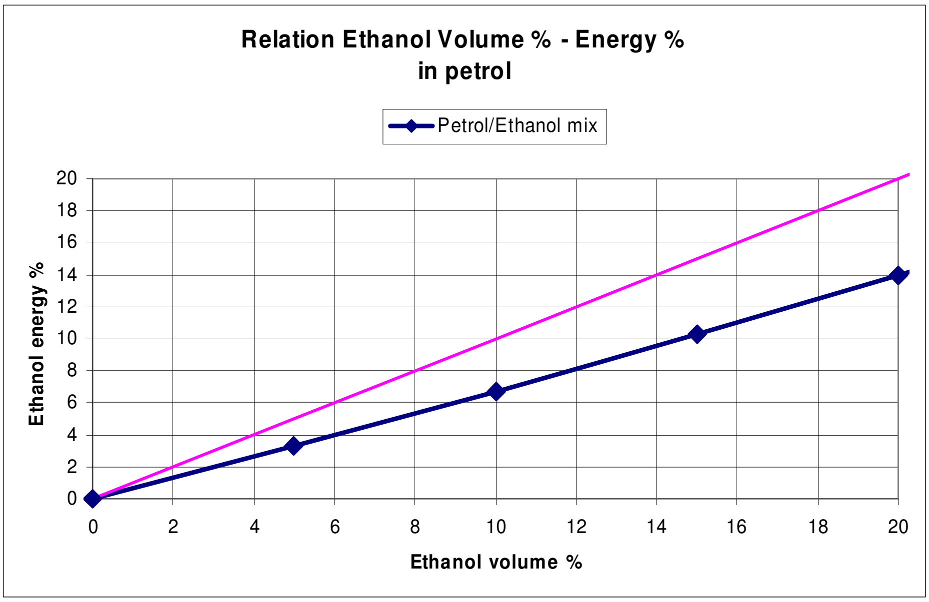


Figure 5.19 Relationship between volume % and energy % of ethanol in petrol

A 5.75 % biofuel ethanol blend on energy base requires a 8.7 vol.% blend. If a 10% energy biofuel petrol blend is required and this would be produced with ethanol, a 15 vol.% ethanol blend is needed. The LCV per volume unit of this 15 vol.% blend decrease 5.3%. RVP also increases significantly. A gasoline with a 15 vol.% ethanol blend requires an adaptive engine management control.

Ethanol is applied in petrol as a blend, is hygroscopic and tends to dissolve in water. In a tank or dead volume of a transportation system could water easily be stored and the available ethanol will dissolve in water. Corrosion of fuel system materials and separation of ethanol from the base fuel is possible. The fuel properties may change significantly. Extra attention must be paid to possible water contamination.

For the so called FFV (Flexible Fuel Vehicle) a dedicated fuel system/calibration is needed. For the use of higher biofuel concentrations (up to 85 vol.%), FFVs are expected to dominate the market for ethanol-driven light-duty vehicles. These vehicles have the advantage that they can run on normal petrol and on a wide range of blends. Ford, Saab, Volvo and Cadillac introduced FFVs which are running on E85 (a mixture of 85% ethanol and 15% petrol). Engines can be developed to run on pure ethanol, but E85 is preferred as the 15% petrol improves (cold) startability and flame visibility. Start-problems with pure ethanol are related to the low vapour pressure.

### *5.9.1 Emission impacts*

In several studies the effects of ethanol as automotive fuel/blend is reported and in Figure 5.20 to Figure 5.24 the emission effects of several ethanol blends are plotted. Due to the applied aftertreatment systems and their high conversion rates the absolute emission levels are low, emission effects of ethanol have relatively big impact. Positive as well as negative effects are measured. The FFV vehicles with E85 fuel performs good. From this point of view it is clear that ethanol has a good emission performance, a dedicated engine and or adjustment is required.

### *5.9.1.1 Regulated Pollutants*

The tables in this chapter are based on [Jeuland 2004], Larsson 2006], Terrier 2005], [De Serves 2005], [Orbital 2003], [Varde 2004], [Delgado 2003]

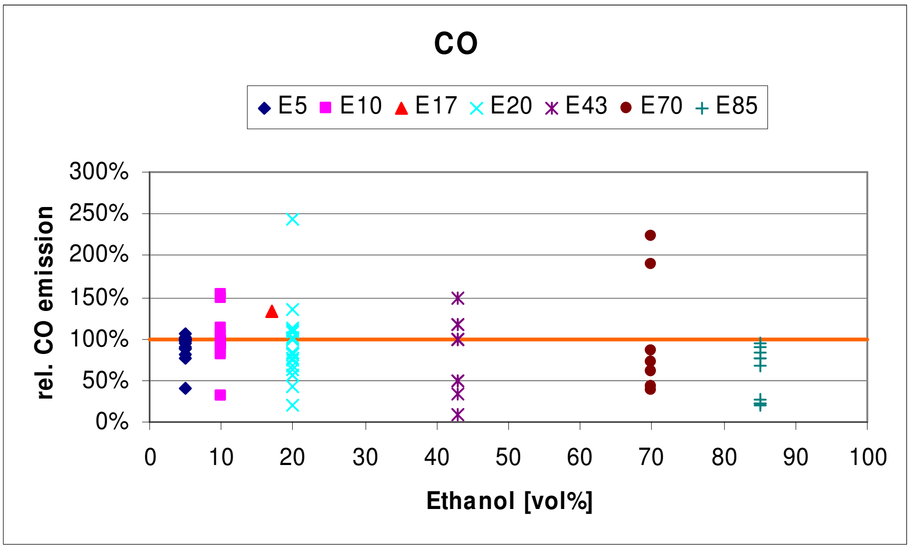


Figure 5.20 CO emissions from LD vehicles on ethanol blends

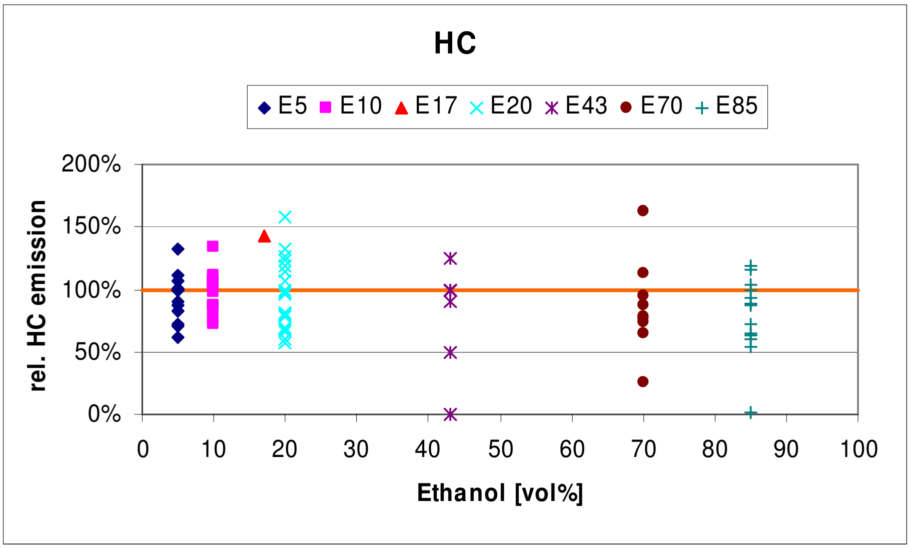


Figure 5.21 HC emissions from LD vehicles on ethanol blends

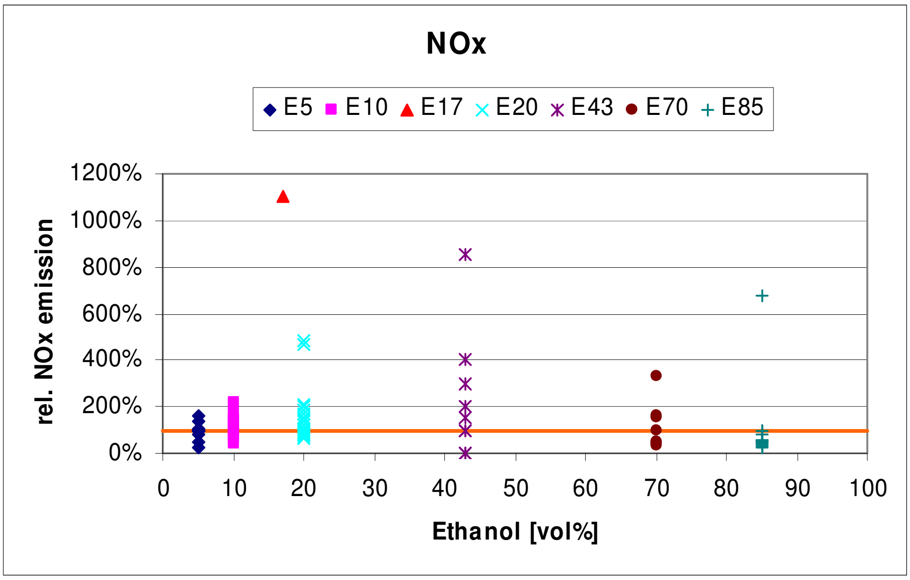


Figure 5.22 $NO_x$ emissions from LD vehicles on ethanol blends

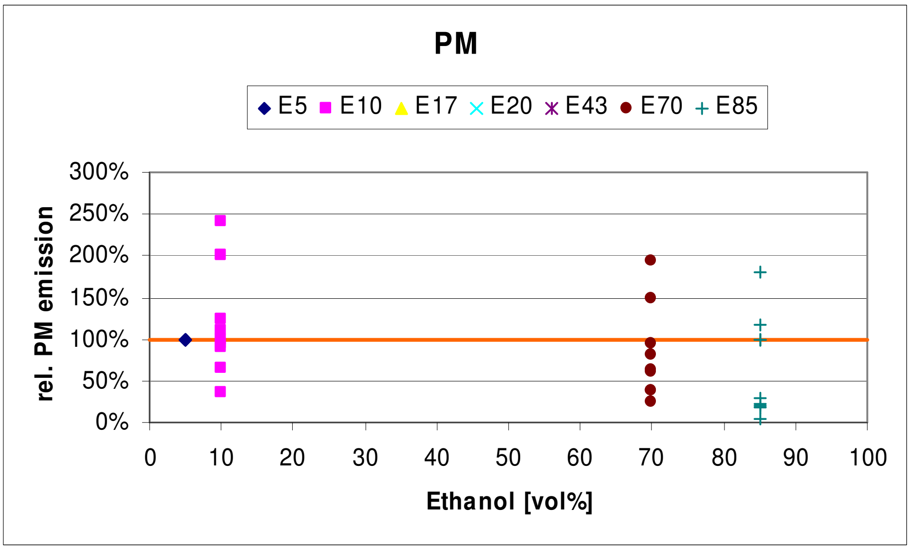


Figure 5.23 PMemissions from LD vehicles on ethanol blends

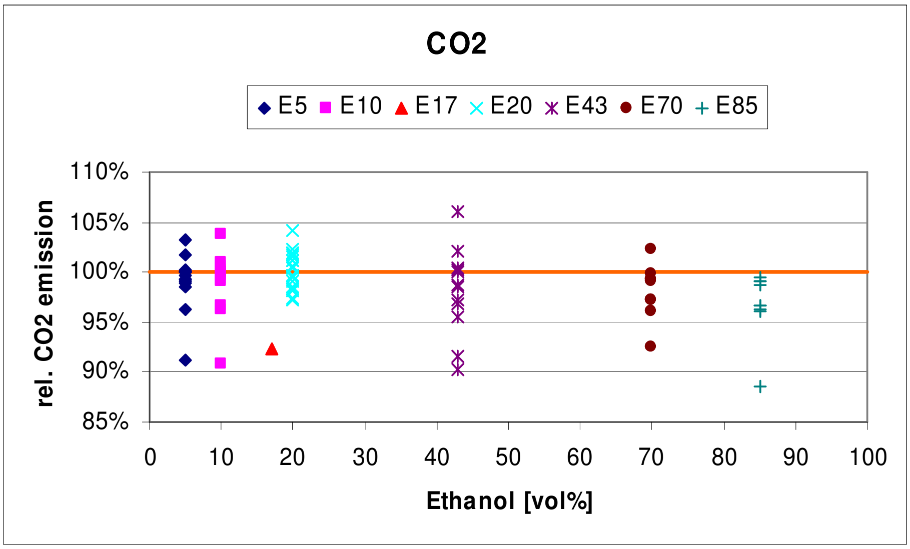


Figure 5.24 $CO_2$ emissions from LD vehicles on ethanol blends

### 5.9.1.2 *Unregulated pollutants*

[Orbital 2003] investigated the emission effects of a 20 vol.% ethanol blend in petrol. Addition of ethanol to a petrol fuel results in an increase of Acetaldehyde. The other toxic components were not influenced by the ethanol blend.

### 5.9.2 *Exhaust gas aftertreatment and evaporative emission reduction*

As already reported in [Ecofys 2003] ethanol blends may have a problem concerning vapour pressure. Ethanol by itself has a very low vapour pressure, but in petrol-ethanol blends the vapour pressure increases in first instance with an increasing share of ethanol (10% higher vapour pressure for blends between 5 – 15 vol.% ethanol). Already at the relatively low volume percentages necessary to reach the 2010 target of the EU biofuels directive the vapour pressure exceeds the limit of 60 kPa as set by the European Directive 98/70/EC. This can in principle be overcome by changing the composition of the petrol used for the blend. Increased vapour pressure has possible safety implications, but may also affect evaporative emissions. Above 15-20 vol.% ethanol the vapour pressure of petrol-ethanol blends again decreases, eventually even dropping below the level of conventional petrol. E85 therefore does not have a problem with respect to vapour pressure limits.

The storage capacity of a carbon cannister is determined by the volume of carbon. Due to the relative high boiling point of ethanol the lighter hydrocarbons evaporate and enter the carbon cannister. If ethanol is added to a standard base fuel vapour pressure is relatively high and more lighter hydrocarbons will evaporate. The carbon cannister might be overloaded and emits a hydrocarbon vapour from its exhaust.

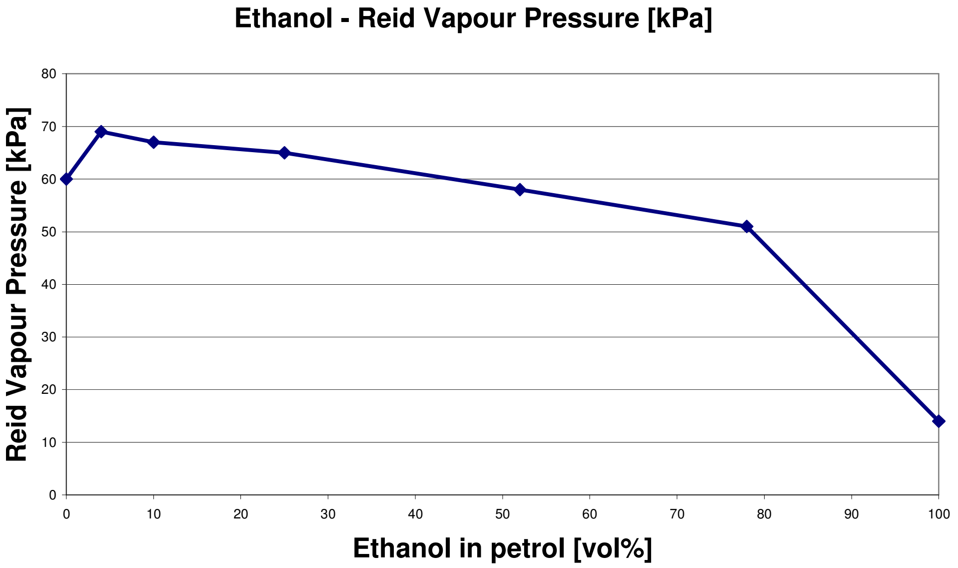


Figure 5.25 Ethanol versus Reid Vapour Pressure

*Fuel specifications*

The European petrol fuel specification (EN228) allows 5 vol.% ethanol in petrol. For E85 the ASTM standard ASTM D5798-99 is applicable. Within CEN a CEN Workshop Agreement CWA 15293 : 2005 (consensus between limited number of stakeholders) has been established and will be upgraded to an official CEN specification in near future.

### *5.9.3 Conclusions ethanol*

Ethanol mostly is applied as a low blend (E5) in petrol as an octane improver. It must be noted that only a very few data are available. Due to the low emissions of petrol vehicles the relative effects of ethanol as low blend are substantial.

Ethanol as low blend increases Reid Vapour Pressure and as a result of this evaporative emissions increase. This can be avoided by adaptation of the base fuel.

E85 is applied as high blend in FFV-vehicles. The emissions of these vehicles are optimised and equal to petrol vehicles. If a lower blend is applied (E43 or E70) emission levels increase. Probably this is caused by the fact that vehicles are not optimised for lower blends.

## 5.10 Bio-ETBE

Ethyl Tertiary Butyl Ether (ETBE) has been applied as a gasoline octane number improver. ETBE is produced from bio-ethanol (37%) and isobutylene (63%) and refinery handling is cost effective [Koseki 2007]. The isobutylene fraction can not be marked as a biofuel. An ETBE blend of 17 vol.% in regular gasoline results in a 5.6 vol% biofuel content. In chapter 5.9 (Table 22) petrol, ethanol and ETBE parameters are reported. ETBE has a high RON number and low and stable RVP and the specific energy content is more near to gasoline than ethanol. The density is very close to gasoline density. From a technical point of view ETBE is a blending component with very good properties.

### *5.10.1 Emission impacts*

[Koseki 2007] even blended 8 and 16 vol.% (13.5 energy%) ETBE to gasoline. Two modern petrol cars (MPI and SIDI) and 10 gasoline products were tested according to the Japanese vehicle certification procedure. In general ETBE blends have no impact on vehicle emissions.

### *5.10.1.1 Regulated pollutants*

In

Table 23 the range of measured regulated components for all fuel blends are reported. The test results show a very stable emission behaviour. Only minor differences are measured. Based on these test results ETBE as a blend doesn't change significantly CO, NMHC, $NO_x$ and $CO_2$ emissions. Due to the relative low ETBE specific energy content at higher ETBE contents volumetric fuel consumption will increase slightly.

Table 23 Petrol-ETBE regulated emissions [Koseki 2007]

| | | Limit 2005 | 0% ETBE | 17% ETBE | 0% ETBE | 17% ETBE |
|---|---|---|---|---|---|---|
| | | | Vehicle 1 | Vehicle 1 | Vehicle 2 | Vehicle 2 |
| CO | [g/km] | 1.2 | 0.07 | 0.11 | 0.07 | 0.09 |
| $CO_2$ | [g/km] | - | 205 | 208 | 173 | 175 |
| $NO_x$ | [g/km] | 0.027 | 0.011 | 0.013 | 0.012 | 0.015 |
| NMHC | [g/km] | 0.05 | 0.009 | 0.011 | 0.009 | 0.010 |
| Fuel cons. | [km/l] | - | 11.5 | 11.81 | 13.85 | 14.10 |

### *5.10.1.2 Unregulated Pollutants*

Aldehyde emissions are measured in all emission tests. The 0 and 8% blends give very stable results. The 16 vol.% ETBE blend result in a slightly increased formaldehyde and acetaldehyde emission.

Table 24 Petrol-ETBE unregulated emissions [Koseki 2007]

| | | ETBE blend vol% | Minimum | Maximum | Minimum | Maximum |
|---|---|---|---|---|---|---|
| | | | Vehicle 1 | Vehicle 1 | Vehicle 2 | Vehicle 2 |
| Formaldehyde | [mg/km] | 0-8 | 0.8 | 1.6 | 0.8 | 1.6 |
| Acetaldehyde | [mg/km] | 0-8 | 0.4 | 1.2 | <0.4 | 1.3 |
| Acrolein | [mg/km] | 0-8 | <0.25 | <0.25 | <0.25 | <0.25 |
| Formaldehyde | [mg/km] | 16 | 1.6 | 1.7 | 1.6 | 1.7 |
| Acetaldehyde | [mg/km] | 16 | 1.5 | 1.6 | 1.6 | 1.7 |
| Acrolein | [mg/km] | 16 | <0.25 | <0.25 | <0.25 | <0.25 |
| | | | | | | |

### 5.10.2 *Exhaust gas aftertreatment and evaporative emission reduction*

Based on the test results and the chemical fuel properties of ETBE no change of exhaust emission behaviour is expected.

Evaporative emissions will be equal to regular gasoline fuel. Based on the ETBE boiling point of 73 °C and the single pressurized fuel line in a modern vehicle no ETBE evaporative emissions are expected. The other more volatile hydrocarbons (i.e. C4 and C5 molecules) will evaporate and enter the carbon canister. Vehicles with a fuel supply and return line in tropical countries may produce ETBE evaporative emissions. In very hot conditions (50 °C) gasoline temperature may exceed 73 °C.

### 5.10.3 *Fuel specifications*

The EN 228 fuel specifications allow 15 vol.% ethers (5 or more C atoms). From exhaust emission point of view gasoline cars with fuel injection and aftertreatment systems are able to handle 15 vol.% ETBE blended fuels.

### 5.10.4 *Conclusions ETBE*

ETBE is applied as a low blend in petrol as an octane improver. The properties are very similar to regular petrol and it can very well used as low blend. ETBE partly can be a biofuel (37%) and the complementary part has a fossil nature.
No significant emission impact is measured with ETBE. It must be noted that only a very few data are available

## 5.11 Evaporative emissions and carbon canisters

From 1990 on vehicle evaporative emissions from petrol vehicles are regulated. Due to the boiling range of petrol even at 10 °C the lighter hydrocarbons tend to evaporate. Vehicles produced before 1990 have “open” petrol tanks. In order to avoid overpressure in the tank a small open connection is created to ambient air. Due to fuel evaporation these vehicles emit volatile hydrocarbons.

In order to reduce evaporative emissions from 1990 onwards a carbon canister is installed in the open connection line. During warming up of the fuel the volatile hydrocarbons are absorbed by the carbon of the canister and during engine operation the engine soaks “backwards” ambient air through the same canister. The canister will be purged and the volatile fractions are consumed by the engine.

Evaporative emissions from a 50% filled fuel tank were investigated by [Delgado 2003]. In this experiment evaporation of petrol start at 5 °C and during warming up of the tank (2 °C per hour) evaporation continues. From 18.5 kg fuel (25 litres) petrol which is warmed up in a tank from 5 to 40 °C evaporates approximately 60 g fuel. A carbon canister is able to store appr. 99% of this 60 g fuel. In Europe the average temperature variation per day is far less. In summer the average minimum temperature is 12.6 °C and the average maximum temperature is 22,3 °C. Normal vehicle use with day/night temperature variations and hot soak petrol temperature variations create evaporative emissions. This evaporative fuel is stored in the carbon canister. During vehicle operation the canister is purged by ambient air.

[Delgado 2003] tested petrol (E0 and E5). The E5 petrol has an increased vapour pressure and more fuel is evaporated during a fixed warming up period. At the end of the warming up of the tank the canister did not absorb fuel anymore and started to emit evaporated E5 fuel. Given the results of this experiment it can be concluded that the required dimensions of a carbon canister are directly dependant from fuel RVP pressure and fuel (tank) volume.

LPG and CNG bifuel vehicles have relatively long petrol stand times. A full petrol tank sometimes won't be refilled in a year. In this period the volatile fractions are stored in the canister and consumed during CNG/LPG operation. Probably the standard carbon canister capacity is sufficient for bifuel cars. It is not expected that evaporative emissions from bifuel vehicles are higher than petrol vehicles.

Carbon canister load mainly is determined by fuel Reid Vapour Pressure (RVP) and temperature variations. If a bioblend is added to petrol and RVP is kept within EN 228 fuel specifications no extra evaporative emissions are expected. Carbon canister laboratory experiments with E5 blends did not harm the canister functionality.

FFV vehicles which run on E85 normally have a canister with more capacity than petrol vehicles. The E85 fuel properties (low energy density) require a bigger tank to create a certain vehicle range. As a result of the increased tank volume more volatile hydrocarbons are produced and this requires a carbon canister with more capacity.

Long term carbon canister behaviour results (with alcohol blended fuels) are not available.

## 5.12 DACHNLS meeting

The findings and conclusions of this project and especially this chapter were discussed during the 22nd D-A-CH-NL-S meeting on April 17 & 18, which was held in Berlin. This meeting is held twice a year to exchange experiences and knowledge on vehicle emissions and vehicle emission modelling. The meeting was attended by policy makers and technical experts from Germany, Swiss, Austria, Sweden, Spain, Norway, France and The Netherlands. The focus of the first day was on biofuels. This was done via two presentations on biofuels, which present the outcomes of the "BOLK" project of TNO and CE from The Netherlands:

- The emission effects of the use of biofuels in the current fleet, which was presented by Gerrit Kadijk (TNO).
- The expectations for the future, which was presented by Gerben Passier.

At the end of each presentation, several propositions were stated to initiate the discussion.

The main objectives were:

- To inform the D-A-CH-NL-S group about the findings from the BOLK project and
- To get valuable feedback from the experts in the D-A-CH-NL-S group.

The presentations showed that the emission effects of biofuels can not be ignored. However, currently there is too little real-world data to clearly estimate the real-world emissions effects. This was acknowledged by the DACH-NL-S group. It was suggested that an international measurement campaign is necessary produce the data needed to fill the knowledge gaps. The main discussion items are described in more detail in the minutes of the meeting in Appendix F.

## 5.13 Conclusions

*Relationship biofuels-emissions:*
The relationship biofuels-emissions is very diffuse because vehicle technology and human behaviour are two primary factors which influence this relationship. The application of biofuel (blend or neat fuel) in different vehicles may influence exhaust emissions, evaporative emissions, driveability of a vehicle, maintenance schedule or sustainability of a fuel system. Therefore, it is not possible to use biofuels to achieve a gain in air quality - rather, a serious risk of air quality deterioration is also present. However, in niche applications improvements in emissions are possible for specific biofuel-vehicle combinations.

Below, the main findings and conclusions per biofuel are summarized. The collected laboratory data have a non-systematic (random) character and are laboratory-based. A fundamental systematic investigation (broad and practical approach) of biofuel emission effects in combustion engines has not been reported yet by any country or research institute.

*LPG:*
LPG offers emission benefits to petrol if the LPG-installation has been installed by the vehicle manufacturer (OEM), retrofit LPG installations generally offer emission detereorations. LPG is a fossil fuel and applied in The Netherlands as a third possibility (after petrol and diesel). LPG vehicles which are built by car manufacturers (OEM) have a good quality standard and comply with emission standards. The emission levels of an OEM LPG vehicle are somewhat lower than petrol vehicles.
The emission behaviour of retrofit G3-LPG vehicles often exceed the legislative emission levels. Due to the type approval family approach of a group of vehicles, the restricted amount of required emission tests and the different installation companies some vehicles exceed their type approval emission limits.

*CNG/Biogas:*
CNG/Biogas offers emission benefits if the CNG-installation has been installed by the vehicle manufacturer (OEM). CNG is a fossil fuel and nowadays most CNG vehicles are produced by car manufacturers. Retrofit CNG vehicles are rare. CNG-vehicles (OEM) have a lower emission level than petrol vehices. If biogas is upgraded to CNG quality it is expected that biogas vehicles have similar emissions to CNG-vehicles.
Due to non-stable biogas quality variations raw biogas is not a favourable automotive fuel. If biogas is upgraded to CNG quality specifications (ISO 15403) vehicle emission behaviour will not deviate from standard CNG application.

*Biodiesel:*
Application of biodiesel results in positive as well as negative emission effects The chemical structure and the source of biodiesel differs from regular EN-590 diesel and this results in a different combustion behaviour. Emission impacts of biodiesel are substantial and scatter more dominant in LD vehicles than in HD vehicles. Fuel injection systems and combustion chamber configurations mainly determine the result

of combustion quality and emission levels. In most cases oil drain intervals should be shortened. For low blends (0-10%) only a few data are available.

*VPO:*
Application of VPO as automotive fuel requires modifications of fuel systems and sometimes fuel injectors. The cold start of the engine should be done on regular diesel fuel. VPO is applied as a niche fuel and has substantial effects on engine emissions. HC and PM10 emissions decrease and NOx emission increases. Additional thorough research is needed to clarify the relationship of fuel properties and mutagenicity.
There are durability concerns with respect to fuel systems and combustion chamber. Due to oil dilution oil drain intervals are shortened.

*BTL/GTL/XTL:*
BTL is very good applicable as automotive fuel (blend) and (after engine optimisation) the expected emission advantages are substantial. Nowadays no substantial quantities of BTL are available, the production facilities still are under development.
The chemical structure (parafine) of BTL is equal to GTL. GTL is a fossil fuel and in larger quantities available. BTL/GTL is very compatible with standard diesel and is applied as a blend. It also can be used as a neat fuel, a dedicated engine calibration is recommended. Emission data of low blend GTL/BTL fuel are not available.

*Ethanol:*
Ethanol mostly is applied as a low blend (E5) in petrol as an octane improver. It must be noted that only a very few data are available. Due to the low emissions of petrol vehicles the relative effects of ethanol as low blend are substantial.
Ethanol as low blend increases Reid Vapour Pressure and as a result of this evaporative emissions increase. This can be avoided by adaptation of the base fuel.
E85 is applied as high blend in FFV-vehicles. The emissions of these vehicles are optimised and equal to petrol vehicles. If a lower blend is applied (E43 or E70) emission levels increase. Probably this is caused by the fact that vehicles are not optimised for lower blends.

*ETBE:*
ETBE is applied as a low blend in petrol as an octane improver. The properties are very similar to regular petrol and it can very well used as low blend. ETBE partly can be a biofuel (37%) and the complementary part has a fossil nature.
No significant emission impact is measured with ETBE.

In Table 25 to Table 27 the emission effects of most frequently applied biofuels are summarised.

