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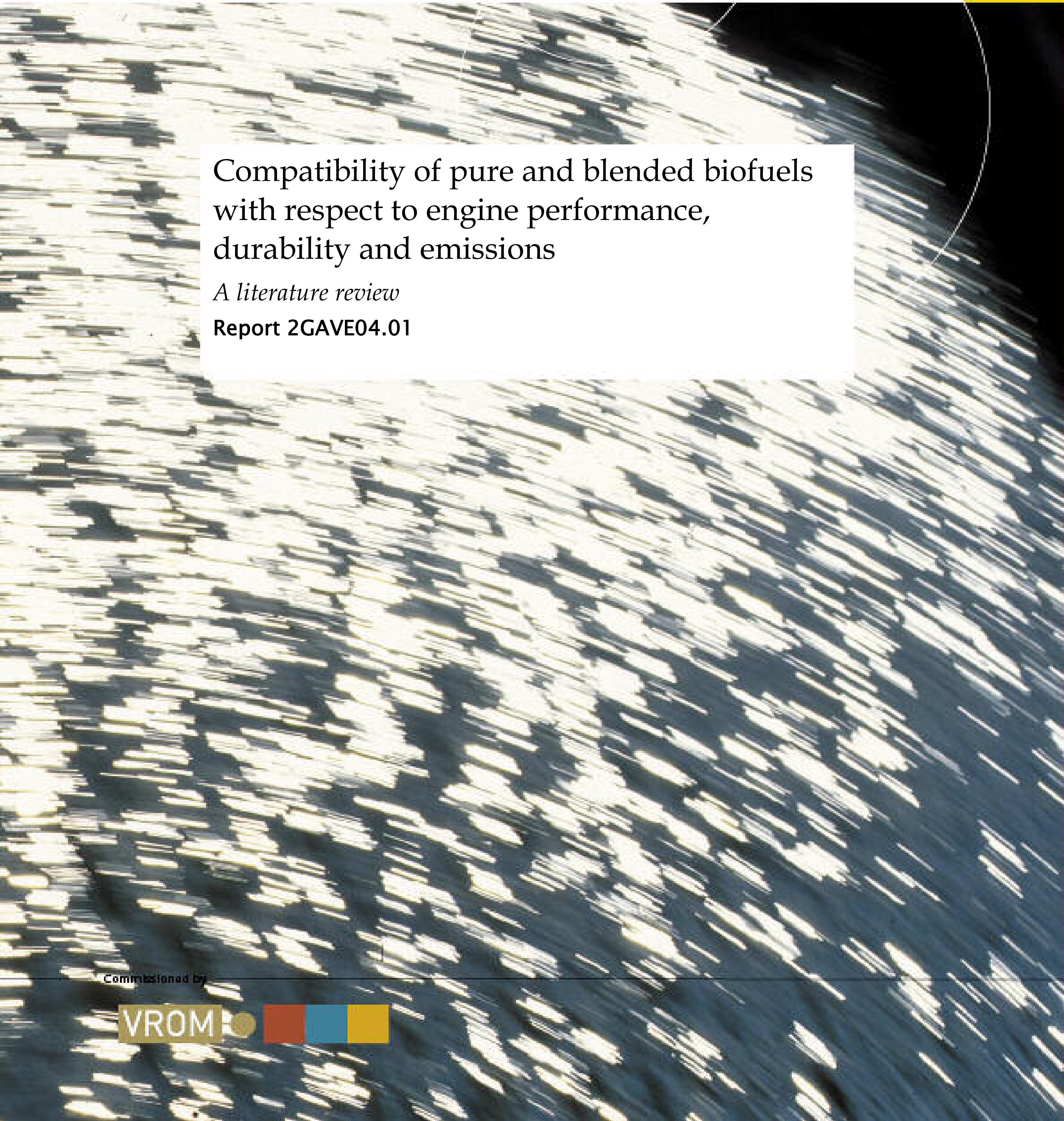

Compatibility of pure and blended biofuels with respect to engine performance, durability and emissions

A literature review

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Summary

This report presents the results of a concise literature survey (quick scan) on the compatibility of pure and blended biofuels with respect to engine performance, durability and emissions. More specifically, information is collected and analysed to find indications for potential problems (or advantages) with respect to the following questions:

1. Will vehicles using biofuels, pure or in blends, be able to meet the emission limits foreseen for the period 2015-2020, given the expected developments in conventional fuels and engine technology?
2. Will the application of biofuels, pure or in blends, have negative impacts on performance and durability of engines (torque, power) and aftertreatment systems? And if so, are there technical measures available to solve these problems?
3. Will biofuels, pure or in blends, be able to meet future fuel specifications? Can possible problems be solved by the use of additives and does this have costs implications?
4. Are there possible negative impacts of the use of biofuels with respect to the emissions of unregulated components?
5. Will biofuels maintain their advantage on fossil fuels with respect to greenhouse gas emissions in the future?

The survey has been carried out for bio-ethanol, biodiesel, virgin plant oil (VPO), bio-FT-diesel (or BTL, biomass-to-liquid), biogas, and DME.

Some interesting conclusions are:

- For many fuels the available literature does not present a consistent picture with respect to the impact on performance and emissions when applied in current engine technology. In view of the possible role of these fuels (pure or in blends) in the context of the implementation of the EU biofuels directive, more coherent research seems justified to generate statistically significant data regarding the impacts on emissions with modern and older vehicles.
- With the exception of VPO, all fuels are compatible with future, more stringent emission legislation. For most fuels dedicated improvements to engine and aftertreatment technology are necessary.
- No indications have been found that biofuels would lead to significant reductions in engine efficiency or that biofuels would be incompatible with technologies that are being developed to improve the efficiency of future combustion engines.
- Existing fuel standards and regulations for type approval of light-duty vehicles and heavy duty engines pose limitations on the technical options available to meet the 2010 goal of the EU biofuels directive. Fuel standards will have to be adapted to allow the use of higher percentage blends of biofuels in conventional petrol and diesel. Type approval regulations require adaptation with respect to test procedures for dedicated biofuel vehicles and with respect to controlling the emissions of conventional vehicles running on blends of biofuels and conventional fuel.

Contents

1 Introduction

1.1 Background

In recent years the interest in biofuels has been increasing, motivated on the one hand by the need for reducing greenhouse gas emissions and on the other hand by the desire to improve energy security by reducing our dependence on imported oil. Through Directive 2003/30/EC the European Commission has obliged all EU member states to develop and implement policies to promote the use of biofuels in the transport sector. Goals are set at 2% replacement of the transport sector's energy use by biofuels by the end of 2005 and 5.75% replacement by the end of 2010. EU member states have the freedom to choose fuels and policy instruments that fit to their national situation. For the Netherlands an inventory of the technical options has been made by Ecofys [Ecofys 2003]. The intention of the Dutch government is to implement the EU Directive mainly by promoting the use of ethanol blended into petrol and biodiesel blended into diesel fuel, as has been laid down in the recent "Beleidsnota Verkeersemissies".

Through GAVE and other programmes on behalf of the Dutch government, SenterNovem is co-ordinating a large share of the research in support of developing a biofuels policy for the Netherlands. Furthermore, SenterNovem co-ordinates government funding of R&D in the field of biofuel production and application. Within the context of that work questions have arisen on the longer term compatibility of biofuels with the ongoing developments in engine and exhaust gas aftertreatment technology aimed at reducing exhaust gas emissions and improving engine efficiency.

1.2 Problem definition

Combustion engines are continuously being improved to reduce emissions and fuel consumption. Technologies applied to meet the increasingly stringent emission limits (Euro 4, Euro 5, etc.) impose increasingly stringent requirements on the quality of the fuels applied in order to reach the prescribed emission levels and to guarantee durability of the technology. In the past the introduction of unleaded petrol has been a prerequisite for applying three-way catalysts on petrol vehicles. Currently the sulphur content of fuels is being reduced to allow further improvements of catalyst technology and the application of effective aftertreatment on diesel vehicles. Also in terms of fuel composition oil companies are making improvements as illustrated by e.g. Shell Pura and V-Power.

Biofuels can be applied to combustion engine vehicles in three different ways:

- blending of biofuels into conventional petrol and diesel for use in all conventional cars;
- as dedicated / niche fuels (e.g. pure biodiesel or E85) in vehicles adapted for the use of biofuels by means of retrofit systems;

- as dedicated / niche fuels in dedicated vehicles, specifically developed for the use of biofuels (e.g. flexible fuel vehicles).

Before policies can be implemented to promote the use of biofuels in any of these applications it must be clarified that biofuels can meet future fuel quality requirements and that the use of biofuels does not in any way:

- increase emissions of regulated components causing a conflict with the short and medium term goals set by emission legislation;
- interfere with the EU's and member states' policy striving for zero-effect level emissions in the longer term;
- cause problems with regard to unregulated emission components;
- interfere with the governments' and industry's strive to improve fuel economy (and thereby reduce CO_2 emissions);
- harm the interests of consumers by negatively affecting engine performance and durability.

1.3 Goal of this study

The goal of this study is to carry out a literature survey to collect information that provides indications on whether or not the above mentioned problems may occur with the introduction of biofuels. More specifically, information is collected and analysed to find indications for possible problems (or advantages) with respect to the following questions:

1. Will vehicles using biofuels, pure or in blends, be able to meet the emission limits foreseen for the period 2015-2020, given the expected developments in conventional fuels and engine technology?
2. Will the application of biofuels, pure or in blends, have negative impacts on performance and durability of engines (torque, power) and aftertreatment systems? And if so, are there technical measures available to solve these problems?
3. Will biofuels, pure or in blends, be able to meet future fuel specifications? Can possible problems be solved by the use of additives and does this have costs implications?
4. Are there possible negative impacts of the use of biofuels with respect to the emissions of unregulated components?
5. Will biofuels also in the future maintain their advantage on fossil fuels with respect to greenhouse gas emissions?

