Alternative fuels

Investigation on emission effects of alternative fuels

Literature overview

For the Norwegian Environment Agency (Miljødirektoratet)

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1 Summary

AVL was asked by the Norwegian Climate and Pollution Agency (KLIF, now Norwegian Environment Agency/Miljødirektoratet) to give a scientific overview of the emissions from alternative fuels compared to conventional fuels.

The latest scientific findings have been reviewed and interviews with AVL in-house experts have been carried out in order to create an overview of the current market concerning conventional and alternative fuels. There are reasons to believe that the field of alternative fuels, and especially biofuels, will develop fast in the near future.

In this literature study, scientific reports involving biofuels have been summarized. The different methods for sampling and analysing the unregulated compounds make comparison difficult. The main conclusion drawn from this study is that the exhaust emissions from different biofuels and blends with biofuels have to be studied more thoroughly, including both regulated and unregulated compounds. The exhaust emissions generated during testing should be further evaluated regarding health effects.

The fuel quality provided on the national market is an important factor for improving local air quality and for reducing health effects from exhaust emissions. The future emission legislation will lead to reduced emissions from new vehicles through more extensive use of exhaust aftertreatment systems (such as SCR and diesel particulate filters) and other technological improvements. This does however not affect the emissions from existing vehicles. The major benefit when improving the fuel quality is that this also affects emissions from all existent vehicles and non-road mobile machinery.

There are some conclusions concerning emissions from alternative fuels that can be drawn. Table 1 below gives an overview of alternative and conventional fuels and the emission components from each fuel. The fuels currently available on the Norwegian market are outlined with yellow.

The effect on the exhaust when adding biodiesel to fossil diesel is dependent on the concentration of the blend, as well as operating conditions (urban driving vs mtorway). For both light duty and heavy duty vehicles the regulated emissions of CO, HC and PM are generally reduced when biodiesel is blended into fossil diesel. Emissions of NOx are generally increased with biodiesel blends. In addition to contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with a number of adverse effects on the respiratory system.

Table 1: Overview of fuels

Renewable fuel	Fuel, commercially available	Raw material(s)	Highlighted emission components	Is conversion of the engine/vehicle required in order to use this fuel?
	Fossil Petrol	Crude oil		
	Fossil Diesel	Crude oil	Aromats, PAH, Mutagenic, NOx, particles	
BioMethane (upgraded Biogas)	CNG/LNG (biogas origin)	Biomass	CH4, NOx (technology dependent)	YES. Major adjustments
BioDiesel (FAME)	B100	E.g. vegetable oils, wood and animal fat	Nox	YES. Minor adjustments
	Low blends in fossil diesel	E.g. vegetable oils, wood and animal fat	NOx B20 mutagenic (inconclusive evidence!)	Compatible if complying with blending requirements in EN590
Hydrogenated Vegetable Oil (HVO)	Renewable petrol and diesel (high blend)	E.g. vegetable oils, wood and animal fat	--	Compatible if compliant with EN228/EN590
	Low to medium blends in fossil fuel	E.g. vegetable oils, wood and animal fat	--	Compatible if compliant with EN228/EN590
Ethanol	ED95	E.g. crops/biomass with sugar and/or starch content	Ultrafine particles, aldehydes (mainly acetaldehyde)	YES. Minor adjustments
	E85/E100	E.g. crops/biomass with sugar and/or starch content	Aldehydes (mainly acetaldehyde)	YES. Minor adjustments
	Low blends in fossil petrol	E.g. crops/biomass with sugar and/or starch content	--	Compatible if complying with blending requirements in EN228
DME, DiMethylEther	DME	Natural gas, coal or biomass	Inconclusive	YES. Major adjustments
Synthetic diesel (Fischer-Tropsch diesel)	Renewable petrol and diesel (high blend)	Natural gas (GTL), coal (CTL), any kind of biomass (BTL)	Inconclusive	Compatible if compliant with EN228/EN590
	Low to medium blend in fossil fuel	Natural gas (GTL), coal (CTL), any kind of biomass (BTL)	--	Compatible if complying with blending requirements in EN228/EN590
Methanol	M85/M100	Methane (natural gas, biogas) steam reformed coal, woody biomass	Toxic when handling! Aldehydes (mainly formaldehyde)	Insufficient experience
Butanol	High blend	Biomass or fossil fuels	Inconclusive	Insufficient experience
	Low blend in fossil petrol	Biomass or fossil fuels	Aldehydes (formaldehyde and acetaldehyde) Carbonyls	Compatible if compliant with blending requirements in EN228

When adding bioethanol to fossil petrol, the effects on CO and NOx are contradictive, probably due to engine calibration. The THC and NMHC increases for E85 blend. The emissions consist mainly of unburnt ethanol. Significant increases of aldehydes (mainly acetaldehyde) were observed for E85, whereas lower blends showed decreases of

formaldehyde. Ethanol is the main precursor of acetaldehyde in vehicle emissions. Acetaldehyde is considered a probable carcinogen, and formaldehyde is carcinogenic.

In Table 2 the NOx and PM emissions for the different fuels are summarized. The evaluations are based on concordant test results (when applicable), and are presented in comparison with the respective conventional fossil fuel. Please note that it is important to combine the emission result with the specific testing conditions (for further details, see chapter for respective fuel).

Table 2: Summary of NOx and PM emissions, as compared to conventional fossil fuel

Fuel	NOx emissions	PM emissions
Fossil Petrol	Low	Low
Fossil Diesel	High	High
BioMethane	- (technology dependent)	Low
BioDiesel (FAME)	High	Low
Hydrogenated Vegetable Oil (HVO)	-	Low
ED95	Low	Low (overall; high levels of ultrafine particles)
E85	-	-
DME	Low	Low
Synthetic diesel (Fischer-Tropsch diesel)	-	Low
Methanol	?	?
Butanol	?	?

Table of content

Abbreviations

ADEME	”Agence De l'Environnement et de la Maîtrise de l'Energie”, French Environment and Energy Management Agency
B20	20% Biodiesel
B100	100% Biodiesel ("neat" Biodiesel)
BRA	Braunschweig City Driving Cycle
BTEX	Short for Benzene, Toluene, Ethyl benzene and Xylenes
BTL	Biomass To Liquid
CARB	California Air Resource Board
CBG	Compressed Bio Gas
CI	Compression Ignition
CNG	Compressed Natural Gas
CONCAWE	CONservation of Clean Air and Water in Europe, the oil companies' European association for environment, health and safety in refining and distribution
CTL	Coal To Liquid
DPF	Diesel Particle Filter
DTT	Dithiothreitol
EEV	Enhanced Environmentally friendly Vehicle
EGR	Exhaust Gas Recirculation
EPA	See US EPA
EUCAR	European Council for Automotive R&D
FAME	Fatty Acid Methyl Ester
F-T	Fischer- Tropsch, collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons
FTP75	Federal Test Procedure 75, emission certification of light duty vehicles in the U.S.
GHG	Greenhouse Gas
GTL	Gas To Liquid
HDV	Heavy Duty Vehicle
IARC	International Agency for Research on Cancer
IEA	International Energy Agency
ILUC	In-Direct Land Use Change
JE05	Japanese 2005 emission standards, transient test based on Tokyo driving conditions.
LBG	Liquified Bio Gas
LNG	Liquified Natural Gas
MSS	Micro Soot Sensor
MTBE	Methyl Tertiary Butyl Ether
NEDC	New European Driving Cycle
NYBUS	New York Bus cycle, chassis dynamometer test for heavy-duty vehicles,

	particularly for urban buses
OEM	Original Equipment Manufacturer
PAH	Polycyclic Aromatic Hydrocarbons
PME	Palm oil Methyl Ester
RED	Renewable Energy Directive
RME	Rapeseed Methyl Ester (oil)
ROS	Reactive Oxygen Species
ROW	Rest Of the World
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SME	Soybean oil Methyl Ester
TEF	Toxic Equivalence Factor
TEOM	Tapered Element Oscillating Microbalance
THC	Total Hydro-Carbon emission
UDDS	US EPA Urban Dynamometer Driving Schedule
UFOME	Used Frying Oil Methyl Esters
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds
VTT	Valtion Teknillinen Tutkimuskesk, Technical Research Center, Finland
WHO-IPCS	World Health Organization - International Program on Chemical Safety
WHVC	Worldwide Harmonized Vehicle Cycle

2 Background

In November 2012 AVL was asked by the Norwegian Climate and Pollution Agency (KLIF, now Norwegian Environment Agency) to give an overview of scientific findings regarding emissions from alternative fuels in comparison with conventional fuels. The focus is on the Norwegian market, but the report does also include information regarding Europe and ROW (Rest Of the World).

3 Scope

The objective of this report is to provide the Norwegian authorities with information regarding biofuels. The fuels described in this report are either used today, or under development. A scientific overview of emission components has been performed. Facts concerning practical issues have been investigated, i.e. blends, conversion possibilities and raw material needed to produce the fuel.