Table 25 Effect of ethanol blends on SI engines. Euro 3 and older based on experimental data.

| | | Euro 3 and older |
|---|---|---|
| | | 2000 - 2005 |
| NOx | E5 | $NO_x$ - 50% to + 50% |
| | E10 - E20 | $NO_x$ - 50% to + 100% |
| | E40 - E85[1)] | $NO_x$ - 50% to + 300% |
| HC | E5 | HC - 40% to + 30% |
| | E10 - E20 | HC - 40% to + 40% |
| | E40 - E85[1)] | HC - 40% to + 30% |

[1)] FFV vehicle

Table 26 Effect of biofuel (blends) and synthetic diesel on passenger car diesel engines. Euro 3 and older based on experimental data.

| | | Euro 3 and older |
|---|---|---|
| | | 2000 - 2005 |
| PM | B5 - B10 | PM - 20% to + 20% |
| | B20 - B100 | PM - 80% to + 40% |
| | pure XTL, HVO | PM reduction 0 - 40% |
| $NO_x$ | B5 - B10 | $NO_x$ reduction 0 - 20% |
| | B20 - B100 | $NO_x$ - 10% to + 20% |
| | pure XTL, HVO | $NO_x$ reduction 0 - 20% |

Table 27 Effect of biofuel (blends) and synthetic diesel on heavy-duty diesel engines. Euro 3 and older based on experimental data.

| | | Euro 3 and older |
|---|---|---|
| | | 2000 - 2005 |
| PM | B5 - B10 | no significant effect |
| | B20 - B100 | PM reduction 0 - 70% |
| | XTL, HVO | PM reduction 0 - 30% |
| | | |
| $NO_x$ | B5 - B10 | no significant effect |
| | B20 - B100 | $NO_x$ increase 0 - 30% |
| | XTL, HVO | $NO_x$ reduction 0 - 20% |

A biofuel with a deviating chemical structure and different primary parameters (viscosity, chain length) may result in the different applied technologies in a different emission behaviour of unregulated components. The collected data have a random character and are laboratory-based. A fundamental broad and practical approach of biofuel emission effects in combustion engines is not reported by any country or research institute.

*Local air quality and policy:*

The emission effects of biofuels on the actual vehicle fleet are very diverse and there are no clear benefits for local air quality (except $CO_2$ emissions). If biofuel will be applied in a certain region a thorough investigation of possible air quality improvements is necessary.

*DACHNLS meeting*

The findings and conclusions of this chapter were discussed and reviewed during the DACHNLS meeting. Minutes of the meeting can be found in Appendix F.

## 5.14 Literature

| | |
|---|---|
| [Aakko 2000] | Aakko et. Al. (2000), *Emission performance of selected biodiesel fuels - VTT's contribution*, ENE5/33/2000 |
| [Aakko 2002] | Aakko et. Al. (2002), *Emissions from HD engine with and without aftertreatment using selected biofuels*, F02E195 |
| [Ahlvik 2001] | Ahlvik, P. & Brandberg A. (2001), *Well to Wheel Efficiency for Alternative Fuels from Natural Gas or Biomass*, ISSN 1401 9612. |
| [Ahlvik 2002] | Ahlvik, P. & Brandberg A. (2002), *Sustainable Fuels, Introduction of Biofuels*, ISSN 1401 9612. |
| [Alleman 2003] | Alleman & McCormick (2003*), FT diesel fuels - properties and exhaust emissions*, SAE 2003-01-0763 |
| [Amaral 2001] | Amaral, R.A. & Sodre, J.R. (2001) *Aldehyde emissions from an ethanol-fuelled vehicle as influenced by engine geometric parameters*, SAE Technical Paper Series, Paper No. 2001-01-1998. |
| [Arapaki 2007] | Arapaki et al. (2007), *Regulated and Unregulated Emissions Characteristics of a Diesel Vehicle Operating with Diesel/Biodiesel Blends*, SAE 2007-01-0071 |
| [Barsic 1981] | Barsic, N.J. & Humke, A.L. (1981), *Performance and emissions characteristics of a naturally aspirated diesel engine with vegetable oil fuels*, SAE Technical Paper Series, Paper No. 810262 |
| [Blassnegger 2005] | Blassnegger (2005), *Emissionsminderungspotenziale durch optimierten Biodiesel und Nachrustbare Abgasnachbehandlung* |
| [Bünger 2007] | Bünger et al, (2007), *Strong mutagenic effects of diesel engine emissions using vegetable oil as fuel*, Arch Toxicol 2007 |
| [Chuepeng 2007] | Chuepeng et al. (2007), *A study of Quantitative Impact on Emissions of High Proportion RME-Based Biodiesel Blends*, SAE 2007-01-0072 |
| [Clark 2005] | Clark et. Al (2005), Future fuels and lubricant base oils from Shell Gas to Liquids (GTL) technology, SAE 2005-01-2191 |
| [Czerwinski 2007] | Czerwinski et al. (2007), *Injection, combustion and (Nano) particle emissions of a Modern HD-Diesel Engine wit GTL, RME & ROR*, SAE 2007-01-2015 |
| [De Serves 1999] | De Serves, C. (1999), *Particle Emissions from Two HD Vehicles Fuelled with RME and Biogas Respectively*, MTC AB, Report No. MTC 6809b, ISSN 1103-0240 |

[De Serves 2005] De Serves, C. (2005), *Emissions from Flexible Fuel Vehicles wit different Ethanol Blends*, MTC AB, Report No. MTC 5509

[Delgado 2003] Delgado (2003), *Comparison of fuel tank evaporative emissions from E0 and E5 petrol*, IDIADA report LM030411

[Ecofys 2003] Ecofys (2003), van den Broek, R, van Walwijk, M, Niermeijer, P. & Tijmensen, M., *Biofuels on the Dutch market: a fact finding study*, GAVE Report 2GAVE03.12

[Elsbett 2008] Elsbett (2008), www.elsbett.com

[EU 2008] Commission of the European Communities (2008), Proposal for a Directive of the European parliament and of the Councel on the promotion of the use of energy from renewable sources. COM(2008) 30 final, SEC(2008) 57, SEC(2008) 85.

[Fontaras 2006] Fontaras et al. (2006), *Evaluation of cottonseed oil - diesel fuel blends a fuel for automotive diesel engines*, F2006P380

[Fort 1982] Fort, E.F. et al. (1982), *Evaluation of cottonseed oils as diesel fuel*, SAE Technical Paper Series, Paper No. 820317.

[Hausberger 2007] Hausberger and Vuckovic (2007), *Emissions and fuel consumption of Clean City Bus concepts*, FVT-85/06/ Haus Em 29/04-6770, Graz

[Hu Li 2007] Hu Li et al. (2007*), Study of Emission and Combustion Characteristics of RME, B100 Biodiesel from a HD DI Diesel Engine*, SAE 2007-01-0074

[IEA/AFIS 1996] IEA/AFIS (1996), van Walwijk, M. et al., *Automotive fuels survey, Part 2, Distribution and use*, INNAS 1996

[IEA 1999] IEA (1999), *Automotive Fuels for the Future – The Search for Alternatives*, International Energy Agency

[Jeuland 2004] Jeuland (2004), *Potentiality of Ethanol as a fuel for dedicated engine*, IFP 2004

[Kadijk 2008] Kadijk et.al. (2008), *Uitlaatgasemissies van PPO en biodiesel in heavy duty motoren*, TNO report MON-RPT-033-DTS-2008-00153.

[Karlson 2006] Karlson (2006), *Emissions from conventional gasoline vehicles driven with ethanol blend fuels*, AVL-MTC 5524

[Kitano 2007] Kitano et. Al (2007), *GTL fuel impact on DI Diesel Emissions*, SAE 2007-01-2004

[Koseki 2006] Koseki, et al. (2006), *Investigations of Compatibility of ETBE Gasoline with Current Gasoline with Current Gasoline Vehicles*, SAE 2006-01-3381

[Koseki 2007] Koseki, et al. (2007), *Investigations of Compatibility of ETBE Gasoline with Current Gasoline Vehicles II*, SAE 2007-01-2039.

[Krahl 2005] Krahl, et al. (2005), *Fuel economy and environmental characteristics of biodiesel and low sulphur fuels in diesel engines*, Federal Agricultural Research Centre Braunschweig

[Krahl 2006] Krahl, et al. (2006), *Comparison of Shell Middle Distillate Premium Diesel Fuel and Fossil Diesel Fuel with Rapeseed Oli Methyl Ester*, 2006

[Kremer 1996] Kremer, F.G., Jardim, J.L.F. & Maia, D.M. (1996) *Effects of alcohol composition on gasohol vehicle emissions*, SAE Technical Paper Series, Paper No. 962094.

[Krist 2007] Krist, et al. (2007), *Prüfung der Mutagenität von Inhaltstoffen partikulärer Abgasbestandteile in Ames-Test*, BIFA project 630094

[Lance 2004] Lance and Anderson (2004), *Emissions Performance of Pure Vegetable Oil in two European Light Duty Vehicles*, SAE 2004-01-1881

[Landahl 2003] Landahl (2003), *Biogas as Vehicle Fuel – A European Overview*, Trendsetter Report No. 2003:3, October 2003

[Larsson 2006] Larsson (2006), *Exhaust emissions from light vehicles run on alternative fuels*, NTM 2006.

[Lenaers 2008] Lenaers et al. (2008), *Vergelijkende metingen van emissies en verbruik aan een bus van De Lijn rijdend op PPO, biodiesel en diesel*, Vito contract 061708

[Martini 2007] Martini et.al. (2007), *Effects of gasoline vapour pressure and ethanol content on evaporative emissions from modern cars* EC-DGJRC-EUR 22713 EN, ISBN 978-92-79-05249-1

[McCormick 2006] McCormick et al. (2006), *Effects of Biodiesel Blends on Vehicle Emissions*, NREL/MP-540-40554

[McDonnell 1999] McDonnell, K.P., Shane, M.W., and McNulty, P.B. (1999), *Results of engine and vehicle testing of semi-refined rapeseed oil*, Proceedings of the 10th International Rapeseed Congress, Canberra, Australia, 1999

[Montero 2006] Montero et al. (2006), *Determination of ozone preciursor hydrocarbons and other pollutans emitted by HD-engines using biodiesel*, 2006

[Nylund 2000] Nylund, N.O. & Lawson, A. (2000), *Exhaust Emissions From Natural Gas Vehicles*, IANGV Technical Committee, 31 March 2000

[Orbital 2003] Orbital engine company (2003), *Market barriers to the uptake of biofuels study, a testing based assessment to determine impacts of a 205 Ethanol Gasoline Fuel blend on the Australian Passenger vehicle fleet*

[Pana 2007] Pana et al. (2007), *Aspects of the use of ethanol in spark ignition engine*, SAE 2007-01-2040.

[Schuemann 2005] Schuemann and Berndt (2005), *Aspekte der Rapsoelqualitaet, Lagerung und Versorgung*, University of Rostock Germany.

[Sharp 2000] Sharp, C., Howell, S.A. & Jobe, J. (2000) *The effect of biodiesel fuels on transient emissions from modern diesel engines, part I regulated emissions and performance*, SAE Technical Paper Series, Paper No. 2000-01-1967.

[Schaberg 2005] Schaberg et. Al. (2005), *Emissions Performance of GTL Diesel Fuel and Blends with Optimized Engine calibrations*, SAE 2005-01-2187

[Terrier 2005] Terrier et al. (2005), *Comparison of emissions and fuel consumption between gasoline and E85 in a simulated Hybrid Electric Vehicle*, SAE 2005-01-3829

[Thompson 2004] Thompson et. Al (2004), *Fuel effects on regulated emissions from advanced diesel engines and vehicles*, SAE 2004-01-1880

[Tibbet 2005] Tibbet et al. (2005), *Air toxics and particulate emissions from diesel engines*, ET/IR804

[TNO 2003a] *Future emissions of passenger cars: Expert judgement of the long term possibilities of conventional emission abatement technology*, Rijkeboer, R. et al., TNO-report 03.OR.VM.018.1/RSM

[TNO 2003b] *Evaluation of the environmental performance of modern passenger cars running on petrol, diesel, automotive LPG and CNG*, Hendriksen, P. et al., TNO-report 03.OR.VM.055.1/PHE.

[TNO 2003c] *In-use compliance programme: overview of automotive LPG vehicles*, van de Burgwal, H. et al., TNO report 03.OR.VM.037.1/HVDB

[TNO 2007a] *Uitlaatgasemissies van PPO en biodiesel in Heavy Duty motoren*, Kadijk, G. et al., TNO report MON-RPT-033-DTS-2008-00153

[TNO 2007b] *Kwartaalrapportage 2e kwartaal 2006, Steekproefcontroleprogramma Vrachtwagens 2006-2008,* TNO report MON-RPT-033-DTS-2007-00169, Delft 2007

[Tzirakis 2007] Tzirakis et al. (2007), *Impact of Diesel/Biodiesel Blends on Emission from a Vehicle Operated in Real Driving conditions*, SAE 2007-01-0076

[Umierski 2001] Umierski, M. et al. (2001), *Fuel consumption and exhaust emissions of diesel, gasoline and natural gas fuelled vehicles*, SAE Technical Paper Series, Paper No. 2001-28-0068

[Varde 2004] Varde and Clark (2004), *A comparison of burn characteristics and exhaust emissions from off-highway engines fuelled by E0 and E85*, SAE 2004-28-0045

[Verhaeven 2005] Verhaeven et al. (2005), *Result of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on LD and HD vehicles*, SAE 2005-01-2201

[Williams 2006] Williams et al. (2006), *Effect of Biodiesel Blends on diesel Particulate Filter Performance,* SAE 2006-01-3280

[Yamane 2004] Yamane, K.et. al. (2004) *Characteristics of DPF for diesel engine fueled with biodiesel fuel – first report: self-regeneration behaviour on vehicle road test and engine bench rig test*, SAE Technical Paper Series, Paper No. 2004-01-1883.

# 6 Future emissions of biofuels

## 6.1 Introduction

In chapters 2 to 4 an overview has been given of short, medium and long term developments with respect to (bio)fuels and engine technologies. In this chapter these insights are first of all combined to create an overview of relevant fuel-engine combinations that are most likely to be applied in the longer term. In relation to the objectives of BOLK especially insights in possible fuel-engine combinations for the longer term are relevant (2020 and beyond). To focus the work for the assessment of longer term impacts of biofuels on emissions an attempt is made to define most likely scenarios for application of biofuels in future engines rather than to further expand the vast variety of theoretically possible combinations.

In sections 6.4 and 6.5 a review is presented of the available information on impacts of future biofuels on emissions of engine technologies that may be available in the 2015 – 2025 period. Sections 6.6 and 6.7 present some first considerations on impacts on emissions at the national level and possible impacts on non-regulated emission components. Section 6.8 summarizes the blanks in our knowledge to-date as a starting point for defining the work to be performed in the follow-up of this inventory project.

All in all there are two ways of looking at the issue. One view is that European and national policies that further tighten the emission limits for engines / vehicles to improve air quality on the one hand and promote or enforce the application of biofuels to reduce greenhouse gas emissions on the other hand are independent processes. In this situation the climate policy that promotes application of biofuels may have (unexpected negative or positive) impacts on the effectiveness of the vehicle emission legislation and the National Emission Ceilings policy. This is the central question of BOLK. From another perspective, however, the situation can also be the other way around, if application of new, high quality fuels based on biomass allows further tightening of the vehicle emission legislation. This could especially be the case for synthetic biofuels such as BTL.

## 6.2 Fuel-engine combinations for the longer term (2020 and beyond)

As discussed in chapter 2 the existing EU strategy for biofuels aims at 5.75% by 2010 and 10% by 2020. The Dutch government is exploring a possible target of 20% by 2020. However, in the light of the recent discussion on the sustainability of especially 1st generation biofuels, we assume that the ambitions for application of biofuels in 2020 will more likely be reduced than increased. For the moment the assumption is that by 2020 at least 10% of all road fuel in Europe is biofuel.

### 6.2.1 *Most likely fuel-engine combinations for the longer term*

The assumption this is that by 2020 about 10% of all road transport fuel use is covered by biofuels. A large share of this will be implemented by means of low percentage blending of biofuels in conventional petrol and diesel used in non-dedicated engines. Part of the 10% will be used as high percentage blends or neat biofuels used in dedicated engines. Table 28 indicates the most likely options.

Table 28 Fuel-engine combinations for the longer term (2015 – 2025)

| **SI engines** | | | **diesel engines** | |
|---|---|---|---|---|
| **petrol<br>low % blends** | **high % blends<br>neat fuels** | **gaseous fuels** | **diesel<br>low % blends** | **high % blends<br>neat fuels** |
| E5 - E10<br>ethanol | E85 | CNG | FAME | B100 (FAME) |
| Bu5* – Bu10*<br>butanol | Bu85* | CBG (biogas) | GTL | E95** |
| ETBE | | | BTL | 100% XTL |
| Biopetrol | | | HVO | |
| (bio)methanol | | | | |

*) BuX = X% butanol / (100 – X)% petrol

**) 95% ethanol / 5% diesel, mainly for application in HD engines

*Low percentages blends in petrol*

- Future SI engines will accept up to 10% ethanol or butanol without engine modifications.
- ETBE is now already used as an octane increasing additive. It is expected that ETBE will continue to be used and that part of the future ETBE will be derived from bio-ethanol. Within the present legislation regarding maximum oxygen content ETBE can be blended into petrol up to 15% vol.[19].
- Although not receiving much attention at the moment the Fischer-Tropsch process can also be made to produce FT petrol from natural gas or biomass (GTL vs. BTL). As soon as the FT process is used at large scale to produce Fischer Tropsch diesel from natural gas or biomass (GTL resp. BTL, or as a group identified by XTL), it is not unlikely that some synthetic products from the FT process will also be blended into petrol. The amount will, however, be more limited than for diesel, as in the present European market there is a shortage of diesel and a surplus of petrol. This unbalance between supply and demand is related on the one hand to existing refinery lay-outs and the associated energy-optimal fuel mix of outputs from the refining proces, and to a sharp increase in the share of diesel vehicles in recent years on the other hand. This unbalance is expected to remain to some extent also in the longer term future.

*High percentage blends / neat fuels in SI engines*

- Given the present successful market developments for flex fuel vehicles on ethanol in Sweden and some other countries it is expected that flex fuel vehicles will have a significant market share in Europe at least, and possibly also in the Netherlands by 2020.
- Flex fuel engines by 2020 will also run on lower percentage ethanol blends and pure petrol but may be optimised for use of high percentage blends.
- It is not yet clear to which extent similar technology for high percentage butanol blends will become available, but given the favourable characteristics of butanol over ethanol such developments are considered quite likely.

*Gaseous fuels in SI engines*

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[19] See e.g. http://www.wbfevent.com/ebio_pdf/051102_eBIO_presentation_World_Ethanol_Conference_2005pdf(22).pdf and http://www.ethanol-gec.org/clean/cf04.htm

- At present natural gas as a transport fuel is enjoying renewed attention. Many municipalities are converting municipal vehicle fleets and public transport fleets to run on natural gas. This development is largely driven by shorter term concerns over local air quality in relation to European air quality standards, but the transition route towards sustainable fuels that is offered by the use of biogas (BNG) in NGVs is also appealing to many of these municipalities.
- Given the present levels of investments in NGV fleets throughout Europe it is expected that niche applications for vehicles running on natural gas and biogas will still exist in 2020.

*Low percentage blends in diesel*
- Future diesel engines will accept up to 10% FAME in diesel without engine modifications. Blends containing GTL and/or BTL can be used in these engines without problems at any blending percentage (provided overall fuel specs are met).
- Although the environmental benefits of 1st generation biofuels are currently questioned it is expected that a certain share of FAME in diesel will continue to be used until 2020 and beyond. One reason for this is that growing rapeseed may remain economically interesting for European farmers. The main reason, however, will be that building the production capacity necessary to meet a 10% target for 2nd generation biofuel use will require more time than available between now and 2020.
- It is very well possible that future diesel will contain both FAME and synthetic (bio)diesel components.
- The premium quality of synthetic diesels (GTL, BTL, HVO) can be used to compensate for the impacts of the use of heavier crudes on the availability and quality of conventional diesel.

High percentage blends / neat fuels in diesel engines
- It is considered that the use of pure biodiesel (B100) in small niche applications still exists to some extent in 2020. Depending on price differential diesel-B100, controlled with tax incentives.
- Application of 2nd generation diesels from biomass (BTL, HVO) as pure / neat fuels is considered unlikely as the premium quality of these fuels has more added value when it is blended into conventional diesel.

The above scenario is largely based on expert insight at TNO and CE. An important addition to this will be to collect information on the views that various automotive manufacturers as well as fuel producers have on this issue. This work will be done in the follow up of this project.

## 6.3 Development of emissions legislation

### *6.3.1 Development of emission standards*

As consultant to the Dutch government and the European Commission TNO is deeply involved in the international process of emission standard setting and emission legislation through e.g. UN-ECE / GRPE (Geneva) and MVEG (Brussels). In these groups at present no concrete ideas are being discussed with respect to post Euro 6 (LD) / Euro VI (HD) emission limits. Also no concrete developments are taking place with respect to including various biofuels and blends in the emission test procedures.

Euro 6 legislation for passenger cars and vans and Euro VI legislation for HD vehicles will be in effect by 2014. For Euro 6 the emission limits for petrol and diesel are already almost identical. If a next step in emission legislation will be implemented this is likely to enter into force around 2020. A very likely characteristic of a possible Euro 7 legislation is that the limits will a further harmonisation of the emission limits for petrol and diesel and for all other allowed fuels. Both for LD and HD the legislation may be expected to focus more on controlling real-world emissions in contrast to emissions as measured under the well-controlled type approval test conditions.

As is already the case for Euro 6 / VI, the limits for Euro 7 / VII legislation for LD and HD diesel vehicles will require full application of exhaust aftertreatment technology. As a result it may be generally expected that for diesel engines the differences in emissions between the various fuels on which they can be operated will diminish because the advanced aftertreatment system with closed loop control systems will result in extremely low emissions anyway and will be able to deal with variations in engine-out emissions without exceeding the limits.

### 6.3.2 *Recommendation for amendment of type approval and emission legislation with biofuels*

An important issue for impacts of biofuels on emissions of future vehicles is the extent to which biofuels will be included in the Type Approval test. At the moment vehicles are only tested on prescribed reference fuels that do not contain biofuels.
According to a EU proposal low and high blends ethanol and FAME will be phased in the Euro 5 emission legislation for passenger cars and light-duty vehicles. The following is proposed and likely to be accepted:

- Introduction of 5% bio-ethanol in reference petrol (E5), resp. 5% biodiesel (FAME) in reference diesel (B5) as standard test fuels with Euro 5 (phase in October 2009-2010) [EC 2007b].
- For FFV tests with E85, same as with petrol with Euro 5b (phase in October 2011-2012). This includes a -7° C test , probably using E75, with separate limits for HC and CO.

Still missing in this proposal are requirements for high blend FAME (B100). These are however the first and very important steps to include requirements for biofuels into the emission legislations. This is very important to secure the emissions on biofuels (blends).

For the longer term (Euro 6/VI and Euro 7/VII), it is important to continue this work to synchronise the fuel composition for the type approval tests with the fuels that are expected during the life time of the vehicles. In that respect a projection of the fuel composition between 2015 and 2030 is needed as input for the emission legislation. The type approval procedure should also include requirements for OBD, durability and real world emissions.

## 6.4 Impact of future biofuels on regulated vehicle emissions

Fuel properties generally influence the performance and emission behaviour of engines. Changing fuel chemistry and composition can therefore be a tool to improve performance or lower vehicle emissions. Examples of the latter are the addition of oxygenates in petrol to reduce emissions responsible for smog and ozone formation, and the reduction of sulphur content in diesel to lower PM emissions. The use of biofuels for reduction of greenhouse gas emissions is expected to influence fuel properties and may thus be expected to have an impact on emissions of regulated and unregulated components.

Although many fuel characteristics can be directly related to combustion properties, the prediction of emissions based on fuel properties is very difficult [McMillian 1998], especially when another type of fuel is introduced with a number of different characteristics. With the introduction of exhaust gas aftertreatment, of which the effectiveness often depends on the composition of the raw exhaust gases (e.g. CO and HC acting as reducing reagent for $NO_x$ in a three-way catalyst) the relation between fuel properties and emissions has become even more complex.

Biofuels will generally have different fuel characteristics than the conventional petrol and diesel they replace, or alter the fuel properties of these fuels when used in blends. Biofuels may thus be expected to have an impact on emissions of regulated and unregulated components.

In this paragraph we will introduce the most important fuel characteristics, and –where possible– give an indication of the resulting effect on emissions and engine performance if these characteristics are changed due to the use of future biofuels. These mechanisms will prove helpful to give a rough quantitative or at least qualitative estimation of the expected impact of future biofuel use in future vehicles.

Starting point for the analysis has been an overview of the relations between fuel characteristics and engine performance and emissions as presented in [Smokers 2004]. This report was made for SenterNovem (an agency of the Dutch Ministry of Economic Affairs) in the context of the so-called “GAVE” programme (inventory of new gaseous and fluid energy carriers for a sustainable energy supply) Since this report was already published in 2004, the project team has searched for more recent information from literature, papers and through personal contacts to update the overview and especially to make it applicable to the issue of applying future biofuels in future engines (2020 time frame). The definitions of the fuel characteristics and how they are determined can be found in Annex B.

The discussion below focuses on fuel characteristics that impact vehicle emissions. In contrast to [Smokers 2004] possible compatibility issues, e.g. with respect to corrosive properties of biofuels, fuel injection problems resulting from high viscosity and cold start behaviour will not be discussed as it may be expected that such issues have been resolved by 2020.

This section will start with a general discussion of possible impacts for the main engine types. A further focus on the various fuels discerned for 2020 is presented further on.

### 6.4.1 *SI engines*

For SI engines (four-stroke Spark-Ignition, Otto engines) the following fuel characteristics are relevant from the point of view of emissions:

Octane number is an important property of fuels used in SI engines. The higher the octane number, the better the knock resistance of the fuel and the higher the compression ratio (and hence its efficiency) that is possible. Knock is spontaneous and uncontrolled auto-ignition with resulting pressure waves that can cause severe engine damage, especially when the knock occurs before the piston has reached its highest point in the compression stroke. Fuel with too low RON (research octane number) or MON (motor octane number) will cause the engine to knock at high loads [IEA 1999]. Future biofuels or blends that raise the octane number and require a dedicated engine will lead to higher compression ratios in order to benefit from the higher engine efficiency. The exhaust flow will decrease by roughly the same degree as the efficiency is raised, leading to lower engine-out emissions if the combustion process would be similar. However, due to the increased compression ratio the combustion temperatures will be higher. This will in effect lead to higher $NO_x$ emissions while CO and HC emissions are reduced.

A high volatility is important for a good mixture formation and engine start in cold weather, but on the other hand causes high HC emissions and the risk of vapour lock in warm weather conditions. Petrol is a mixture of components with different boiling points. Components with a low boiling point are important for cold-start, while heavy components with a high boiling point are important for fuel economy. It is important to create the right mix to meet the contradictory requirements posed on petrol [IEA/AFIS 1996].

The Reid Vapour Pressure of petrol is regulated. A high vapour pressure causes evaporative emissions (HC) and may form a safety risk. At the same time, engine-out HC emissions will be lower for high RVP fuels since highly volatile HC fractions are combusted easier.

### 6.4.2 *CI engines*

The most important parameters specified in diesel fuel standards for CI engines are cetane number, viscosity, cold behaviour, flash point, volatility, lubricity, sulphur and additives [Dieselnet 2008]. In terms of emissions from biodiesels, cetane number, density, carbon residue, viscosity, iodine number, heating value, oxygen content, aromatics content, sulphur content and fatty acid profile are relevant (see e.g. [Graboski 2003]).

The cetane number is a measure of the ignition delay (i.e. interval between reaching combustion conditions in a compressed air-fuel mixture and actual ignition), which represents the “readiness” of the fuel to ignite spontaneously under the temperature and pressure conditions in the combustion chamber of the engine [IEA 1999]. The higher the cetane number, the easier a fuel ignites.

The cetane number is also related to the number of C atoms as well as the structure of the molecule. A higher number of C atoms enhances the cetane number (highest numbers for the straight structure of paraffins), while compact molecules, double bondings and oxygen atoms reduce the self-ignition tendency. This is illustrated in Figure 6.1.

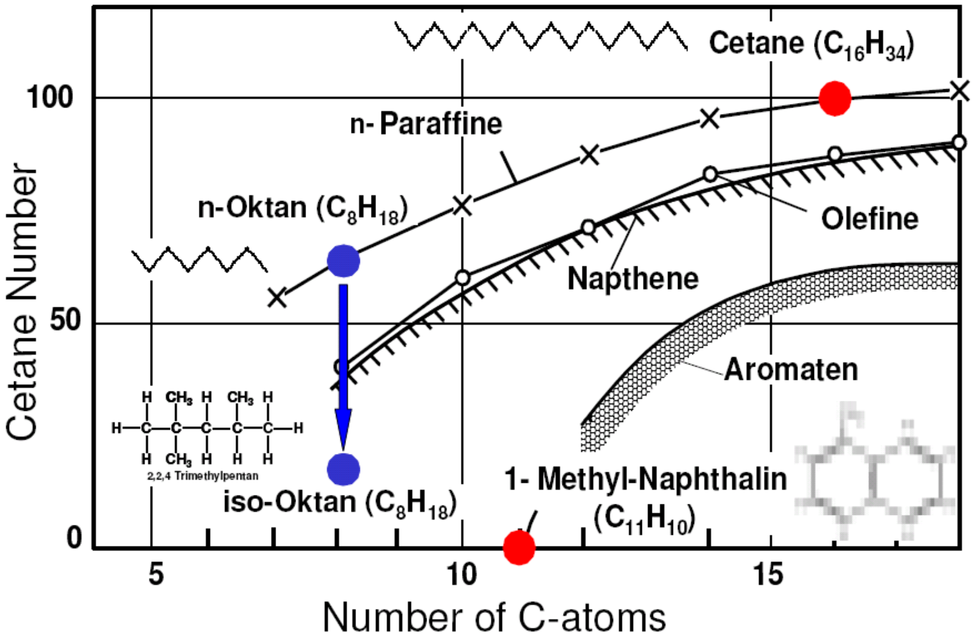


Figure 6.1 Cetane number as a function of C atom number for different kinds of molecule structures [Fricke 2007][Pischinger 2007]

In conventional diesel a high paraffin content yields a high cetane number and thus good ignition quality of the fuel. Aromatics and other hydrocarbons with a highly non-linear structure (with branched or cyclic carbon skeletons) lower the cetane number. For fuels with high aromatics content cetane number improvers are used as fuel additives [Dieselnet 2008].