The survey concentrates on the following biofuels in pure form or when applicable in blends:

- bio-ethanol;
- biodiesel;
- virgin plant oil (VPO);
- bio-FT-diesel (or BTL, biomass-to-liquid);
- biogas;
- DME.

Information found in literature is complemented with expert views from TNO Automotive.

It has to be emphasised that this study has the nature of a quick scan. Relevant literature has been collected and scanned for indications of possible problems. For those cases where indications are found, in-depth analysis of the problems and possible solutions will have to be carried out in future projects to be able to draw more definitive conclusions.

1.4 General considerations

1.4.1 Selection of literature for this study

Given the short time-frame and the screening nature of this study, effort has been focussed on recent publications. 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 2000 onwards have been comprehensively reviewed and included in order to present the most up-to-date information and to capture ongoing developments in this area. Information from studies before 2000 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).

1.4.2 Biofuels and engine concepts

For fuels to be used in spark ignition (SI or otto) engines, most studies cited in this report consider application in conventional port-injected engines. These engines operate on stoichiometric air-fuel mixtures ($\lambda = 1$) to create a reducing environment in the three-way catalyst. Recently, however, direct injection otto (SIDI) engines have been developed and introduced on the market. These engines operate with complex combustion strategies varying with the engine load. Under certain circumstances they will operate with lean mixtures ($\lambda > 1$), in which case the aftertreatment system operates as an oxidation catalyst. Already for petrol vehicles the emission performance (especially under real-world operating conditions) is not yet completely known and understood. Data on the use of biofuels in SIDI engines is limited so that few conclusions can be drawn on the effects on emissions or engine performance for this type of engines.

Modern compression ignition (diesel) engines are all directly injected (CIDI). A decade ago most diesel passenger cars had indirectly injected engines (IDI), but technological improvements in direct injection technology have created an engine with high efficiency and performance characteristics that can compete with petrol engines. Data from older studies may be based on IDI engines and are not necessarily representative for the effects of biofuels in CIDI engines.

New combustion concepts are currently being investigated, also in the context of application of biofuels (see e.g. [Ahlvik 2002]). The most important candidates are:

- *HCCI or homogeneous charge compression ignition* – is developed using the compression ignition principle (diesel engine) and is based on evaporating and premixing of fuel and air before ignition in a somewhat similar fashion as in the otto engine. However, ignition is carried out using compression ignition. HCCI could significantly reduce, or eliminate NOx and PM emissions, two of the main problems for diesel engines.

- *CAI or controlled auto ignition* – is developed for petrol-like fuels, and is somewhat similar to HCCI since it also uses air/fuel premixing and compression ignition. Due to the poor compression ignition properties of otto engine fuels, ignition must be enhanced in some other way (e.g. use of hot residual gases).

With these developments otto and diesel engines may develop into a more or less common concept. In this context also the use of alternative fuel compositions (e.g. naphta-like fuels, or dedicated "designer fuels") is discussed. At present very little is known about the required optimum fuel specifications and the emission levels that can be attained. Based on literature and expert views indications are presented in this report of the possible advantages or disadvantages that various biofuels may have for use in these advanced engine concepts.

1.4.3 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 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 5 and 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 has so far been considerably less due to a lack of effective aftertreatment technology. Emission legislation for diesel vehicles is less stringent allowing NO_x emissions typically a factor of 10 higher than for petrol vehicles. Modern diesel vehicles are equipped with oxidation catalysts which have fairly low conversion efficiencies. Impacts of the use of biofuels are therefore expected to be more prominent in current diesel engines 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 diesel particulate filters and effective NO_x-reduction technologies such as NO_x-storage catalysts and SCR-deNOx. These technologies are expected to be applied on a large scale with the introduction of Euro 5 emission limits for diesel vehicles. As with the case of petrol 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.

1.4.4 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, a higher volumetric fuel consumption leads to a 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.

In the review of literature with respect to impacts of biofuels on engine efficiency, as presented in the next chapters, the focus will be on the energy efficiency in MJ/MJ.

1.4.5 Biofuels and CO2

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.

1.4.6 Biofuels and fuel specifications

For conventional fuels the quality of the fuel is to some extent regulated by means of standards and legislation. In response to environmental requirements and technical requirements posed by engine technology these fuel specifications are continuously adapted and improved [TNO 2004a; TNO 2004b]. The application of advanced aftertreatment systems requires a low sulphur content. From 2005 onwards, the sulphur content of European petrol and diesel has to be below 50 ppm (mg/kg), and a development towards sulphur-free fuel (< 10 ppm) is foreseen as this enables the use of more advanced aftertreatment systems. To improve emissions also a lower aromatics content is prescribed. When used in blends, inherently clean biofuels such as ethanol, FT-diesel and DME are compatible with these developments and can play a role in meeting objectives with respect to sulphur and aromatics content.

2 Bio-Ethanol

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 automative 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]. All petrol sold in Sweden currently contains 5% ethanol. In response to the EU biofuels directive many EU member states are considering blending of ethanol into regular petrol.

For the use of higher biofuel concentrations, so-called flexible fuelled vehicles (FFVs[1]) 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. In Sweden already several thousands of Ford Focus FFVs are running on E85 (a mixture of 85% ethanol and 15% petrol), sold at numerous petrol stations [TW 2004], and also Saab recently introduced a FFV which can run on E85 [Rai 2004].

Although different studies have indicated that (modified) heavy-duty engines running on ethanol (up to 100% is possible) are capable of the same, or better, performance, durability and emissions as diesel engines [e.g. NREL 1997], it appears from the literature [e.g. Ahlvik 2002] that future production of HD ethanol engines is not yet seriously considered.

In contrast to other existing alternative fuels, ethanol usually comes from biomass. Hence, the majority of data on emissions, engine performance, etc. directly provides information with respect to bio-ethanol. In this study, a distinction is made between petrol/ethanol and diesel/ethanol blends, which are denoted as E××P and E××D, respectively, where ×× represent the volume percentage ethanol. On the next page, Table 1 presents an overview summarising the effects of ethanol (blends) on the various aspects that are of interest to this study as reported by different literature sources. The information presented in this table is discussed in more detail in subsequent sections.

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[1] These vehicles have a single fuel tank. The engine can adapt automatically to the type of fuel using a sensor which measures the ethanol/petrol ratio and a computer controlling fuel flow, ignition timing and mixture

Table 1 Effects of ethanol (pure & blends) on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO_x	PM			CO_2	CO_2						
Ethanol	E5P					0									IDIADA 2003
Ethanol	E100P	+	+	+						+ d)					Brusstart 2002 (LDV)
Ethanol	E85P	+ f)		+ f)	+ f)		- f)								US EPA 2002b
Ethanol	E85P						+ & -								NREL 2002 (LDV)
Ethanol	E12-E95	+	+	+ & -			-								NREL 2002 (LDV)
Ethanol	E85P									+					Aubin 2001
Ethanol	ExxxP	+	+	+			-								Amaral 2001
Ethanol	E85P	-	-	+	+	-	+ & -			+ & -			0 a)		EC 2000 (R)
Ethanol	E95P	- c)	- c)	+ c)	+ c)	- (?)									Beer 2000 (HDV)
Ethanol	E85P	-	+ & -	+			- & +	+							Dodge 1998(a)
Ethanol	E85P									+		+			Dodge 1998(a)
Ethanol	E10P	+	+	0		- (?)	+ & -					0	0		Apace & NSW EPA 1998
Ethanol	E50/85P	+	+	+		0	+ & -	+							Kelly 1996 (LDV)
Ethanol	E42P	+	+	-			+ & 0	0							Guerrieri 1995 (LDV)
Ethanol	E85P	0	-	+		+	-								Benson 1995 (LDV)
Ethanol	E??D	-	-	0	+		-								Corkwell 2003
Ethanol	E10/30D	-	-	+	+ g)		-	+							He 2003 (LDE)
Ethanol	E??D												+ & -		Corkwell 2002
Ethanol	E10/15D	+ & -	-	+ & -	+ e)							-	0		Hansen 2001 (R)
Ethanol	E15D	0	-	+	+		+ & -			+ & -			0 b)	-	EC 2000 (R)

a) up to 20% ethanol, b) up to 15% ethanol, c) compared to diesel bus, d) US TIER II LDV, e) depends on engine speed and load, f) potential reductions, g) smoke

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

2.1 Emission Impacts

2.1.1 Regulated Pollutants

Table 1 shows that use of ethanol in both petrol and diesel engines reduces PM emissions. For the other regulated pollutants (CO, HC and NO_x) less consistent results are reported. The effect of ethanol on these pollutants can be either positive, negative or negligible. In general low ethanol blends tend to decrease CO emissions as ethanol acts as a oxygenate. This effect, however, is most prominent in older vehicles without closed-loop catalysts [Bechtold 1997].

The variation in published results cannot be easily explained by ethanol content or major vehicle class (light-duty versus heavy-duty). It may in part be explained by variations in fuel composition as ethanol fuels from different origins and production processes may have ethanol contents ranging from 50 to 100% and may contain various other components. Also variations in test procedures and in engine types and emission control technology will cause variation in results of emissions measurements [e.g. Kremer 1996].