4 Deliverables

This report gives an overview of the latest scientific findings regarding emissions from biofuels. In addition to a literature study, interviews with in-house experts have been carried out in order to create an overview of the current market concerning conventional and alternative fuels.

The report has a focus on renewable fuels. Fossil petrol and fossil diesel are mentioned as references.

The fuels available on the Norwegian market and the efforts put on renewable fuels do not differ substantially from the European market. Therefore, the report does not specifically state the situation on the Norwegian market.

5 Result

The information and data stated in the report have been collected from scientific articles and corporate publications, as well as data provided by in-house experts.

5.1 Overview of different fuels

Different fuels currently existing on the market as well as fuels that are under development are presented in Table 3. Fuels currently available on the Norwegian marked are outlined with yellow colour.

Table 3: Overview of fuels

Renewable fuel	Fuel, commercially available	Raw material(s)	Highlighted emission components	Is conversion of the engine/vehicle required in order to use this fuel?
	Fossil Petrol	Crude oil		
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Butanol	High blend	Biomass or fossil fuels	Inconclusive	Insufficient experience
	Low blend in fossil petrol	Biomass or fossil fuels	Aldehydes (formaldehyde and acetaldehyde) Carbonyls	Compatible if compliant with blending requirements in EN228

The emission components listed in Table 3 are based on the studies summarized in this literature study. The listed effects are the known negative effects to date. The biofuels have been compared to the conventional fuel (i.e. biodiesel has been compared to fossil diesel).

The overview of fuels presented in Table 3 does not include any details on availability of fuels on different markets. Several fuels are under development with limited supply, but the situation changes rapidly as the development progresses and modifications and improvements are introduced and different feedstocks are tested. Any information on current production capacity is therefore omitted from this report.

Data on current fuel prices is omitted due to the difficulties in obtaining correct information on fuel prices excluding taxes and environmental charges to give a correct picture of current fuel prices.

It is important to notice that under the current emission legislation for engines/vehicles, requirements must be met and can already today be a challenge. The introduction of Euro VI emission levels will further increase the complexity.

5.2 Overview of fuels suitable for different vehicles

Some fuels are more suitable for urban traffic than for long distance haulage, due to higher fuel consumption and limited fuel storage on the vehicle (compared to fossil diesel or petrol). When the mileage range will be a limitation, the availability of filling stations becomes a decisive factor.

Table 4 show fuels suitable for different vehicle sizes, driving patterns and combustion types.

Table 4: Overview of fuels suitable for different vehicles.

Fuel	Light vehicles, CI engines	Light vehicles, SI engines	Heavy vehicles, haulage	Heavy vehicles, urban
Fossil diesel	X	-	X	X
Fossil petrol	-	X	-	-
Biomethane	-	X	-	X (SI engines)
Biodiesel, B100	X	-	X	X
Biodiesel, low blend in fossil fuel	X	-	X	X
HVO, high blend (renewable diesel/petrol)	X	X	X	X
HVO, low to medium blend in fossil fuel	X	X	X	X
Ethanol, high blend	-	X	-	-
Ethanol, low blend in fossil petrol	-	X	-	-
ED95	-	-	X	X
DME	-	-	-	X
Synthetic diesel (F-T diesel), high blend	X	-	X	X
Synthetic diesel (F-T diesel), low blend in fossil fuel	X	-	X	X
Methanol, low blend in fossil petrol	-	X	-	-
Butanol, low blend in fossil petrol	-	X	-	-

5.3 Emission requirements and aftertreatment systems

For all new vehicles sold, emission standards must be met. In Europe, the European Emission Standards define the acceptable limits for exhaust emissions.

Currently, emissions of nitrogen oxides (NOx), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated. For diesel vehicles, main focus in development is put on reducing the emissions of NOx and PM, which are the most challenging emission requirements to meet.

In *Figure 1*, the evolution of emission regulations for NOx and PM for heavy duty vehicles are illustrated.

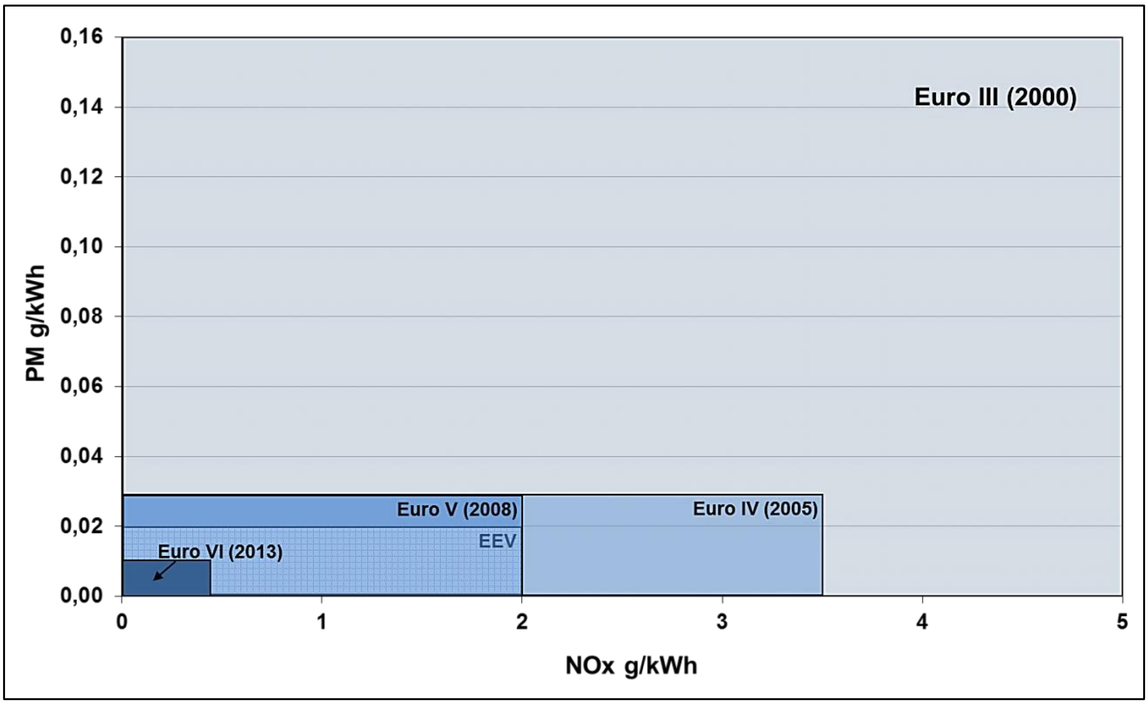

Figure 1: Illustration of emission requirement development for NOx and PM for heavy duty vehicles.

To meet the emission standards, different aftertreatment systems are developed. Depending on the aftertreatment system, the level of NOx and PM will vary even when using the same fuel and the same engine. Technologies applied include (but is not limited to): EGR, SCR and DPF.

EGR, Exhaust Gas Recirculation, is a method where exhaust gases are returned to the engine to reduce the combustion temperature. Since NOx is formed when a mixture of nitrogen and oxygen is subjected to high temperature, a reduced combustion temperature reduces the amount of NOx. By replacing some of the oxygen in the combustion chamber with EGR, the effect will be a slower burn of the fuel that results in a lower temperature.

The EGR-system can be internal or external. The internal EGR works through timing of the intake valves and exhaust valves opening and closing in a way that traps some exhausts in the combustion chamber to be part of the next combustion. The external EGR works by routing gases externally on the engine, usually through an EGR-cooler to reduce the gas temperature before it is mixed with the engine intake air. The amount of exhaust gas that is re-circled has to be controlled since too high ratio of exhaust gas re-circulation will have a negative effect on the combustion process, and could prevent a full combustion of all the fuel in the combustion chamber leading to deterioration of emissions from unburned fuel. Each engine is designed for a specific amount of EGR and these limitations must be kept to ensure the exhaust emission content.

SCR, Selective Catalytic Reduction, is a process to convert NOx with a reducing agent and a catalyst into nitrogen (N2) and water. For diesel engine emission control, urea is used as a reducing agent that is injected in the exhaust before a catalytic converter. Urea is commercially known as AdBlue or DEF (Diesel Exhaust Fluid). The urea system needs to be heated since urea freezes at temperatures below -11° C, and the system also needs to be able to detect urea concentration to prevent drivers from filling the urea tank with other fluids, thereby making the emission control inefficient. The SCR system is therefore a complex system but is together with a DPF in many cases the only way to reach Euro VI emission standards.

DPF, Diesel Particulate Filter, is a filter designed to remove diesel particulate matter from the exhaust gas of a diesel engine. During engine operation, the filter accumulates particles and needs to be cleaned. This is achieved through temporarily increased temperatures to reach soot combustion temperatures in a process known as filter regeneration. The strategies for cleaning are presented in *Figure 2*.