Fuels with higher cetane number which have shorter ignition delays provide more time for the fuel combustion process to be completed. Hence, higher speed diesels operate more effectively with higher cetane number fuels. In diesel engines an increased cetane number results in lower $NO_x$ due to a slower combustion pressure rise, which gives more time for cooling through heat transfer and dilution and leads to lower gas temperatures [Dieselnet 2008]. Some researchers found larger effects of cetane number on older high $NO_x$ engines compared to modern low $NO_x$ engines [Stavinoha 2000]. The effect of cetane number on PM emissions depends also on the aromatics content. On its own, a lower cetane number will result in a lower soot production, as more fuel is being burnt in the premixed combustion phase. However, if the lower cetane number is the result of a higher aromatics content with an associated increase in PM production, this effect will be masked, resulting in a lower PM emission [Boot 2007]. CO and HC emissions have been reported to decrease with increasing cetane number [Dieselnet 2008; Martin 1997] (although especially for HC this may be more related to the lower aromatics content than to the slower combustion). Even for modern engines, cetane numbers well above 50 are desirable for optimum operation. There is no performance or emission advantage when the CN is raised past approximately 55; after this point, the fuel's performance hits a plateau [Wikipedia 2008].

Long term requirements will depend on the evolution of diesel combustion technologies. If homogeneous charge compression ignition (HCCI) is adopted for diesel engines, very high cetane numbers may no longer be advantageous [Dieselnet, 2008]. Other effects of cetane number on the engine performance involve an increase in engine noise with lower cetane number. Some increase in fuel consumption with higher cetane number may also occur due to lower heating value of the higher cetane blends. [Dieselnet 2008]

$NO_x$ emissions in biodiesels are well correlated with either cetane number or density [Graboski 2003]. In biodiesel more saturated esters give higher cetane numbers and lower densities than less saturated esters. [Graboski 2003] reports a highly linear relationship between increasing number of double bonds (i.e. higher iodine number and lower cetane number) and increasing $NO_x$ emissions. Rapeseed and soybean oil derived methyl esters are dominated by unsaturated methyl esters and they tend to have average cetane numbers in the range of 50-55 that is reflective of this. Palm oil methyl esters are rich in saturates and have cetane numbers varying between 50 and 70 but generally well over 60 [Dieselnet 2007].

Ignition delays for alkyl ester biodiesel fuels have higher activation energies than typical hydrocarbons found in diesel fuel. In practice, this means that cetane number will not be a good indicator of ignition delay for biodiesel in engines other than for the CFR engine used to determine the cetane number. This is illustrated for a particular engine in Figure 6.2 below. The B100 had a cetane number of 49.9 but gave an ignition delay comparable to that of an 80 cetane number primary reference fuel blend.

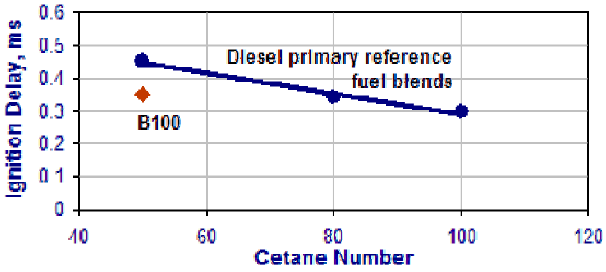


Figure 6.2 Effect of cetane number for three primary reference fuel blends and B100 [Dieselnet 2007]

High cetane number fuels (such as GTL) have high reactivity at low combustion temperature and are therefore capable of reducing the unburned fractions, i.e. HC and CO [Kitano 2007].

Other effects of cetane number on the engine performance involve an increase in engine noise with lower cetane number. Some increase in fuel consumption with higher cetane number may also occur due to lower heating value of the higher cetane blends. [Dieselnet 2008]

Viscosity is important to diesel engines because it can affect the operation of the fuel injection equipment and the development of the fuel spray. For some engines, a minimum viscosity specification helps prevent power loss due to injection pump and injector leakage and is one requirement for sufficient fuel system component lubrication. Maximum viscosity however is limited by engine design, size and fuel injection equipment size. Fuels with high viscosity tend to form larger droplets on injection into the cylinder, which can result in poor combustion and increased emissions. [Dieselnet 2007]. The viscosity of vegetable oils is much higher as compared to diesel, see Figure 6.3 below. Using these as fuel will require a fuel heating system to lower the viscosity to a suitable value.

Issues regarding the fuel injection system operation, such as leakage, correct injection quantities and lubricity may expect to be resolved for the biofuel dedicated engines in 2020.

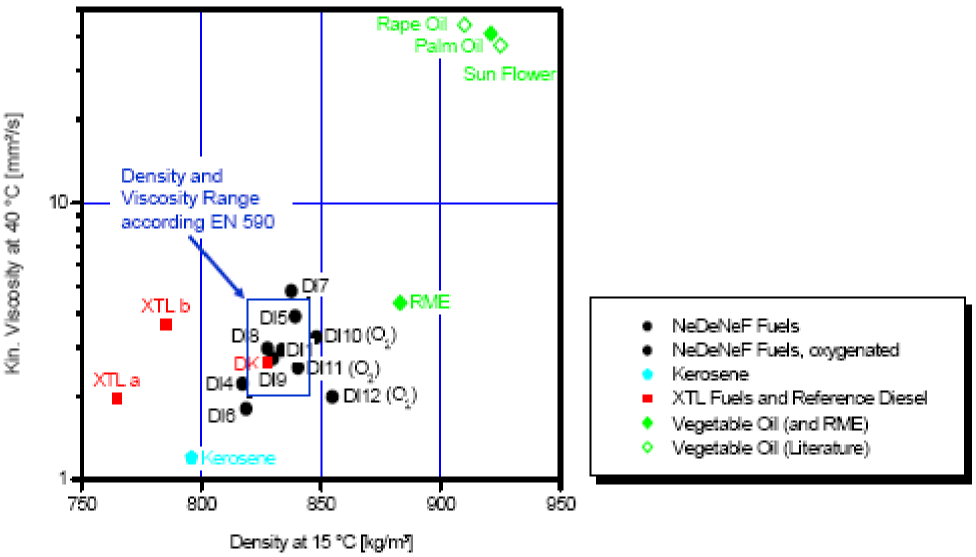


Figure 6.3 Kinematic viscosity and density of different fuels (EN590 window shows the boundaries for diesel) [Fricke 2007]

Cold behaviour can be described by different properties including cloud point (CP), pour point and cold filter plugging point (CFPP). For conventional diesel these are affected by distillation characteristics. At low temperatures, precipitation of (paraffinic) waxes can cause clogging of the fuel filter and an interruption in fuel supply. Additives can be used to prevent precipitation, e.g. winter fuels, or addition of petroleum products or filter heating [Dieselnet 2008]. Issues regarding the cold behaviour may expect to be resolved for the biofuel dedicated engines in 2020

Flash point is the temperature at which a combustible liquid gives off just enough vapour to produce a vapour/air mixture that will ignite when a flame is applied. For diesel flash point is not significant for engine performance, as it does not influence combustion characteristics. For diesel it is mainly a safety issue [Dieselnet 2008].

Volatility characteristics are for diesel fuel expressed in terms of distillation temperatures of successive fuel portions (distillation or boiling range – initial boiling point IBP, final boiling point FBP), which is a function of the chemical fuel composition [Dieselnet 2008]. Volatility has a small effect on HD engine emissions: reduced volatility leads to a small $NO_x$ reduction and small increases of HC and CO.

Lubricity of diesel fuel is very important for the fuel injection equipment, since many injection pumps and injectors rely on the lubricity of the fuel to protect their components from excessive wear. Sulphur increases lubricity, whereas lubricity is reduced when aromatics content and fuel sulphur are lowered [Dieselnet 2008]. Issues regarding the lubricity may expect to be resolved for the biofuel dedicated engines in 2020, if necessary by using additives for increased lubricity characteristics.

Sulphur in diesel depends on the quality of the crude oil, but refineries can reduce sulphur content of diesel by treatment with hydrogen. Low sulphur fuels typically require lubricity additives to avoid potential damage to fuel injection equipment. On the other hand sulphur may lead to corrosion and wear in e.g. EGR systems [Stavinoha 2000]. Clearly sulphur leads to $SO_2$ and $SO_3$ emissions, of which the latter contributes to PM formation and binds with water to form sulphuric acid. Sulphur deactivates $NO_x$ adsorbers (one of the most important obstacles for this technology), leads to catalyst poisoning, and to increased PM emissions when oxidation catalysts are used ($SO_2/SO_3$ shift). Sulphate particles are also generated in catalytic particulate filters (CRT, catalysed traps). In the past reductions in sulphur were necessary to accomplish regulated reductions in PM emissions (and also $SO_2$ emissions). Nowadays, ultra low sulphur diesel (10-50 ppm) is required to enable application of advanced $NO_x$ aftertreatment technologies as well as DPFs [Dieselnet 2008].

Reduced sulphur content produces a reduction in sulphate particulates. The effect of reducing sulphur on PM emissions, however, has its limitations, especially at lower sulphur levels (sulphates comprise no more than about 10% of total PM in a 0.1 g/bhp-hr PM engine operated with 300 ppm S fuel). Sulphur, however, plays a special role due to its adverse effect on several catalytic emission control technologies. Emission aftertreatment is the main driver behind the worldwide push for reformulated fuels of ultra low sulphur content.

A literature survey by [Larsen 2007] over multiple emission investigations confirmed that the emission reduction by using FT diesel (GTL) instead of reference diesel fuel increases when the reference fuel contains a larger amount of sulphur. This relation is especially visible for HC and PM, but also to some extent for $NO_x$ and CO. These findings are also apparent in literature, except for $NO_x$. The lower $NO_x$ emission might be related to the fact that the lower sulphur fuels are also lower in aromatic content, leading to a higher cetane number and a lower flame temperature. At the same time, there are indications that oxidation rates of DOCs and DPFs increase if the sulphur content of the fuel is lower, and even $NO_x$ reducing aftertreatment may benefit from ultra low sulphur fuels [Larsen 2007].

Towards lower sulphur levels in the reference fuel (below 150 ppm) the reductions in engine-out emissions from switching to XTL are not significant anymore [Larsen 2007]. This means that by 2020 the absence of sulphur in biofuels will no longer be a significant advantage as conventional fuels will by then also have a very low sulphur content.

Also the phosphorous content in the fuel is receiving more attention, since this element acts as a poison to catalysts, just as sulphur does [Krahl et al. 2006]. In a 1000 hours accelerated aging test, an SCR system lost activity regarding $NO_x$ and PM by using RME fuels with a (artificially added) high phosphorous content. It was also found that the higher phosphorous content led to an increase in the ultra-fine particle emissions, and the aging of the SCR catalyst led to higher emissions as well as an increase in mutations of the PM. Higher PM emissions for the phosphorous containing fuel were attributed to the formation of phosphates, which are measured as PM. It was recommended that the current European maximum of 10 ppm is lowered.

Additives are specialized compounds or mixtures which are used to correct deficiencies in the properties of the refinery blends. The overall concentration of additives in diesel fuel (e.g. ignition improvers, detergents, corrosion inhibitors, anti-foaming agents, demulsifiers, lubricity additives, biocides) is generally below 0.1%, so that physical fuel properties are not affected [Dieselnet 2008; Stavinoha 2000]. On the other hand, some additives may impose a secondary effect on emissions by enhancing other fuel properties, e.g. cetane improvers.

According to [Smokers 2004] most studies reviewed in that report indicate no influence of aromatics content on HC, CO or PM emissions from HDVs. Decreasing total aromatics from 30 to 10% produces a small benefit (0-5%) for $NO_x$ [Dieselnet 2008]. According to [Stavinoha 2000] the effect of aromatics on diesel emissions is uncertain. The overall trend in the recent literature is that reducing aromatics has a small benefit, if any, on $NO_x$ and PM emissions. According to [Martin 1997] particulates, smoke and PAH are influenced by aromatic content.

More recent papers reviewed for this study do report some impacts of aromatics on various emission components but also partially confirm the conclusion from [Smokers 2004]. One example of the relation between aromatic (as well as oxygen) content and soot formation is demonstrated by [Fricke 2007], see Figure 6.4. The overall picture is that the higher cetane number associated with lower aromatic s content leads to an increase in PM emissions. On the other hand the lower aromatics content itself reduces PM emissions, and this effect is stronger than the former.

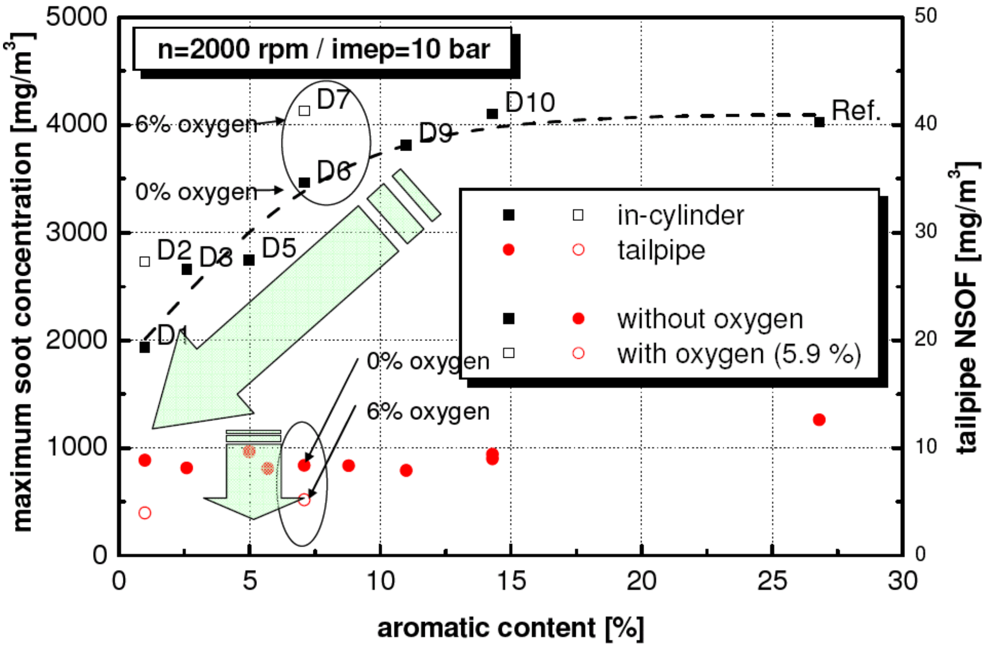


Figure 6.4 Maximum soot concentration (in-cylinder and at the tailpipe) as a function of aromatic and oxygen content in the fuel [Fricke 2007][Pischinger 2007]

From Figure 6.4 it is apparent that for aromatic contents below 12% the maximum soot concentrations inside the cylinder increase for fuels with higher aromatic contents. However, soot concentrations at the tailpipe are almost independent of the aromatic content. More than 99.5% of the soot formed is oxidised during combustion. Therefore, almost no influence of the aromatic content on the soot concentration in the tailpipe emissions can be seen. The tailpipe soot concentration (fully coloured red circles) does appear to show a weak but still visible positive correlation with the aromatics content. The oxygen containing fuels show higher maximum in-cylinder soot concentrations for nearly similar aromatic contents. But in contrast to that, the tailpipe soot emissions are lower than for the oxygen free fuels. This result indicates a better soot oxidation process for oxygen-containing fuel mixtures [Pischinger 2007].

A study by CONCAWE found significant lower $NO_x$ emissions for very low aromatic fuels, especially in HD engines [Thompson 2004]. On the other hand [Kalghatgi 2005] claims that higher aromatic concentrations are known to reduce $NO_x$ by improving the conversion efficiency of the catalyst. [Kalghatgi 2005] acknowledges that high aromatic levels may increase benzene levels in the exhaust, but states that this is becoming less relevant with modern aftertreatment systems leading to near-zero emission vehicles. Nevertheless it may be expected that higher aromatics content of the fuel leads to higher tailpipe aromatics emissions.

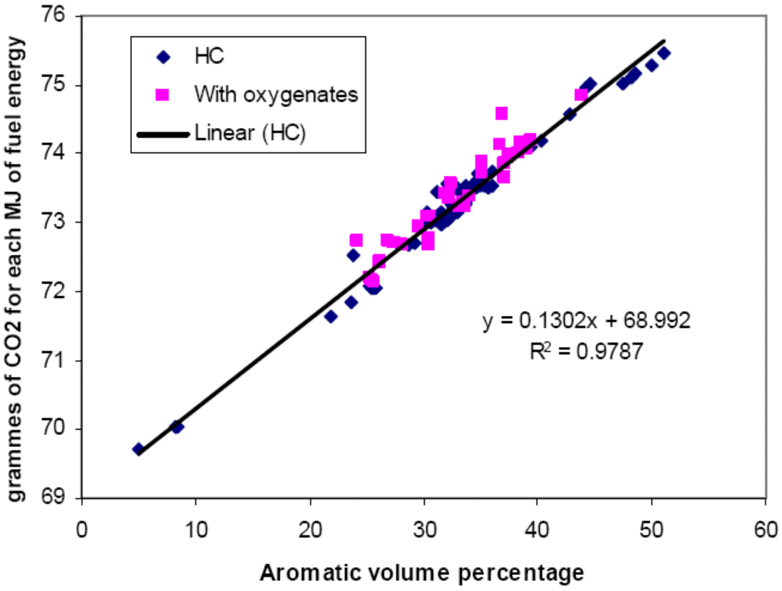


Figure 6.5 Effect of aromatic volume percentage on $CO_2$/MJ [Kalghatgi 2005].

High aromatic contents lead to higher $CO_2$ emissions per MJ fuel [Kalghatgi 2005] so that the 10% reduction of Well-to-Tank greenhouse gas emission from fuels between 2011 and 2020 as recently proposed in relation to the Fuel Quality Directive may induce lower aromatic contents in fuels. [Kahgatgi 2005] however states that the improvements in engine efficiency and refinery efficiency that can be obtained from relaxing requirements with respect to aromatics content may outway the increase of $CO_2$/MJ leading to net WTW greenhouse gas benefits from increased aromatics content.

A literature survey by [Larsen 2007] over multiple emission investigations confirmed that the emission reduction by using GTL instead of reference diesel fuel increases when the reference fuel has a higher aromatic content. This relation is especially visible for HC and PM, but also to some extent for $NO_x$ and CO. The lower $NO_x$ emission was thought to be explained by the lower flame temperature.

Fuel density is an important fuel property with respect to volumetric fuel economy and maximum power, but also with respect to emissions (due to complex physical interactions with fuel injection system). For HD vehicles lower PM emissions are reported with lower density in old engines, while modern engines show very little or no change. According to [Dieselnet 2008] a lower density leads to a small reduction in $NO_x$, but slightly higher CO emissions and a particularly large increase in HC. Density and cetane number in biodiesels are highly correlated [Graboski 2003]. According to [Martin 1997] particulates, smoke and PAH are influenced by density.

A high cetane number and a low density –such as found for GTL fuels- will reduce $NO_x$ emissions [Krahl 2005].

Data regarding the effect on emissions of adding oxygenates (biodiesel, ethanol) to diesel used in HD vehicles should be considered tentative, since the majority of emission studies fail to decouple the addition of oxygenate from changes in other fuel parameters such as density that occur as the diesel fuel is diluted by the oxygenate. The engine must be recalibrated to its original power output before valid comparisons can be made. PM emission reduction is reported to be proportional to oxygen content in biodiesels with cetane numbers > 45 or density > 0.89 [Graboski 2003]. The oxygen content in the fuel has a pronounced effect on PM reduction, but differences in chemical structure of the oxygenate are found to have effects of almost of the same order of magnitude. The effectiveness of oxygenates in PM reduction changes with the engine load condition [Boot et.al. (2007)]. It appears that only a large amount of oxygenates can produce significant PM emissions improvements [Stavinoha 2000]. The oxygen content of the fuel has an almost linear relationship with the heating value, as is illustrated in Figure 6.6.

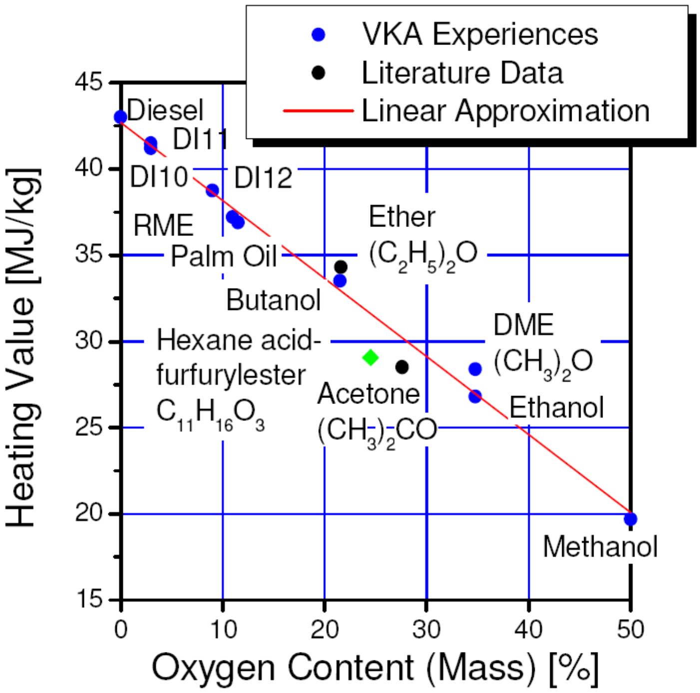


Figure 6.6 Heating value as a function of oxygen content for different fuel types [Fricke, 2007][Pischinger 2007]

Using a fuel with a lower heating value means that more fuel is needed to obtain the same engine output. Therefore, the injection duration will be longer so the combustion process is extended further in the expansion stroke. If the injection timing is kept the same, $NO_x$ emissions will be lowered while PM emissions are increased. The lower caloric value of oxygenated fuel will have little or no effect on the combustion temperature, since this is balanced by the lower stoichiometric air-fuel ratio [Boot et.al. 2007].

Carbon residue - Although the results of carbon residue tests are not directly related to engine deposits, this property is considered an indication of the carbon deposit forming tendency of petroleum diesel fuels. It is known that non-volatile coke forming compounds that were not adequately separated during distillation and other refinery processes can contribute to engine deposits if they end up in diesel fuel.
It is not known if a correlation exists between carbon residue values in biodiesel and engine deposits [Dieselnet 2007].

In general fuel sensitivity of (CO, HC, PM) emissions from LD diesel engines appears to be larger than of HD diesel engines, with the exception of $NO_x$ [Dieselnet 2008]. Other extreme fuel property changes studied in [Thompson 2004] influenced $NO_x$ emissions in heavy duty engines, and in light duty vehicles on the ARTEMIS motorway cycle, but not on the NEDC. Fuel effects on $NO_x$ emissions were smaller in light duty vehicles than in heavy duty engines.

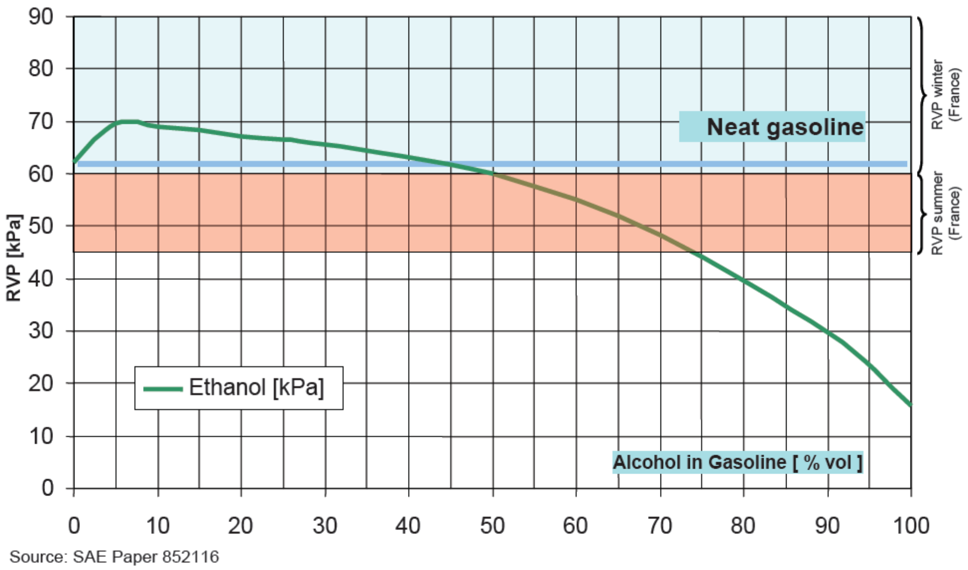
### 6.4.3 *Effect of low-percentage ETBE blends on emissions of future SI engines*

Especially in the US ETBE has been used as an oxygenate in reformulated gasoline because of its positive impacts on CO, HC and $NO_x$ emissions. The available evidence, however, is all related to older vehicles. No new information has been obtained so far on possible emission impacts of the use of ETBE in future vehicles.

### 6.4.4 *Effect of low-percentage ethanol blends on emissions of future SI engines*

In the literature search so far no information has been found on possible impacts of the use of low-percentage ethanol blends on exhaust gas emissions from future SI vehicles.

One of the practical problems of using low percentage ethanol blends is the higher vapour pressure, leading to higher amounts of evaporative HC emissions. The relation between ethanol content and the so-called Reid Vapour Pressure (specific test method to determine vapour pressure for liquid fuels) is a very non-linear one, as is illustrated in the graph below.



Source: SAE Paper 852116

Figure 6.7 Relation between ethanol content of ethanol/petrol blends and the Reid Vapour Pressure [Rouveirolles 2007]

For an ethanol content of up to 40-50% the vapour pressure is elevated as compared to neat petrol, while for higher percentage blends it is much lower. The maximum increase lies at 5-10% ethanol, which is the range in which blends are currently commercially available.

According to [Martini 2007] evaporative emissions clearly appear to be influenced by vapour pressure. However, this effect is not linear, and only the fuels with a vapour pressure close to 75 kPa gave visibly higher evaporative emissions as the base fuel. The increase in emissions from 60 to 70 kPa was not significant. The non-linearity of the vapour pressure influence on evaporative emissions can be easily explained. Carbon canisters are very efficient at trapping petrol vapours until they become saturated (known as breakthrough). Once the breakthrough condition is reached, the canister can no longer adsorb all the vapour generated in the tank, and some is emitted to atmosphere. Evaporative emission control systems are usually developed to cope with fuels having a vapour pressure close to 60 kPA (the maximum allowed in reference fuel), but apparently also allow for some engineering margin.

Another source for evaporative emissions resulting from ethanol use is the increased effect of fuel permeation through plastic and rubber components in the fuel system, e.g. fuel hoses.

In measurements reported by [Martini 2007] the volumetric fuel consumption increased with increasing ethanol content, roughly proportional to the oxygen content of the fuel. However, there was no noticeable effect on $CO_2$ emissions and energy consumption (in MJ/100 km). The relation established by statistical analysis between fuel consumption (in l/100 km) and oxygen content was: FC = 1 + 0.0109 x oxygen content (% m/m), relative to the oxygen free reference fuel. Expressed in ethanol content, this relation is: FC = 1 + 0.00397 x fuel ethanol content (% v/v), relative to a test on ethanol free fuel. This is very close to the loss in energy content, which is 3.4% for a 10% ethanol blend (3.97% according to this formula).

### 6.4.5 *Effect of high-percentage ethanol blends on emissions of future SI engines*

[Benninger 2007] explores the requirements for flexible-fuel systems and especially engine management systems for use of ethanol in direct injection SI engines. As general problems with the use of ethanol in SI engines [Benninger 2007] mentions low-temperature starting and catalyst heating. Using multiple injection is seen as a starting point for solving these problems. The challenge of using ethanol in future SI engines is to utilise the potential offered for efficiency improvement by the high octane number and high evaporation enthalpy of E85 and other high-percentage ethanol blends. The combination of direct injection and turbo-charging offers maximum synergies.

According to [Benninger 2007] running on E85 requires a higher cold start enrichment than running on conventional petrol, causing higher cold-start emissions for E85. This is further augmented by the high evaporation enthalpy of E85 which leads to lower combustion temperatures, lower exhaust gas temperatures and consequently slower catalyst heating after start-up. With single injection the enrichment for winter grade E85 (class III) is about double that for winter grade petrol (S98). With multiple injection this additional enrichment can be significantly reduced resulting in lower cold start emissions. Using high-pressure stratified injection at engine start-up brings further improvements. Reducing cold start enrichment for E85 has the additional benefit of reducing oil dilution from ethanol migrating into the engine oil.

According to [Benninger 2007] HC emissions for running on E85 are generally higher than for premium petrol especially for engines calibrated for petrol. Multiple injection can bring these HC emissions down but only at the expense of engine smoothness.

Measurements in [Benninger 2007] on a production DI SI engine with a 200 bar Bosch fuel injection system indicate that under part load $NO_x$ emissions of a DI SI engine may be reduced for E85 compared to petrol, while at high loads $NO_x$ emissions for E85 are higher than for petrol. Overall results on the NEDC cycle are given in Table 29. Despite application of multiple injection to reduce cold start enrichment and optimise catalyst heating the HC emissions from running on E85 are higher than for running on petrol. Once the engine has reached its operating temperature HC emissions on E85 are lower than on petrol. $NO_x$ and PM emissions over the complete cycle are 60% resp. 75% lower for E85 than for premium petrol in this DI SI engine, and for this specific engine are about 15% of the limits for Euro 5.

[Taniguchi 2007] showed an up to about 50% lower HC and $NO_x$ emissions under part load conditions (warm engine), but higher CO emission. This was with a DI engine adapted for ethanol. HC emission under full load was much higher on ethanol but could be reduced with a “swirl control valve” in the inlet port. It can be concluded that indeed for engines primarily optimised and developed for petrol, HC emissions with E85 can be higher under certain conditions. However, the expectation is that with the appropriate development effort, HC emissions with E85 can be brought within desirable levels. This can be enforced by including the appropriate tests on E85 in the type approval test procedure.