A few studies have examined the potential of high ethanol blends to achieve future emission standards with modified vehicles [Dodge 1998; 1998a; Aubin 2001]. These studies were generally successful, which suggests that attainment of future standards should be expected for high ethanol blends, provided that adequate engine modifications are being made. In this respect, a potentially significant advantage is noted in using ethanol in spark-ignition direct injection (SIDI) engines because of a reduction in soot and PM formation [e.g. Ahlvik 2001].

2.1.2 Unregulated Pollutants

With respect to unregulated emissions, experimental data consistently indicates increased aldehyde emissions with increasing ethanol content, and in particular substantial increases in acetaldehyde emissions, which are a by-product of ethanol combustion. In contrast, the literature consistently reports a reduction in benzene and 1,3-butadiene emissions with increasing ethanol content.

2.2 Exhaust Gas Aftertreatment & Evaporative Emission Reduction

Not a lot of experimental data is available with respect to evaporative emissions from ethanol blends and again the test results reported in the literature are mixed. Some studies report on increased evaporative emissions [e.g. Apace & NSW EPA 1998], whereas others found no changes [e.g. Kelly 1996; IDIADA 2003] or even reduced evaporative emissions [e.g. Benson 1995]. These differences may in part be explained by ethanol content (i.e. Reid Vapour Pressure is a function of ethanol content, see also section 2.5), test procedures and type of evaporative emissions (e.g. diurnal versus hot-soak). It is noted that addition of ethanol to diesel may produce a significant problem since evaporative emissions are uncontrolled in diesel vehicles. No emissions data could be found in the literature that enabled examination of the validity of this issue.

It appears that ethanol-blends are in most instances compatible with conventional vehicle catalysts [e.g. NREL 2002], although more efficient catalysts may be required. The use of ethanol reduces sulphur content in fuel blends, which gives it an advantage over conventional petrol and diesel with respect to conventional and future emission reduction technologies. In addition, there are some indications that the unburned hydrocarbon composition from ethanol fuels have better regeneration properties than the hydrocarbon composition from petrol and diesel fuel with respect to NO_x storage and lean NO_x catalysts [Ahlvik 2001].

Some researchers suggest that higher CO and HC emissions in diesel-ethanol blends may offer a means to enhance advanced emission control systems that require regeneration, such as NO_x adsorbers, by supplying reducing agent [Hansen 2001]. There are some indications that unburned ethanol from high ethanol-diesel blends may react on the catalyst surface and cause odour problems [EC 2000].

2.3 Engine Performance

There have been reports of equivalent or improved performance (engine power) of high ethanol-petrol blends compared to petrol [e.g. Pike 1995; Davis 2000] and equivalent or reduced performance of ethanol-diesel blends compared to diesel [Hansen 2001].

There seems to be a consensus that low ethanol blends in fuel (e.g. less than 20% in petrol and less than 15% in diesel) can generally be used in unmodified SI- and CI engines without any material problems or operating problems [e.g. EC 2000]. The use of additives in fuel blends may be required. For instance, ignition (cetane) improvers and emulsifiers/co-solvents are needed in diesel-ethanol blends [e.g. Hansen 2001].

For the use of high ethanol blends fuel tank, fuel pump, fuel filter, fuel lines and hoses and inlet system must be ethanol resistant. Injectors need a higher flow capacity due to the low density of ethanol. Power may be increased due to the high octane number of ethanol and the high latent heat of vaporisation which causes intake charge cooling effects [Bechtold 1997].

Cold-start problems (starting problems, elevated emissions) have been indicated repeatedly in the literature, but they are usually noticed in high ethanol blends. Research into feasible solutions to this problem are ongoing [e.g. Sales 2002]. There are some expectations that with the further development of direct injection SI engines, the cold start problem could be resolved [e.g. Ahlvik 2002].

The use of ethanol may cause engine corrosion, but the actual effect is strongly dependent on ethanol quality. Freshly formulated blends containing pH neutral dry ethanol would be expected to have relatively little corrosive effect. Corrosion inhibitors have been added to some ethanol-diesel blends [Hansen 2001]. Non-metallic components (elastomers, resinbonded or resin-sealed) may also be affected by ethanol. In addition, the low lubricity of ethanol may cause engine wear. These problems appear not to be an issue for low ethanol blends [e.g. NREL 2002].

Older vehicles using ethanol blends after many years of petrol use may experience filter plugging as the ethanol acts as a solvent for deposits in tank and fuel system [Bechtold 1997].

2.4 Engine Efficiency

Because ethanol has a lower energy content than petrol (and diesel) and a lower stoichiometric air/fuel ratio, more fuel must be delivered to the engine (i.e. higher volumetric fuel consumption). However, exhaust CO_2 emissions are slightly reduced due to the lower carbon content of ethanol per unit of energy compared to petrol [e.g. Kelly 1996] and diesel [He 2003]. Due to the high octane number and heat of evaporation of ethanol the compression ratio of engines running on pure ethanol or E85 can be increased, resulting in a higher energy efficiency.

Ethanol is superior to petrol for HCCI combustion because of the constant composition and other characteristics. With ethanol higher thermal efficiencies can be reached in HCCI engines.

2.5 Fuel Specifications

Ethanol can be produced with high purity and consequently a very low sulphur and aromatics content.

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. However, for ethanol blends these are not necessarily higher as the de carbon canisters applied in modern petrol vehicles more effectively absorb ethanol than conventional petrol vapours. Whether this counteracting effect takes place, however, depends on the vapour composition. No information was found on that. 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.

Engines can be developed to run on pure ethanol, but E85 is preferred as the 15% petrol improves startability and flame visibility. Start-problems with pure ethanol are related to the low vapour pressure.

3 Biodiesel

Biodiesel is a generic name for fuels obtained by esterification of vegetable oils and animal fats. To this end the oils are mixed with methanol or ethanol, which reacts with the triglycerides of the oil to form esters and glycerol. The latter is a by-product of this process. Biodiesel can be produced from a variety of feedstocks including rapeseed oil (product is RME or rape methyl ester, common in EU), soybean oil (product is SME soybean methyl ester or SOME, common in USA), sunflower oil and palm oil. RME and SME are collectively known as FAME or fatty acid methyl esters. UVOME (Used Vegetable Oil Methyl Ester) is the most common vegetable oil source of biodiesel in Japan. FAME is currently being used world-wide (Germany, France, Austria, USA) as a mixture with diesel fuel, which can range from 5 volume percent to neat FAME fuel (B100), on existing vehicles without any modifications [EC 2000].

It is noted on beforehand that most of the existing biodiesel experience has been accumulated with FAME, and extrapolating the results with respect to performance, emissions, etc. to biodiesels made from other feedstocks may not be justified. In Table 2 an overview is presented with respect to the effects of biodiesel (pure and blends) on the various aspects that are of interest to this study. The information presented in this table is discussed in subsequent sections.

3.1 Emission Impacts

3.1.1 Regulated Pollutants

Although the literature indicates that biodiesel generally provides significant emission benefits with respect to CO, HC and PM (soot), but (slightly) higher NO_x, Table 2 shows that these conclusions are not always supported by experimental data. The exceptions are CO emissions, which are consistently reduced. These, however, are already very low for diesel engines, while the critical components are NO_x and PM, which are generally a factor of ten higher than in otto engines with three-way catalysts. The contradictory findings may be due to variation in fuel properties, vehicle types, test cycles and lack of optimum engine tuning for biodiesel. Some researchers suggest that engine optimisation may lead to better results (e.g. NO_x mitigation).

According to [Graboski 2003] NOx emissions in engines running on biodiesels are well correlated with either cetane number or density. 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 NOx emissions.

Table 2 Effects of biodiesel (pure & blends) on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO_x	PM			CO_2	CO_2						
Biodiesel	5/20%	+	+	+ & 0& -	+		+	0				+ & -			Souligny 2004 (HDE)
Biodiesel	20/100%			-	+		0								Graboski 2003 (HDE)
RME	100%	+	+	-	+		+								Krahl 2003 (LDE)
Biodiesel	30/100%			-	+		0 & +								McGill 2003 (HDE,LDV)
RME	30%				+										Aakko 2003 (LDV)
RME	30%				-										Aakko 2003 (MDE)
Biodiesel	NA	+	+	-	+ & -		+ & -								Dieselnet 2003 (R)
Biodiesel	0-100%	+	+	-	+		+								US EPA 2002 (R)
FAME	20-30%	+	+	0	+		+ & -			+ & 0		-	0 or -	+	EC 2000 (R)
FAME	Neat	+	+	[-]	0		+ & -			+ & -		-	-	+	EC 2000 (R)
HySEE	50/100%	+	+	-	+		+	-				-	0		Chase 2000 (HDV)
Biodiesel	20/100%	+	+	0 & -	+			-				-			Sharp 2000 (HDE)
R&SME	30/100%	+ & 0	+ & 0	- & 0	+		0								Aakko 2000
Biodiesel	NA	+	-	- & 0	+ & -		+	-							Schramm 1999 (LDV)
REE	100%	+	+	+	-								0		Taberski 1999 (LDV)
T&RME	5-20%	-		+ & -	+ & -		-								Aakko 1999 (HDE, LDV)
Biodiesel	20/50%	+	+ & -	-	+										Chang 1997 (MDE)
Biodiesel	0-100%	+	+	-	+ & -			0				0			IEA/AFIS 1996
RME	NA	+	+	-	0										Hohl 1995 (R)
Biodiesel	20/30%	+	+	-	+							+ & -			Marshall 1995 (HDE)
RME	20/100	+	+	+	+ & -			-				-			Reece 1995 (LDV)
S&CME	6-40%	+	+	-				-							Spatura 1995 (HDE)
RME	100%	+	+	+ & -	+		+ & 0	-					-		Staat 1994/1995

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

3.1.2 Unregulated Pollutants

There is rather consistent evidence in the literature that emissions of aromatic HCs, PAHs and nitro-PAHs and mutagenicity are reduced when biodiesel is used. Pure biodiesel fuels have been tested and found to be non-toxic in animal studies [EMA 2003]. Some researchers also report reductions in aldehyde and ketone emissions [e.g. Souligny 2004], whereas others report no change [e.g. McGill 2003] or even increased emissions [EC 2000]. There are reports that biodiesel may substantially increase the odour intensity of diesel exhaust.