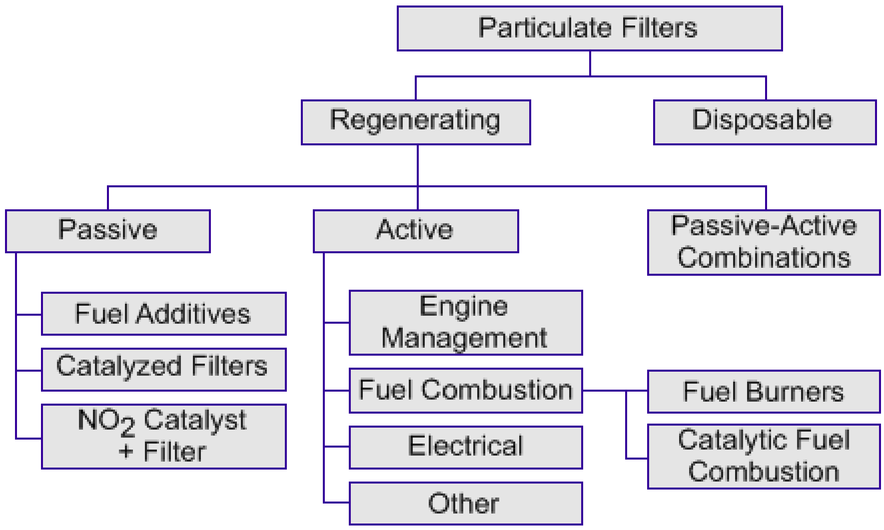

Figure 2: Classification of Filter Systems by Renegeration Method. [1]

DPFs typically use a porous ceramic or cordierite substrate or metallic filter, to physically trap particulate matter (PM) and remove it from the exhaust stream. After it is trapped by the DPF, collected PM is reduced to ash during filter regeneration. Regeneration occurs when the filter element reaches the temperature required for combustion of the PM. "Passive" regeneration occurs when the exhaust gas temperatures are high enough to initiate combustion of the accumulated PM in the DPF, without added fuel, heat or driver action. "Active" regeneration may require driver action and/or other sources of fuel or heat to raise the DPF temperature sufficiently to combust accumulated PM. The frequency of regeneration is determined by the engine's duty cycle, PM emission rate, filter technology and other factors. [2]

In passive systems the soot oxidation is lowered to a level allowing for auto-regeneration during regular vehicle operation – a task commonly achieved by introducing an oxidation catalyst to the system. The catalyst can promote oxidation of carbon through two mechanisms:

- Oxygen mechanism – catalytic oxidation of carbon by oxygen, or
- Nitrogen dioxide mechanism – catalytic oxidation of NO to NO2, followed by the oxidation of carbon by nitrogen dioxide.

NO2 based regeneration can be conducted at lower temperatures than oxygen regeneration, and is the dominant regeneration mechanism in most catalytic (passive and active) DPF systems. [1]

It is possible to combine the DPF with an SCR system in order to reduce NOx/NO2 emissions.

5.4 Health impacts

Exhaust emissions from vehicles can cause many different health effects. The most commonly known compounds from vehicle exhausts and their health effects are described in the following.

Particulate Matter (PM)
Caused by: Incomplete combustion (motor vehicles primarily emits particles in the size of 2.5 micrometers or smaller).
Particulate matter (PM) is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.
The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometers in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects. [2]

Carbon monoxide (CO)
Caused by: Incomplete combustion.
Carbon monoxide (CO) is a colorless, odorless gas emitted from combustion processes. In urban areas the majority of CO emissions to ambient air come from mobile sources. CO can cause harmful health effects by reducing oxygen delivery to the body's organs (like the heart and brain) and tissues. [2]

Nitrogen oxides (NOx)
Caused by: High temperature reaction between nitrogen and oxygen.
Nitrogen oxides (NOx) consist mainly of the sum of nitric oxide (NO) and nitric dioxide (NO2). For health and environmenal effect issues, NO2 is the component of greatest interest and is also used as an indicator for the larger group of nitrogen oxides. NO2 forms quickly from emissions from cars, trucks and buses, power plants, and off-road equipment. In addition to

contributing to the formation of ground-level ozone, and fine particle pollution, NO2 is linked with a number of adverse effects on the respiratory system. [2]

Hydrocarbons (THC – Total Hydrocarbons)
Caused by: Incomplete combustion.
Hydrocarbons are a type of Volatile Organic Compound (VOC). VOCs are chemicals containing hydrogen, carbon, and possibly other elements, that evaporate easily. Hydrcarbons, and other VOCs, contribute to the formation of ozone. A number of exhaust hydrocarbons are also toxic, with the potential to cause cancer. [2]

Many factors affect the exhaust emissions generated in an engine/vehicle, i.e. engine technology, emission standard, sampling methods, driving cycles and exhaust aftertreatment. To be able to distinguish the influence of the different factors, extensive test programs have to be performed.

It is also of importance to look at the real-life emissions from fuels and vehicles. The testing performed on engine test benches are performed under certain conditions which may not reflect the exhaust emissions from the vehicle when driven on-road. Another concern is exhaust aftertreatment systems, like SCR, which reduces NOx very efficiently in the test cell. If an SCR-equipped bus is driven in urban areas where the engine load and exhaust temperature is low, the reduction of NOx can be temporarily inactivated.

In this literature study, scientific reports have been investigated and summarized and the main factors affecting emissions have been described. For some fuels it has been possible to draw general conclusions regarding decreases and increases of specific emission components. Some of the fuels included in this study are still under development and more research is crucial to be able to estimate the effects regarding both environmental and health issues.

It is important to remember that engine technologies, fuel standards etc develop fast and scientific reports soon become out-of-date. This especially concerns the fuels that are still under development.

5.4.1 Health effects

As discussed earlier, the exhaust emissions are affected by vehicle emission standard, exhaust aftertreatment, driving cycle etc, in addition to the influence of the fuel. When studying the health effects of different fuels there are more factors affecting the results, such as sampling method (i.e. gaseous phase, filter, semivolatile compounds etc), methodology, exposure levels and endpoints.

Health effect studies from exhaust emissions from different fuels are a research area that should be highlighted. The US EPA categorized scientific studies into different fields, and found that despite rapid growth in biofuel production worldwide, it is uncertain whether decision-makers possess sufficient information to fully evaluate the impacts of the industry and avoid unintended consequences. Doing so requires rigorous peer-reviewed data and analyses across the entire range of direct and indirect effects. To assess the coverage of scientific research, the authors analyzed over 1600 peer-reviewed articles published between 2000 and 2009 that addressed 23 biofuels-related topics within four thematic areas: environment and human well-being, economics, technology and geography. The least studied topics, excluding geographical categories, were human health, trade and biodiversity. Human health and trade, in particular, were represented by a very limited number of articles (15 and 34, respectively). [3]

The paucity of studies addressing human health, trade, and biodiversity has several implications. With the escalation of biofuel production and use locally and globally, a renewed examination of risks and hazards for human populations facing chemical exposures is certainly warranted. [3]

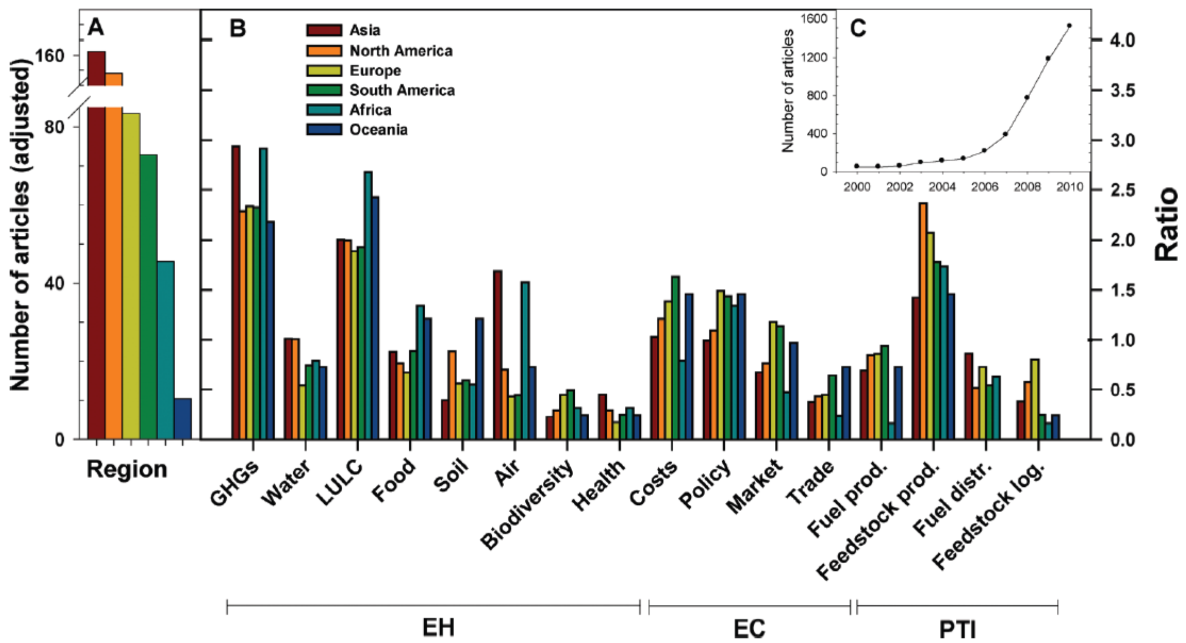

Figure 3: Biofuels publishing trends by geographic region, topic and year. (A) Total numbers of articles retrieved per region. (B) Ratio of the number of articles per topic for a region to the average number of articles per topic for that region. Topics are grouped by thematic areas. EH = Environment and Human Well-being, PTI = Production-Distribution Technology and Infrastructure, EC = Economy. (C) Raw number of articles retrieved per year from 2000 to 2010, unadjusted by a relevancy ratio. [3]

In addition to the need for more research regarding health effects, the methods used to analyze the effects have to be standardized.