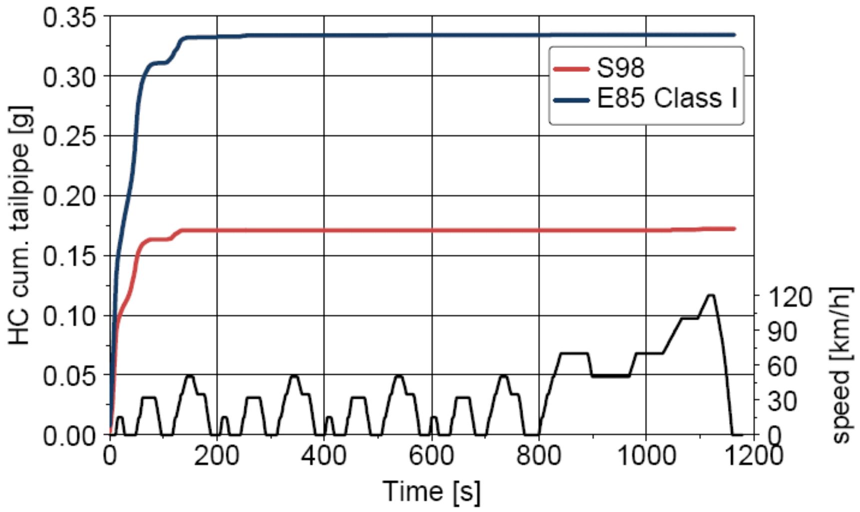


Figure 6.8 Cumulative HC emissions over the NEDC Cycle for a vehicle running on premium petrol (S98) and on Class 1 E85 [Benninger 2007]

Table 29 Comparison of S98 (premium petrol) and E85 Class 1 and 3 applied in a DI SI engine wrt emissions on the NEDC cycle with normal start at 20 °C and cold start a -7 °C [Benninger 2007]

| Euro5 Limits [%] | NEDC | | | |
|---|---|---|---|---|
| | S98 @-7°C | S98 @20°C | E85/Class3 @ -7°C | E85/Class1 @ 20°C |
| HC | 17 | 20 | 11 | 33 |
| NMHC | | 23 | | 29 |
| CO | 19 | 27 | 1 | 35 |
| NOx | | 35 | | 14 |
| PM | | 68 | | 16 |

A vision on the development of ethanol SI engines is also given in [Pischinger 2006]. First of all, the higher octane number (RON = 111) of ethanol will allow for an increase of the compression ratio by 2 to 4 units. In addition, the unburned HC emissions are reduced significantly, leading to an efficiency increase of up to 10%. [Taniguchi 2007] also shows an engine efficiency increase of 5-10% with a DI engine with an increased compression ratio by 1.5 units. The marketability of dedicated ethanol engines, however, remains questionable.

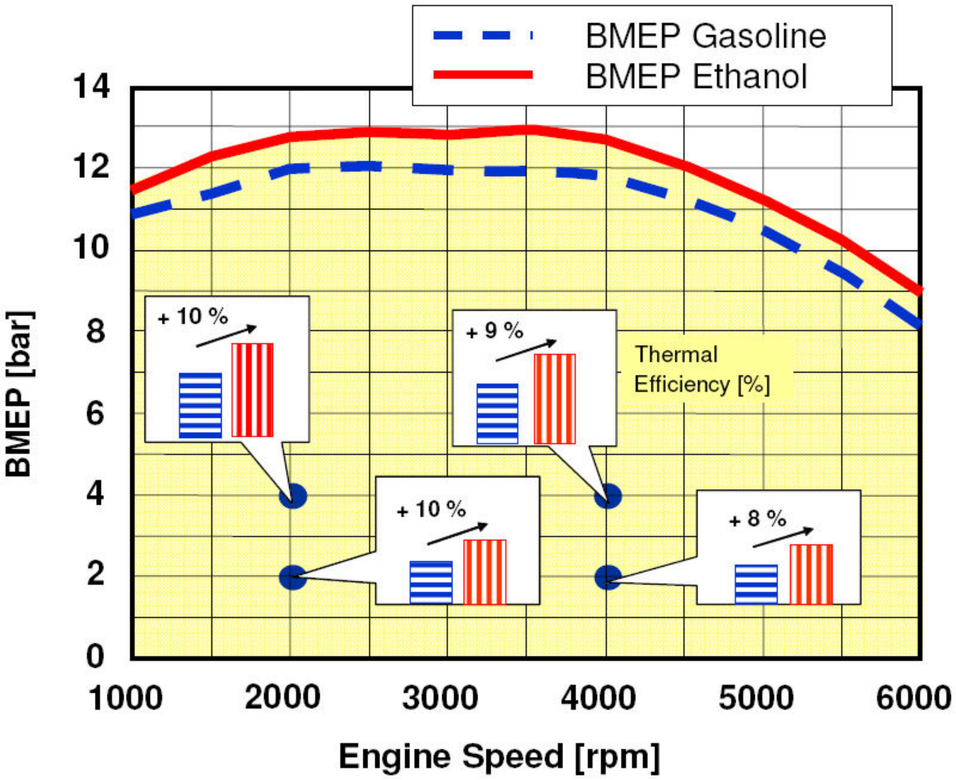


Figure 6.9 Thermal efficiency increase and engine performance for ethanol (E95) compared to regular petrol [Pischinger 2006 & 2007]

Additional efficiency benefits can be gained from the lean burn capability of ethanol, by applying homogeneous lean operation (air-to-fuel ratio of 1.8 to 2.0). The higher heat of evaporation from ethanol can be used to improve the volumetric efficiency, leading to an improved full load performance. Improvement of the starting behaviour of ethanol engines is expected when direct injection is used instead of port fuel injection, due to reduced wall film effects and the possibility for a direct start.

### 6.4.6 *Effect of low-percentage butanol blends on emissions of future SI engines*

In the literature search so far no information has been found on possible impacts of the use of low-percentage butanol blends on exhaust gas emissions from future SI vehicles.

Important differences between butanol and ethanol are the lower pressure, reducing possible risks related to evaporative emissions, the lower octane number (RON / MON resp. 98/78 against 129/102) which reduces possible efficiency benefits, and the higher energy density (29.2 MJ/l for butanol against 19.6 MJ/l for ethanol).

### 6.4.7 *Effect of high-percentage butanol blends on emissions of future SI engines*

In the literature search so far no information has been found on possible impacts of the use of high-percentage butanol blends on exhaust gas emissions from future SI vehicles.

### 6.4.8 *Effect of GTL/BTL petrol on emissions of future SI engines*

Although not receiving much attention at the moment the Fischer-Tropsch process can also be made to produce FT petrol from natural gas or biomass. FT petrol is a rather complex product of syngas-derived products that are liquefied via a high temperature FT process. The naphta from the FT-process is treated by ordinary refinery methods such as hydro treating, alkylation, isomerisation and platforming. Olefins originating from the FT process are treated by the “Conversion of Olefins to Distillate” (COD) process. The final product consists of several types of molecules such as normal and branched alkanes, cyclo-alkanes, alkenes and aromatic hydrocarbons. It is oxygenated with ethanol and MTBE. Other ingredients such as xylene, benzene and toluene are present too.

In literature, not much is reported on the use of FT petrol in SI engines. This lack of information was acknowledged by [Larsen 2007], and therefore followed up by some research of their own on a VW Golf 1.6 FSI (MY 2003). A 70% FT petrol blend was tested together with Aspen 4T, a fully alkylate petrol that can be seen as the best quality fuel that could be obtained from a FT process. Results of the emission tests (starting with a conditioned cold engine) as compared to regular petrol showed that CO was reduced by 20-30% for both FT petrol and Aspen. $NO_x$ emissions decreased about 20% for Aspen, while this increased slightly for FT petrol. This result could not be explained. The reduction of HC amounted to 20% for both fuels. PM was lowered by 25-50%. $CO_2$ was 9% lower for Aspen fuel, while the FT petrol increased $CO_2$ by a few percent. PAH emissions were 50% lower for Aspen, while the FT petrol showed an increase of some 50%. This is not surprising, since the FT petrol contained significant amounts of aromatics (due to the COD process). It is therefore necessary to have a well described fuel standard for FT petrol, in order to exploit the full advantage of the emission reducing qualities of this fuel.

### 6.4.9 *Emission of future SI engines on CNG and CBG*

Stoichiometric SI engines on natural gas will be able to comply with Euro 6 and Euro VI emission legislation. Differences in emissions between CNG on the one hand and petrol and diesel on the other hand are expected to decrease. Remaining differences by 2020 may be a small advantage of CNG in the area of unregulated emissions. Assuming that all CBG is upgraded to CNG quality and mixed into the gas grid, the use of CBG instead of CNG will not affect emissions from gas fuelled vehicles.

### 6.4.10 *Effect of low-percentage FAME blends on emissions of future CI engines*

In [May 2007] emission measurements are reported on a modified Euro IV HD engine running on B30. For this test on the ESC cycle, which was carried out by AECC, the engine was equipped with a number of additional aftertreatment systems The base engine was developed to meet US2007 standards, by applying cooled EGR and a ceramic DPF. First, the DPF fitted to the US2007 production version was replaced by a new catalysed DPF, suited to meet expected Euro VI requirements. Then, a catalyst system was added, consisting of an oxidation catalyst (DOC), a catalysed DPF, followed by an SCR system and a second oxidation, or Ammonia Slip Catalyst. Consequently, these results bear relevance to the investigation of impacts of biofuels on emissions of future engines.

[May 2007] concludes that compared with diesel the catalyst efficiencies on B30 biodiesel were the same for CO, slightly reduced for $NO_x$ and HC, and slightly higher for PM. Comparing B30 and conventional diesel there was no significant difference in particle numbers (see Table 30). It should be noted here that with very high catalyst conversion efficiencies a relatively small change in the conversion efficiency leads to a relatively high change in tailpipe emissions.

Table 30 Effects of B30 compared to reference diesel on the emissions of a pre-Euro VI HD engine equipped with cooled EGR, DOC, SCR, ASC, and catalysed DPF [May 2007]

| **Test Procedure** | **Emissions [g/kW.h]** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **THC** | | | **NOx** | | | **CO** | | | **PM** | | |
| | Engine Out | **Tail pipe** | Conv. Effy. | Engine Out | **Tail pipe** | Conv. Effy. | Engine Out | **Tail pipe** | Conv. Effy. | Engine Out | **Tail pipe** | Conv. Effy. |
| **Tests on Standard European Diesel Fuel** | | | | | | | | | | | | |
| **ESC (RF06 fuel)** | 0.15 | **0.06** | 63% | 1.54 | **0.15** | 90% | 1.10 | **0.00** | 100% | 0.151 | **0.009** | 94.3% |
| **Tests on B30 Biodiesel Fuel** | | | | | | | | | | | | |
| **ESC (B30 fuel)** | 0.13 | **0.05** | 58% | 1.64 | **0.27** | 83% | 0.87 | **0.00** | 100% | 0.513 | **0.002** | 99.6% |

### *6.4.11 Effect of high-percentage FAME blends and B100 on emissions of future CI engines*

The overall tendencies found for the impact on emissions of using high percentage or pure FAME instead of normal diesel is a reduction of CO, HC and PM, while $NO_x$ is increased [Krahl 2005]. This is confirmed by the conclusions of chapter 5. These effects may vary as function of the quality of the fuel and the feedstock from which the FAME fuel is produced (especially for PM, but also for $NO_x$), but the trends still remain the same. Also the mutagenicity of FAME is much lower than that of normal diesel fuel. This particular investigation showed that all of the FAME qualities observed showed better emission performance than GTL, except for $NO_x$.

Most of the literature sources report a higher $NO_x$ emission for biodiesel, as compared to normal diesel fuel. This $NO_x$ increase can be brought back to the level of normal diesel $NO_x$ emissions by changing the injection timing. There are sensors on the market that allow for the determination of the biodiesel fraction in the fuel, that will adjust the timing accordingly. Also the fuel quality and feedstock of biodiesel has an effect on the $NO_x$ emissions. According to [Krahl 2005] for some FAME qualities the $NO_x$ emission may be almost the same as for normal diesel.

[Krahl 2006] has done research with RME on a Euro 4 HD engine equipped with SCR, however without adjusting the urea dosing strategy. In comparison with regular diesel fuel, all emissions were reduced (HC and CO more than 50%, PM even more) except for $NO_x$. After the SCR had received 1000 hours of accelerated ageing with 10 ppm phosphorous RME, some of the catalyst activity had been lost ($NO_x$ emissions were higher, as well as the ammonia slip). Also the PM emission was raised, and the difference in emissions between normal diesel and RME was decreased.

In [Kawano 2007] 100% RME was tested in a turbocharged CI engine with variable EGR and a DPNR aftertreatment system. This Diesel-Particulate-$NO_x$-Reduction system combines the properties of a diesel particulate filter (DPF) and a $NO_x$ storage catalyst (NSR). It was found that RME increases engine-out $NO_x$ emissions by roughly 10 to 50%, depending on the operating point, and reduces the conversion efficiency of the NSR catalyst. On diesel the NSR has a reduction rate of up to 99%, while this is reduced to less than 50% when RME is used. As a result the emissions after the catalyst are an order of magnitude higher on RME than on diesel (see Figure 6.10). The latter could not be overcome by increasing the quantity of rich spike injection. [Kawano 2007] suggests that engine adaptations need to be made to improve atomisation and vaporisation of RME in the rich spike injection. $NO_x$ emissions could be strongly reduced by adapting the EGR rate, which also leads to lower PM emissions due to improved catalyst performance resulting from the higher EGR rate.

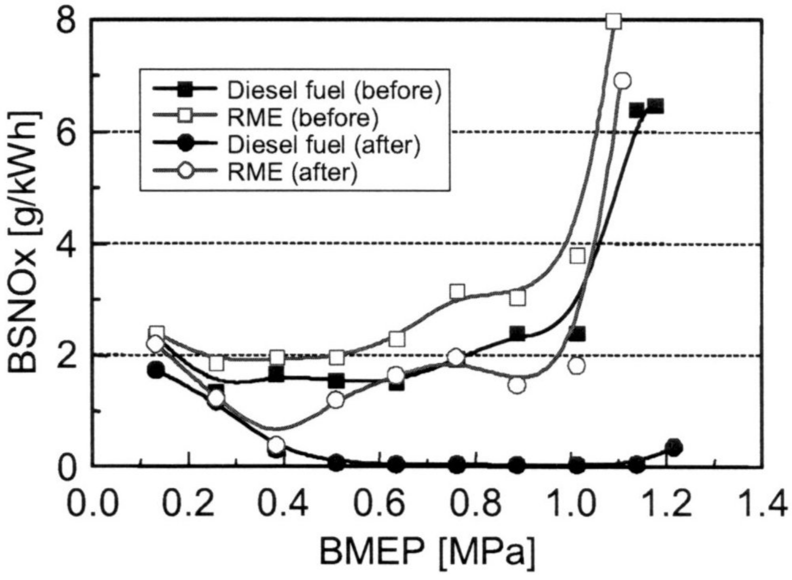


Figure 6.10 Emissions of 100% RME compared to reference diesel on $NO_x$ emissions before and after catalyst of a turbocharged CI engine with variable EGR and a DPNR aftertreatment system [Kawano 2007]

### 6.4.12 *Effect of low-percentage GTL/BTL blends on emissions of future CI engines*

Interestingly, research on the effects of blending GTL with conventional diesel has shown that the emission reducing effect is higher than the fraction of GTL would indicate. The reductions are roughly twice as big as the blending percentage, i.e. a 50/50 blend of FT and conventional diesel will almost produce the same emissions as a neat GTL fuel [Larsen 2007]. This conclusion can be generalised for all XTL diesel fuels.

### 6.4.13 *Effect of high-percentage GTL/BTL blends and pure GTL/BTL on emissions of future CI engines*

Generally, XTL has another chemical composition than conventional diesel fuel. The high n-paraffin content yields a high cetane number, low density, as well as poor lubricity and cold flow properties. Furthermore, the sulphur and aromatics content of FT fuels is much lower compared to conventional diesel. The general trend following these characteristics is a reduction of PM, HC, CO, $NO_x$ and PAH emissions [Larsen 2007].

[Tsujimura 2007] reports for GTL in a HD truck somewhat lower $NO_x$ emissions, significantly lower PM (possibly also a smaller fraction of ultra-small particles in the particle size distribution), lower PAH and HC.

[Schaberg 2007] have successfully reduced $NO_x$ emissions from a Mercedes engine on GTL by applying a lower compression ratio.

Based on a review of papers available up to 2003 and statistical analysis of the reported emission measurement results [Alleman 2003] concludes that GTL leads to lower emissions for all regulated components. Another –more recent- comprehensive literature survey on earlier performed emission measurements on vehicles fuelled by GTL also confirmed these findings: CO, HC, PM and PAH are reduced considerably, meaning more than 25%, while $NO_x$ is reduced by some 10% and $CO_2$ by a few percent

[Larsen 2007]. The average reductions over all of the 23 studies observed are listed in Table 31.

Table 31 Average emission reductions of GTL compared to conventional diesel [Larsen 2007]

| | **HC** | **CO** | **$CO_2$** | **$NO_x$** | **PM** |
|---|---|---|---|---|---|
| Average reduction HD vehicles[%] | 43 | 35 | 3.2 | 13 | 27 |
| Standard deviation | 32 | 30 | 2.3 | 10 | 19 |
| Average reduction LD vehicles[%] | 34 | 43 | 3.9 | -1 | 32 |
| Standard deviation | 33 | 40 | 2.2 | 13 | 27 |

Also the PAH emissions dropped by 35% on average, which is the result of a lower aromatics content in the fuel (17% on average in the reference fuel, while the GTL diesel contained on average 1.3%). There is another FT process called FTCOD (Conversion of Olefins to Distillate) that may produce fuel with an aromatic content of around 10%.

Of course, these figures are averaged over different vehicles, different test cycles and different fuels, but still the trends seem significant. It also needs to be stressed here that for many of these investigations the engine management strategy will not have been changed. If all of the engines were to be tuned to the specific fuel characteristics, with the aim of maximising emission reductions, the effects would certainly be higher.

Though there is not much evidence to support it, there are indications that the relative improvement of GTL on cold start emissions is higher than found for the emissions under warm running conditions. [Larsen 2007] found in one investigation that the reduction in emissions increases when the test cycle is more aggressive (or more real-life oriented than a relatively static NEDC).

Emission impacts of XTL can be partly correlated to fuel characteristics. [Kitano 2007] states that GTL fuels reduce PM emitted from the engine. Especially GTL fuel with a lower distillation range than diesel fuel shows a remarkable reduction of PM in the exhaust gas. It is considered that lowering the distillation characteristics improves fuel evaporation and mixing with surrounding air, which results in the reduction of smoke and PM. However, [Boot 2007] gives a somewhat different interpretation of the same effects: “Notwithstanding its short ignition delay (high CN), syndiesel has a considerably lower soot level than the EN590 fuel. Of course this is linked to its lower aromatics content.” Exhaust aftertreatment, in this case DPNR, reduces the relative impacts of GTL on PM emissions. Interestingly [Boot 2007] finds no impact on $NO_x$, leading to the hypothesis that GTL has no influence on combustion temperature $NO_x$ aftertreatment.

Engine improvements can further optimize the emissions of engines running on XTL. GTL/BTL also offers the possibility to lower the compression ratio of the engine. This leads to a lower compression end temperature, which has a positive effect on the $NO_x$-PM trade-off through a larger ignition delay and a lower combustion temperature. However, for diesel driven engines this would also lead to a lower fuel efficiency and raised HC emissions. These negative effects are not present if the engine is run on GTL, but the advantages in reduced emissions still remain. This is a promising development path for dedicated GTL engines [Kitano 2007]. [Kitano 2007] states that besides the low compression ratio also a high flow rate injection nozzle was beneficial in further reduction of emissions and improvement of engine output power. According to [Kitano 2007] the lower engine out PM, HC and CO emissions also allow application of higher EGR rates to further reduce $NO_x$ emissions (by up to 50%).

[Pischinger 2007] summarizes the results from [Lepperhof 2006] as follows: "Without any hardware modifications or a recalibration of the injection settings, a reduction of the PM-emissions by 25 % was possible by the transition from conventional Diesel fuel to GTL Diesel fuel at low engine load conditions. An additional optimization of the engine calibration to the needs of GTL fuel allows a reduction of the PM-emissions by 50 % compared to the operation with conventional fuel while advantages with respect to CO- and HC-Emissions could be maintained. This improvement could be realized without drawbacks regarding engine efficiency or acoustic behaviour. Additional improvements can be gained from the operation with GTL-fuel if the combustion system layout is optimized to the needs of these specific fuels."

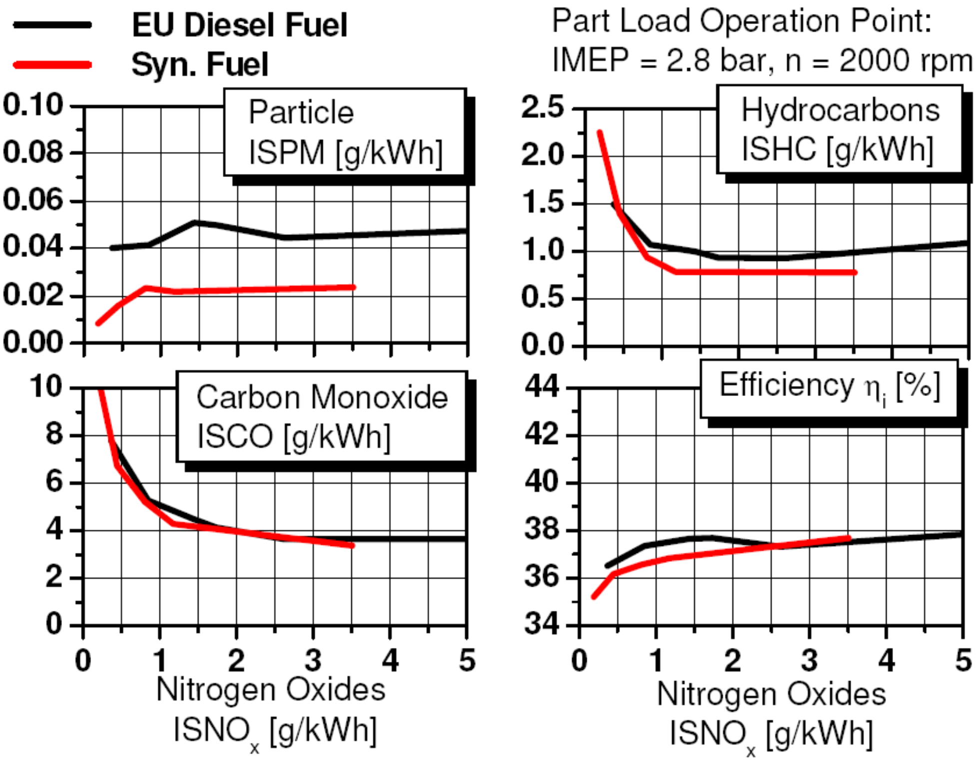


Figure 6.11 Impact of synthetic diesel fuel on emissions [Lepperhoff 2006][Pischinger 2007]

[Lepperhoff 2006] reports tests done with a post Euro 4 single cylinder test engine, which was optimised to find the best emission performance on neat GTL fuel, including EGR rate, rail pressure, and variations of pilot injection timing and quantity (some of these results are also reported in [Pischinger 2007]). For CI engines running on conventional diesel, many of the measures that can be taken aim at a better homogenisation of the in-cylinder air/fuel mixture in order to avoid locally rich areas, which are responsible for the generation of PM (more spray holes, smaller hole diameter, higher rail pressure, reduced compression ratio, lower charge temperature). Significant benefits towards a lower $NO_x$/PM trade-off can be realised (e.g. by lower compression ratio), however this may result in a penalty with regard to fuel efficiency and HC/CO emisssions, especially at lower engine loads. Some of these benefits can be realised with GTL, without having the drawbacks that would be encountered using normal diesel fuel. This confirms the statements by [Kitano 2007].

According to [Lepperhoff 2006] GTL leads to significant improvements on HC and CO emissions, as well as on the fuel efficiency, over the whole range of EGR variation. At the lowest $NO_x$ values the thermal efficiency is increased from 36 to 38%, which is comparable to a diesel engine without any EGR. The increased efficiency results from a fast pilot combustion in combination with an increased effective pilot quantity, leading to a more efficient combustion phasing. However, this finding concerns part load conditions, at full load the benefits are much smaller. If fuel consumption and HC/CO emissions are allowed to have the same level as for an engine running on conventional diesel, [Lepperhoff 2006] finds that the $NO_x$/PM trade-off becomes even more advantageous for GTL in part load conditions.

An investigation by [Degen 2007] into the effects of BTL on emissions also showed that a significant reduction of CO, HC and particulates (soot) could be obtained. The hardware of the HD engine used for the test was not modified, but the software parameters were adjusted for optimal emission performance (EGR rate, start of main injection, time between pre- and main injection, injection pressure). According to [Degen 2007] the high cetane number enabled the use of higher EGR rates. Using the $NO_x$/PM trade-off, $NO_x$ could be reduced by about 50% while PM was kept on the same level. An investigating into the effect of BTL blends on the emission performance showed that the $NO_x$/PM trade-off behaves almost proportionally with the BTL content in the fuel blend. Another interesting point from [Degen 2007] is that blends with different amounts of hydrocracked BTL in straight-run BTL are reported to show a very similar effect on emissions. Also the final boiling point of BTL fuels does not bring a change in emissions. However, the upper boiling range limit is restricted by the cold flow properties of the fuel. The addition of oxygenates to the BTL (in the form of 10-20% FAME) is reported to show a further slight improvement in the $NO_x$/PM trade-off

[Heinl 2007] reports tests on a VW Golf Euro 4 diesel engine which was adjusted to investigate the effects of BTL on emissions. Conclusions of the work is that BTL leads to considerable lower HC and CO emissions, and had the potential to decrease either $NO_x$ by 35% or PM by 45% by adjusting the fuel injection strategy. This trade-off can be utilised to reach overall low emissions e.g. by optimising the engine for engine-out $NO_x$ emissions and applying a DPF to reduce PM emissions. The fuel consumption is not increased, but $CO_2$ emissions are lowered. Also non-regulated emissions are lower for BTL. If the BTL has a proper CFPP, the cold start behaviour is better than for conventional diesel.

An interesting point from [Heinl 2007] is this: The combustion period of BTL is longer in comparison with diesel. The two reasons for this are that the injection takes longer due to the lower heating value and that the high share of n-paraffins ignite leads to quick combustion but a slow burning process. As a result, the peak temperatures are reduced, leading to a lower $NO_x$ emission and an increased HC and CO emission. Important conclusion is that the influence of the high cetane number and the low aromatic content (leading to a lower HC and CO emission) outways the effects of a longer combustion period.

### 6.4.14 *Effect of low- and high-percentage HVO blends and pure HVO on emissions of future CI engines*

In [Kuronen 2007] measurement results by VTT are reported obtained on Euro IV HD vehicles without engine adjustments running on NExBTL. Results are 28 to 46% lower PM emissions, 7 to 14% lower $NO_x$, HC emissions lowered by 0 to 48% and CO emissions lowered by 5 tot 78%, with the latter two results strongly dependent on type of aftertreatment technology that is applied. Measurements of unregulated components showed lower PAH levels and lower particle numbers for NExBTL. [Kuronen 2007] also quotes tests by MAN and Scania on Euro IV engines which show similar results.

The chemical composition of HVO fuel is very comparable than that of GLT / BTL (or X-TL in general). For that reason the same effects on emissions are expected for HVO as for X-TL.

### 6.4.15 *Effect of high-percentage ethanol blends in diesel on emissions of future CI engines*

For 20% ethanol in diesel [Mohammadi 2005] reports an improvement of the $NO_x$/PM trade-off, with more than 60% improvement in PM emissions achieved under a $NO_x$ emission level of 0.52 g/kWh. Ethanol in diesel, however, does increase the ignition delay.

## 6.5 Biofuels and advanced combustion concepts

HCCI combustion allows petrol-like fuels to be burnt in a CI engine. Based on measurements on a range of petrol-like fuels [Risberg 2004] concludes that the auto-ignition quality of these fuels correlates linearly with a so-called octane index OI which is defined as OI = (1-K) x RON + K x MON = RON – K x (MON-RON) with the value for K dependent on engine design and operating conditions. This relationship also holds when EGR is applied. If blending in biofuels or other components changes the difference between RON and MON this will thus affect the auto-ignition quality of the blend. For ethanol the difference between RON and MON is much larger than for normal petrol so that blending ethanol into petrol will affect the fuel's behaviour under HCCI combustion. For butanol RON and MON are close to the values for petrol so that blending butanol will not affect auto-ignition quality.

Using the same relation as mentioned above [Kalghatgi 2005] concludes that measures applied to improve the efficiency of SI engines (e.g. direct injection, higher compression ratios, engine downsizing and turbocharging) will push the K value downwards and that for modern SI engines in Europe and Japan K values are already negative. This means that for a given RON a lower MON value leads to a higher OI, resulting in better performance (provided that the engine is equipped with a knock sensor). [Kalghati 2005] states that fuels with this property are also most appropriate for HCCI combustion. This would imply that ethanol would be a very good fuel for HCCI since it has high RON and a large difference between RON and MON. [Kalghatgi 2005] furthermore states that present trends with respect to standardising fuel composition from the point of view of emission control tend to lead to petrol with lower RON and lower (RON – MON). This is opposed to the fuel requirements for future engines. The restrictions would also be unnecessary as [Kalghatgi 2005] claims that modern engines and aftertreatment systems are becoming less sensitive to fuel composition (with the exception of sulphur and other such "contaminants").

The impact of various synthetic fuels on emissions of HCCI engines is measured and discussed in [Pöttker 2005]. A test engine was run on diesel, a diesel/petrol mix, a synthetic diesel, , a synthetic diesel with toluol added, a primary reference furl PRF 0 (100% n-heptane) and PRF 50 (PRF 0 with 50% iso-octane). Quantitative results are given for HC and CO. Impacts on $NO_x$ are not reported. The influence of different fuel compositions on CO is found to be at most a factor of 2. With the exception of the diesel/petrol mix (for which HC emission triple) this is also true for HC.

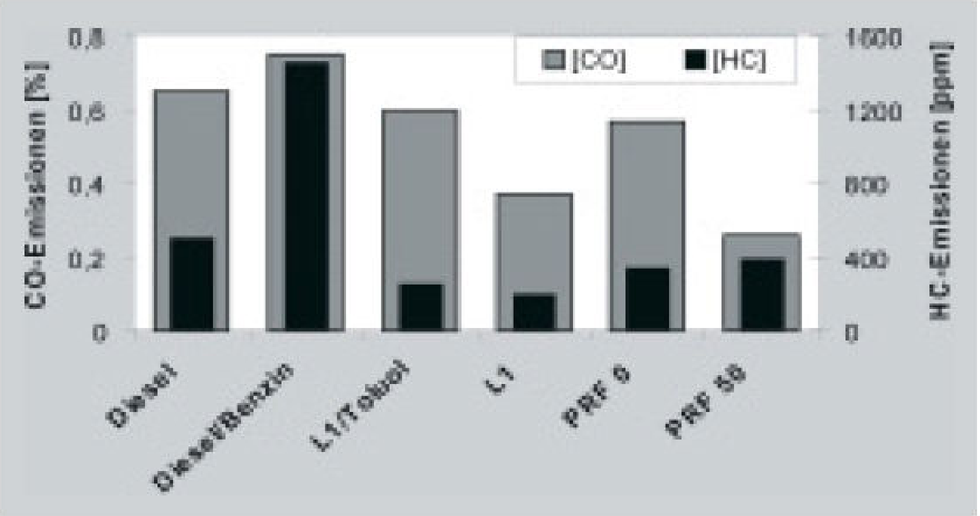


Figure 6.12 Effect of different fuel compositions on CO and HC emissions in HCCI combustion [Pöttker 2005]

## 6.6 Estimation at national level

The information reviewed and summarized in the previous sections does not yet allow quantitative conclusions on the average impact of various biofuels and future fuel compositions on the emissions of future vehicles in the 2015- 2025 period.