3.2 Exhaust Gas Aftertreatment & 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 [e.g. EC 2000]. 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.

3.3 Engine Performance

The literature indicates that low biodiesel blends (say B30 or less) can be used in existing diesel engines without modification. For higher precentage blends, and particularly B100, there are some concerns about the interaction with components of the fuel injection system such as filter plugging, injector coking and lubrication degradation, which can limit durability [e.g. EMA 2003]. It is noted though that there is also proof of equivalent or better durability than diesel fuel [e.g. Chase 2000; US EPA 2002a]. Biodiesel has good lubrication properties.

There is some evidence that biodiesel attacks certain coatings and elastomers [IEA 1999] and causes corrosion with certain metals [Bessee 1997]. Use of biodiesel compatible materials should in principle solve these problems. It is noted that aged or poor quality biodiesel fuels may cause several problems such as corrosion and blockage.

There are also reports of a measurable loss of engine power [e.g. Chase 2000]. Again, others have found no reduction [IEA/AFIS 1996], or even a small increase, in engine power [e.g. Taberski 1999; Souligny 2004] and noticed no changes in driveability.

Finally, low-temperature behaviour of biodiesel is not as good as conventional diesel and this affects cold-start performance [EC 2000]. Additives are needed to reduce these (high viscosity) problems in areas with low ambient temperatures [Dieselnet 2003].

With respect to combustion of biodiesel in HCCI engines a better performance is expected than diesel fuel due to the more constant composition and the narrow range of components.

3.4 Engine Efficiency

Some researchers report on a measurable increase in fuel consumption [e.g. Sharp 2000; Chase 2000] and increased CO_2 emissions [Spataru 1995], whereas others found that these variables were not significantly affected [e.g. Taberski 1999; Souligny 2004].

3.5 Fuel Specifications

Several standard-setting organisations world-wide have recently adopted biodiesel specifications (ASTM International: D6751, Germany: DIN51606, Europe CEN: EN14214) [EMA 2003].

4 Virgin Plant Oil (VPO)

Apart from past experimental studies on plant oils in older technology diesel engines [e.g. Fort 1982] and reactors or one-cylinder engines [e.g. Barsic 1981], there is little 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 (refer to section 2 on "Biodiesel"). Nevertheless, current interest in the use of pure plant oils is growing [e.g. Lance 2004].

VPO can be used in pure form but can also be blended into diesel up to 25%vol. [e.g. 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 2004]. 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[2]. 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.

Table 3 presents an overview regarding the effects of VPO (pure and blends) on the various aspects that are of interest to this study. The information presented in this table is discussed in subsequent sections.

4.1 Emission Impacts

4.1.1 *Regulated Pollutants*

Table 3 reveals mixed results with respect to all regulated pollutants, although a general reduction in NO_x emissions due to VPOs may be seen. For the other pollutants, it is not possible to discern any clear trends in the use of VPOs compared to diesel fuel. There are several factors that may contribute to these variations such as type of VPO, type of engine, test procedure, diesel base fuel, et cetera.

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[2] [Elsbett 2004] does not specify the exact contents of the conversion kits.

Table 3 Effects of virgin plant oil (pure & blends) on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO_x	PM			CO_2	CO_2						
VPO	100%	-	-	+	-		-								Lance 2004 (LDV)
VPO	100%	+	+	+ & -	+ 3)								0		Aberson 2004 2)
VPO	30%			-	+										Senda 2004 (HDV)
VPO	100%	-	-	+	- 1)								0		Kumar 2001
VPO	0-25%											-	-		McDonnell 1999
VPO	100%	+		+	+ 1)		+ & -								Niemi 1997
VPO	0-100%											0	-		IEA/AFIS 1996
VPO	50/100%	-	+	+	+ 1)										Ziejewski 1992
VPO	100%	-	-	+	-		-						-		Hammerlein 1991 (DI)

1) Smoke, 2) Unclear whether this information is based on test data, 3) Soot

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

4.1.2 Unregulated Pollutants

There is limited and contradicting information on the emissions of unregulated emissions from CI engines running on VPOs. [Hemmerlein 1991] reported increased emissions of aldehydes, ketones benzene, toluene, o-xylene, PAHs and odour in turbo-charged DI HD engines and “swirl chamber” LD engines. In contrast, [Niemi 1997] tested a turbo-charged DI tractor engine and found higher olefins but reduced acetylene, aldehydes, alcohols and aromatics than with diesel fuel. A difference between the two studies is that [Niemi 1997] used an optimised engine and mustard seed oil, whereas [Hemmerlein 1991] used a non-optimised engine and rapeseed oil. This again demonstrates the general difficulty in comparing the results from a limited number of studies with different experimental set-ups.

4.2 Exhaust Gas Aftertreatment & Evaporative Emission Reduction

No information has been found on these aspects.

4.3 Engine Performance

There are some contradicting reports on engine durability varying from equivalent durability as diesel fuel [Togashi 1998; Kumar 2001; Aberson 2004] to reports of a wide range of problems [Hemmerlein 1991; McDonnell 1999; Beer 2000]. These problems include cold start problems, filter plugging, build-up of carbon deposits in the injection nozzles and cylinder heads, sticking of injector needles and piston rings and dilution of lubrication oil [IES/AFIS 1996]. Solutions are reported for many of these problems but it is not clear to what extent these are satisfactory.

For many engines it is not possible to start an engine with VPO. Therefore, duel fuel tanks are utilised, so that the engine starts up on conventional diesel and after warm-up switches to VPO [e.g. Lance 2004; Aberson 2004, Elsbett 2004]. In addition, heated fuel lines are necessary to mitigate the problem with high viscosity of VPOs. It has been reported that torque and power output with rapeseed oil are slightly (2%) lower than with diesel fuel [Hemmerlein 1991]. [McDonnell 1999] reports a power loss of 0.06% for every 1% of (semi-refined) rapeseed oil blended into diesel.

4.4 Engine Efficiency

For blends up to 25% [McDonnell 1999] reports increases of the volumetric fuel consumption which are consistent with the lower energy density of rapeseed oil. Clear reports on energy efficiency have not been found.

4.5 Fuel Specifications

No information has been found on these aspects.

5 (Bio)-FT-Diesel

Fischer-Tropsch (FT) fuels have been used to some degree since the 1920s, but are not widely used today. The exception is South Africa in which 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 would behave in a similar way as GTL fuels.

FT diesel fuel 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.

Table 4 presents an overview regarding the effects of FT fuel (pure and blends) on the various aspects that are of interest to this study. The information presented in this table is discussed in subsequent sections.

5.1 Emission Impacts

5.1.1 Regulated Pollutants

Examination of Table 4 teaches that FT-diesel shows rather consistent results with respect to regulated emissions, i.e. CO emissions are reduced in all cases, whereas a reduction in HC and PM emissions are reported in all publications except one. 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. 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].

Table 4   Effects of Fischer-Tropsch diesel (pure & blends) on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO$_x$	PM			CO$_2$	CO$_2$						
FTDiesel	100%	+	+	0	+			+							Thompson 2004 (LDV)
FTDiesel	100%			+	+			+							Thompson 2004 (HDE)
FTDiesel	100%	+	+	0	+		+								Myburgh 2003 (LDE)
FTDiesel	100%	+	+ & - $^{4)}$	+	+		+								Myburgh 2003 (HDE)
FTDiesel	100%	+	+	0	+										Friess 2003 (LDV & LDE)
HnPF $^{3)}$	-	+	+	+	+										Nakakita 2003 (LDE)
FTDiesel	-	+	+	+	+							+	[-]		Dieselnet 2002 (R)
FTDiesel	100%						+ & -								Lev-On 2002 (Bus)
FTDiesel	100%				+										Gonzalez 2002 (LDE^{2})
FTDiesel	100%			+	+ & - $^{5)}$										Kenney 2001 (LDE)
FTDiesel	30-100%	+	+	+	+			+							Schaberg 2000 (HDE)
FTDiesel	100%	+	+	0	+			+							Payri 2000 (TDI LDE)
FTDiesel	100%	+	+	+	+			+							Atkinson 1999 (HDE)
FTDiesel	100%	+	+	+	+										Norton 1999 (Bus^{1})
FTDiesel	100%	+	+	+	+		+/0								Aakko 1999 (HDE & LDV)
FTDiesel	100%	+	+	+	+			0							Norton 1998 (HDVs)

1) with and without oxidation catalysts, 2) with and without EGR, 3) Highly n-Paraffinic Fuel representative of FT fuel, 4) depending on the test cycle, 5) depending on engine tested

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

According to [VW 2003] field tests with 25 Volkswagen Golf vehicles running on GTL-diesel supplied by Shell have shown reductions of HC and CO emissions by 63 and 91% respectively. NO_x and PM emission were only affected marginally. [VW 2003] also stated that the use of GTL-naphta or GTL-kerosene would lead to NO_x and PM reductions of a factor 2 to 3.