In the scientific research different methodologies are acknowledged, such as:

- In-vitro (f.ex. cell cultures, Ames' bioassay etc)
- In-vivo (animal exposure)

There are also more theoretical methods, where factors for different compounds are used to calculate the potential effects (i.e. the US EPA use Toxic Equivalence factors (TEF) for different compounds). This method assumes that compounds have additive effect, and that the effect is linear.

In an IEA (International Energy Agency) activity, research regarding health effects are gathered [4]. The toxic compounds may be in gaseous, semi volatile and solid form. Some are not regarded by the respective legislation; some new substances may appear, due to the progressing technical developments and new systems of exhaust gas aftertreatment. [4]

There are a lot of worldwide activities concerning health effects worldwide. The challenge lies in the fact that they have different objectives, different approaches and methodologies and the results can rarely be directly compared to each other. The IEA project was initiated in order to investigate the possibility to develop harmonized methods. [4]

The report describes a new method for assessing health effects of exhaust compounds. The toxicological effects of exhaust gases as whole aerosols (i.e. all gaseous components together with particle matter and nanoparticles) can be investigated by exposing the living cells, or cell cultures to the aerosol, which means a simultaneous superposition of all toxic effects from all active components. Researchers have shown that this method offers more objective results for validation of toxicity, than other methods used up to date. It also enables a relatively quick insight in the toxic effects with consideration of all superimposed influences of the aerosol. According to the author, this new methodology can be applied for all kinds of emission sources. [4]

The IARC Monographs Program identifies environmental factors that can increase the risk of human cancer. The Monograph is a comprehensive and critical review and evaluation of the published scientific evidence on the carcinogenicity of human exposures. National health agencies can use this information as scientific support for their actions to prevent exposure to potential carcinogens. [5]

The World Health Organization (WHO) has established Air quality guidelines for different compounds [6]. These guidelines were updated in 2000 based on new scientific evidence. In the guidelines, there is distinction between short-term and long-term exposure, where appropriate. For some compounds, there are threshold levels (below these levels, no effect has been noted). The guidelines are changed and/or updated continuously, for example, the

limits for nitrogen dioxide and PM were updated in 2005 [7]. In Table 5, some compounds related to exhaust emissions are described.

Table 5: Examples of Air quality guidelines [6] [7].

Substance	**Time-weighted average**	**Averaging time**	**Comment**
Benzene	n.a.	n.a.	Carcinogenic, no safe level of exposure
Butadiene	n.a.	n.a.	Varying cancer risk estimations
Carbon monoxide (CO)	100 mg/m3 (90 ppm)	15 min	
	60 mg/m3 (50 ppm)	30 min	
	30 mg/m3 (25 ppm)	1 hour	
	10 mg/m3 (10 ppm)	8 hours	
Formaldehyde	0.1 mg/m3	30 min	Low concentration – nose and throat irritation; carcinogenic
Nitrogen dioxide (NO2)	40 microG/m3	Annual	
	200 microG/m3	1 hour	
PM 2.5	10 microG/m3	Annual	
	25 microG/m3	24 hour	
PM 10	20 microG/m3	Annual	
	50 microG/m3	24 hour	

The numerical guideline values and the risk estimates for carcinogens (examples are given in Table 5) should be regarded as the shortest possible summary of a complex scientific evaluation process. Nevertheless, the information given in the tables should not be used without reference to the rationale given in the chapters (please see "WHO: Air quality guidelines" [7] for reference material) on the respective pollutants. [6]

5.5 Health effects and exhaust emissions – biofuels vs conventional fuels

In this literature study, some of the fuels that are available on the market, or will be in the near future, are described. Relevant parts of scientific reports have been cited in "Summary of studies on health effects and emissions" and the opinions and conclusions in this part are the respective authors'.
Where appropriate and possible, main objectives for respective fuel are summarized in "General conclusions" – these are opinions/conclusions from the author of this report.
Some figures from the reports have been edited in order to focus on the respective fuel.

5.5.1 Fossil petrol

5.5.1.1 Basic facts – Fossil petrol

Raw material:
Crude oil

Applicable standard:
EN228

Current use:
- All over the world in SI (spark ignited) applications;
- Potential to blend with different biofuels.

Current limitations for increased usage:
Increased demand from emerging markets.

Outlook for future use:
- Limited amount of raw material;
- Possibly less use in the future due to European legislation (EU Renewable Energy Directive [8]) to increase use of renewable fuels;
- Continued usage as blending component in biofuels.

Vehicle application:
Light duty vehicles, SI engines

Engine/vehicle conversion:
-

Highlighted emission components:
-

5.5.1.2 Summary of studies on health effects and emissions – fossil petrol

In a study performed by the University of Southern California, several light duty vehicles were tested with the objective to investigate the toxicology of particulate exhaust emissions [9]. The vehicle tests were conducted at the light-duty dynamometer facility of the Laboratory of Applied Thermodynamics at Aristotle University in Thessaloniki, Greece.

Three vehicles in a total of five configurations were tested, see Table 6. The Honda Accord and the VW Golf vehicles were tested with two different configations.

Table 6: Test vehicles – general information.

Make / model	**Emission standard**	**Emission control**	**Fuel**
Honda Accord i-CTDi	Euro 4	Closed-couped oxidation catalyst (pre-cat) + EGR + main underbody oxidation catalyst	Diesel 10 ppm S
- " -	Euro 4+	Pre-cat + EGR + Ceramic catalyzed DPF	Diesel 10 ppm S
Toyota Corolla	Euro 3	Three-way catalytic converter	Unleaded Gasoline RON95
VW Golf TDi	Euro 2	Oxidation catalyst	Neat soybean biodiesel
- " -	Euro 1	-	Diesel 50 ppm S

Each vehicle/configuration was tested according to the NEDC and the CADC driving cycles. PM was collected on filters which were analyzed for elemental and organic carbon; water-soluble and water-insoluble organic carbon; inorganic ions (chloride, sulfate, nitrate, phosphate, sodium and ammonium); trace elements and metals, and speciated organic compounds. For the toxic assays an in-line impinger was used to collect PM in de-ionized water. The aqueous PM suspensions were used in DTT and ROS toxicity assays.

The DPF-equipped diesel and the gasoline vehicle had substantially lower PM mass emission rates compared to the other vehicles/configurations. The baseline Golf diesel vehicle with the oldest emission control standard had the highest PM emissions, and the other two non-DPF equipped diesel and biodiesel-fuelled vehicles also had high emission rates.

The analysis of organic and elementary carbon; water-soluble and water-insoluble organic carbon and PAHs resulted in significantly lower levels for the DPF-equipped diesel and the

gasoline vehicle compared to the other vehicles/configurations. The PAHs were analyzed according to the molecular weight, differentiated into three stages (<228, 229-275, >276 g/mole). The PAHs in the lighter phase are important in terms of the potential to generate oxidative stress. The lighter PAHs are primarily found in the semi-volatile phase, whereas the heavier PAHs are typically found in the filter phase.

The analysis of selected trace elements and metals showed the highest sulfur emissions for the gasoline vehicle. The reason for this is, according to the authors, due to secondary air injection equipment on this particular vehicle. The gasoline vehicle was also characterized by higher emissions of Mn, Fe and Cu compared to the DPF-equipped diesel vehicle. Mn is a known knock improver and is probably used in the gasoline car at trace concentration levels in order to improve the octane number of the fuel. [9]

As mentioned earlier, two toxicity assays were conducted on the liquid PM suspension. The dithiothreitol (DTT) assay provides a measure of the overall redox activity of a given sample based upon its ability to catalyze electron transfer between DTT and oxygen in a simple chemical system. It is sensitive to the redox activity of organic compounds and is particularly appropriate for motor vehicle exhaust. The electron transfer is monitored by the rate at which DTT is consumed under a standardized set of conditions. The rate is proportional to the concentration of the catalytically-active, redox-active species in the sample. [9]

The redox activity/ROS production of exhaust emission PM was also measured using a biological ROS assay in addition to the DTT test. The biological assay involves in vitro exposure to rat alveolar macrophage cells, and examines the production of ROS as well as the response of the alveolar macrophage cells.