In the Netherlands emission factors for existing road vehicles are determined by the Task Force Traffic and Transport of the National Emission Inventory in which TNO, CBS, MNP and the Ministry of VROM participate. The overall methodology for determination of emission factors is described in [Klein 2007]. The underlying VERSIT+ LD and HD models are described in [Smit 2006] and [Smit 2007]. Emission factors for future vehicles are determined by TNO on the basis of emission factors of existing vehicles, information about of future emission limits that are under preparation and expert knowledge and judgement.

For the quantification of emission impacts of biofuels on existing vehicles it needs to be explored whether VERSIT+ must be extended to include measurement data obtained on various fuels, or whether information on impacts of various fuels can be translated into correction factors that can be applied to the VERSIT + emission factors generated on the basis of measurements on conventional fuel.

The ambition for the second phase of this project under the BOLK programme is to arrive at (semi-)quantitative estimates of the impact of various fuels and fuel compositions on the average emissions of future vehicles which can be used as correction factors for the emission factors that are valid for conventional fuels.

## 6.7 Possible impact on toxic and carcinogen emissions

In the literature review undertaken for this project only a limited amount of information has been found on impacts of biofuels on unregulated components or more specific on the impact on toxic and carcinogen emissions. An extended literature search will be carried out in the second phase of this project.

## 6.8 Blank spots in information

Overall the amount of literature found so far containing information relevant to the assessment of impacts of biofuels on future engines is rather limited. An attempt has been made to draw more general conclusions on the basis of considerations regarding impact of biofuels on fuel characteristics and the impacts of those characteristics on emissions. This route needs to be further explored through interaction with external experts in the field. For the second phase of this project interviews are foreseen with experts from the academic research community and from the industry.

More information is required for all fuels covered by the assessment in chapter 6, but so far the least information has been available for the following fuels:
- low percentage blends of ethanol and ETBE in petrol;
- low and high percentage blends of butanol;
- GTL/BTL petrol in future SI engines;
- CNG/biogas (emission behaviour of future engines on CNG/biogas);

For a better selection of the most relevant or likely engine-fuel combinations for the 2015-2025 period also more information is needed on the view of the automotive and fuel industry on the development of the market for biofuels in the longer term. Interaction with the industry is also necessary to create more insight in the extent to which modifications / innovations in engine and aftertreatment technology can help to overcome possible problems identified above or to further increase the potential of biofuels for reduction of vehicle emissions.

In the next phase of the project also more attention needs to be paid to the assessment of possible impacts of biofuels on the toxicity of exhaust emissions from existing vehicles as well as from future vehicles with more advanced engine and aftertreatment technology.

## 6.9 Conclusions

Based on the review presented above the following conclusions can be drawn with respect to the various fuels assessed in this chapter:
- Low-percentage ETBE blends in future SI engines: No information has been found so far relating to impacts of low-percentage blends of ETBE in petrol on emissions of future vehicles with SI engines.
- Low-percentage ethanol blends in future SI engines: No information has been found so far relating to impacts of low-percentage blends of ethanol in petrol on emissions of future vehicles with SI engines. Low percentage ethanol blends have a higher vapour pressure which may lead to increased evaporative emissions. This can be

resolved by blending ethanol into a base petrol with lower vapour pressure or by possibly improved carbon canister technology.

- <u>High-percentage ethanol blends in future SI engines:</u>
  - Use of E85 may lead to higher cold start emissions due to higher cold start enrichment and slower catalyst heating after start-up. With multiple injection and high-pressure stratified injection at engine start-up this problem may be resolved.
  - HC emissions for running on E85 are generally higher than for petrol especially for engines calibrated for petrol.
  - Measurements by [Benninger 2007] indicate that under part load $NO_x$ emissions of a DI SI engine may be reduced for E85 compared to petrol, while at high loads $NO_x$ emissions for E85 are higher than for petrol. $NO_x$ and PM emissions over the complete cycle were 60% resp. 75% lower for E85 than for premium petrol in this DI SI engine, and for this specific engine are about 15% of the limits for Euro 5.
  - The higher octane number of ethanol will allow for an increase of the compression ratio by 2 to 4 units resulting in lower HC emissions and an efficiency increase of up to 10%.
- <u>Low-percentage butanol blends in future SI engines:</u> No information has been found so far relating to impacts of low-percentage blends of butanol in petrol on emissions of future vehicles with SI engines.
- <u>High-percentage butanol blends in future SI engines:</u> No information has been found so far relating to impacts of high-percentage blends of butanol in petrol on emissions of future vehicles with SI engines. It is not yet clear to what extent FFV vehicles designed for E85 are also able to run on high-percentage butanol blends.
- <u>GTL/BTL petrol in future SI engines:</u> For this option only one source of emission information has been found so far. In [Larsen 2007] a 70% FT petrol blend with high aromatics content and a fully alkylate FT petrol have been tested in a VW Golf 1.6 FSI (MY 2003). Both fuels led to significant reductions in CO (20-30%), HC (20%) and PM (25-50%) emissions compared to conventional petrol. The 70% FT petrol blend with high aromatics content caused increases in emissions of $NO_x$ and PAH, while the 100% alkylate FT petrol led to lower emissions of these components.
- <u>Emission of future SI engines on CNG and CBG:</u> This combination has not been reviewed so far but will receive further study in the follow-up of this project. Compared to CNG the use of CBG (upgraded to CNG quality and possibly even used in a “virtual” way through green gas contracts rather than direct use in the engine) will not affect emissions. Stoichiometric SI engines on CNG are expected to meet Euro 6 / VI limits.
- <u>Low-percentage FAME blends in future CI engines:</u> [May 2007] reports impacts on the conversion efficiency of catalytic convertors for CI engines due to the use of B30 biodiesel. The conversion is slightly reduced for $NO_x$ and HC, and slightly higher for PM. Due to the very high catalyst conversion efficiencies a relatively small change in the conversion efficiency leads to a relatively high change in tailpipe emissions.
- <u>High-percentage FAME blends and B100 in future CI engines:</u> The overall tendencies found for the impact on emissions of using high percentage blended or pure FAME instead of normal diesel is a reduction of CO, HC and PM, accompanied by an increase in $NO_x$ emissions. This applies to current engines without $NO_x$ aftertreatment (see above), but is also reported for a Euro 4 HD engine equipped with SCR [Krahl 2006]. For 100% RME tested in a turbocharged CI engine with variable EGR and a DPNR aftertreatment system (combining the

properties of a diesel particulate filter (DPF) and a NOx storage catalyst (NSR)) [Kawano 2007] found that RME significantly increases engine-out $NO_x$ emissions and reduces the conversion efficiency of the NSR catalyst, leading to tailpipe $NO_x$ emissions which are an order of magnitude higher than on conventional diesel. Improvements in injection and EGR rate may reduce these problems.

- Low-percentage GTL/BTL blends in future CI engines: Research on the effects of blending XTL with conventional diesel has shown that the emission reducing effect is higher than the fraction of XTL would indicate. A 50/50 blend of XTL and conventional diesel will almost produce the same emissions as a neat XTL [Larsen 2007].
- High-percentage GTL/BTL blends and pure GTL/BTL in future CI engines: High percentage or pure GTL/BTL is generally found to lead to reductions of all regulated emissions components, with reductions of around 25% for PM, HC, CO, and 10% for $NO_x$. PAH emissions also drop as a result of the lower PAH content of GTL/BTL. When engines are optimised for use of GTL/BTL (increase EGR rate, adjusted injection, lower compression ratio) these reductions can even be higher. With GTL/BTL the $NO_x$/PM trade-off can be further utilised to reach overall low emissions e.g. by optimising the engine for engine-out NOx emissions and applying a DPF to reduce PM emissions.
- Low- and high-percentage HVO blends and pure HVO in future CI engines: Test results on advanced engines are not available, but several results obtained on Euro IV HD engines without engine adjustments running on HVO show much lower emissions of PM, HC and CO and somewhat reduced (about 10%) emissions of $NO_x$. Based on the chemical composition of HVO, the same effects on emissions are expected as for X-TL
- High-percentage ethanol blends in diesel in future CI engines: The limited amount of information on this option found so far does not allow us to draw conclusions on emission impacts.
- Biofuels and advanced combustion concepts: Blending in biofuels or other components changes the auto-ignition quality of the blend. Ethanol would be a very good fuel for HCCI since it has high RON and a large difference between RON and MON [Kalghati 2005]. For butanol RON and MON are close to the values for petrol so that blending butanol will not affect auto-ignition quality. Based on the available information no conclusions can be drawn on the impacts of biofuels on the emissions of CAI and HCCI engines.

## 6.10 References

| | |
|---|---|
| [Alleman 2003] | Alleman, T.L./ R.L. McCormick (2003*), Fischer-Tropsch Diesel Fuels – Properties and Exhaust Emissions: A Literature Review*, SAE paper 2003-01-0763 |
| [Benninger 2007] | Benninger K, et al. (2007), *Flexible Fuel Systems for Spark-Ignition Engines with Direct Injection*, in proceedings of conference on "The spark-ignition engine of the future, Technologies to meet the $CO_2$ challenge, Strasbourg, November 28 & 29, 2007. |
| [Blades 2005] | Blades, T. (2005), *BtL SunFuel from CHOREN;s Carbo-V Process*, 1st International Biorefinery Workshop, Washington DC, July 20-21, 2005 |

[Boot 2007] Boot, M.D. et. al. (2007), *Oxygenated Fuel Composition Impact on Heavy-Duty Diesel Engine Emissions*, SAE paper 2007-01-2018

[Degen 2007] Degen, W., *The results of motor tests of BTL by Daimler-Chrysler*, 2nd European SUmmer School on Renewable Motor Fuels, Warsaw, Poland, August 2007, handout of presentation slides

[Dieselnet 2002] Dieselnet (2002), *DieselNet Technology Guide »What Is Diesel Fuel » Fuel Properties and Emissions*, Revision 2002.01a, www.dieselnet.com

[Dieselnet 2007] Dieselnet (2007), *DieselNet Technology Guide » Alternative Diesel Fuels » Biodiesel*, Revision 2007.07d, www.dieselnet.com

[Dieselnet 2008] Dieselnet (2008), *DieselNet Technology Guide »What Is Diesel Fuel*, Revision 2008.01b, www.dieselnet.com

[EC 2007a] COM(2007) 18, *Proposal for a directive of the European Parliament and of the Council, amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and the introduction of a mechanism to monitor and reduce greenhouse gas emissions from the use of road fuels and amending Council Directive 1999/32/EC, as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC*, Brussels, 31 January 2007

[EC 2007b] *Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on the type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and 6) and on access to vehicle repair and maintenance information*, 20 June 2007

[EC 2008] COM(2008)yyy final, *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewables*, version 15.4, Brussels 23.01.2008

[EPA 2002] EPA (2002), *A comprehensive analysis of biodiesel impacts on exhaust emissions*, Draft Technical Report EPA420-)-02-001

[Fricke 2007] Fricke, F. (2007), *New generation of biofuels for future combustion engines*, RWTH Aachen / FEV, presentation at ATC workshop September 27, 2007

[Hauet et al. 2007] Hauet, B. et al. (2007), *E85: Impact of the fuel properties on "flex fuel" engine tuning*, in proceedings of conference on "The spark-ignition engine of the future, Technologies to meet the $CO_2$ challenge, Strasbourg, November 28 & 29, 2007.

[Heinl 2007] Heinl, E., *The results of motor tests of BTL by VW*, 2nd European Summer School on Renewable Motor Fuels,

| | |
|---|---|
| | Warsaw, Poland, 29-31 August 2007, handout of presentation slides |
| [IEA 1999] | IEA (1999), *Automotive Fuels for the Future – The Search for Alternatives*, International Energy Agency |
| [IEA/AFIS 1996] | IEA/AFIS (1996), van Walwijk, M. et al., *Automotive fuels survey, Part 2, Distribution and use*, INNAS 1996 |
| [Graboski 2003] | Graboski, M.S., McCormick, R.L., Alleman, T.L. & Herring, A.M. (2003), *The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Diesel Engine*, National Renewable Energy Laboratory (NREL), Report No. NREL/SR-540-33793 |
| [Kalghatgi 2005] | Kalghatgi, G.T. (2005), *Auto-ignition quality of practical fuels and implications for fuel requirements of future SI and HCCI engines*, SAE paper 2005-01-0239 |
| [Kattenwinkel 2008] | Kattenwinkel, H. (2008), Presentation on biofuels from an industry perspective |
| [Kawano 2007] | Kawano, D. et al. (2007), *Optimisation of Engine System for Application of Biodiesel Fuel*, SAE paper 2007-01-2028 |
| [Kitano et al. 2007] | Kitano, K. et.al.(2007), *GTL Fuel Impact on DI Diesel Emissions*, SAE paper 2007-01-2004 |
| [Klein 2007] | Klein, J., et al. (2007), *Methods for calculating the emissions of transport in the Netherlands*, and (in Dutch): *Methoden voor de berekening van de emissies van mobiele bronnen in Nederland,* Task Force Traffic and Transport of the National Emission Inventory |
| [Krahl et al. 2006] | Krahl, J. et al. (2006), *Influence of the Phosphorus Content in Rapeseed Oil Methyl Esters During a 1000 Hours Endurance Test on the Function of a SCR-system Measured by Exhaust Gas Emissions and Health Effects*, SAE paper 2006-01-3282 |
| [Krahl 2005] | Krahl, J. et al. (2005), *The Influence of Fuel Design on the Exhaust Gas Emissions and Health Effects*, SAE paper 2005-01-3772 |
| [Kuronen 2007] | Kuronen, M. and S. Mikkonen (2007), *Hydrotreated Vegetable Oil as fuel fro Heavy Duty Diesel Engines*, SAE paper 2007-01-4031 |
| [Larsen 2007] | Larsen et al., Emissions from Diesel and Gasoline Vehicles Fuelled by Fischer-Tropsch Fuels and Similar Fuels, SAE paper 2007-01-4008 (Technical University of Denmark). |
| [Lepperhof 2006] | Lepperhoff, G. et al., *Potentoal of Synthetic Fuels in Future Combustion Systems for HSDI Diesel Engines*, SAE paper 2006-01-0232 |
| [Martini 2007] | Martini, G. et al., *Effects of Gasoline Vapur Pressure an Ethanol Content on Evaporative Emissions form Modern European Cars*, SAE paper 2007-01-1928 |

[Mohammadi 2005] Mohammadi et al. (2005), *Fuel Injection Strategy for Clean Diesel Engine Using Ethanol Blended Diesel Fuel*, SAE-paper 2005-01-1725

[Pischinger 2006] Pischinger, S. et al. (2006), *Future of Combustion Engines*, SAE paper 2006-21-0024

[Martin 1997] Martin, B. et al. (1997), *Influence of future fuel formulations on diesel engine emissions – a joint European study*, SAE Technical Paper Series, Paper No. 972966

[May 2007] May, J. et al., *The Application of Emissions Control Technologies to a Low-Emissions Engine to Evaluate the Capabilities of Future Systems for European and World-Harmonised Regulations*, Aachener Kolloquium Fahrzeug- und Motorentechnik 2007

[McMillan 1998] McMillian, M.H. & Gautam, M. (1998), *Consideration for Fischer-Tropsch derived liquid fuels as a fuel injection emission control parameter*, SAE Technical Paper Series, Paper No. 982489.

[Pischinger 2007] Pischinger, S. et al. (2007), *From Fuel to Wheel: How Modern Fuels Behave in Combustion Engines*, in „Opportunities and Challenges at the Interface between Petrochemistry and Refinery“, DGMK-Tagungsbericht 2007-2, ISBN 978-3-936418-70-5

[Pöttker 2005] Pöttker, S. et al. (2005), *Homogene Dieselverbrennung unter Verwendung synthetischer Kraftstoffe*, MTZ 12/2005, p. 988-993

[Risberg 2004] Risberg, P. et al. (2004), The influence of EGR on auto-ignition quality of gasoline-like fuels in HCCI engines, SAE paper 2004-01-2952

[Rouveirolles 2007] Rouveirolles, P. (2007), *The results of motor tests of sythetic fuels by Renault*, 2nd European Summer School on Renewable Motor Fuels, Warsaw, Poland, 29-31 August 2007, handout of presentation slides

[Schaberg 2007] Schaberg, P. et.al.(2007), *HSDI Diesel Engine Optimisation for GTL Diesel Fuel*, SAE paper 2007-01-0027

[Smit 2006] Smit, R., Smokers, R., Schoen, E. & Hensema, A. (2006) *A New Modelling Approach for Road traffic Emissions – VERSIT+ Light Duty*, TNO Report 06.OR.VM.016.1/RS

[Smit 2007] Smit, R., Smokers, R.T.M. and Rabé, E. *A new modelling approach to road vehicle emissions VERSIT+,* Transp. Res. Part D, Volume 12, Issue 6, August 2007, Pages 414-422

[Smokers 2004] Smokers, R.T.M. and Smit, R. (2004), *Compatibility of pure and blended biofuels with respect to engine performance, durability and emissions*, SenterNovem report nr. 2GAVE04.01.

| | |
|---|---|
| [Stavinoha 2000] | Stavinoha, L.L., Alfaro, E.S., Dobbs, H.H., Villahermosa, L.A. & Heywood, J.B. (2000), *Alternative fuels: gas to liquids as potential 21st century truck fuels*, SAE Technical Paper Series, Paper No. 2000-01-3422 |
| [Taniguchi 2007] | Taniguchi, S. et al. (2007), Feasibility study of ethanol applications in a direct injection gasoline engine, SAE paper JSAE 20077079 / SAE 2007-01-2037 |
| [Thompson 2004] | Thompson et al. (2004), *Fuel Effects on Regulated Emissions From Advanced Diesel Engines and Vehicles*, SAE paper 2004-01-1880 |
| [Tsujimura 2007] | Tsujimura, T. et.al. (2004), *A Study of PM Emission Characterstics of Diesel Vehicle Fueled with GTL*, SAE paper 2007-01-0028 |

# 7 Conclusions and recommendations for government policy

Extensive technical conclusions are presented at the end of each chapter. In this chapter the conclusions and recommendations for government policy are presented.

Based on the findings of this BOLK study, Table 5 shows the recommended (bio)fuels mix up to 2020.

Table 32 Recommended fuel mix up to 2020

| | Otto engines | Diesel engines |
|---|---|---|
| Main Stream | E5 for main stream and old vehicles<br>Optionally E10<br>E85 for Flexible Fuel Vehicles | B5 or B7<br>B20 – B100 for dedicated heavy-duty vehicles |
| Niche | CNG / biogas | E95 with ignition improver |

**1) Biofuels mix up to 2020; low blends for mainstream, high blends for niche applications. The Dutch 20% target is not recommended.**
The desired share of biofuel components up to 2020 can best be made up of low blends for main stream in combination with high blends for specific (captive) fleets of vehicles. For petrol engines E5 and optionally E10 is recommended for main stream, in combination with up to E85 for flexible fuel vehicles. For diesel engines B5 or B7 is recommended for main stream in combination with B20 to B100 for dedicated heavy-duty vehicles. This means that the 20% biofuel target that the Dutch government will be very hard to achieve. Having a different standard fuel than the rest of Europe would lead to complicated infrastructural, legislative and practical issues. With the above mentioned B5-7 and E5 blends only a reduction of 3-5% on energy content is feasible, which means that for an overall 20% energy share of biofuels around 15% of the replacement should be achieved with high percentage blends.

**2) Short-term emission effects: in general no win-win situation, large variability**
Based on the data and findings of this study, it cannot be concluded that biofuels can both decrease $CO_2$ emissions and lead to a significant and consistent reduction of atmospheric pollutants when applied in currently available engines. In other words, in general there is no win-win situation. Emission data show a large variability. For specific diesel engines types (especially Euro III and older truck engines) engine particulate emissions can be reduced with no or a small NOx increase. For Euro IV and V truck engines, special engine software is needed to prevent a (steep) rise in NOx emissions.
In the case of synthetic fuels (BTL, GTL) a consistent emission reduction is expected.

**3) Emission effects up to 2020**
Given that future diesel engines will be equipped with particulate filters and closed-loop NOx control, the impacts are in general expected to become insignificant. A major concern however are possible incompatibilities between biofuels and the operation of advanced emission control systems. This requires further research. With Otto engines

possible negative emissions impacts will disappear due to the implementation of low and high blend ethanol in the European emissions legislation.

**4) Emission legislation is the main tool for avoiding excessive emissions**
In order to avoid undesirable effects on exhaust emissions with the use of biofuels (blends) in general, the most important point is to implement the desired biofuels (blends) into the European emission legislation. Due to the long lead time of development of legislation and the life time of the vehicles it is necessary to plan for 20 years ahead. Even though a lot of work is currently being done, much more is required to avoid problems in the period from 2020 to 2030. Future emission legislation should not only refer to the type approval test as such but also to OBD-requirements, durability and in-use compliance.

**5) Risk of excessive $NO_x$ emissions can be avoided by regulation**
Clear communication and (national) regulations can avoid undesirable side effects such as NOx increase with high blends biodiesel (B20-B100). Regulations that should be considered are:

- Type approval, in particular for Euro IV and V heavy duty engines
- Avoid usage of high blend biodiesel in passenger cars
- Monitoring of flex fuel vehicles with high blend ethanol.

**6) Synthetic diesel is promising from an emissions and engine durability point of view, but available quantities up to 2020 are expected to remain limited**
Further increase in biocomponents share without any adverse effects on vehicle durability and exhaust emissions is possible with the stimulation of synthetic diesel fuels (hydrotreated vegetable oil and biomass-to-liquid diesel fuels).

**7) Pre-introduction of EEV or EURO VI will help**
Stimulation of heavy duty EEV vehicles or pre introduction of Euro VI vehicles before 2015 can likely improve air quality. These vehicles can be equipped with engines running on (bio)diesel fuel, CNG or ethanol.

# 8 Recommendations for future work

This chapter provides recommendations for future work inside or outside of the BOLK programme, based on the assessments made in the previous chapters. Recommendations deal with:
– a proposal for an extensive measurement programme to further improve our understanding of the impacts of biofuels on vehicle emissions and to provide input data for emission factor modelling;
– the need for international co-operation in experimental and theoretical work to increase the knowledge on emission impacts of biofuels;
– options for work in phase 2 of this project under the BOLK programme.

## 8.1 Proposal for a measurement program

As described in chapter 5 and paragraph 6.8, there is a clear need for a coordinated and systematic measurement program to fill blanks in the information on emission impacts of biofuels.

In the Netherlands emission factors for road transport are determined in a well-defined methodology[20] based on the VERSIT+ emission factor model[21] developed by TNO, which is fed with input data from an extensive in-use compliance measurement programme sponsored by VROM and executed by TNO. Official emission factors concern vehicles in the present and historical vehicle fleet in the Netherlands, based on actual measurement data. For use in future outlooks and other scenario analysis indicative emission factors are generated for future generation vehicles, based on available technical knowledge, information on future emission limits and expert judgement.

The objective of the proposed measurement program would thus be to generate emission data for the use of biofuels in existing LD and HD vehicles that enable determination of emissions factors with the level of accuracy that is necessary for national and international emissions inventories and for quantification of average emission behaviour of specific vehicles classes (e.g. Euro class, fuel type. size class) under specific traffic conditions (urban / rural / highway, or more detailed categories).

This can be achieved by:
– execution of a systematic measurement programme for selected fuel – engine combinations to determine tank-to-wheel emissions (regulated components and $CO_2$) resulting from the use of biofuels compared to conventional fuels;
– application of statistical analysis and additional modelling to calculate emissions factors and emission profiles for national and international emissions inventories;

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[20] See: John Klein et al. (2007), Methoden voor de berekening van de emissies door mobiele bronnen in Nederland, CBS, MNP, TNO, RIZA RWS-AVV, October 2007

[21] See:
Smit, R., Smokers, R., Schoen, E. & Hensema, A. (2006), A New Modelling Approach for Road traffic Emissions – VERSIT+ Light Duty, TNO Report 06.OR.VM.016.1/RS
Smit, R., Smokers, R., Rabé, E. (2007), A new modelling approach for road traffic emissions: VERSIT+, Transportation Research Part D 12 (2007) 414–422
Riemersma, I.J. & Smokers, R. (2004), Ontwikkeling van het Versit+ HD emissiemodel, TNO, Delft.

- determination of dedicated emission factors for biofuels or correction factors to be applied to emission factors valid for vehicles running on conventional fuels.

### 8.1.1 *Basic measurement program*

The measurement programme should at first focus on those fuels for which possible emission benefits or problems might occur. At a later stage it could be considered to extend the programme to cover all important fuels on the market. In first instance the most important choice will thus be regarding the selection of the fuel-engine combinations to be tested. The following selection of main fuel-engine combination is recommended, based on the result of this study:

- light duty diesel vehicles with low percentage blends of biodiesel (up to B10)
  - From Chapter 5, it can be concluded that the emissions of particulate matter increase about +20% on average (range from 0% to +40%) for current (up to Euro 4) light duty diesel vehicles with low blend biodiesel (up to B10).
  - From Chapter 5, it can also be concluded that current heavy duty engines will not have a significant increase in PM or $NO_x$ emissions.
  - From Chapter 6 (in particular Figure 6.10), it can be concluded that there is a significant influence of the biodiesel component on the conversion efficiency of $NO_x$ after-treatment systems. For future (Euro 5/6) engines, where $NO_x$ aftertreatment will be increasingly applied, this will be important.
- light duty petrol vehicles with ethanol
  - From paragraph 6.8 it has been concluded that there is limited emission data available for use of low blend ethanol (up to E10) in future (Euro 5/6) petrol vehicles and high blend ethanol (E85) in future (Euro 5/6) flex fuel vehicles.

An essential characteristic of the measurement programme is that it has to be systematic. This means that vehicles need to be tested on the same fuels and the same set of test cycles and under the same test conditions to deliver results that are comparable and suitable for further statistical analysis. Each biofuel needs to be tested in sufficiently large samples of vehicles from different Euro classes over a number of real world driving cycles.

For a basic measurement programme, the following aspects should be considered:

- Regarding choice of vehicle models:
  - Testing of at least 7 vehicles per fuel-engine type combinations. From statistics and experience[22], it can be concluded that 7 tests on comparable vehicles generally give a representative and reliable image of differences in performance. In the end the number of vehicles to be tested depends on the variance in measurement results. Testing a larger number of vehicles will always improve accuracy.
  - Availability on the market can be an issue (e.g. the number of FFV models is currently still limited);
  - Test recent technology, that is:
    - Euro 4 or Euro 5 vehicles;
      - for diesel: common rail, double overhead camshaft, diesel particulate filter
      - for petrol: both homogeneous direct injection and indirect injection
- Regarding choice of fuel:
  - As a reference standard petrol or diesel should be used;

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[22] See e.g. P. Hendriksen et al. *Evaluation of the environmental impact of modern passenger cars on petrol, diesel, automotive LPG and CNG*, TNO report 03.OR.VM.055.1/PHE, 2003

  - Analysis of biofuel tested, to be able to reproduce results and possibly determine relation with chemical composition;
  - It still needs to be determined whether reference fuel and biofuels need to be further standardised or whether the use of commercial grade fuels with some minimum requirements is sufficient;
- Regarding the test cycle, vehicles should be tested on at least:
  - the standard type approval drive cycle (NEDC);
  - a real world representative drive cycle (preferably the ARTEMIS cycle);
- Regarding emissions components to be measured:
  - fuel consumption (through $CO_2$)
  - regulated emissions components: PM, $NO_x$, CO, HC, THC
  - unregulated emission components: at least $NO/NO_2$, and possibly other components.

In addition to this basic measurement program, it should be considered to add more specific measurements. Such extensions can be considered in the following directions:

a) additional (unregulated) emissions components;
b) additional niche fuel engine combinations;
c) additional indirect effects (e.g. ageing and deterioration, sensitivity for servicing).

### 8.1.2 *Additional emissions components*

As concluded in section 6.7, there is very little if any data available about emissions of unregulated and toxic components resulting from the use of blends of biofuels in (present and) future vehicles. As has been investigated in [Verbeek 2008] the application of retrofit particulate filters has influence on unregulated components. To ensure there are no negative effects on unregulated components from the use of biofuels, it is recommended to measure for the mainstream fuel engine combinations (B7 and B100 for diesel; E10 and E85 for petrol) the following regulated and unregulated components:

- Related to health effects
  - 2A, 2B PAHs (possibly also Oxy and Nitro-PAHs)
  - BaP
  - 1,3 butadiene
  - BTX
  - Light aldehydes
  - CO
  - primary PM (PM mass)
  - secondary PM ($NO_x$, $SO_2$, $NH_3$)
  - PM size distribution
  - PM EC/OC
  - $NO_2$
  - $SO_2$
- Related to smog (ozone equivalent potential);
  - TOPF
  - POCP
- Related to ecological effects
  - Eutrophication: $NO_x$ and $NH_3$
  - Acidification: $NO_x$ and $NH_3$
- Regarding climate change

- Global Warming Potential: $CO_2$, $N_2O$, $CH_4$
- Ozone Depletion Potential: $N_2O$

### *8.1.3 Additional measurements on niche fuel-engine combinations*

From section 6.8 it can be concluded that for the following niche fuel engine combinations very little emissions data is available:

- CNG, biogas, LPG in future (Euro 5/6) gaseous fuel engines;
- butanol (all blends) in petrol engines.

General comments are the same as for the basic program. These measurements are particularly important for determination of effects of captive fleet application, especially with respect to local air quality.