The significant reductions in regulated emissions by using FT-diesel may not be enough to achieve by itself compliance with current and even stricter future emission standards [e.g. Kenney 2001] and advanced aftertreatment systems may still be required. Nevertheless, reduction in PM generates opportunities such as (increased) EGR to further abate NO_x emissions [e.g. González 2002]. It is noted that in HD engines with advanced engine/emission control (e.g. Euro 4 and Euro 5) the positive FT-fuel effects on NO_x and PM emissions are small in absolute terms.

5.1.2 Unregulated Pollutants

There are a few reports that FT-fuel has lower PAH [Lev-On 2002] and aldehyde [Myburgh 2003] emissions than conventional diesel, but also elevated carbonyl (which consist of ketones and aldehydes) emissions [Lev-On 2002].

5.2 Exhaust Gas Aftertreatment & 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].

5.3 Engine Performance

FT-diesel fuels are compatible with existing engines and there is no need for engine modifications. The lower energy content of FT-diesel in comparison to conventional diesel fuel may result in a reduction in engine power [IEA/AFIS 1996].

FT-diesel has a constant quality and a narrow component range which makes it very suitable for HCCI combustion.

5.4 Engine Efficiency

As is clear from Table 4, CO_2 emissions are reportedly reduced when FT-diesel is used. Fuel consumption may increase [e.g. IEA/AFIS 1999, Myburgh 2003], decrease [e.g. Kenney 2001] or exhibit no change [e.g. Norton 1998] compared to market diesel.

5.5 Fuel Specifications

Fischer-Tropsch diesel has ideal 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.

As FT diesel has a low lubricity so that an additive is needed. 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].

6 Biogas

Biogas 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 impuruties.

Raw biogas can be used in combustion engines, but for use in modern vehicles upgrading to natural gas qualities is generally required.

Natural gas and biogas are usually 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 stiociometric 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]). In Table 5 an overview is presented with respect to the effects of biogas on the various aspects that are of interest to this study. The information presented in this table is discussed in subsequent sections.

Table 5 Effects of biogas on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO_x	PM			CO_2	CO_2						
Biogas	100%	+ 2)	+ 2)	+ 2)	+ 2)										Landahl 2003 (Bus)
Biogas	100%	+ 3)	+ 3)	- 3)	+ 3)										Landahl 2003 (Bus)
Biogas	100%	- 1)	- 1)	+ 1)	+ 1)										De Server 1999 (HDV)

1) Compared to Biodiesel (RME); 2) compared to diesel; 3) compared to natural gas

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

6.1 Emission Impacts

6.1.1 Regulated Pollutants

The emission benefits (CO, NO_x, PM) of natural gas are reasonably well-established [e.g. Nylund 2000; Umierski 2001, TNO 2003b]. Recent 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.

With respect to biogas, only limited information is available. For biogas upgraded to natural gas quality the regulated emissions may be expected to be similar to those of vehicles running on natural gas. Table 5 indicates that the use of biogas results in lower PM emissions compared to (bio)diesel, and even compared to natural gas. The data also suggests that biogas would lead to lower NO_x emissions compared to (bio)diesel, but higher NO_x emissions compared to natural gas. CO and HC emissions may be expected to be lower compared to conventional diesel and natural gas, but not with respect to biodiesel. In addition, it has been found that the number of particles is many times lower for biogas when compared to biodiesel [De Serves 1999].

6.1.2 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. When it is assumed that 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.

6.2 Exhaust Gas Aftertreatment & 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 as presently under discussion 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.

When similar fuel systems are used as in natural gas vehicles, evaporative losses would be negligible.

6.3 Engine Performance

Based on known issues with natural gas, the following remarks can be made with respect to biogas. Similar to CNG, on-board storage of biogas would take several times more volume than petrol or diesel. Engine performance will depend on the sophistication of the engine and whether the engine is dedicated for biogas or not. As for natural gas, some power loss may be expected when switching from petrol to biogas, although in most cases performance should probably be satisfactory [e.g. Nylund 2000]. Pure methane generally leads to a power loss < 10 % in stoichiometric engines. Not-upgraded bio-gas (60 % methane) leads to a 15 % power loss. Deterioration rates of vehicles using gaseous fuels appear to be higher than for vehicles fuelled with petrol or diesel [EC 2000]. Since methane is in gaseous state no cold start enrichment is necessary. Hence, low emissions can be achieved.

Dealing with the much bigger gas quality variations of biogas compared to natural gas requires more advanced (and sometimes dedicated) biogas engine management systems. Lean burn engines still have problems due to characteristics of universal oxygen sensor. A reliable NOx sensor should be developed. Whereas vehicle driveability on biogas might be good, vehicle emissions may suffer. Not only will it be necessary to enlarge the dynamic range of fuel control equipment, but also major control software concept changes are required, to ensure performance, fuel consumption, emissions and durability. The capacity of the fuel system is sometimes critical with low calorific gas.

For gas engines special low ash oil is necessary in most cases to avoid deposits in the combustion chamber. With respect to exhaust manifold and turbocharger, λ=1 HD engines need special materials due to the higher exhaust temperature.

HCCI combustion requires a constant gas composition.

6.4 Engine Efficiency

Gaseous fuels are "natural" SI engine fuels due to their high octane number. This allows a high compression ratio (12:1 to 13:1), which increases efficiency compared to petrol [Ahlvik 2002; Ahlvik 2001]. Without modification of the compression ratio the efficiency of port-injected otto engines is comparable to that of gasoline engines. With increased compression ratio the efficiency goes up by ~ 5 % at part- and full load. Dedicated turbocharged engines can have better a part load efficiency (10 to 15 %). Also in direct injection otto engines full load efficiency can be higher due to the possibility of applying higher compression ratio and/or earlier ignition timing. Part load efficiency can be considerably higher when applying lean mixtures. The highest efficiencies will be achieved when applying stratified lean combustion because of the elimination of pumping losses and due to combustion taking place within a heat insulating air mass. However, the quality of the stratification needs to be sufficient.

6.5 Fuel Specifications

Depending on the source the composition of biogas 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 λ-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 methane content through Europe (Wobbe Index). The engine must comply with the delivered fuel.

The knocking resistance of methane fuels is much higher than that of petrol, due to higher octane number of CNG.

7 Bio-DME (Dimethyl Ether)

Dimethyl ether (DME) is the simplest ether (CH_3-O-CH_3) and a gas at ambient temperature and pressure. Hence, it must be stored and handled under pressure as a liquid, similar to LPG (liquefied petroleum gas). It can be applied compression ignition (diesel) engines, but this requires modification of the diesel fuel system. Compared to other alternative fuels DME has appeared as an automotive fuel fairly recently [e.g. Sorenson 1995, TNO 1996].

DME can be produced from biomass by gasification (syngas production) and subsequent catalytic conversion into bio-DME. Another route is production by dehydrogenation of methanol, which in turn is produced from syngas. At this point in time DME is principally produced from natural gas. As a result, the limited number of publications that report on DME aspects have used DME that is derived from natural gas. Hence, no information was found with respect to bio-DME. Nevertheless, given the narrow composition of DME, it may be assumed that bio-DME would behave in a similar way as natural gas based DME fuels. It is noted that the production of bio-DME is currently being investigated [e.g. Gardmark 2004].

In contrast to most other fuels investigated in this study, it is commonly remarked that DME cannot be mixed with diesel fuel and dedicated or modified fuel injection systems have to be used. Nevertheless, the literature reports on one recent demonstration project [Eirich 2003] which showed that a bus can be successfully operated on DME-diesel blends (<25%).

Although this alternative fuel has a number of benefits over conventional diesel fuel (as will be seen later), this fuel can probably be considered a “niche” fuel for the foreseeable future. Table 6 presents an overview regarding the effects of DME on the various aspects that are of interest to this study. The information presented in this table is discussed in subsequent sections.

7.1 Emission Impacts

7.1.1 Regulated Pollutants

One strong and consistently reported advantage of DME is its practically smoke-free combustion, which results in very low PM emissions. Most studies also report substantial reductions in NO_x. These benefits are considered to enable attainment of future emissions standards, e.g. well below Euro 4 standards [EC 2000]. For CO and HC emissions, the results are mixed. This difference in emissions results may in part be explained by whether DME was used in an optimised or non-optimised engine [e.g. Eirich 2003].

Table 6 Effects of DME on emissions, energy efficiency, engine performance and durability

Fuel Type	Blend	Regulated Emissions				Evap. Emis.	Unreg. Emis.	Energy Efficien. Current	Energy Efficien. Future	Future Emis. Stand.	Fuel Spec.	Effect Engine Perfor.	Effect Durab. Engine / Modific.	Effect Exh. Treatm.	Reference
		CO	HC	NO$_x$	PM			CO$_2$	CO$_2$						
DME	100%									+					Narusawa 2004
DME	100%	+ & - 2)	+ & - 2)	0	+										Kinoshita 2003
DME	14-25%	-	-	-	+										Eirich 2003
DME	100%	-	+	+	+										Umierski 2001 (HDE)
DME		[-]		+	+		+			+	?		-		EC 2000 (R)
DME	100%	-		+				+							Sato 2000 (HDE)
DME	100%		+	- 4)	+										Kajitani 1997
DME	100%	+	+	+	+		+								Verbeek 1997 (LDE)
DME	100%	-	0	+	+		+								Verbeek 1997 (MDE)
DME	100%	0	0	+	+										Sorenson 1995 (LDE) 3)
DME	100%	-	-	+	+		+			+ 1)					Kapus 1995 (LDE)

1) with application of an oxidation catalyst, 2) depending on engine operation, 3) single cylinder, 4) "+" after engine optimisation (delayed injection timing)

+ = positive / yes, **0** = no effect, **-** = negative / no, **[-]** = negative, but solution is suggested, **?** = unknown or potentially postive or negative effect

7.1.2 Unregulated Pollutants

Although there are limited experimental data, there are a few consistent reports that HC emissions from DME operation are less harmful (e.g. no PAHs, BTX) than HC-emissions from conventional diesel [e.g. Sorenson 1995].