The oxidative activity rate, analyzed in the DTT assay, was lower for the gasoline vehicle compared to the other vehicles/configurations, with the exception of the DPF-equipped diesel vehicle which showed even lower activity rates.

The macrophage ROS assay is sensitive to transition metals because of their ability to catalyze redox-reactions in which they are not consumed. The distance-based ROS response provides the actual toxicological activity imparted on the environment and humans by these vehicles. The ROS activity is highest for the gasoline vehicle despite its relatively low mass emissions. This is due to its higher elemental content compared to the other four configurations. The lowest level of ROS activity was shown by the Euro 4 diesel vehicle. [9]

Emission factors of particulate-bound PAHs including benzo(a)pyrene but also highly carcinogenic dibenzopyrene isomers from two diesel- and two gasoline-fuelled light-duty vehicles, have been investigated in a research article [10]. In the study, two gasoline-fuelled vehicles complying with emission standard Euro 3 and 2 respectively were used, together with two diesel-fuelled vehicles complying with Euro 4. The vehicles were tested on a chassis dynamometer, according to the driving cycle NEDC and the three Artemis driving cycles

(representing the different patterns of urban, rural and motorway driving). The regulated components were investigated in the driving cycles, but the PAH content in the PM emissions was analyzed for the Artemis driving cycles.

When comparing the gasoline-fuelled vehicles with the diesel-fuelled it is important to have in mind the differences in emission standard. The gasoline-fuelled vehicles clearly emit larger amounts of HC and CO and lower amounts of NOx and particulates than the diesel-fuelled vehicles.

The main focus in the study is to thorougly investigate the PAHs in the PM emissions. Benzo(a)pyrene is the most thorougly studied PAH, and is classified by IARC [5] as carcinogenic to human beings. The dibenzopyrene isomers dibenzo(a,l)pyrene, dibenzo(a,e)pyrene, dibenzo(a,i)pyrene and dibenzo(a,h)pyrene are considered to be potential human carcinogens by the US Department of Health and Human Services [11]. The relative carcinogenic activities of the compounds were calculated by multiplying the emission factors of the individual PAHs by their respective TEF values, obtained from a literature review from 2002 (referenced in the article). The highest TEF values were selected from different studies, with the rationale to simulate the worst case scenario. The large variation in reported TEF values stems from the different ways of deriving them and the results of this present study will of course highly depend on the TEFs selected for the different PAHs. However, the same TEFs are used for both the gasoline-fuelled and the diesel-fuelled vehicles thereby making a relative comparison possible between the different vehicles and driving cycles.

The obtained results showed the diesel-fuelled vehicles to emit higher amounts of PAHs than the gasoline-fuelled vehicles per km driving distance at low average speed in the Artemis Urban driving cycle, while the gasoline-fuelled vehicles emitted higher amounts of PAHs per km driving distance at higher average speeds in the Artemis Rural and Motorway driving cycles (Figure 4). Furthermore, the study showed an increase in PAH emissions per km driving distance with increasing average speed for the gasoline-fuelled vehicles, with the opposite trend for the diesel-fuelled vehicles. The gasoline-fuelled vehicles generated particulate matter with higher PAH content then the diesel-fuelled vehicles in all three driving cycles tested, with the highest concentrations obtained in the Artemis Rural driving cycle. The diesel-fuelled vehicles displayed higher sum added potential carcinogenicity of the measured PAHs than the gasoline-fuelled vehicles in the Artemis Urban driving cycle, with the opposite trend found in the Artemis Rural and Motorway driving cycles (Figure 5). [10]

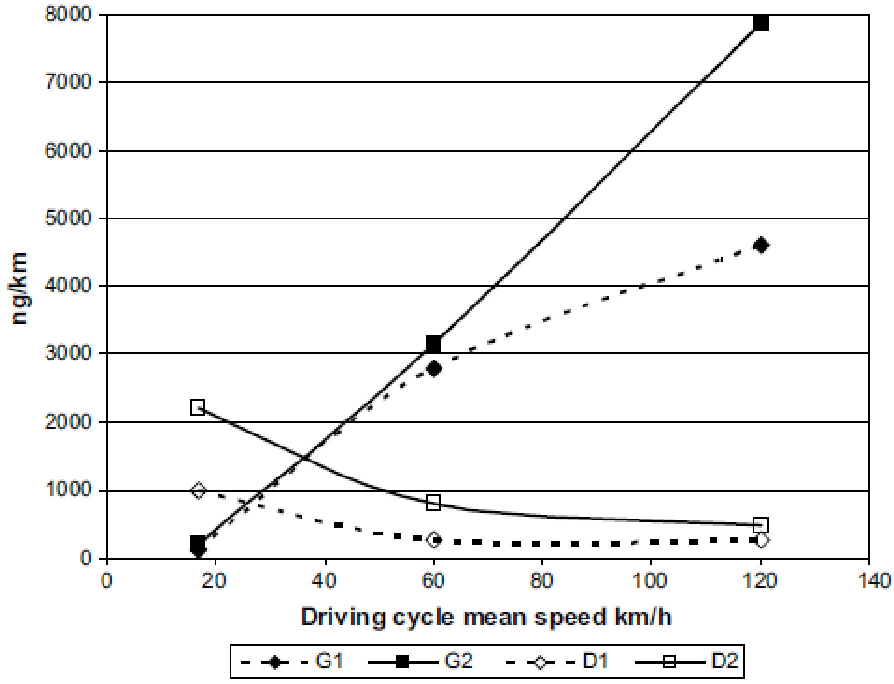

Figure 4: PAH emissions per km driving distance as a function of the average speed for the two gasoline- (G1 and G2) and the two diesel (D1 and D2)-fuelled vehicles operated in the Urban, Rural and Motorway transient Artemis driving cycles. [10]

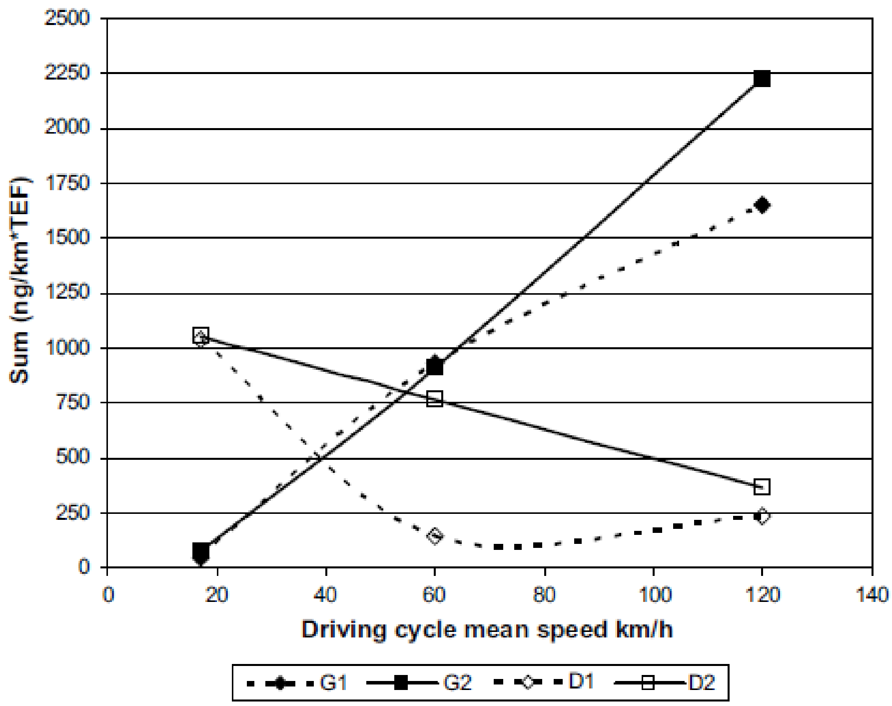

Figure 5: Sum added potential carcinogenicity of the measured PAHs as a function of the average speed for the two gasoline- (G1 and G2) and the two diesel (D1 and D2)-fuelled vehicles operated in the urban, Rural and Motorway transient Artemis driving cycles. [10]

The findings of this study show the importance of including the dibenzopyrenes in vehicle exhaust chemical charcterizations to avoid potential underestimation of the carcinogenic activity of the emissions. The lower emissions and the lower sum added potential carcinogenicity of the measured PAHs found in this study for the gasoline-fuelled vehicles, compared to the diesel-fuelled, in the Artemis Urban driving cycle indicate the gasoline-fuelled vehicles to be preferred in dense urban areas with traffic moving at low average speeds with multiple start and stops. However, the obtained results suggest the opposite to be true at higher average speeds with driving at rural roads and motorways. Further studies are however needed to establish if the observed differences between gasoline-fuelled and diesel-fuelled vehicles are generally valid, as well as to study the effects on variations in vehicle/engine type, ambient temperature, fuel and driving conditions on the emission factors. [10]

5.5.1.3 General conclusions – fossil petrol

The studies have compared fossil petrol and fossil diesel, and from these comparisons the following conclusions can be outlined:

- Emissions of **CO and HC are higher** for gasoline-fuelled vehicles;
- Emissions of **NOx are lower** for gasoline-fuelled vehicles;
- Emissions of **PM are lower** for gasoline-fuelled vehicles, although:
    - **ROS activity was highest** for the gasoline-fuelled vehicle (as presented in one study), and
    - **PAH content** was lower in the Urban driving cycle, and higher in the Rural and Motorway driving cycles (as presented in one study).