### *8.1.4 Additional measurements of indirect effects (e.g. ageing deterioration, sensitivity for servicing)*

Especially for future aftertreatment systems (Euro 5/6) the impact of biofuels on performance of these systems is not well-known. Therefore at first a discussion with industry (Tier 1 suppliers) might give a clearer overview of the issues. Investigation and possibly measurements should focus on:

- effects on aftertreatment systems: SCR deNOx, $NO_x$ storage (deactivation, thermal load, poisoning, fuel quality);
- effects on engine and engine control: DI, common-rail, multi-jet, HP pumps, injectors (fuel quality, wear);
- effects on future engine concepts: CAI, HCCI, CCS.

## 8.2 Need for international co-operation

### *8.2.1 Co-operation with networks in which TNO / VROM already participates*

As indicated in the previous paragraph, for reliable detailed emissions factors for vehicles running on biofuels it is essential to gather a significant amount of emission measurement data in a systematic way. With both vehicle technology and fuel composition being similar in all countries of the EU, these countries face the same challenges regarding reliable assessment of emission factors. For all countries the impact of biofuels on NEC emissions and local air quality will be a relevant issue, although not necessarily to the same extent.

The required reliability of emission factors is obtained by state-of-the-art statistical analysis and modelling. These statistical models require a large amount of systematically collected data as input. Exchange and sharing of measurement data among countries allows a larger set of data without the need to increase national measurement programs. However, to allow a common database, the emissions measurements have to be comparable regarding (real world) driving cycle, fuel characteristics and preparation of the vehicle.

Sharing of emissions data and (detailed) emission factors also allows creation of a common understanding about the impacts of biofuel-engine combinations on emissions per emission class (Euro class) and per traffic situation. Such a common understanding will support the necessary consensus for European legislation regarding biofuels.

The following international platforms could be suitable for international collaboration in terms of the exchange of information regarding biofuels and co-ordination of national measurement programmes:

- DACHNLS: co-operation between Germany (D), Austria (A), Switzerland (CH), Netherlands (NL), Sweden (S) regarding emission factors;
- IEA: International Energy Agency, especially the Implementing Agreement for Advanced Motorfuels (IA AMF);
- EC: direct consultancy or as research project (Framework Programme).

### 8.2.2 *Possible other opportunities for cooperation*

Concawe (research branch of the European association of fuel producers Europia), together with Eucar and JRC, are also carrying out projects that are similar to or otherwise relevant to the BOLK programme. The following work is ongoing or recently completed at Concawe:

- Impact of ethanol in gasoline on vehicle evaporative emissions: This 2+ year programme was completed to evaluate the impact of ethanol on evaporative emissions with SHED testing being completed at the JRC facilities in Ispra. The work was reported at the July 2007 SAE Conference[23].
- Impact of ethanol on fuel consumption and regulated emissions: This JEC programme is in progress with testing at JRC's facilities planned for the 2Q-3Q08 and is intended to measure how quantitatively modern cars can adapt to the oxygen content of low-level ethanol blends. Results from this work should be available by the end of this year.
- Impact of biodiesel on fuel consumption and regulated emissions: This programme has the same objective as the one on ethanol in gasoline but will be conducted jointly by JRC and CONCAWE at JRC's facilities in Ispra. Testing is expected to start in the 3Q08 with analysis completed by the 1Q-2Q09.
- JEC Biofuels Programme: The three JEC partners have also agreed to work together to better understand the barriers and opportunities to meet the biofuel ambitions proposed in recent EU legislation, specifically to include at least 10% biofuels (on an energy basis) in road fuels by 2020 (see attached sheet). This is expected to be a 3-year programme that began in February 2008 with a Workshop involving technical experts from the JEC partners, three EC Directorates, and the bio industry. Key targets for this year include developing a better picture of the availability of different types of biofuels between now and 2020 and then using this analysis to assess the fleet problems that may arise from this penetration of biofuels in road fuels.
- CONCAWE has also completed some limited testing at a third-party lab to evaluate the short-term impact of ethanol and FAME on performance and emissions of an advanced combustion (Euro 6) bench engine. Although the primary focus of this work was on the fuel appetite of advanced combustion engines, the work did include some biofuel component up to 10% v/v in order to look for short-term advantages and disadvantages.
- Furthermore Concawe is working on several surveys of the published literature related to the impact of biofuels on fuel consumption, emissions, advanced combustion, and product quality. These reports are in various stages of completion and may or may not be available for external publication.

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[23] JSAE 20077109 - SAE 2007-01-1928 titled "Effects of Gasoline Vapour Pressure and Ethanol Content on Evaporative Emissions from Modern European Cars"

In the second phase of BOLK opportunities for further interaction or cooperation will be explored.

## 8.3 BOLK phase 2

As indicated earlier, this report presents the results of the inventory phase of this project, providing a first survey on future biofuels, future powertrain technology and the resulting future emissions associated with the use of biofuels.

In phase 2 of the BOLK programme more in-depth analyses are foreseen for the different subjects under study. In the case of the 2nd phase of the biofuels project the following activities are proposed:

- further literature study
  - collection of additional information to fill identified knowledge gaps
- interviews with experts and representatives from R&D, fuel industry and car industry to:
  - improve insight in the future biofuels market and stakeholder interests
  - increase knowledge on the interactions between fuels, engines and aftertreatment technologies with emphasis on technologies under development that may be applied around 2020
  - create an overview of state-of-the-art R&D on future engine and aftertreatment technologies and their interaction with different fuels
- further fine-tuning of the vision on the most likely fuel-engine combinations for 2020 and beyond
  - in cooperation with the project carried out by Ecofys on emissions in the fuel production chain
- more detailed assessment of other niche fuels
- further assessment of interaction between fuels and engine developments
- further assessment of possible impacts of biofuels on aftertreatment system conversion efficiencies
- generation of a preliminary set of emission factors (or correction factors to be applied to emission factors for conventional fuels) for the most important fuels applied by 2020
- generation of policy relevant information, e.g. for use in the update fact sheets for emission reduction measures
- supporting activities for setting up international collaboration for measurement programmes and knowledge exchange beyond the scope and lifetime of the BOLK programme:
  - further interaction with country representatives and laboratories from countries in DACHNLS
  - development of the necessary measurement protocols and other test requirements

The above options are indicative of the work that could be a logical follow-up to the analysis presented in this report. A more detailed project plan will be separately worked out and discussed with the BOLK project team.

## 8.4 References

| | |
|---|---|
| [Verbeek 2008] | Verbeek, R. et al (2008) *Investigation into the effect of retrofit particulate filters on the exhaust gas emissions of diesel passenger cars*, TNO Report MON-RPT-033-DTS-2008-00804 |

# Signature

| | |
|---|---|
| <City>, March 2008 | TNO Science and Industry |
| Dr. Ir. B. Bos<br>Head of department | Ir. E. Rabé<br>Author |

# A Abbreviations

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| B# | mixture of #% biodiesel (FAME) in (1-#)% diesel |
| B100 | 100% biodiesel (FAME) |
| BTL | biomass-to-liquid |
| BTX | benzene, toluene, xylene |
| Bu85 | mixture of 85% butanol and 15% petrol |
| CAI | controlled auto-ignition |
| CBG | compressed biogas |
| CEN | European Committee for Standardisation |
| CI | compression ignition |
| CIDI | compression ignition direct injection |
| CNG | compressed natural gas |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| CRT | continuously regenerating trap |
| CTL | coal-to-liquid, FT diesel from coal |
| DME | dimethyl-ether |
| DPF | diesel particulate filter |
| DPNR | diesel-particulate-$NO_x$-reduction |
| E# | mixture of #% ethanol in (1-#)% petrol |
| E85 | mixture of 85% ethanol and 15% petrol |
| EC | European Commission |
| EEV | Enhanced Environmentally friendly Vehicle |
| EGR | exhaust gas recirculation |
| FAME | fatty acid methyl ester |
| FFV | flexible fuel(led) vehicle |
| FT | Fischer-Tropsch |
| GRPE | UN-ECE working party on pollution and energy |
| GTL | gas-to-liquid, FT diesel from natural gas |
| HC | hydocarbons |
| HCCI | homogeneous charge compression ignition |
| HD | heavy duty |
| HHV | higher heating value |
| HVO | hydro-treated vegetable oil |
| IDI | indirectly injected engines (diesel) |
| IEA | International Energy Agency |
| ISO | International Organisation for Standardisation |
| LD | light duty |
| LHV | lower heating value |
| LPG | liquefied petroleum gas |
| MON | motor octane number |
| MVEG | Motor Vehicles Emissions Group |
| NGV | natural gas vehicles |
| NMHC | non-methane hydrocarbons |
| $NO_x$ | nitrogen oxides (NO, $NO_2$) |
| NSR | $NO_x$ storage catalyst |
| OBD | on-board diagnostics |
| PAH | poly-aromatic hydrocarbons |

| | |
|---|---|
| PM | particulate matter |
| PPO | pure plant oil (VPO) |
| RME | rapeseed methyl ester |
| RON | research octane number |
| RVP | Reid vapour pressure |
| SAE | Society of Automotive Engineers |
| SCR | selective catalytic reduction |
| SI | spark ignition |
| SIPI | spark ignition port injection |
| SIDI | spark ignition direct injection |
| SME | soybean methyl ester |
| THC | total hydrocarbons |
| UVOME | used vegetable oil methyl ester |
| VPO | virgin plant oil |
| XTL | FT diesel made from natural gas (GTL), coal (CTL) or biomass (BTL) |

# B Definition of fuel characteristics

Fuel properties affect many aspects of engine design, engine operation, fuel storage and handling and safety hazards. The following fuel specification parameters are of relevance to the compatibility of biofuels for use in road vehicle combustion engines (see [Smokers 2004][Bechtold 1997][Ermers 2001]).

## B.1 Fuel characteristics

Octane number
A measure of the resistance of a fuel to combustion knock, determined in standardised engines using standardised test procedures (ASTM Method D 2699 for Research Octane Number and ASTM Method D 2700 for Engine Octane Number). Octane numbers are defined in comparison to n-heptane (octane number = 0) and iso-octane (octane number = 100).

Cetane number
The ignition quality of a diesel fuel, determined by measuring the ignition delay of a fuel or fuel mixture in an standardised Co-operative Fuel Research (CFR) engine (according to ASTM Method D 613 or ISO 5165), and comparing the result with that of different mixtures of two pure reference fuels: cetane (cetane number = 100) and heptamethylnonane or isocetane (cetane number = 15). The cetane number is calculated on the basis of the concentration of heptamethylnonane in a mixture having the same ignition delay as the test fuel: cetane number = vol.% cetane + 0.15 * vol.% heptamethylnonane.

Note:

- Based on a test programme [Aakko 1997] concludes that the traditional cetane number does appropriately describe ignition delay in heavy-duty engines, but that it is more suitable for conventional than for alternative fuels. Moreover the method does not adequately describe the combustion process in advanced light-duty engines, and the reference fuels do not function properly in these engines. For biodiesels the cetane number is claimed to overestimate the effect of cetane improvers.

Auto-ignition temperature
Minimum temperature of a substance to initiate self-sustained combustion independent of any ignition source.

Flammability limits
Minimum and maximum concentrations of vapour in air below and above which the mixtures are unignitable.

Flash point
Minimum temperature of a liquid at which sufficient vapour is produced to form a flammable mixture with air.

Cold filter plugging point (FCPP)

A measure of the ability of a fuel to operate satisfactorily at low temperatures. CFPP is the highest temperature at which wax formation seriously reduces flow through a standard test filter under specified conditions.

Density
Mass per unit volume in kg/l or kg/m$^3$.

Heating value
Energy content of the fuel, expressed as the heat released when a fuel is combusted completely, corrected to standard pressure and temperature. The higher heating value (HHV) is complete combustion with the water vapour in the exhaust gas condensed. The lower heating value (LHV) is when the water vapour in the exhaust gas is in the vapour phase. As this is the way in which water leaves the engine, engine efficiency and fuel consumption are generally expressed in terms of LHV.

Note:
- LHV: petrol: 31.2 MJ/l, diesel: 35.7 MJ/l, ethanol: 21.2 MJ/l, biodiesel: 32.8 MJ/l and DME: 18.2-19.3 MJ/l [IEA 1999].

Latent heat of vaporisation
The quantity of heat that is absorbed by a fuel in passing from the liquid to the gaseous phase, measured at the boiling point under atmospheric pressure.

Vapour density
Weight of a volume of pure (no air present) vapour compared to an equal volume of dry air at the same temperature and pressure.

Vapour pressure
Equilibrium pressure exerted by vapours over a liquid at a given temperature. The Reid Vapour Pressure is typically used to describe the vapour pressure of petroleum fuels without oxygenates (ASTM Method D 323). A low vapour pressure leads to low evaporative emissions but may also cause cold-start problems.

Note:
- According to [Bechtold 1997] the Reid Vapour Pressure test involves saturating the fuel with water before testing and cannot be used for petrol-alcohol blends or neat alcohol fuels. A procedure has been developed which does not use water, measuring the so-called Dry Vapour Pressure Equivalent (ASTM D4814-95c). Other studies, however, explicitly mention the use of ASTM D 323 for measuring the RVP of ethanol-petrol blends [e.g. Guerreri 1995].

Viscosity
The resistance of a fuel to flow.

Iodine number
For biofuels the iodine number is a relevant property that provides information on chemical composition (level of saturation). It is a measure of the degree of saturation or number of double bonds (higher IN = more double, i.e. unsaturated, bonds). Iodine number has a strong inverse correlation with cetane number [Graboski 2003]. The reaction with iodine (titration) was long used for analyzing the number of double bonds, that is, the degree of saturation. Iodine solutions have a violet colour. In the reaction

with a double bond, the iodine molecule will lose its colour. The iodine number is determined by the quantity of iodine which will just still be decoloured by the fat or oil. Nowadays iodene number can be easily determined by spectroscopic measurement (See e.g. http://www.ft-nir.com/Nutrition/iodzahl.htm).

## B.2 Literature

[Aakko 1997] Aakko, P. & Nylund, N.O. (1997), *Characterisation of new fuel qualities*, VTT report ENE24/21/97.

[Bechtold 1997] Bechtold, R.L. (1997), *Alternative Fuels Guidebook*, SAE Order No. R-180, ISBN 0-7680-0052-1.

[Ermers 2001] Ermers, R. (2001), *Brandstofkarakteristieken die belangrijk zijn voor de keuze van een alternatieve diesel en het effect ban Fischer-Tropsch diesel, biodiesel en oxygenates op emissies*, stageverslag TU Eindhoven, rapportnummer WVM 2001.05.

[Graboski 2003] Graboski, M.S., McCormick, R.L., Alleman, T.L. & Herring, A.M. (2003), *The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Diesel Engine*, National Renewable Energy Laboratory (NREL), Report No. NREL/SR-540-33793

[Guerreri 1995] 55. Guerrieri, D.A., Caffrey, P.J. & Rao, V. (1995) *Investigation into the vehicle exhaust emission of high percentage ethanol blends*, SAE Technical Paper Series, Paper No. 950777

[IEA 1999] IEA (1999), *Automotive Fuels for the Future – The Search for Alternatives*, International Energy Agency

[Smokers 2004] Smokers, R.T.M. and Smit, R. (2004), *Compatibility of pure and blended biofuels with respect to engine performance, durability and emissions*, SenterNovem report nr. 2GAVE04.01.

# C Fuel specifications (standards)

## C.1 EN 228 Petrol

EN 228 is an international standard that describes the minimum requirements for petrol.

**Table 1 - Requirements and test methods for premium grade unleaded petrol**

| **Property** | **Units** | **Limits** | | **Test Method** [a] |
|---|---|---|---|---|
| | | **Min.** | **Max.** | (See 2. Normative references) |
| **Research octane number, RON** | | **95,0** | -- | prEN ISO 5164 [b] |
| **Motor octane number, MON** | | **85,0** | -- | prEN ISO 5163 [b] |
| **Lead content** | **mg/l** | -- | **5** | prEN 237 |
| Density (at 15 °C) [c] | kg/m$^3$ | 720 | 775 | EN ISO 3675<br>EN ISO 12185 |
| **Sulfur content** [c] | **mg/kg** | -- | **150** (until 2004-12-31)<br>or<br>**50,0** | EN ISO 20846<br>EN ISO 20847<br>EN ISO 20884 |
| | | -- | **10,0** | EN ISO 20846<br>EN ISO 20884 |
| Oxidation stability | minutes | 360 | -- | EN ISO 7536 |
| Existent gum content (solvent washed) | mg/100 ml | -- | 5 | EN ISO 6246 |
| Copper strip corrosion (3 h at 50 °C) | rating | class 1 | | EN ISO 2160 |
| Appearance | | clear and bright | | visual inspection |
| **Hydrocarbon type content** [c,] | ***% (V/V)*** | | | ASTM D 1319 [d, e, f]<br>prEN 14517 |
| **- olefins** | | -- | **18,0** | |
| **- aromatics** | | -- | **42,0** (until 2004-12-31) | |
| | | | or | |
| | | -- | **35,0** | |
| **Benzene content** [c] | ***% (V/V)*** | -- | **1,00** | EN 12177<br>EN 238<br>prEN 14517 |
| **Oxygen content** [c] | ***% (m/m)*** | -- | **2,7** | EN 1601<br>EN 13132 |
| **Oxygenates content** [c] | ***% (V/V)*** | | | EN 1601<br>EN 13132 |
| **- methanol** [g] | | -- | **3,0** | |
| **- ethanol** [h] | | -- | **5,0** | |
| **- iso-propyl alcohol** | | -- | **10,0** | |
| **- iso-butyl alcohol** | | -- | **10,0** | |
| **- tert-butyl alcohol** | | -- | **7,0** | |
| **- ethers (5 or more C atoms)** | | -- | **15,0** | |
| **- other oxygenates** [i] | | -- | **10,0** | |

NOTE Requirements in bold refer to the European Fuels Directive 98/70/EC [1], including Amendment 2003/17/EC [2]

[a] See also 5.7.1

[b] A correction factor of 0,2 for MON and RON shall be subtracted for the calculation of the final result, before reporting according to the requirements of the European Directive 98/70/EC [1], including Amendment 2003/17/EC [2]

[c] See also 5.7.2

[d] The content of oxygenate compounds shall be determined as prescribed in Table 1 in order to make the corrections when necessary according to clause 13.2 of ASTM D 1319.

[e] When Ethyl-tert-butyl ether (ETBE) is present in the sample, the aromatic zone shall be determined from the pink brown ring downstream of the red ring normally used in the absence of ETBE. The presence or absence of ETBE can be concluded from the analysis as required in footnote d.

[f] For the purpose of this standard ASTM D 1319 shall be applied without the optional depentanisation step. Therefore clauses 6.1, 10.1 and 14.1.1 shall not be applied.

[g] Stabilising agents shall be added.

[h] Stabilising agents may be necessary.

[i] Other mono-alcohols and ethers with a final boiling point no higher than prescribed in Table 3.

### Table 2 - Requirements and test methods for regular grade unleaded petrol until 2004-12-31 (see clause 5.5)

| Property | Units | Limits<br>Min. | <br>Max. | Test Method [a]<br>(See 2. Normative references) |
|---|---|---|---|---|
| **Research octane number, RON** | | [k] | -- | prEN ISO 5164 [b] |
| **Motor octane number, MON** | | [k] | -- | prEN ISO 5163 [b] |
| **Lead content** | **mg/l** | -- | **5** | prEN 237 |
| Density (at 15 °C) [c] | kg/m$^3$ | 720 | 775 | EN ISO 3675<br>EN ISO 12185 |
| **Sulfur content** [c] | **mg/kg** | -- | **150<br>or<br>50,0** | EN ISO 20846<br>EN ISO 20847<br>EN ISO 20884 |
| | | -- | **10,0** | EN ISO 20846<br>EN ISO 20884 |
| Oxidation stability | minutes | 360 | -- | EN ISO 7536 |
| Existent gum content (solvent washed) | mg/100 ml | -- | 5 | EN ISO 6246 |
| Copper strip corrosion (3 h at 50 °C) | rating | class 1 | | EN ISO 2160 |
| Appearance | | clear and bright | | visual inspection |
| **Hydrocarbon type content** [c,] | **% *(V/V)*** | | | ASTM D 1319 [d, e, f]<br>prEN 14517 |
| **- olefins** | | -- | **21,0** | |
| **- aromatics** | | -- | **42,0<br>or<br>35,0** | |
| **Benzene content** [c] | **% *(V/V)*** | -- | **1,00** | EN 12177<br>EN 238<br>prEN 14517 |
| **Oxygen content** [c] | **% *(m/m)*** | -- | **2,7** | EN 1601<br>EN 13132 |
| **Oxygenates content** [c] | **% *(V/V)*** | | | EN 1601<br>EN 13132 |
| **- methanol** [g] | | -- | **3,0** | |
| **- ethanol** [h] | | -- | **5,0** | |
| **- iso-propyl alcohol** | | -- | **10,0** | |
| **- iso-butyl alcohol** | | -- | **10,0** | |
| **- tert-butyl alcohol** | | -- | **7,0** | |
| **- ethers (5 or more C atoms)** | | -- | **15,0** | |
| **- other oxygenates** [i] | | -- | **10,0** | |

NOTE Requirements in bold refer to the European Fuels Directive 98/70/EC [1], including Amendment 2003/17/EC [2]

[a] See also 5.7.1

[b] A correction factor of 0,2 for MON and RON shall be subtracted for the calculation of the final result, before reporting according to the requirement of the European Fuels Directive 98/70/EC [1], including Amendment 2003/17/EC [2]

[c] See also 5.7.2

[d] The content of oxygenate compounds shall be determined as prescribed in Table 2 in order to make the corrections when necessary according to clause 13.2 of ASTM D 1319

[e] When Ethyl-tert-butyl ether (ETBE) is present in the sample, the aromatic zone shall be determined from the pink brown ring downstream of the red ring normally used in the absence of ETBE. The presence or absence of ETBE can be concluded from the analysis as required in footnote d

[f] For the purpose of this standard ASTM D 1319 shall be applied without the optional depentanisation step. Therefore clauses 6.1, 10.1 and 14.1.1 shall not be applied

[g] Stabilising agents shall be added

[h] Stabilising agents may be necessary

[i] Other mono-alcohols and ethers with a final boiling point no higher than prescribed in Table 3

[k] When regular grade is marketed, RON and MON shall be specified in a national annex to this European Standard, **but not lower than 81,0 MON and 91,0 RON**

## C.2 EN 590 Diesel

EN590 describes the physical properties that all diesel fuel must meet if it is to be sold in the European Union, Iceland, Norway and Switzerland.

| **Property** | **Units** | **lower limit** | **upper limit** |
|---|---|---|---|
| Cetane number | | 51,0 | - |
| Cetane index | | 46,0 | - |
| Density at 15°C | kg/m³ | 820 | 845 |
| Polycyclic aromatic hydrocarbons | %(m/m) | - | 11 |
| Sulphur content | mg/kg | - | 350 (until 2004-12-31) or 50,0 |
| | | | 10,0 (on the 01-01-2009) |
| Flash point | °C | Above 55 | - |
| Carbon residue (on 10% distillaiton residue) | %m/m | - | 0,30 |
| Ash content | % (m/m) | - | 0,01 |
| Water content | mg/kg | - | 200 |
| Total contamination | mg/kg | - | 24 |
| Copper strip corrosion (3 hours at 50 °C) | rating | Class 1 | Class 1 |
| Oxidation Stability | g/m³ | - | 25 |
| Lubricity, corrected wear scar diameter (wsd 1,4) at 60 °C | µm | - | 460 |
| Viscosity at 40 °C | mm²/s | 2,00 | 4,50 |
| Distillation recovered at 250 °C, 350 °C | %V/V | 85 | <65 |
| 95%(V/V) recovered at | °C | - | 360 |
| Fatty acid methyl ester content | % (V/V) | - | 5 |

## C.3 EN 14214 Biodiesel

EN 14214 is an international standard that describes the minimum requirements for biodiesel.

| **Property** | **Units** | **lower limit** | **upper limit** |
|---|---|---|---|
| Ester content | % (m/m) | 96,5 | - |
| Density at 15°C | kg/m³ | 860 | 900 |
| Viscosity at 40°C | mm²/s | 3,5 | 5,0 |
| Flash point | °C | > 101 | - |
| Sulfur content | mg/kg | - | 10 |
| Tar remnant (at 10% distillation remnant) | % (m/m) | - | 0,3 |
| Cetane number | - | 51,0 | - |
| Sulfated ash content | % (m/m) | - | 0,02 |
| Water content | mg/kg | - | 500 |
| Total contamination | mg/kg | - | 24 |
| Copper band corrosion (3 hours at 50 °C) | rating | Class 1 | Class 1 |
| Thermal Stability | - | - | - |
| Oxidation stability, 110°C | hours | 6 | - |
| Acid value | mg KOH/g | - | 0,5 |
| Iodine value | - | - | 120 |
| Linolenic Acid Methylester | % (m/m) | - | 12 |
| Polyunsaturated (>= 4 Double bonds) Methylester | % (m/m) | - | 1 |
| Methanol content | % (m/m) | - | 0,2 |
| Monoglyceride content | % (m/m) | - | 0,8 |
| Diglyceride content | % (m/m) | - | 0,2 |
| Triglyceride content | % (m/m) | - | 0,2 |
| Free Glycerine | % (m/m) | - | 0,02 |
| Total Glycerine | % (m/m) | - | 0,25 |
| Alkali Metals (Na+K) | mg/kg | - | 5 |
| Phosphorus content | mg/kg | - | 10 |

## C.4 Proposed specs for high percentage ethanol blend

Proposed specs for petrol fuel containing up to 10% ethanol.

See: COM(2007) 18, *Proposal for a directive of the European Parliament and of the Council, amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and the introduction of a mechanism to monitor and reduce greenhouse gas emissions from the use of road fuels and amending Council Directive 1999/32/EC, as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC*, Brussels, 31 January 2007

# ENVIRONMENTAL SPECIFICATIONS FOR MARKET FUELS TO BE USED FOR VEHICLES EQUIPPED WITH POSITIVE-IGNITION ENGINES

*Type:* **High biofuel Petrol**

| Parameter (1) | Unit | Limits (2) | |
|---|---|---|---|
| | | Minimum | Maximum |
| Research octane number | | 95 | — |
| Motor octane number | | 85 | — |
| Vapour pressure, summer period (3) | kPa | — | 60,0 (4) |
| Distillation: | | | |
| — percentage evaporated at 100 °C | % v/v | 46,0 | — |
| — percentage evaporated at 150 °C | % v/v | 75,0 | — |
| Hydrocarbon analysis: | | | |
| — olefins | % v/v | — | 18,0 |
| — aromatics | % v/v | — | 35,0 |
| — benzene | % v/v | — | 1,0 |
| Oxygen content | % m/m | — | 3,7 |
| Oxygenates | | | |
| — Methanol | | | 3 |
| — Ethanol (stabilising agents may be necessary) | % v/v | | 10 |
| — Iso-propyl alcohol | % v/v | — | 12 |
| — Tert-butyl alcohol | % v/v | — | 15 |
| — Iso-butyl alcohol | % v/v | — | 15 |
| — Ethers containing five or more carbon atoms per molecule | % v/v | — | 22 |
| — Other oxygenates(5) | % v/v | — | 15 |
| Sulphur content | mg/kg | — | 10 |
| Lead content | g/l | — | 0,005 |

(1) Test methods shall be those specified in EN 228:1999. Member States may adopt the analytical method specified in replacement EN 228:1999 standard if it can be shown to give at least the same accuracy and at least the same level of precision as the analytical method it replaces.

(2) The values quoted in the specification are 'true values'. In the establishment of their limit values, the terms of ISO 4259 'Petroleum products - Determination and application of precision data in relation to methods of test' have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account (R = reproducibility). The results of individual measurements shall be interpreted on the basis of the criteria described in ISO 4259 (published in 1995).

(3) The summer period shall begin no later than 1 May and shall not end before 30 September. For Member States with arctic or severe winter conditions, the summer period shall begin no later than 1 June and shall not end before 31 August.

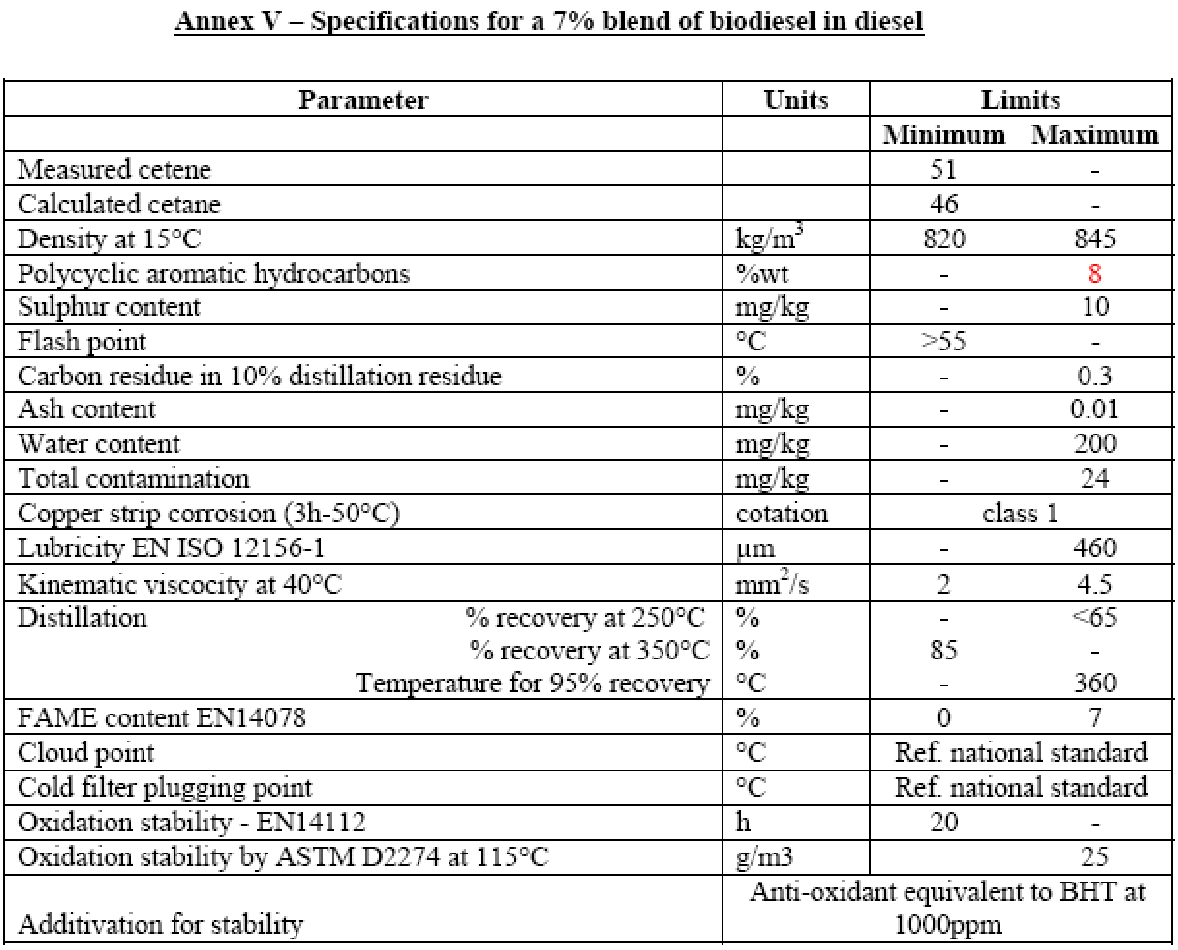
(4) For Member States with arctic or severe winter conditions the maximum vapour pressure shall not exceed 70.0 kPa. Where fuel contains ethanol, the maximum permitted summer vapour pressure may exceed 60kPa by the amount shown in the table in annex VI

(5) Other mono-alcohols and ethers with a final boiling point no higher than that stated in EN 228:1999.