7.2 Exhaust Gas Aftertreatment & Evaporative Emission Reduction

The low PM emissions avoid the need for PM traps and allow for substantial NO_x reductions through a high EGR rate and retarded injection timing (and perhaps a deNOx-catalyst). In addition, because DME contains no sulphur, it is also possible to reduce CO and HC with an oxidation catalyst.

7.3 Engine Performance

DME is a liquefied gas comparable with propane and butane. However, it has a very low octane number, which makes the gas not suitable for Otto engines. Instead the liquefied gas is an ideal fuel for diesel combustion due to the high cetane number (> 55), but a purpose-built fuel injection system is required. International research into appropriate fuel injection systems for DME is ongoing [e.g. EC 2000].

Some problems with DME may be mitigated with relatively simple solutions. For instance, a lubricating additive can be added to DME to prevent enhanced wear of moving parts within the fuel injection system. Similarly, DME has no corrosive effects on metals, but it can dissolve a number of elastomers, including those used in conventional diesel fuels. Use of materials that are resistant to DME such as "Teflon" are recommended. The lower viscosity of DME can cause leakages in the fuel system [e.g. TNO 1996]. Improved sealing or adequate fuel additives are required [e.g. Wain 2004].

In order to reach the same power an increased liquid fuel injection rate is needed. DME is a suitable fuel for rate shaping and application of EGR. DME has good cold-start characteristics.

The use of DME in potential new engine systems (HCCI) are being investigated [Kaimai 1999] and look promising. DME should have ideal characteristics for HCCI combustion because of the constant composition, the high cetane number and the gaseous fuel/air mixture after injection.

7.4 Engine Efficiency

Engine efficiency (part load, full load) is higher for DME than for diesel.

7.5 Fuel Specifications

The physical properties of DME are similar to LPG. At 20 °C DME is a liquid at pressures above 5 bar. DME vapour is heavier than air. The cetane number of DME is between 55 and 60, compared t0 46 – 55 for diesel. This makes DME very suitable for use in diesel engines. DME can be produced with high purity and is inherently free of sulphur and aromatics.

Fuel specifications for DME remain a matter of discussion [EC 2000]. These concern aspects such as maximum water content, methanol content, maximum impurities, odour and lubricant content. It is in these aspects that DME form biomass may differ from fossil-based DME. No information, however, has been found on this issue.

8 Standards and Legislation

In the previous chapters an inventory has been made of possible technical problems associated with fuel-engine compatibility that may hinder large-scale introduction of biofuels. Legal obstacles, associated with codes & standards or with EU legislation on vehicles and fuels, may pose similar problems. In order to be able to market alternative fuels they must comply with applicable legislation and standards on fuel quality. Similarly, in order to be allowed on the road, vehicles using alternative fuels require type approval, covering aspects of safety (e.g. storage of fuels) and emissions.

To some extent the problems posed by standards and legislation are connected to the technical aspects studied in previous chapters as many aspects of standards and legislation on vehicles and fuels are based on technical considerations, e.g. related to durability and safety. Purely legal problems arise when standards and legislation do not include or explicitly exclude certain fuels or vehicles, so that these can formally not be allowed on the market. Provided that these alternative fuels and vehicles can meet the same safety standards as imposed on conventional fuels and vehicles, standards and legislation can be amended to include these alternative technologies. Changing directives and regulations, however, is a very time-consuming process. In Europe and also in the UN-context regulations and procedures are developed in close co-operation between representatives from governments and industry. This process makes sure that new legislation can actually be met by the involved industry. The downside is that it may take a lead time of between 3 and 5 years for the complete process of preparing new proposals or amendments for existing directives and regulations, and having these approved and implemented by the authoritative bodies in charge of the directives and regulations. It is clear that this may seriously slow down the market implementation of promising options.

8.1 Standards and legislation on fuels

Fuel quality is covered by standards such as EN590 (diesel and blends up to 5%) en EN14214 (biodiesel) and by the European Directive 98/70/EC. EN590 allows blending of FAME up to 5 vol.%. Directive 98/70/EC states that in petrol a share of 5 vol.% ethanol is allowed. As also indicated in [Ecofys 2003] these maximum shares are insufficient to meet the 2010 target by means of blends alone. Therefore, if these limitations are not resolved in time, the use of pure fuels in mainly niche markets will have to be promoted to meet the 2010 targets. This may seriously hinder the gradual increase of the share of biofuels in the energy supply of the European transport sector.

8.2 Standards and legislation on vehicles and engines

European directives and UN regulations (UN-GRPE) for type approval of vehicles comprise procedures for measuring emissions and fuel consumption of vehicles. European emission legislation is based on emission values measured according to Directive 70/220/EEC for passenger cars and light vans and Directive 88/77/EEC for heavy-duty vehicles. The directives at present do not cover fuels other than petrol, diesel, LPG and natural gas. Also no official procedure exists for determination of the fuel consumption of vehicles running on blends. Vehicles allowing the use of blends and bi-fuel vehicles, than can run on conventional petrol or diesel and an alternative biofuel, can receive type approval based on measurements carried out while driving on conventional petrol or diesel. Emissions of vehicles driving on blends of conventional and biofuels are, however, in principle not regulated. Dedicated vehicles running on pure biofuels, which can not run on conventional fuel, can formally not even receive type approval, unless by exception for small numbers of vehicles. The latter is governed by national type approval.

Various studies e.g. report slightly increased NO_x emissions from the use of biodiesel. As the emissions of diesel vehicles tend to be close to the limits, emissions while running on biodiesel may exceed the emission limits applicable to diesel. This can be solved by improved engine calibration or application of EGR, but this will only happen when manufacturers are legally obliged to meet emission limits also when vehicles are running on biofuels or blends.

The European biofuels directive 2003/30/EC explicitly states that member states should see to it, and if necessary apply measures to make sure, that the use of biofuels in blends higher than 5% is done in compliance with existing emission limits. It is at present not clear how individual countries work out this obligation. In any case it seems worthwhile to start development of European legislation on type approval of biofuel vehicles in parallel with the implementation of (temporary) national measures.

In addition to the emissions during the type approval test also attention needs to be paid to the effects of the use of biofuels on real-world emissions. Several EU member states have great difficulty meeting the European NEC directive for NO_x and the requirements for local NO_2 and PM concentrations imposed by the new European legislation on air quality. As these problems are to a large extent caused by emissions from the transport sector, even a limited increase of emissions at the vehicle level as a result of the large-scale use of biofuels may have significant policy implications.

8.3 Conclusion

European legislation and other regulations (CEN, GRPE) will have to be adapted in time to enable the EU member states to meet the 2010 targets set by the biofuels directive. It is obvious that this process should be handled at the European / international level.

9 Conclusions

Based on the inventory presented in this report the following conclusions can be drawn with regard to the research questions as stated in section 1.3:

Will vehicles using biofuels, pure or in blends, be able to meet the emission limits foreseen for the period 2015-2020, given the expected developments in conventional fuels and engine technology?

<u>Ethanol</u>

- For ethanol blends measurements on current engine technology tend to show small benefits with regard to regulated emissions. Reported cases of emission increases do not seem significant or problematic with respect to reaching future emission standards.
- The somewhat higher CO and HC emissions reported for the use of ethanol-diesel blends may even be helpful with regard to the application of effective NO_x-aftertreatment as CO and HC act as reducing agents.
- Research on vehicles optimised for the use of high ethanol blends (e.g. E85) shows that these are able to reach very stringent future emission levels.
- In low ethanol-petrol blends the vapour pressure may increase to levels exceeding the limit of 60 kPa as set by the European Directive 98/70/EC. (10% higher vapour pressure for blends between 5 – 15 %vol. ethanol). This could be problematic with respect to reaching the 2010 target of the EU biofuels directive by using ethanol-petrol blends. Increased vapour pressure is a safety issue and may lead to increased evaporative emissions, but the net effect is not clear from available data. The problem can in principle be overcome by changing the composition of the petrol used for the blend.

<u>Biodiesel</u>

- The majority of reviewed literature indicates lower CO, HC and PM emissions and slightly higher NO_x emissions for the use of biodiesel in existing engines compared to conventional diesel. Results, however, are not entirely consistent. As NO_x and PM emissions from diesel vehicles are critical for reaching mid-term environmental goals as set by the National Emission Ceilings and European air quality legislation, small variations in emissions at the vehicle level may have significant policy impacts. This requires further study.
- The low sulphur content of biodiesel is favourable for application of advanced exhaust gas aftertreatment. The influence of biodiesel on the exhaust gas composition may also be beneficial for the conversion efficiency of oxidation catalysts and regeneration of Diesel Particulate Filters (DPF).

Virgin Plant Oil

- Compared to conventional diesel the limited amount of available literature tends to show a decrease in NO_x emissions. For other regulated components the emission behaviour is not clear.
- No information is available on the interaction between VPO and future engine and exhaust gas aftertreatment technology.