5.5.2 Fossil diesel

5.5.2.1 Basic facts – Fossil diesel

Raw material:
Crude oil

Applicable standard:
EN590.
All diesel fuel sold in Europe must fulfill the standard specifications.
Some countries, like Sweden, have additional and more stringent specifications, for the so-called Mk1 (Miljöklass 1, or denoted EC1 (environmental class 1) in English).

Current use:
- All over the world in CI (compression ignited) applications;
- Potential to blend with different biofuels.

Current limitations for increased usage:
Increased demand from emerging markets.

Outlook for future use:
- Limited amount of raw material;
- Possibly less use in the future due to European legislation (EU Renewable Energy Directive [12]) to increase use of renewable fuels;
- Continued usage as blending component in biofuels.

Vehicle application:
Heavy duty vehicles – haulage and urban
Light duty vehicles, CI engines

Engine/vehicle conversion:
-

Highlighted emission components:
- Aromats
- PAH
- NOx
- Particles

5.5.2.2 Summary of studies on health effects and emissions – fossil diesel

An extensive investigation regarding health effects from diesel fuels were performed in Sweden in 2011-2012 [13]. The objective of the study was to compare two diesel fuels – Swedish environmental class 1 (Mk1 (English: EC1)) and Swedish environmental class 3 (Mk3) – in respect to emissions and health effects. The Mk3 diesel fuel correlates with the EN590 fuel standard. The Mk1 diesel fuel also correlates with the specification set in EN590 but contains less amounts of aromats and PAH. Aromatics increase the emissions of PAH, of which several are considered to be probable or possible carcinogens to humans.
At AVL MTC, two heavy duty vehicles with emission standard Euro V (one equipped with EGR and one with SCR exhaust aftertreatment) were tested on chassis dynamometer. The regulated emissions were analyzed, in combination with unregulated compounds such as: aldehydes, online particle emissions (gravimetrically and size/number distribution), ethene, propene, benzene and 1,3-butadiene. The PAH emissions were sampled on large filters (particulate phase) and PUF (polyurethane foam) for the semivolatile phase. The filters and PUFs were extracted and analyzed for specified PAH compounds. The PAH extracts were also used for Ames' bioassay test to analyze the mutagenicity of the samples.

The vehicle was driven according to the WHVC (Worldwide harmonized vehicle cycle) driving cycle, which includes three driving patterns – urban, rural and motorway. The tests were performed both with cold and hot start (i.e. start of cold engine and warm engine, respectively, at the beginning of the test).

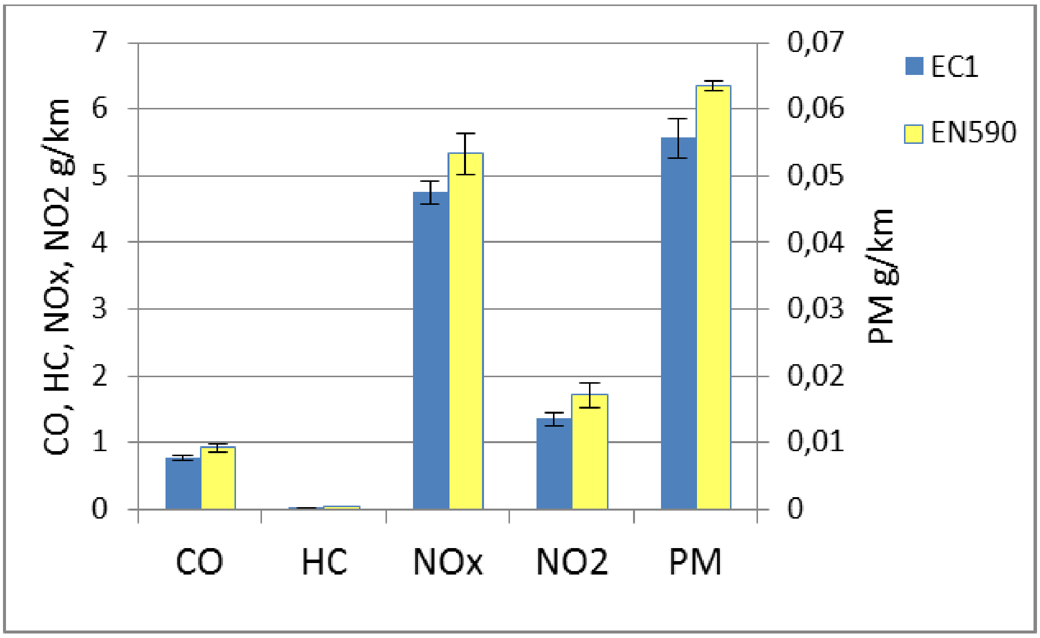

Figure 6: Comparison of regulated emissions and NO2 from tests with EC1 (Mk1 diesel) and EN590 (Mk3 diesel, the regular fossil diesel available on the Norwegian marked). Hot start, SCR vehicle. [14]

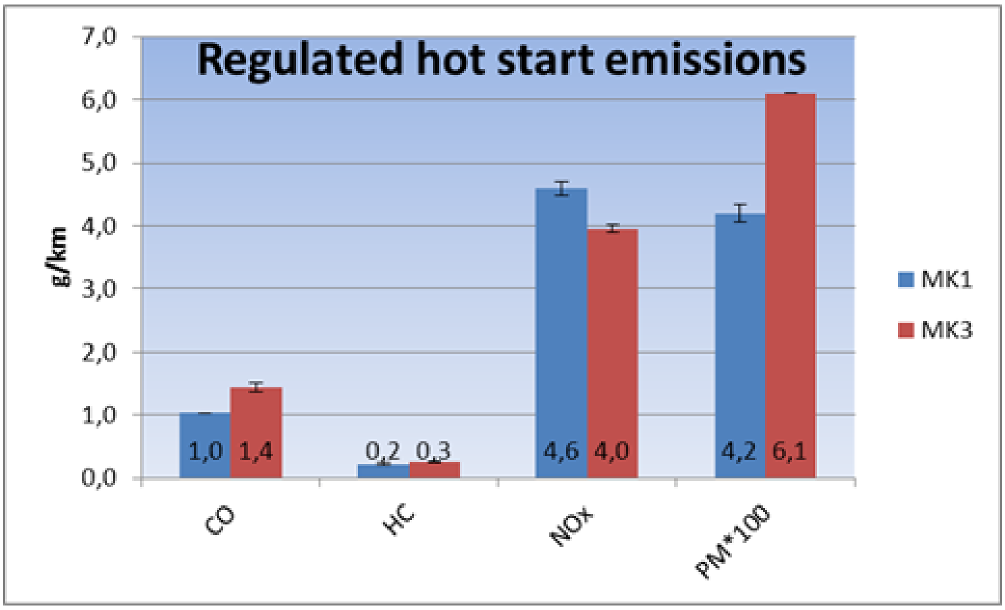

Figure 7: Regulated hot start emissions from the EGR vehicle when using Mk1 and Mk3 diesel fuel. Mk3 diesel is the regular fossil diesel available on the Norwegian marked, while Mk1 refers to the Swedish environmental class 1-diesel [13]

The NOx and PM emissions from the different driving patterns included in the WHVC test cycle are presented in *Figure 8* and *Figure 9*. The NOx emissions are significantly higher for Mk3 diesel compared to Mk1 during phase 3 representing highway driving. The transient PM emissions were measured with a TEOM (Tapered Element Oscillating Microbalance), with elevated levels for Mk3 diesel during urban driving.