## C.5 Proposed specs for high percentage biodiesel in diesel blends

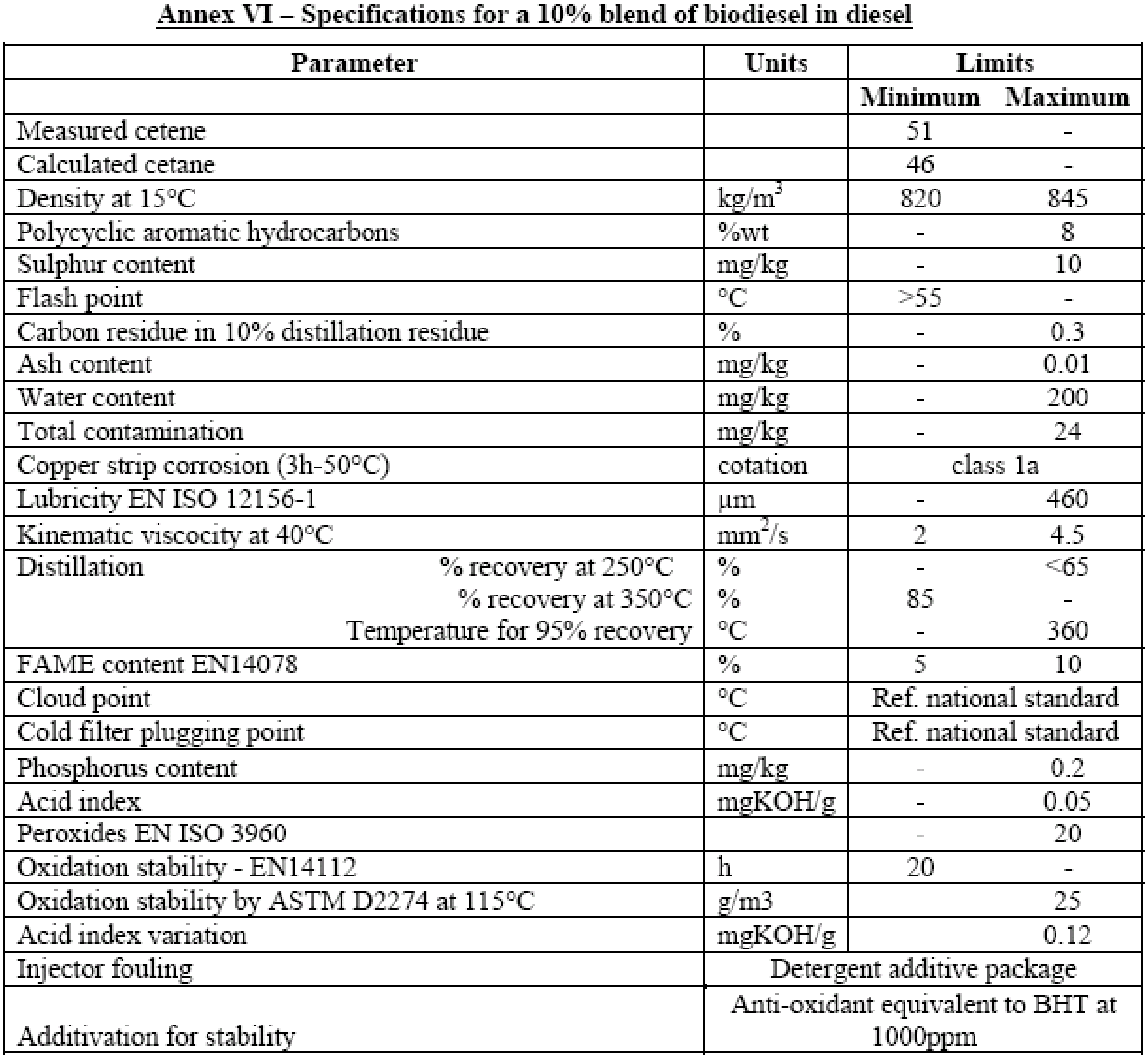
Proposed specs for diesel fuel containing 7% resp. 10% biodiesel.

See: COM(2008)yyy final, *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewables*, version 15.4, Brussels 23.01.2008



**Annex V – Specifications for a 7% blend of biodiesel in diesel**

| Parameter | | Units | Limits | |
|---|---|---|---|---|
| | | | Minimum | Maximum |
| Measured cetene | | | 51 | - |
| Calculated cetane | | | 46 | - |
| Density at 15°C | | kg/m$^3$ | 820 | 845 |
| Polycyclic aromatic hydrocarbons | | %wt | - | 8 |
| Sulphur content | | mg/kg | - | 10 |
| Flash point | | °C | >55 | - |
| Carbon residue in 10% distillation residue | | % | - | 0.3 |
| Ash content | | mg/kg | - | 0.01 |
| Water content | | mg/kg | - | 200 |
| Total contamination | | mg/kg | - | 24 |
| Copper strip corrosion (3h-50°C) | | cotation | class 1 | |
| Lubricity EN ISO 12156-1 | | µm | - | 460 |
| Kinematic viscocity at 40°C | | mm$^2$/s | 2 | 4.5 |
| Distillation | % recovery at 250°C | % | - | <65 |
| | % recovery at 350°C | % | 85 | - |
| | Temperature for 95% recovery | °C | - | 360 |
| FAME content EN14078 | | % | 0 | 7 |
| Cloud point | | °C | Ref. national standard | |
| Cold filter plugging point | | °C | Ref. national standard | |
| Oxidation stability - EN14112 | | h | 20 | - |
| Oxidation stability by ASTM D2274 at 115°C | | g/m3 | | 25 |
| Additivation for stability | | Anti-oxidant equivalent to BHT at 1000ppm | | |



**Annex VI – Specifications for a 10% blend of biodiesel in diesel**

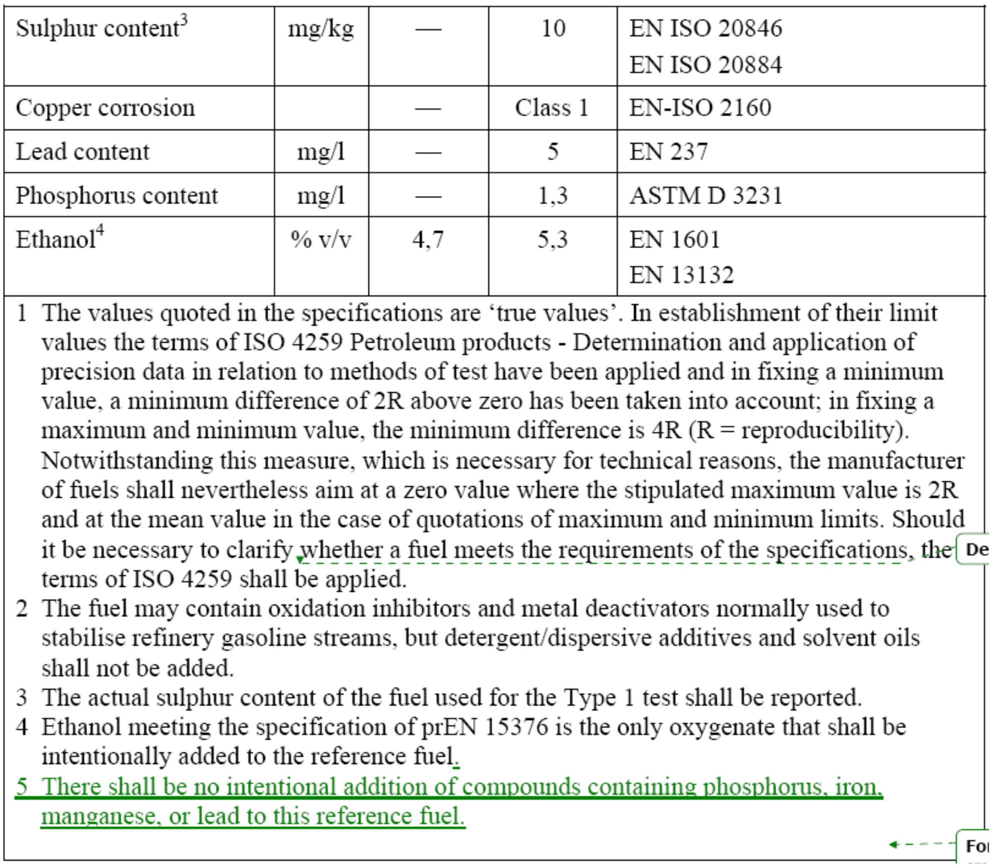
| Parameter | | Units | Limits | |
|---|---|---|---|---|
| | | | Minimum | Maximum |
| Measured cetene | | | 51 | - |
| Calculated cetane | | | 46 | - |
| Density at 15°C | | kg/m$^3$ | 820 | 845 |
| Polycyclic aromatic hydrocarbons | | %wt | - | 8 |
| Sulphur content | | mg/kg | - | 10 |
| Flash point | | °C | >55 | - |
| Carbon residue in 10% distillation residue | | % | - | 0.3 |
| Ash content | | mg/kg | - | 0.01 |
| Water content | | mg/kg | - | 200 |
| Total contamination | | mg/kg | - | 24 |
| Copper strip corrosion (3h-50°C) | | cotation | class 1a | |
| Lubricity EN ISO 12156-1 | | µm | - | 460 |
| Kinematic viscocity at 40°C | | mm$^2$/s | 2 | 4.5 |
| Distillation | % recovery at 250°C | % | - | <65 |
| | % recovery at 350°C | % | 85 | - |
| | Temperature for 95% recovery | °C | - | 360 |
| FAME content EN14078 | | % | 5 | 10 |
| Cloud point | | °C | Ref. national standard | |
| Cold filter plugging point | | °C | Ref. national standard | |
| Phosphorus content | | mg/kg | - | 0.2 |
| Acid index | | mgKOH/g | - | 0.05 |
| Peroxides EN ISO 3960 | | | - | 20 |
| Oxidation stability - EN14112 | | h | 20 | - |
| Oxidation stability by ASTM D2274 at 115°C | | g/m3 | | 25 |
| Acid index variation | | mgKOH/g | | 0.12 |
| Injector fouling | | Detergent additive package | | |
| Additivation for stability | | Anti-oxidant equivalent to BHT at 1000ppm | | |

## C.6 Reference fuels for type approval testing

Draft Regulation (EC) No 715/2007 [EC 2007c] contains amended specifications for the reference fuels to be used in type approval testing, which also contain specifications for 5% (v/v) ethanol in the reference petrol and 5% (v/v) FAME in the reference diesel.

Type: Petrol (E5)

| Parameter | Unit | Limits[1] | | Test method |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| Research octane number, RON | | 95,0 | — | EN 25164<br>prEN ISO 5164 |
| Motor octane number, MON | | 85,0 | — | EN 25163<br>prEN ISO 5163 |
| Density at 15 °C | kg/m$^3$ | 743 | 756 | EN ISO 3675<br>EN ISO 12185 |
| Vapour pressure | kPa | 56,0 | 60,0 | EN ISO 13016-1 (DVPE) |
| Water content | % v/v | | 0.015 | ASTM E 1064 |
| Distillation: | | | | |
| – evaporated at 70 °C | % v/v | 24,0 | 44,0 | EN-ISO 3405 |
| – evaporated at 100 °C | % v/v | 48,0 | 60,0 | EN-ISO 3405 |
| – evaporated at150 °C | % v/v | 82,0 | 90,0 | EN-ISO 3405 |
| – final boiling point | °C | 190 | 210 | EN-ISO 3405 |
| Residue | % v/v | — | 2,0 | EN-ISO 3405 |
| Hydrocarbon analysis: | | | | |
| – olefins | % v/v | 3,0 | 13,0 | ASTM D 1319 |
| – aromatics | % v/v | 29,0 | 35,0 | ASTM D 1319 |
| – benzene | % v/v | — | 1,0 | EN 12177 |
| – saturates | % v/v | Report | | ASTM 1319 |
| Carbon/hydrogen ratio | | Report | | |
| Carbon/oxygen ratio | | Report | | |
| Induction period[2] | minutes | 480 | — | EN-ISO 7536 |
| Oxygen content[4] | % m/m | Report | | EN 1601 |
| Existent gum | mg/ml | — | 0,04 | EN-ISO 6246 |



| | | | | |
|---|---|---|---|---|
| Sulphur content[3] | mg/kg | — | 10 | EN ISO 20846<br>EN ISO 20884 |
| Copper corrosion | | — | Class 1 | EN-ISO 2160 |
| Lead content | mg/l | — | 5 | EN 237 |
| Phosphorus content | mg/l | — | 1,3 | ASTM D 3231 |
| Ethanol[4] | % v/v | 4,7 | 5,3 | EN 1601<br>EN 13132 |

1 The values quoted in the specifications are 'true values'. In establishment of their limit values the terms of ISO 4259 Petroleum products - Determination and application of precision data in relation to methods of test have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account; in fixing a maximum and minimum value, the minimum difference is 4R (R = reproducibility). Notwithstanding this measure, which is necessary for technical reasons, the manufacturer of fuels shall nevertheless aim at a zero value where the stipulated maximum value is 2R and at the mean value in the case of quotations of maximum and minimum limits. Should it be necessary to clarify whether a fuel meets the requirements of the specifications, the terms of ISO 4259 shall be applied.

2 The fuel may contain oxidation inhibitors and metal deactivators normally used to stabilise refinery gasoline streams, but detergent/dispersive additives and solvent oils shall not be added.

3 The actual sulphur content of the fuel used for the Type 1 test shall be reported.

4 Ethanol meeting the specification of prEN 15376 is the only oxygenate that shall be intentionally added to the reference fuel.

5 There shall be no intentional addition of compounds containing phosphorus, iron, manganese, or lead to this reference fuel.

Type: Ethanol (E85)

| Parameter | Unit | Limits[1] |  | Test method[2] |
|---|---|---|---|---|
|  |  | Minimum | Maximum |  |
| Research octane number, RON |  | 95,0 | — | EN ISO 5164 |
| Motor octane number, MON |  | 85,0 | — | EN ISO 5163 |
| Density at 15 °C | kg/m$^3$ | Report |  | ISO 3675 |
| Vapour pressure | kPa | 40,0 | 60,0 | EN ISO 13016-1 (DVPE) |
| Sulphur content[3,4] | mg/kg | — | 10 | EN ISO 20846<br>EN ISO 20884 |
| Oxidation stability | minutes | 360 |  | EN ISO 7536 |
| Existent gum content (solvent washed) | g/100ml | — | 5 | EN-ISO 6246 |
| Appearance<br>This shall be determined at ambient temperature or 15°C whichever is higher. |  | Clear and bright, visibly free of suspended or precipitated contaminants |  | Visual inspection |
| Ethanol and higher alcohols[7] | % (V/V) | 83 | 85 | EN 1601<br>EN 13132<br>EN 14517 |
| Higher alcohols (C3-C8) | % (V/V) | — | 2,0 |  |
| Methanol | % (V/V) |  | 0.5 |  |
| Petrol[5] | % (V/V) | Balance |  | EN 228 |
| Phosphorus | mg/l | 0,3[6] |  | ASTM D 3231 |
| Water content | % (V/V) |  | 0,3 | ASTM E 1064 |
| Inorganic chloride content | mg/l |  | 1 | ISO 6227 |
| pHe |  | 6,5 | 9,0 | ASTM D 6423 |
| Copper strip corrosion (3h at 50°C) | Rating | Class 1 |  | EN ISO 2160 |
| Acidity, (as acetic acid $CH_3COOH$) | %<br>(m/m)<br>(mg/l) | — | 0,005<br>(40) | ASTM D 1613 |

| | | | |
|---|---|---|---|
| Carbon/hydrogen ratio | | report | |
| Carbon/oxygen ration | | report | |

1 The values quoted in the specifications are 'true values'. In establishment of their limit values the terms of ISO 4259 Petroleum products - Determination and application of precision data in relation to methods of test have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account; in fixing a maximum and minimum value, the minimum difference is 4R (R = reproducibility). Notwithstanding this measure, which is necessary for technical reasons, the manufacturer of fuels shall nevertheless aim at a zero value where the stipulated maximum value is 2R and at the mean value in the case of quotations of maximum and minimum limits. Should it be necessary to clarify whether a fuel meets the requirements of the specifications, the terms of ISO 4259 shall be applied.

2 In cases of dispute, the procedures for resolving the dispute and interpretation of the results based on test method precision, described in EN ISO 4259 shall be used.

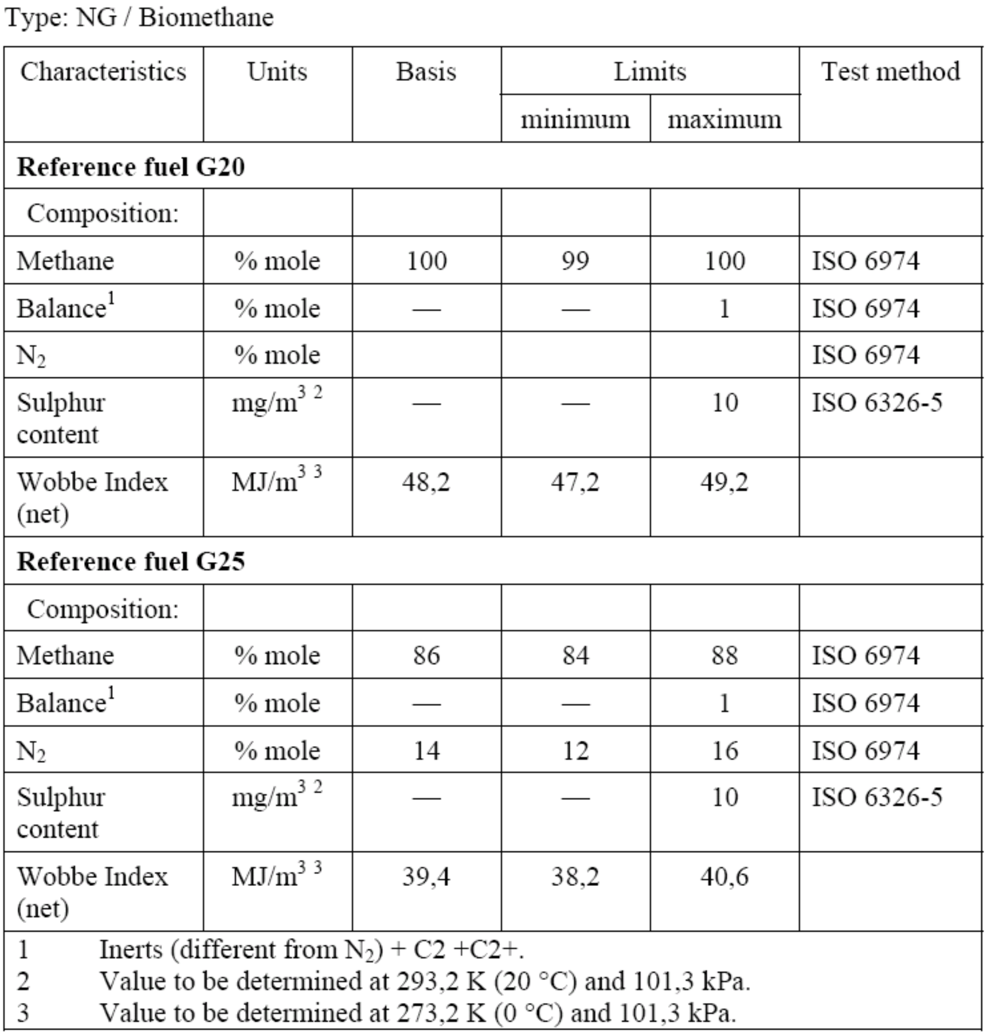
3 In cases of national dispute concerning sulphur content, either EN ISO 20846 or EN ISO 20884 shall be called up similar to the reference in the national annex of EN 228.

4 The actual sulphur content of the fuel used for the Type 1 test shall be reported.

5. The unleaded petrol content can be determined as 100 minus the sum of the percentage content of water and alcohols

6 There shall be no intentional addition of compounds containing phosphorus, iron, manganese, or lead to this reference fuel.

7. Ethanol to meet specification of prEN 15376 is the only oxygenate that shall be intentionally added to this reference fuel.



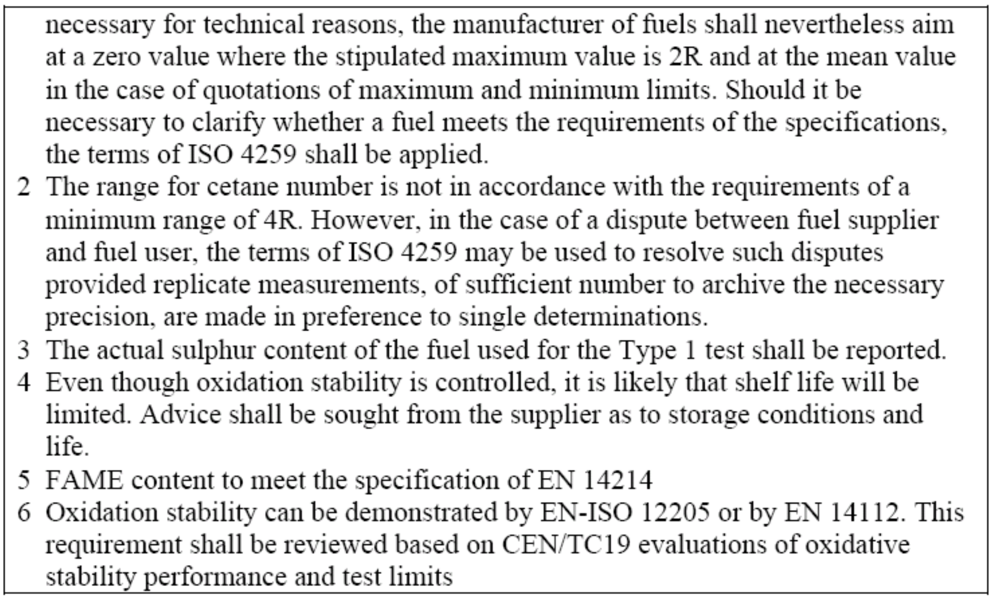
Type: NG / Biomethane

| Characteristics | Units | Basis | Limits | | Test method |
|---|---|---|---|---|---|
| | | | minimum | maximum | |
| **Reference fuel G20** | | | | | |
| Composition: | | | | | |
| Methane | % mole | 100 | 99 | 100 | ISO 6974 |
| Balance[1] | % mole | — | — | 1 | ISO 6974 |
| $N_2$ | % mole | | | | ISO 6974 |
| Sulphur content | $mg/m^3$ [2] | — | — | 10 | ISO 6326-5 |
| Wobbe Index (net) | $MJ/m^3$ [3] | 48,2 | 47,2 | 49,2 | |
| **Reference fuel G25** | | | | | |
| Composition: | | | | | |
| Methane | % mole | 86 | 84 | 88 | ISO 6974 |
| Balance[1] | % mole | — | — | 1 | ISO 6974 |
| $N_2$ | % mole | 14 | 12 | 16 | ISO 6974 |
| Sulphur content | $mg/m^3$ [2] | — | — | 10 | ISO 6326-5 |
| Wobbe Index (net) | $MJ/m^3$ [3] | 39,4 | 38,2 | 40,6 | |

1 Inerts (different from $N_2$) + C2 +C2+.
2 Value to be determined at 293,2 K (20 °C) and 101,3 kPa.
3 Value to be determined at 273,2 K (0 °C) and 101,3 kPa.

Type: Diesel (B5)

| Parameter | Unit | Limits[1] | | Test method |
|---|---|---|---|---|
| | | Minimum | Maximum | |
| Cetane number[2] | | 52,0 | 54,0 | EN-ISO 5165 |
| Density at 15 °C | kg/m$^3$ | 833 | 837 | EN-ISO 3675 |
| Distillation: | | | | |
| - 50 % point | °C | 245 | — | EN-ISO 3405 |
| - 95 % point | °C | 345 | 350 | EN-ISO 3405 |
| - final boiling point | °C | — | 370 | EN-ISO 3405 |
| Flash point | °C | 55 | — | EN 22719 |
| CFPP | °C | — | – 5 | EN 116 |
| Viscosity at 40 °C | mm$^2$/s | 2,3 | 3,3 | EN-ISO 3104 |
| Polycyclic aromatic hydrocarbons | % m/m | 2,0 | 6,0 | EN 12916 |
| Sulphur content[3] | mg/kg | — | 10 | EN ISO 20846 / EN ISO 20884 |
| Copper corrosion | | — | Class 1 | EN-ISO 2160 |
| Conradson carbon residue (10 % DR) | % m/m | — | 0,2 | EN-ISO 10370 |
| Ash content | % m/m | — | 0,01 | EN-ISO 6245 |
| Water content | % m/m | — | 0,02 | EN-ISO 12937 |
| Neutralisation (strong acid) number | mg KOH/g | — | 0,02 | ASTM D 974 |
| Oxidation stability[4] | mg/ml | — | 0,025 | EN-ISO 12205 |
| Lubricity (HFRR wear scan diameter at 60 °C) | µm | — | 400 | EN ISO 12156 |
| Oxidation stability @ 110 °C [4, 6] | h | 20,0 | | EN 14112 |
| FAME[5] | % v/v | 4,5 | 5,5 | EN 14078 |
| 1 The values quoted in the specifications are 'true values'. In establishment of their limit values the terms of ISO 4259 Petroleum products – Determination and application of precision data in relation to methods of test have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account; in fixing a maximum and minimum value, the minimum difference is 4R (R = reproducibility). Notwithstanding this measure, which is | | | | |



necessary for technical reasons, the manufacturer of fuels shall nevertheless aim at a zero value where the stipulated maximum value is 2R and at the mean value in the case of quotations of maximum and minimum limits. Should it be necessary to clarify whether a fuel meets the requirements of the specifications, the terms of ISO 4259 shall be applied.

2 The range for cetane number is not in accordance with the requirements of a minimum range of 4R. However, in the case of a dispute between fuel supplier and fuel user, the terms of ISO 4259 may be used to resolve such disputes provided replicate measurements, of sufficient number to archive the necessary precision, are made in preference to single determinations.

3 The actual sulphur content of the fuel used for the Type 1 test shall be reported.

4 Even though oxidation stability is controlled, it is likely that shelf life will be limited. Advice shall be sought from the supplier as to storage conditions and life.

5 FAME content to meet the specification of EN 14214

6 Oxidation stability can be demonstrated by EN-ISO 12205 or by EN 14112. This requirement shall be reviewed based on CEN/TC19 evaluations of oxidative stability performance and test limits

# D Fuel properties of specific conventional and biofuels

## D.1 Overview of fuel properties of various conventional and alternative fuels

Based on Annex D of [Smokers 2004].

Footnotes regarding table on fuels for SI engines

1) Varying butane/propane ratio, e.g. 70% propane & 30% butane to 100% Propane [IEA 1999]. For some parameters only separate data for 100% propane and 100% butane have been found;
2) Octane number has been developed for liquid fuels and NG exceeds maximum value of 120, and thus the octane scale is not appropriate for CNG/LNG. Instead the methane number has been developed with pure methane as the most knock resistant fuel having a value of 100 [EC 2000];
3) Based on pure methane [dieselnet 2003];
4) Requirement in summer period.
5) Biogas for use as transport fuel is assumed to be upgraded to NG quality.