FT-diesel

- For FT-diesel rather consistent reductions of CO, HC and PM emissions are reported. For NO_x the results vary between no effect and emission reduction.
- Especially due to its practically zero sulphur content, FT-diesel is fully compatible with the demands of future advanced emission aftertreatment technology. In the shorter term the reduced PM emissions associated with the use of FT-diesel may enable reaching Euro 5 emission limits with increased EGR instead of NO_x aftertreatment. The advantages of FT-diesel will diminish in future as also conventional diesel has to meet increasingly stringent requirements on e.g. sulphur content and aromatics.

Biogas

- For biogas upgraded to natural gas quality the regulated emissions are expected to be similar to those of vehicles running on natural gas. Deviating gas qualities will influence emission behaviour, but especially for modern automotive engines the effects are not known and require further research. Effects will be different for stoichiometric engines with three-way catalyst than for lean-burn engines.
- Stoichiometric engines on natural gas will be able to meet Euro 5 and 6 emission limits. For lean-burn technology this is uncertain.

Bio-DME

- Compared to diesel, DME shows strong reductions of PM emissions and substantial reduction of NO_x. As DME is a single component fuel advantages for bio-DME are expected to be similar to those of fossil-based DME.
- The low PM emissions avoid the need for PM traps and allow for substantial NO_x reductions through a high EGR rate and retarded injection timing (and perhaps a deNOx-catalyst). In addition, because DME contains no sulphur, it is also possible to effectively reduce CO and HC with an oxidation catalyst. DME-engines will thus be able to comply fully with future emission legislation.

General conclusions

- 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 5 and Euro 6 emission limits. With improved conventional technology petrol vehicles will be able to reach so-called zero-effect level emissions. For these vehicles it will obviously not be possible to gain large emission benefits in absolute terms for specific pollutants by switching to certain alternative fuels.
- Direct injection otto (SIDI) engines may yield significant benefits with regard to fuel consumption, and are currently being introduced on the market. The emission

performance (especially under real-world operating conditions) of these vehicles is not yet completely known and understood. It is, however, clear that reaching future emission limits for these engines is more difficult than with conventional stoichiometric engines. Data on the use of biofuels in SIDI engines is limited so that no conclusions can be drawn on the effects on emissions or engine performance for this type of engines. More research seems justified as both technologies (SIDI and biofuels) will gain significant market shares of the next decades.

- Due to the absence of, or limited conversion efficiency of exhaust gas aftertreatment in current diesel engines, the impact of fuel composition on emissions is expected to be bigger. However, as with the case of petrol vehicles, the use of effective aftertreatment in the near future will reduce the possible direct emission benefits associated with the use of alternative fuels in diesel engines.

Will the application of biofuels, pure or in blends, have negative impacts on performance and durability of engines (torque, power) and aftertreatment systems? And if so, are there technical measures available to solve these problems?

Ethanol

- There seems to be a consensus that low ethanol blends in fuel (e.g. less than 20% in petrol and less than 15% in diesel) can generally be used in unmodified SI- and CI engines without any material problems or operating problems. The use of additives in fuel blends may be required. Older vehicles using ethanol blends after many years of petrol use may experience filter plugging as the ethanol acts as a solvent for deposits in tank and fuel system.
- The high octane number of ethanol allows an increase of the compression ratio in dedicated engines running e.g. on E85, leading to increased power and better efficiency. Due to the lower volumetric energy density of ethanol the flow capacity of the injectors needs to be increased to maintain power in existing engines. High ethanol blends do require the use of ethanol-resistant materials in the fuel system. The low lubricity of high ethanol blends may cause engine wear.
- Ethanol is compatible with existing and advanced aftertreatment systems.

Biodiesel

- The literature indicates that low biodiesel blends can be used in existing diesel engines without modification. For higher precentage blends, and particularly B100, there are some concerns about the interaction with components of the fuel injection system such as filter plugging, injector coking and lubrication degradation, which can limit durability. Biodiesel attacks certain coatings and elastomers and causes corrosion with certain metals. Use of biodiesel compatible materials should in principle solve these problems. It is noted that aged or poor quality biodiesel fuels may cause several problems such as corrosion and blockage.
- Literature is not consistent on performance aspects such as possible power loss.
- Biodiesel has good lubrication properties.
- Additives may be required to solve cold-start problems with biodiesel in colder climates.
- Biodiesel is compatible with existing and advanced aftertreatment systems.

Virgin Plant Oil

- Especially older studies report various durability problems such as build-up of carbon deposits in the injection nozzles and cylinder heads. Several more recent studies, however, report durability to be equivalent to conventional diesel.
- Torque and power output may be slightly lower than with diesel fuel.
- No information is available with respect to aftertreatment system performance and durability.

FT-diesel

- FT-diesel fuels are compatible with existing engines and existing and advanced aftertreatment systems. There is no need for engine modifications. Additives may be needed to improve lubrication properties.
- The lower energy content of FT-diesel in comparison to conventional diesel fuel may result in a slight reduction in engine power.

Biogas

- Pure methane generally leads to a power loss in stoichiometric engines of less than 10 % compared to petrol. Low calorific bio-gas (60 % methane) leads to a 15 % power loss.
- Adaptations of the engine management system are required to deal with strong variations in gas quality. Sulphur content of biogas should be small to ensure durability of exhaust catalysts.
- Biogas generally requires cleaning to reduce the concentrations of water, sulphur, oxygen, solid particles and various other contaminants which negatively affect engine durability.
- Deterioration rates of vehicles using gaseous fuels appear to be higher than for vehicles fuelled with petrol or diesel.

Bio-DME

- DME is used in CI engines. The use of DME requires dedicated fuel injection systems.
- No indications have been found that bio-DME has different characteristics with respect to engine performance and durability than DME from fossil origins.

Will biofuels, pure or in blends, be able to meet future fuel specifications? Can possible problems be solved by the use of additives and does this have costs implications?

- Starting 2005 the sulphur content of European petrol and diesel has to be below 50 ppm (mg/kg), and a development towards sulphur-free fuel (< 10 ppm) is foreseen to enable application of advanced aftertreatment systems. To improve emissions also a lower aromatics content is prescribed. When used in blends, inherently clean biofuels such as ethanol, FT-diesel and DME can play a role in meeting objectives with respect to sulphur and aromatics content.
- The properties of conventional petrol and diesel are influenced and controlled by the use of a wide range of additives. It may be assumed that these can also be used to make sure that blends with biofuels or even pure biofuels meet present and future fuel specifications and requirements with regard to engine performance and durability. In

the reviewed literature, however, no specific information has been found on the types and costs of additives that can be applied to solve possible problems with biofuels and blends.

Are there possible negative impacts of the use of biofuels with respect to the emissions of unregulated components?

- For ethanol experimental data consistently indicate increased aldehyde emissions (especially acetaldehyde) and a reduction in benzene and 1,3-butadiene emissions with increasing ethanol content.
- For the use of biodiesel, there is rather consistent evidence that emissions of aromatic HCs, PAHs and nitro-PAHs and mutagenicity ofo diesel exhaust are reduced. On the other hand, biodiesel may substantially increase the odour intensity of diesel exhaust.
- For VPO literature data on the unregulated emissions are limited and inconsistent.
- FT-fuel may cause lower PAH and aldehyde emissions than conventional diesel, but also elevated carbonyl (which consist of ketones and aldehydes) emissions.
- OEM-equipped Euro 3 natural gas vehicles emit favourable levels of unregulated components. Assuming that 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. On the other hand, exhaust emissions of methane, which is strong greenhouse gas, are relatively high. Further R&D is required to identify cost-effective reduction measures.
- There are a few consistent reports that HC emissions from DME operation are less harmful (e.g. no PAHs, BTX) than HC-emissions from conventional diesel.

Will biofuels also in the future maintain their advantage on fossil fuels with respect to greenhouse gas emissions?

- No indications are found that biofuels would lead to significant reductions in engine efficiency or that biofuels would be incompatible with technologies being developed to improve the efficiency of future combustion engines.
- The high compression ratios which are possible with the use of ethanol and methane enable significant efficiency improvements in dedicated engines. This may improve the overall greenhouse gas benefits of these fuels compared to petrol and diesel.
- Because of their more homogeneous composition, ethanol and DME, and to a lesser extent biodiesel and FT-diesel, are better suited for use in advanced engine concepts such as HCCI than conventional petrol and diesel. These biofuels are therefore compatible with the long-term strive towards more efficient engines and may even be an enabling technology in this respect. Natural gas can also be used in HCCI-combustion, but the use of biogas requires special attention to control of the fuel composition.

Other conclusions and recommendations

- Existing fuel standards and regulations for type approval of light-duty vehicles and heavy duty engines pose limitations on the technical options available to meet the 2010 goal of the EU biofuels directive. Fuel standards will have to be adapted to allow the use of higher percentage blends of biofuels in conventional petrol and diesel. Existing type approval regulations do not provide proper procedures for measuring emissions and fuel consumption of vehicles running on biofuels and do not cater for the homologation of dedicated biofuel vehicles and engines. Modifications are also required to regulate the emissions of conventional vehicles running on (low percentage) blends and of flexible fuel vehicles when running on pure biofuel or high percentage blends.

- Establishing statistically significant results in experimental emission studies in general require testing a large number of vehicles and proper statistical handling of the test results. This requirement is not fulfilled in many of the studies reviewed for this report. It is recommended, especially for those fuels that are expected to play a role in the implementation of the EU biofuel directive, that a large scale test programme is conducted to investigate the impacts on emissions, efficiency, performance and durability. Durability in various applications can be monitored in demonstration projects and fleet tests.