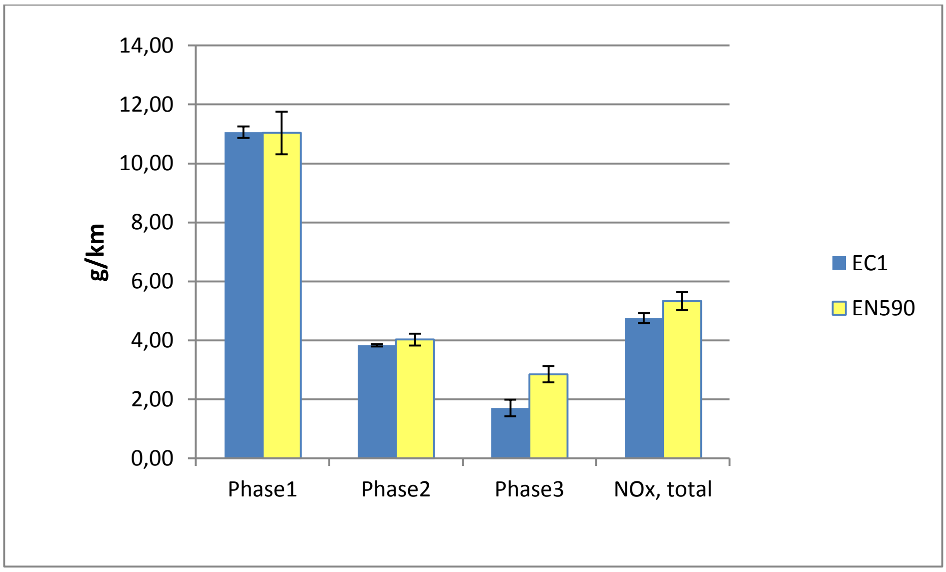

Figure 8: NOx emissions during different phases of the WHVC driving cycle. EC1 refers to the Swedish environmental class 1-diese (Mk1 diesel) and EN590 (Mk3 diesel) is the regular fossil diesel available on the Norwegian marked. Hot start, SCR vehicle. [14]

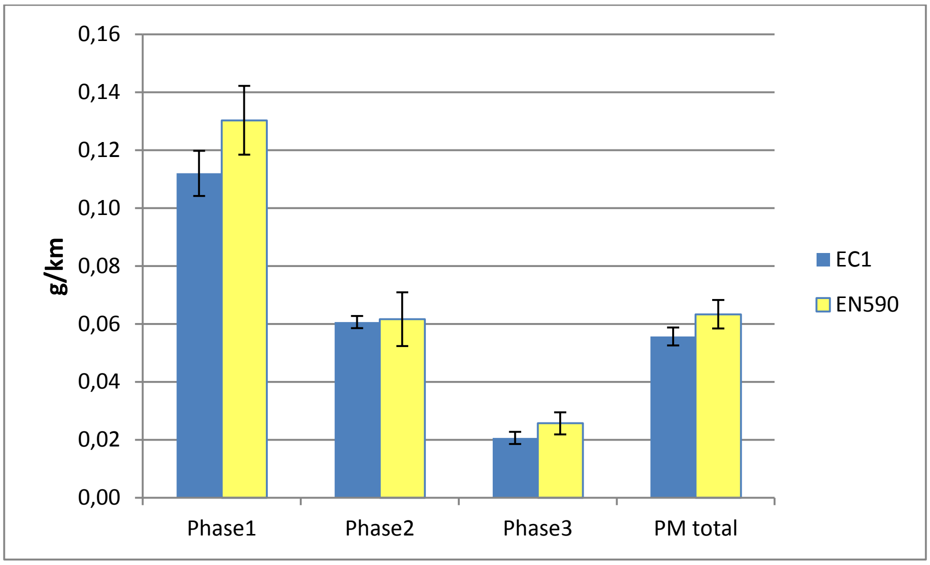

Figure 9: PM emissions during different phases of the WHVC driving cycle. Hot start, SCR vehicle. Online PM measured by TEOM. [14]

The emissions from both vehicles were tested for mutagenicity. Two bacteria strains were used in the Ames' bioassay test – TA98 and TA100 (both of them with and without S9-mix). The effects were different for the two vehicles.
For the SCR vehicle, the TA98 strain gave low but significant effects in most cases, especially in the presence of S9-mix indicating that metabolic activation enhanced the mutagenicity of the sample. Strain TA100 gave a few significant responses.

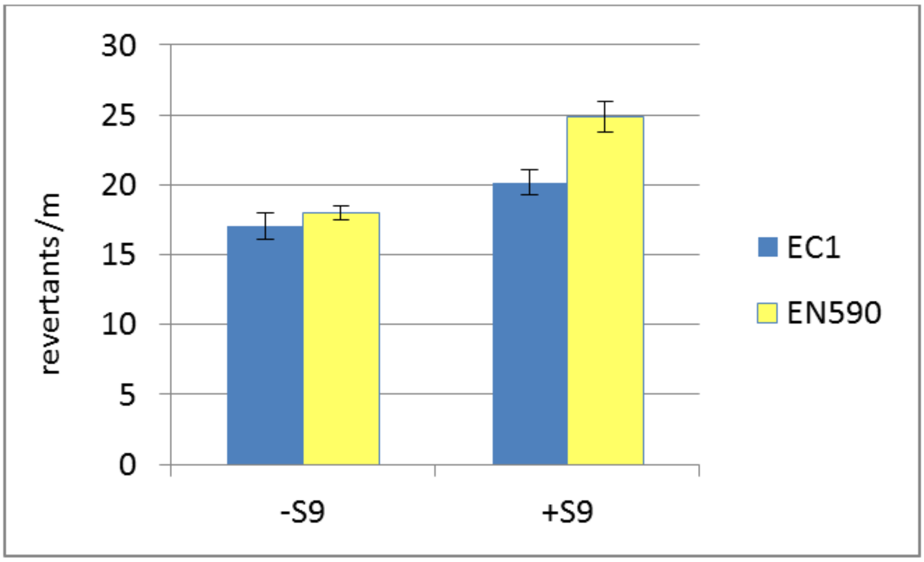

Figure 10: Comparison of results from Ames' bioassay test, strain TA98, revertants per meter. SCR vehicle, hot start [14].

All samples were significantly mutagenic both in the presence and in the absence of the metabolizing system. For the EGR vehicle, the PAH concentrations in the exhaust were much

higher. The exhaust extracts from this vehicle were significantly more mutagenic than the corresponding extracts from the SCR vehicle. For the TA98 strain the hot starts generated higher toxicity with the addition of S9, and the effects were enhanced with Mk3 fuel. For the TA100 strain the hot starts generated higher toxicity without the addition of S9, with higher effects for the Mk3 fuel. To summarize: all samples cause mutagenicity, with the hot start samples and the Mk3 fuel samples having a stronger effect.

The WHO (World Health Organization) classifies diesel engine exhaust as carcinogenic to humans (denoted as Group 1 – "Carcinogenic to humans" in the IARC classification) [15], based on sufficient evidence that exposure is associated with an increased risk for lung cancer.

5.5.2.3 General conclusions – fossil diesel

When comparing the Mk1 and Mk3 (EN590) diesel standard, the following conclusions can be drawn:

- Aromatics and PAH in the emissions can be derived from unburned residues of fuel and as a byproduct from the combustion. Fossil diesel applicable to EN590 standard emits higher levels of these compounds than Mk1 diesel.

- Higher levels of NOx, PM and CO for EN590 than Mk1. The NOx emissions were significantly higher especially during the motorway part of the driving cycle, whereas the PM emissions were significantly higher during the urban part.

- Higher levels of aldehydes, consisting mainly of formaldehyde and acetaldehyde, for EN590.

- Higher mutagenicity for EN590 exhaust (but largest difference due to different exhaust aftertreatment systems in the vehicles).

5.5.3 BioMethane (Biogas)

Biogas is a mixture of biomethane (65-70%) and CO_2 (30-35%) and small amounts of other gases. It is created by anaerobic digestion of organic wastes such as sewage, manure, food wastes etc. After removal of contaminants, biomethane resembles natural gas (of fossil origin). Biogas can be used as a transport fuel in liquefied or compressed form. [16]

CNG (CBG) (Compressed Natural Gas (Compressed BioGas)) is a clean fuel for spark-ignition engines and its low carbon content makes it attractive in terms of CO_2 emissions. It is used in many vehicles around the world, most notably in Italy and Argentina, and the use of CNG increases currently in China. Widespread use would entail a large investment in infrastructure for distributing and compressing CNG/CBG. Specially modified vehicles need high-pressure storage cylinders. Devices that store large amounts of CNG/CBG at lower pressures, possibly adsorbed on a substrate, are desirable but not currently available. Most CNG used in the U.S. transportation system today is in captive fleets with central filling stations, and of these, most are composed of HDVs, such as municipal buses where the size of high-pressure tanks and the distribution issue are not serious detriments.

5.5.3.1 Basic facts – BioMethane

Raw material:
Biomass

Applicable standard:
Swedish standard SS155438; European standard under development

Current use:
Available in small volumes all over the world

Current limitations for increased usage:
- Fuel availability;
- Vehicle availability;
- Infrastructure for high pressure gas delivery (>200 Bar);
- Non-lubricating fuel with possible additional wear on engines.

Outlook for future use:
- Good access to raw material;
- Limited production capacity;
- High investment costs in infrastructure and fuelling equipment.

Vehicle application:
Heavy duty vehicles, SI (gas) engines –urban

Light duty vehicles, SI (gas/bifuel) engines
Engine/vehicle conversion:
Modifications of: pressurized fuel system, engine control system, intake system, valve mechanism.

Highlighted emission components:
- Methane

Comments:
- Biogas needs to be upgraded to be able to use as vehicle fuel;
- Risk for methane slip;
- Possible to mix with compressed natural gas (CNG).