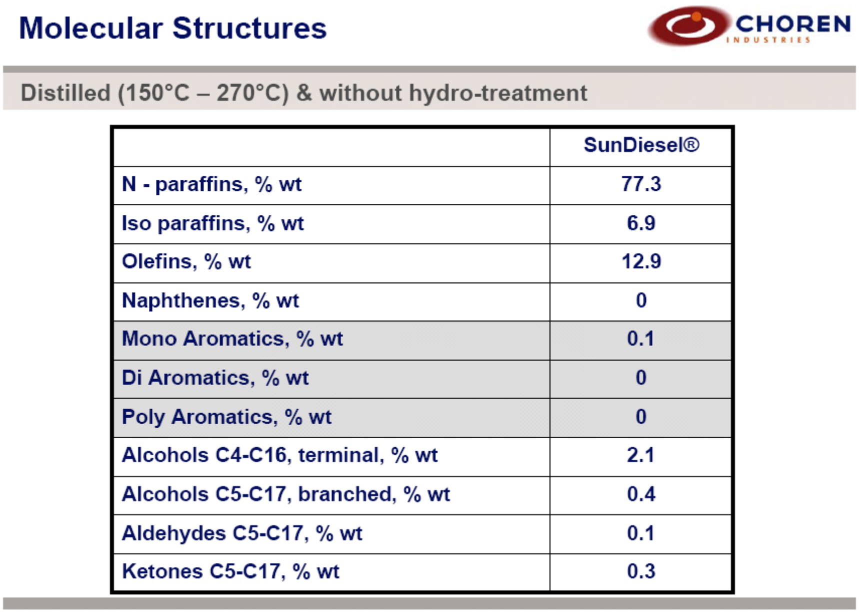
*Fuels for SI engines*

| **Property** | **Units** | **Petrol** | **LPG 1)** | **NG** | **ethanol** | **butanol** | **FT petrol** | **MTBE** | **ETBE** | **biogas** |
|---|---|---|---|---|---|---|---|---|---|---|
| Chemical Formulae | - | $C_4$ to $C_{12}$ | x% $C_3H_8$<br>x% $C_4H_{10}$ | $CH_4$ | $C_2H_5OH$ | $C_4H_{10}OH$ | | $C_5H_{12}O$ | $C_6H_{14}O$ | $CH_4$<br>see NG 5) |
| Applicable Compression Ratios | - | < 11 | 11 – 13 | 11 – 13 | < 18 | | | | | |
| Stoichiometric A/F Ratio | kg/kg | 14.7 | 15.4 | 16.9 | 9 | 11.2 | | | | |
| Chemical Structure | mass% C | 77 / 85 | 82 / 83 | 73.3 – 76.0 | 52.2 – 52.3 | 64 | | | 70 | |
| | mass% H | 11.3 / 15 | 18 / 17 | 23.9 – 25.0 | 13.1 – 13.3 | 14 | | | 14 | |
| | mass% O | 0.0 | 0.0 | 0.4 - 0.0 | 34.8 – 34.4 | 22 | | | 102 | |
| Molecular Weight | g/mole | 98 | 44 - 58 | 17 | 46 | 74 | | 88 | | |
| Liquid Density (at 20 °C) | $kg/m^3$ | 750 | 500 - 580 | | 790 | | | | | |
| Density (at 15 °C) | $kg/m^3$ | 720 – 780 | | 0.83 | 800 | 810 | | 740 | 736 | |
| Cetane Number | - | - | - | - | 40 / 50 | | | | | |
| Research Octane Number (RON) | - | > 95 | 94 – 112 | 120 2) | 106 - 120 | 96 | 40 | 110 - 118 | 118 | |
| Motor Octane Number (MON) | - | > 85 | 89 – 98 | 130 | 90 - 99 | 78 | | 102 | 111 | |
| Methane Number (MN) | - | - | - | 69-99 2) | - | | | | | |
| Energy Density (LHV) | MJ/kg | 41 – 43.7 | 44 – 46 | 38 – 50 | 25 – 29 | | | | 36 | |
| Energy Content (LHV) | MJ/l | 31.5 – 32.2 | 23 – 26 | 0.032 | 21.2 | 29.2 | | | 26.8 | |
| Energy Density (HHV) | MJ/kg | 46.8 – 47.3 | 48 – 50 | 42.2 | 28 - 30 | | | | | |
| Boiling Point | °C | 30 / 190 | -42 – -0.5 | -162 – -89 | 78 | 118 | | 55.2 | 69 - 71 | |
| Autoignition Temperature | °C | 225 – 500 | 365 – 470 | 540 – 650 | 420 | | | | | |
| Vapour Pressure (at 20 °C) | kPa | 45 – 90 | 210 – 810 | | 21 | | | | | |
| | | < 60 4) | | | | | | | | |
| Kinematic Viscocity | cSt | 0.4 – 0.8 | | | 1.52 | 3.64 | | | | |
| Cold Filter Plugging Point CFPP | °C | | | | | | | | | |
| C/H Ratio | | 0.47 – 0.58 | 0.38 | 0.25 – 0.33 | 0.33 | | | | | |
| Heat of Vaporisation (at 20 °C) | kJ/kg | 420 | 358 / 372 | 510 | 845 / 923 | 430 | | | | |
| Specific $CO_2$ Formation | g/MJ | 73.3 | 65.3 - 66.3 | 55 / 56.2 | 71.3 - 71.7 | | | 71.2 | 71.9 | |

*Fuels for CI engines*

| Property | Units | Diesel | VPO / PPO | FAME/biodie | FT diesel | NexBTL | ethanol | DME |
|---|---|---|---|---|---|---|---|---|
| Chemical Formulae | - | $C_nH_{1.8n}$<br>C8 to C25 | | | C8 to C25 | C8 to C25 | $C_2H_5OH$ | $CH_3$-O-$CH_3$ |
| Applicable Compression Ratios | - | 18 DI<br>22 IDI | 18 DI<br>22 IDI | 18 DI<br>22 IDI | 18 DI<br>22 IDI | | < 18 | 18 DI<br>22 IDI |
| Stoichiometric A/F Ratio | kg/kg | 14.6 | 12.4 | 11.2. – 12.6 | | | 9 | 9 |
| Chemical Structure | mass% C | 85.0 – 86.6 | | 77 – 81.5 | 84.9 | | 52.2 – 52.3 | 52.2 |
| | mass% H | 15.0 – 13.4 | | 11 – 12 | 15.0 | | 13.1 – 13.3 | 13.0 |
| | mass% O | 0.0 | | 6.8 – 11 | 0.0 | | 34.8 – 34.4 | 34.8 |
| Molecular Weight | g/mole | ~ 170 | | 300 – 310 | | | 46 | 46 |
| Liquid Density (at 20 °C) | kg/$m^3$ | 800 – 850 | | | 770 – 780 | | 790 | 660 – 668 |
| Density (at 15 °C) | kg/$m^3$ | 820 – 860 | 920 | 860 – 900 | 780 | 775 - 785 | 800 | 660 – 670 |
| Cetane Number | - | 40 – 59 | 41 – 58 | 46 – 67 | 75 | 84 - 99 | 40 / 50 | 55 – 60 |
| Research Octane Number (RON) | - | - | - | - | - | - | 106 - 120 | - |
| Motor Octane Number (MON) | - | - | - | - | - | - | 90 - 99 | - |
| Methane Number (MN) | - | - | - | - | - | - | - | - |
| Energy Density (LHV) | MJ/kg | 38 – 43 | 37 | 36 – 38 | 43.3 | 44 | 25 – 29 | 27.6 – 28.8 |
| Energy Content (LHV) | MJ/l | 35.4 – 36.1 | 34 | 32 - 33 | 33.1 | 34 | 21.2 | 18.2 – 19.3 |
| Energy Density (HHV) | MJ/kg | 45 – 46 | | | 46.6 – 47.7 | | 28 - 30 | |
| Boiling Point | °C | 150 – 380 | | 330 – 350 | | 260 - 320 | 78 | -25 |
| Autoignition Temperature | °C | 250 / 360 | | | | | 420 | 235 |
| Vapour Pressure (at 20 °C) | kPa | < 1 | | < 1 | | | 21 | 510 – 530 |
| Kinematic Viscocity | cSt | 2.8 – 6.0 | | 3.5 – 6.0 | 3.2 - 4.5 | 2.9 - 3.5 | | < 1 |
| Cold Filter Plugging Point CFPP | °C | -43 – -9 | | -15 – -7 | | | | |
| C/H Ratio | | ~0.51 | | 0.55 | 0.47 | | 0.33 | 0.33 |
| Heat of Vaporisation (at 20 °C) | kJ/kg | 300 | | | | | 845 / 923 | 460 – 470 |
| Specific $CO_2$ Formation | g/MJ | 72.8 / 74.1 | | 79 | 70.7 / 73 | | 71.3 / 71.7 | 66 |

## D.2 CHOREN SunFuel

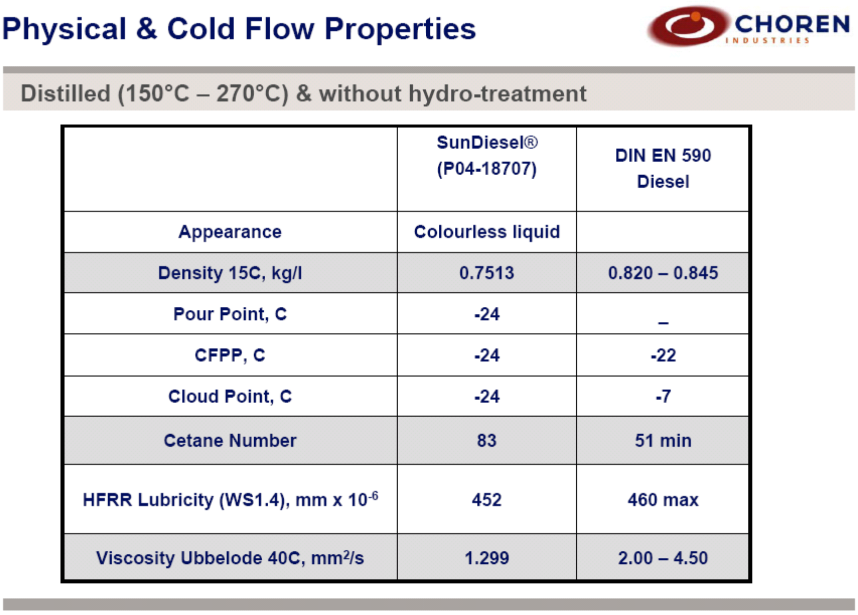


### Molecular Structures

Distilled (150°C – 270°C) & without hydro-treatment

| | SunDiesel® |
|---|---|
| N - paraffins, % wt | 77.3 |
| Iso paraffins, % wt | 6.9 |
| Olefins, % wt | 12.9 |
| Naphthenes, % wt | 0 |
| Mono Aromatics, % wt | 0.1 |
| Di Aromatics, % wt | 0 |
| Poly Aromatics, % wt | 0 |
| Alcohols C4-C16, terminal, % wt | 2.1 |
| Alcohols C5-C17, branched, % wt | 0.4 |
| Aldehydes C5-C17, % wt | 0.1 |
| Ketones C5-C17, % wt | 0.3 |

Chemical components of BTL produced by Choren [Blades (2005)]

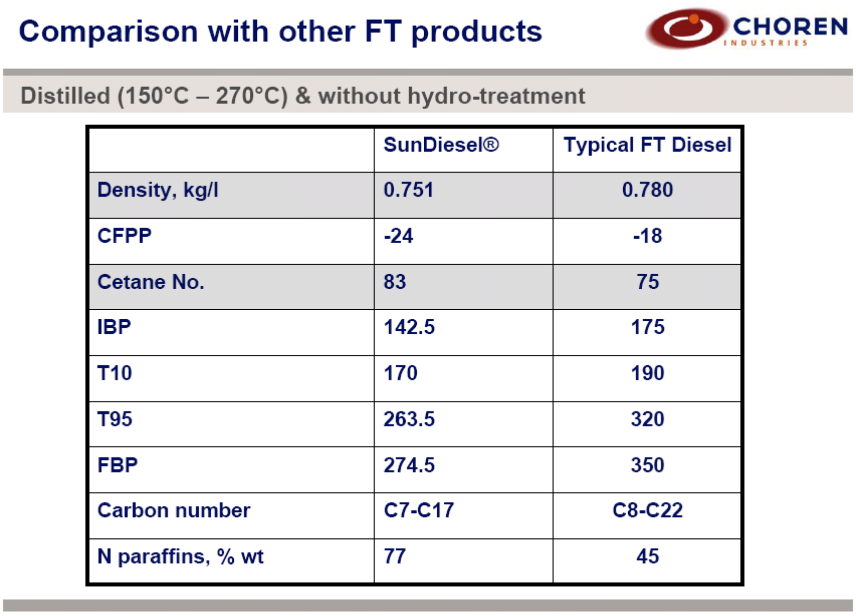


### Physical & Cold Flow Properties

Distilled (150°C – 270°C) & without hydro-treatment

| | SunDiesel® (P04-18707) | DIN EN 590 Diesel |
|---|---|---|
| Appearance | Colourless liquid | |
| Density 15C, kg/l | 0.7513 | 0.820 – 0.845 |
| Pour Point, C | -24 | – |
| CFPP, C | -24 | -22 |
| Cloud Point, C | -24 | -7 |
| Cetane Number | 83 | 51 min |
| HFRR Lubricity (WS1.4), mm x $10^{-6}$ | 452 | 460 max |
| Viscosity Ubbelode 40C, $mm^2/s$ | 1.299 | 2.00 – 4.50 |

Characteristics of BTL produced by Choren [Blades (2005)]



**Comparison with other FT products**

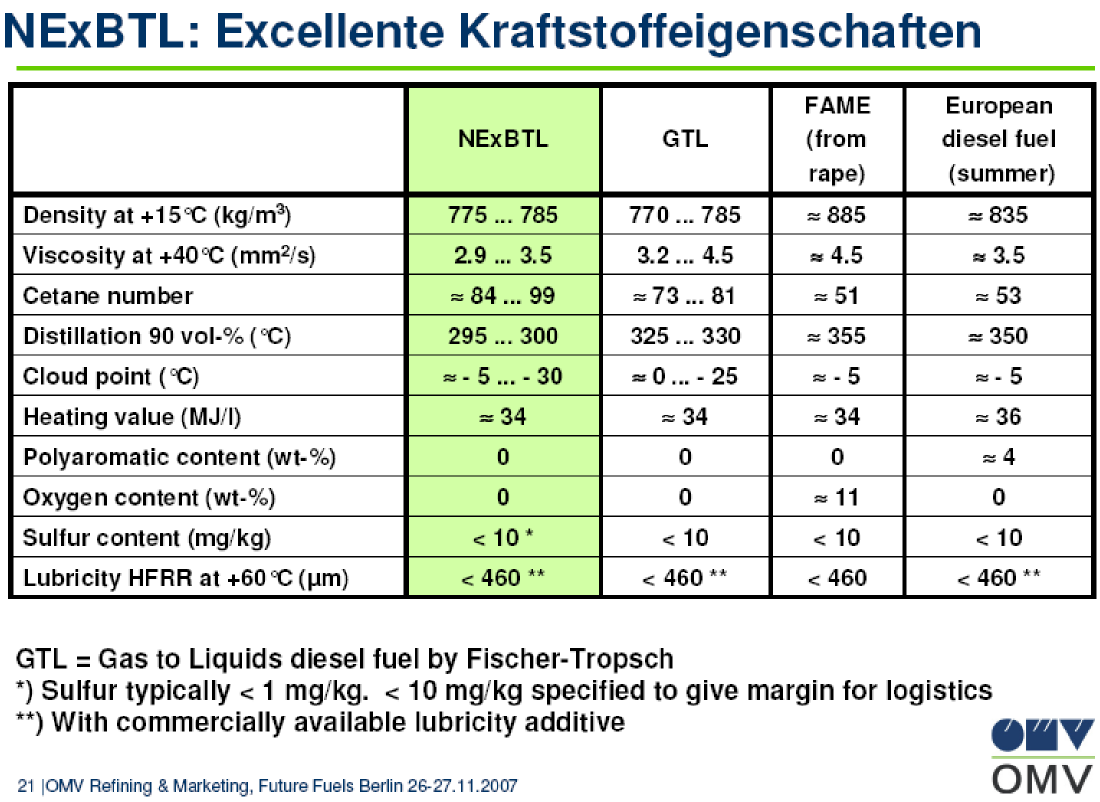
CHOREN INDUSTRIES

Distilled (150°C – 270°C) & without hydro-treatment

| | SunDiesel® | Typical FT Diesel |
|---|---|---|
| Density, kg/l | 0.751 | 0.780 |
| CFPP | -24 | -18 |
| Cetane No. | 83 | 75 |
| IBP | 142.5 | 175 |
| T10 | 170 | 190 |
| T95 | 263.5 | 320 |
| FBP | 274.5 | 350 |
| Carbon number | C7-C17 | C8-C22 |
| N paraffins, % wt | 77 | 45 |

Characteristics of BTL produced by Choren compared to GTL [Blades (2005)]

## D.3 Properties of NExBTL



**NExBTL: Excellente Kraftstoffeigenschaften**

| | NExBTL | GTL | FAME (from rape) | European diesel fuel (summer) |
|---|---|---|---|---|
| Density at +15°C ($kg/m^3$) | 775 ... 785 | 770 ... 785 | ≈ 885 | ≈ 835 |
| Viscosity at +40°C ($mm^2/s$) | 2.9 ... 3.5 | 3.2 ... 4.5 | ≈ 4.5 | ≈ 3.5 |
| Cetane number | ≈ 84 ... 99 | ≈ 73 ... 81 | ≈ 51 | ≈ 53 |
| Distillation 90 vol-% (°C) | 295 ... 300 | 325 ... 330 | ≈ 355 | ≈ 350 |
| Cloud point (°C) | ≈ - 5 ... - 30 | ≈ 0 ... - 25 | ≈ - 5 | ≈ - 5 |
| Heating value (MJ/l) | ≈ 34 | ≈ 34 | ≈ 34 | ≈ 36 |
| Polyaromatic content (wt-%) | 0 | 0 | 0 | ≈ 4 |
| Oxygen content (wt-%) | 0 | 0 | ≈ 11 | 0 |
| Sulfur content (mg/kg) | < 10 * | < 10 | < 10 | < 10 |
| Lubricity HFRR at +60°C (µm) | < 460 ** | < 460 ** | < 460 | < 460 ** |

GTL = Gas to Liquids diesel fuel by Fischer-Tropsch
*) Sulfur typically < 1 mg/kg. < 10 mg/kg specified to give margin for logistics
**) With commercially available lubricity additive

21 |OMV Refining & Marketing, Future Fuels Berlin 26-27.11.2007

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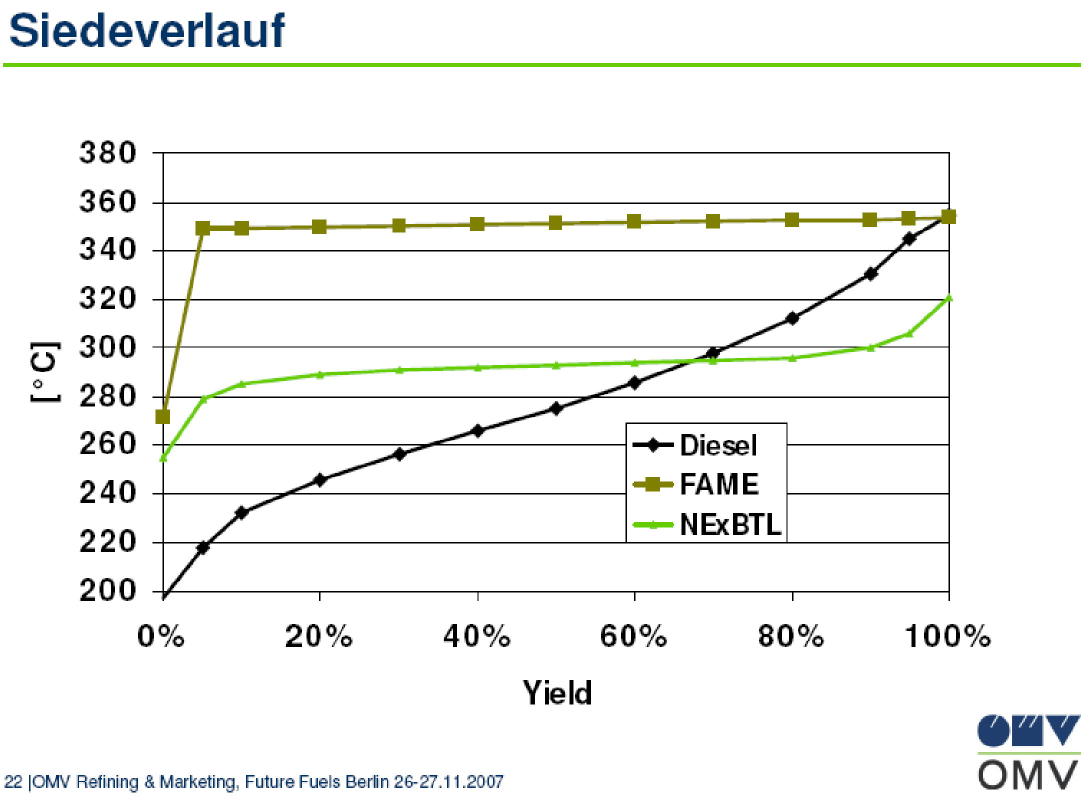

## Siedeverlauf

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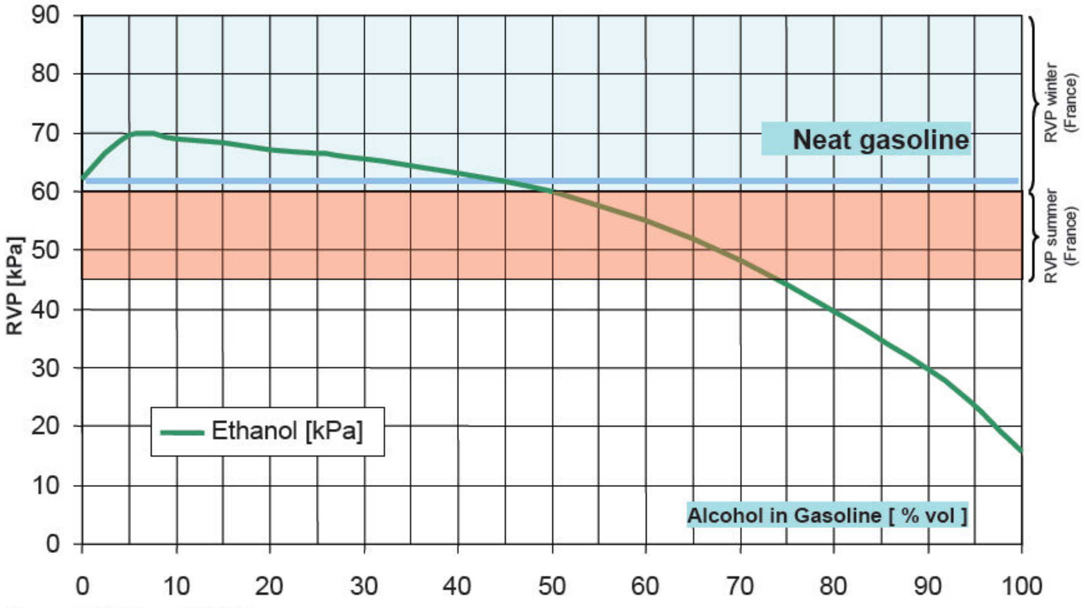
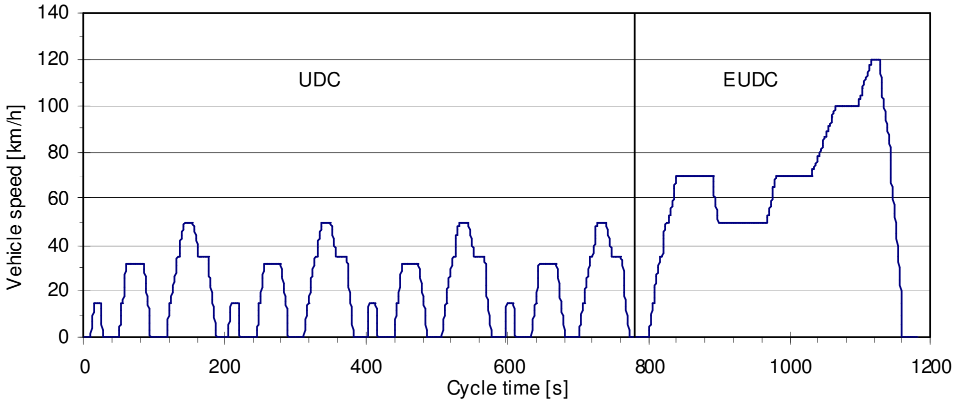
## D.4 Reid Vapour Pressure of petrol-ethanol blends



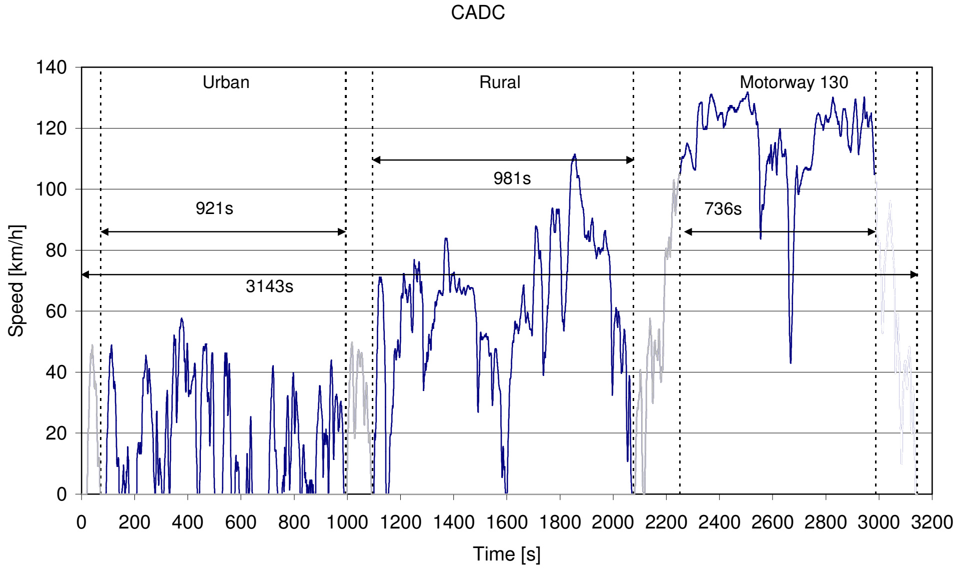
Source: SAE Paper 852116

Graph taken from [Rouveirolles 2007]

# E Emission test cycles



European Driving Cycle EDC (MVEG-B)



Common Artemis Driving Cycle (CADC)

# F Minutes DACHNLS meeting

*Introduction*

April 17 & 18, the 22nd D-A-CH-NL-S meeting was held in Berlin. This meeting is held twice a year to exchange experiences and knowledge on vehicle emissions and vehicle emission modelling. The meeting was attended by policy makers and technical experts from Germany, Swiss, Austria, Sweden, Spain, Norway, France and The Netherlands. The focus of the first day was on biofuels. This was done via two presentations on biofuels, which present the outcomes of the "BOLK" project of TNO and CE from The Netherlands:

- The emission effects of the use of biofuels in the current fleet, which was presented by Gerrit Kadijk (TNO).
- The expectations for the future, which was presented by Gerben Passier.

At the end of each presentation, several propositions were stated to initiate the discussion.

The main objectives were:

- To inform the D-A-CH-NL-S group about the findings from the BOLK project and
- To get valuable feedback from the experts in the D-A-CH-NL-S group.

The presentations showed that the emission effects of biofuels can not be ignored. However, currently there is too little real-world data to clearly estimate the real-world emissions effects. This was acknowledged by the DACH-NL-S group. It was suggested that an international measurement campaign is necessary produce the data needed to fill the knowledge gaps. Below the main discussion items can be found in more detail:

*Feedback on the presentation about biofuels in the current fleet:*

- For LD CI it was shown that a 10% biodiesel blend is likely to result in a reduction of the $NO_x$-emission. However, higher biodiesel blends tend to give increased $NO_x$-emissions. Could an explanation of this phenomenon be given?
- It was mentioned that the fuel quality potentially has an effect on the emissions. In the BOLK study the currently used European standard diesel (low sulphur content) was taken as reference.
- Emission figures for HD were given in g/kWh units. A question was raised if it is realistic to compare type approval test results in g/kWh for different fuels (biofuel versus regular diesel) with a different energy content.
- For VPO it was mentioned that there might be (long term) durability problems (as the VPO might cause damage to the injectors) resulting in drastically increased emissions (over 100 %). Tests in Sweden showed that long term durability can indeed be a problem. In these tests, an increased fuel consumption of only 2-3 % was measured. However, regulated emissions, increased drastically.
- A question was raised if differences are to be expected in emissions of older and newer vehicles? In addition it was felt that a difference needs to be considered between dedicated biofuel vehicles (that could be optimized for running on a specific biofuel) and non-dedicated biofuels vehicles.
- A question was raised if in the study any results were found about the correct functioning of the DPF with biofuels. There is a concern that unburned fuel is stored in the DPF leading to uncontrolled combustion in the filter. As this was not a topic of the current study, no indications were found.

- There was a discussion about the inclusion of biofuels in the type approval tests. Common view was that this should be done, also because of the vision of the Commission to increase the use of biofuels. However, it might not be feasible to include all different mixtures. Two possibilities were mentioned, but no common agreement was found:
  - only testing the endpoints in the biofuel range would be a pragmatic solution (e.g. E05 and E85). However, this does not necessary cover the range in emissions.
  - only testing the most common biofuel blends is also possible. This might not be realistic since any blend percentage can occur by refuelling the vehicle (low blend vs. high blend).
- It was mentioned that the focus of biofuels should be on sustainability (W-T-W CO2) and on really dangerous effects of biofuels like toxicity. A small increase of $NO_x$ en PM emissions in (e.g. 10-20%) was said to be of less interest. This was not the common view of the group.

*Feedback on the presentation about expectations for the future:*

- Regarding the desirable fuel blends it was mentioned that
  - the current focus of customers is mainly on economics of fuels and not on environmental impact. In other words, currently most customers will buy the most economic (cheapest) fuel and do not really consider the environmental impact. As such which biofuels will become mainstream significantly depends on the costs and stimulation measures from the government.
  - in Europe an overcapacity of gasoline exists. Therefore it is likely that currently sustainable substitutes (or blends) for petrol will not be pushed by oil companies.
  - it was mentioned that the majority of ethanol will be low blends as high ethanol blends might cause cost problems. In addition high blend biodiesel is expected to remain a niche fuel because of durability-problems.
  - it was suggested to make a clear distinction between first and second generation of biofuels. In addition it was suggested that regarding sustainability the focus should be on W-T-W and not on T-T-W.
  - The industry currently states that 7% biodiesel blend is the maximum blend they can allow in their vehicles. It was mentioned that this could also be B10 as the exact feasibility limit is not known.
- It was mentioned that Euro V (HD) and Euro 5 (LD) vehicles equipped with a SCR system, the system is likely to be optimized for use of regular diesel. This might become critical when running on biodiesel. Depending on the size of the of adblue injector a significant increase in $NO_x$-emissions can be expected.
- In-use-compliance testing was discussed in relation to the responsibility of the car manufacturer: is the vehicle manufacturer still responsible if a vehicle is driven with a non-certified fuel and emissions are worse in in-use-compliance testing. The evaporation problems with vehicles running on E5 in Sweden were mentioned as an example. In this case the manufacturer mentioned that E5 was not part of the certification (and thus he was not responsible).
- It was mentioned again that the focus for biofuels should be on sustainability. As emissions from Euro V / VI (HD) and Euro 5 / 6 (LD) vehicles are low anyway, a slight increase in $NO_x$ and PM emissions is less important. The effect on total air quality could be limited. Therefore it was suggested not only to look at relative values, but also look to absolute values to see what the real effect of change in emissions could be.

- One attendee mentioned the lack of On Board Diagnostics (OBD)-issues in the presentations. Due to higher blends (B10/E10) the OBD system might detect a failure.
- Due to the high boiling point of high ethanol blends the cold start behaviour of Flexi Fuel Vehicles (FFV) is probably very different from petrol vehicles. Therefore it was suggested that the cold start test of FFV-vehicles should be included in the type approval procedure.