10 References

Note:
References are listed in alphabetical order. In the text of the report references are referred to as e.g.: [Aakko 1997; TNO 2003a].

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Appendix A Abbreviations

ASTM	American Society for Testing and Materials
BTL	biomass-to-liquid
BTX	benzene, toluene, xylene
CAI	controlled auto-ignition
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
DME	dimethyl-ether
DPF	diesel particulate filter
E85	mixture of 85% ethanol and 15% petrol
EC	European Commission
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
HC	hydocarbons
HCCI	homogeneous charge compression ignition
HD	heavy duty
HHV	higher heating value
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
NMHC	non-methane hydorncarbons
NO_x	nitrogen oxides (NO, NO_2)
PAH	poly-aromatic hydorcarbons
PM	particulate matter
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
UVOME	used vegetable oil methyl ester
VPO	virgin plant oil

Appendix 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 [Bechtold 1997; Ermers 2001]:

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.[3]

Autoignition 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

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[3] 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 dos 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.

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 gk/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[4].

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.

Vapor 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.

Vapor 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)[5]. A low vapour pressure leads to low evaporative emissions but may also cause cold-start problems.

Viscosity
The resistance of a fuel to flow.

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[4] 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].

[5] According to [Bechtold 1997] the Reid Vapour Pressure test involves saturating the fuel with water before testing and cannot be used for gasoline-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].

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[6].

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[6] See e.g. http://www.ft-nir.com/Nutrition/iodzahl.htm.

Appendix C Notes on fuel properties of conventional fuels

Fuel properties may strongly 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.

Although many fuel characteristics can be directly related to combustion properties, the prediction of emissions based on fuel properties is very difficult [McMillian 1998]. 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.

Below some notes are collected from which may help to understand the impacts of biofuels on engine performance and emissions as described for the different fuels in this report.

Petrol

- 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].
- A highvolatility 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 (limited to 60 kPa in Europe). A high vapour pressure causes evaporative emissions and may be a safety risk.

Diesel

- The most important parameters specified in diesel fuel standards are: cetane number, viscosity, cold behaviour, flash point, volatility, lubricity, sulphur and additives [Dieselnet 2003b].
- In terms of emissions from biodiesels, cetane number, density, carbon residue, viscosity, iodine number, heating value, oxygen content and fatty acid profile are relevant [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[7]. In conventional diesel a high paraffin content yields a high cetane number and thus good ignition quality of the fuel. Aromatics lower the cetane number. For fuels with high aromatics content cetane number improvers are used as fuel additives [Dieselnet 2003b].
- A high cetane number of around 50 is desirable for optimum engine operation in terms of quiet operation and low PM emissions [Dieselnet 2003b].
- 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 2003b]. Some researchers found larger effects of centane number on older high NO_x engines compared to modern low NO_x engines [Stavinoha 2000]. CO and HC emissions have also been reported to decrease with increasing cetane number [Dieselnet 2003b; Martin 1997]. For Light Duty (LD) engines increased cetane number is also reported to yield lower PM emissions [Dieselnet 2003b].
- 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.
- Viscosityis important for the operation of fuel injection equipment, which has to accurately measure the small quantities of fuel to be injected. High viscosity fuel – i.e. great resistance to flow – could reduce the fuel flow or even pump distortion due to generated heat. Low viscosity fuel can significantly increase leakages from the pumping elements [Dieselnet 2003b].
- 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 2003b].

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[7] Note: petrol has very low cetane number.

- 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 2002b].
- 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 2003b]. 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 2002b].
- 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 leads 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 and contributes to PM formation and binds with water to form sulphuric acid. Sulphur deactivates NO_x absorbers (one of the most important obstacles for this technology), leads to catalyst poisoning, and to increased PM emissions when oxidation catalyst 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 technologies [Dieselnet 2002b].
- 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 2003b; Stavinoha 2000].
- Most studies indicate no influence of aromatics content on HC, CO or PM emissions from HDVs[8]. Decreasing total aromatics from 30 to 10% produces a small benefit (0-5%) for NO_x [Dieselnet 2003b]. According to [Stavinoha 2000] the effects 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.
- 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 2003b] a lower density leads to a small reduction in NO_x, but slightly higher CO emissions and a particularly large increase in HC. Density

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[8] Presumably measured using fuels in which the influence of aromatics content on cetane number was compensated by the use of cetane improvers.

and cetane number in biodiesels are highly correlated [Graboski 2003]. According to [Martin 1997] particulates, smoke and PAH are influenced by density.

- According to [Dieselnet 2003b] current 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]. It appears that only a large amount of oxygenates can produce significant PM emissions improvements [Stavinoha 2000].
- Fuel sensitivity of (CO, HC, PM) emissions from LD diesel engines generally appears to be larger than of HD diesel engines, with the exception of NO_x [Dieselnet 2003b].

Appendix D Fuel specifications of conventional and biofuels

Notes:

- Data in the table below have been extracted from various literature sources. Data from different sources often display a significant spread. This may depend on exact fuel composition which is not constant for fuels like diesel, petrol, LPG, VPO and biogas. Fuel compositions in the US and Europe are also generally different, which may lead to different fuel characteristics.
- PPO may be derived from various sources and will accordingly have a different composition. For biogas the composition depends on the source and the level of upgrading. For these fuels many fuel characteristics can not be specified unless the exact composition is known. Very few general data have been found in the literature.

Table D1 Fuel Specifications in the literature

	Units	Diesel	Petrol	LPG 1)	NG	(Bio)-Ethanol	Biodiesel	VPO	FT-Diesel	Biogas	DME
Chemical Formulae	-	$C_nH_{1.8n}$ C_8 to C_{25}	C_4 to C_{12}	x% C_3H_8 x% C_4H_{10}	CH_4	C_2H_5OH			C_8 to C_{25}	CH_4	CH_3-O-CH_3
Engine Type	-	CI	SI	SI	SI	SI / CI	CI	CI	CI	SI	CI
Applicable Compression Ratios	-	18 DI 22 IDI	< 11	11 – 13	11 – 13	< 18	18 DI 22 IDI	18 DI 22 IDI	18 DI 22 IDI		18 DI 22 IDI
Stoichiometric A/F Ratio	kg/kg	14.6	14.7	15.4	16.9	9	11.2. – 12.6	12.4			9
Chemical Structure	mass% C	85.0 – 86.6	77 / 85	82 / 83	73.3 – 76.0	52.2 – 52.3	77 – 81.5		84.9		52.2
	mass% H	15.0 – 13.4	11.3 / 15	18 / 17	23.9 – 25.0	13.1 – 13.3	11 – 12		15.0		13.0
	mass% O	0.0	0.0	0.0	0.4 - 0.0	34.8 – 34.4	6.8 – 11		0.0		34.8
Molecular Weight	g/mole	~ 170	98	44 - 58	17	46	300 – 310				46
Liquid Density (at 20 °C)	kg/m^3	800 – 850	750	500 - 580		790			770 – 780		660 – 668
Density (at 15 °C)	kg/m^3	820 – 860	720 – 780		0.83	800	860 – 900	920	780		660 – 670
Cetane Number	-	40 – 59	-	-	-	40 / 50	46 – 67	41 – 58	75	-	55 – 60
Research Octane Number (RON)	-	-	> 95	94 – 112	120 2)	106 - 120	-	-	-	> 127 ?	-
Motor Octane Number (MON)	-	-	> 85	89 – 98	130	90 - 99	-	-	-	122 ?	-
Methane Number (MN)	-	-	-	-	69-99 2)	-	-	-	-		-
Energy Density (LHV)	MJ/kg	38 – 43	41 – 43.7	44 – 46	38 – 50	25 – 29	36 – 38	37	43.3	50 3)	27.6 – 28.8
Energy Content (LHV)	MJ/l	35.4 – 36.1	31.5 – 32.2	23 – 26	0.032	21.2	32 - 33	34	33.1		18.2 – 19.3
Energy Density (HHV)	MJ/kg	45 – 46	46.8 – 47.3	48 – 50	42.2	28 - 30			46.6 – 47.7		

	Units	Diesel	Petrol	LPG 1)	NG	(Bio)-Ethanol	Biodiesel	PPO	FT-Diesel	Biogas	DME
Boiling Point	°C	150 – 380	30 / 190	-42 – -0.5	-162 / -89	78	330 – 350			- 164	-25
Autoignition Temperature	°C	250 / 360	225 – 500	365 – 470	540 – 650	420					235
Vapour Pressure (at 20 °C)	kPa	< 1	45 – 90 < 60 4)	210 – 810		21	< 1				510 – 530
Kinematic Viscocity	cSt	2.8 – 6.0	35.14				3.5 – 6.0		3.6		< 1
Cold Filter Plugging Point CFPP	°C	-43 – -9					-15 – -7				
C/H Ratio		~0.51	0.47 – 0.58	0.38	0.25 – 0.33	0.33	0.55		0.47		0.33
Heat of Vaporisation (at 20 °C)	kJ/kg	300	420	358 / 372	510	845 / 923					460 – 470
Specific CO2 Formation	g/MJ	72.8 / 74.1	73.3	65.3 / 66.3	55 / 56.2	71.3 / 71.7	79		70.7 / 73		66

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.

Sources: Sorenson 1995; Sorenson 1998; Konno 1999; Kinoshita 2003; Sato 2000; Kaimai 1999; TNO 1996, Verbeek 1997; Kapus 1995; Dieselnet; IEA/AFIS 1996, IEA 1999; EC 2000; NREL 2002; US EPA 2002; Reece 1995; Bessee 1997; Schramm 1999; He 2003; Hemmerlein 1991; Lance 2004

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