5.5.3.2 Summary of studies on health effects and emissions - biomethane

Whereas most data on CNG/CBG are from vehicles certified to older emission standards, non-methane hydrocarbons (NMHC) and CO emissions associated with CNG/CBG are low. However, NOx emissions may be equal to or a little higher than a gasoline-fuelled counterpart. PM emissions are low. Formaldehyde emissions may be higher than for gasoline and diesel engines, while other toxic emissions are generally low. Methane emissions are higher than for gasoline- or diesel-fuelled vehicles; furthering the design of CNG vehicles with low emissions is an area of active research and development. It should be noted that methane itself, the main constituent of natural gas, is a potent GHG (approximately 20-fold more potent than CO_2), and care must be taken to minimize leakage during production, distribution and use. [16]

PM emissions from a heavy duty bus fuelled with CNG were investigated [17]. The tested bus was of EEV emission standard (i.e. PM emissions are between Euro V and VI standards). The vehicle was tested on a chassis dynamometer and PM was sampled on filters connected to the dilution tunnel. In the investigation, a heavy duty diesel engine was also tested on an engine test bench (due to the differences between the testing of the bus and the engine, the comparison are to be considered as indicative). The CNG bus emitted low PM mass but the comparison was made on a mass basis (i.e. equal mass doses were used for the toxicological setups). The PM emission displayed the strongest potency in MIP-2 (macrophage inflammatory protein 2) production (compared to diesel). The emission PM sample from the CNG bus possessed the weakest genotoxic potency but had the strongest oxidative potency of all the fuel and catalyst combinations. A total of 34 PAH compounds were analyzed. The sum of known genotoxic PAH compounds in particulate samples was calculated on the basis of the WHO-IPCS criteria [18].

The CNG powered bus was anticipated to have the lowest PM mass emission, but when investigated on equal mass doses, these emission PM samples showed highly variable toxic

properties: the strongest oxidative and MIP-2 inducing potency but the weakest genotoxic potency.

The total PAH emission from the CNG bus was the lowest (61,7 ng/mg), and also the smallest amount of genotoxic PAH compounds. The response of emitted PM in MIP-2 production was for the highest dose level larger than the corresponding responses to PM sample from the diesel engine. In the MTT-test (test method for acute cytotoxicity), the emitted PM from the CNG bus and the diesel engine were statistically significantly cytotoxic even at the lowest dose, when compared to controls.

The emission PM sample from the CNG powered bus was the least potent inducer of genotoxicity, which was likely attributable to it's very low PAH content. The ROS production after exposures of 264.7 macrophages showed that the PM sample from the CNG bus was more potent in causing oxidative stress in macrophages on an equal mass basis, but the difference was not significant. In the conclusions, the authors state that the harmfulness of exhaust emissions cannot be determined merely on basis of the emitted mass. The study conditions and the engine type significantly affect the toxicity of the emitted particles. The CNG bus performed best with regard to PM mass and when this low mass is considered, it probably reduces overall harmfulness of these emissions. [17]
As described earlier, the testing was performed differently and comparison can only be considered indicative.

In an extensive study performed by VTT in Finland, buses of different technologies were tested [19]. Among the tested vehicles, there were two CNG buses; one corresponding to EEV emission standard (stoichiometric CNG) and one Euro V (lean-burn CNG). Two diesel fuelled buses with emission standard EEV, one with EGR and one with SCR exhaust aftertreatment, were also included in the testing. The regulated emissions can be studied in *Figure 11*. The vehicles were tested on a chassis dynamometer and driven according to the Braunschweig driving cycle, which is a highly transient cycle simulating urban bus driving.

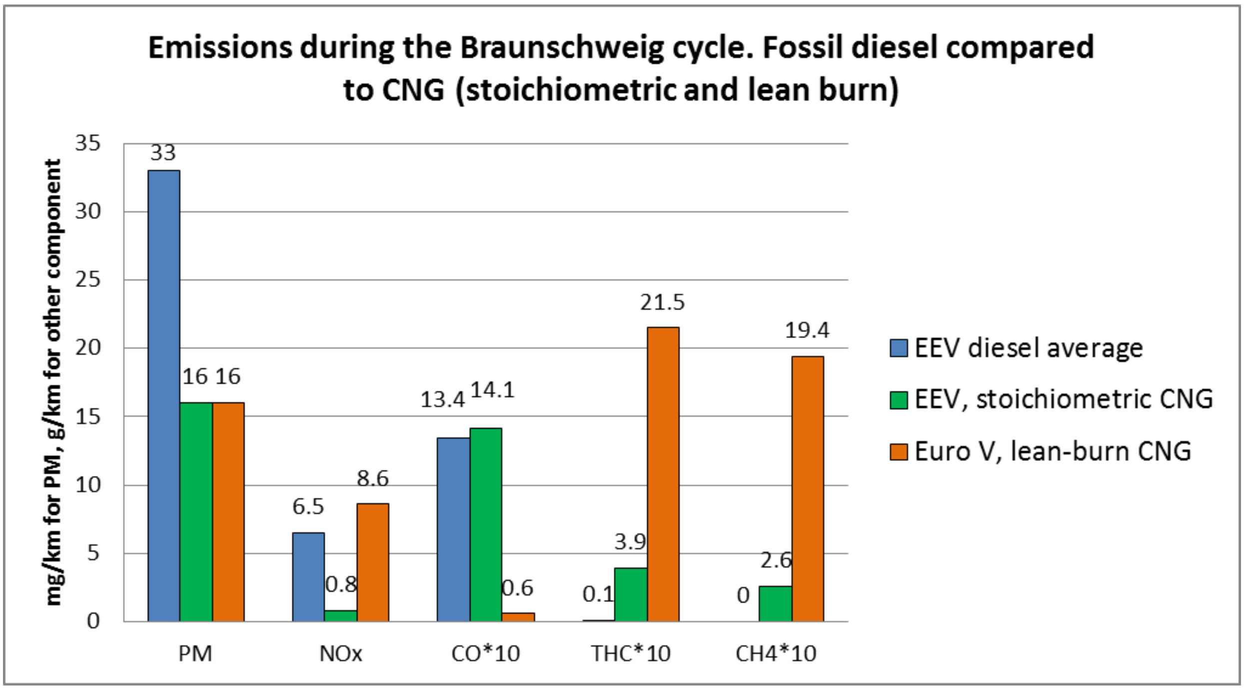

Figure 11: Regulated emissions for diesel vehicle and vehicles using compressed natural gas (CNG). Tests performed with the Braunschweig driving cycle. [19]
(The original figure has been edited in order to focus on specific fuels).

There are differences between the different CNG buses, where the stoichiometric bus have very low emissions of NOx whereas the lean-burn bus emits higher NOx levels than the diesel buses. Both of the CNG buses have low PM emissions. The THC emitted by the CNG buses is mainly CH_4, and the lean-burn bus has much higher emissions compared to the diesel buses and the stoichiometric.

The buses were also tested according to different driving cycles. In *Figure 12* and *Figure 13* the diesel bus equipped with SCR and the stoichiometric CNG bus, respectively, are presented, and the NOx and PM emissions can be compared. The driving cycles typical for city bus driving are ADEME and Braunschweig, whereas UDDS is more representative for truck driving.

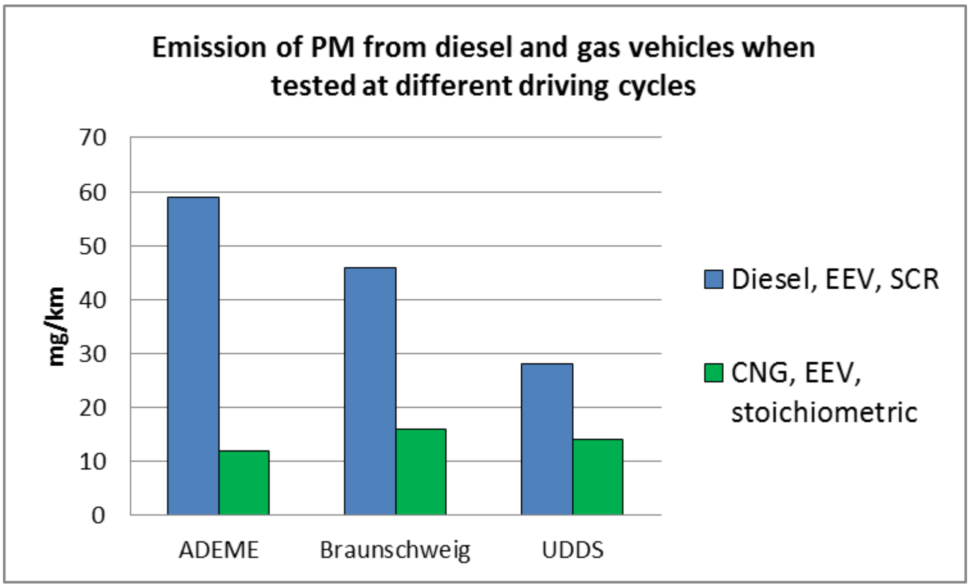

Figure 12: The effect on PM emission when tested at different driving cycles – dieselbus with SCR and CNG bus, stoichiometric. [19]
(The original figure has been edited in order to focus on specific fuels).

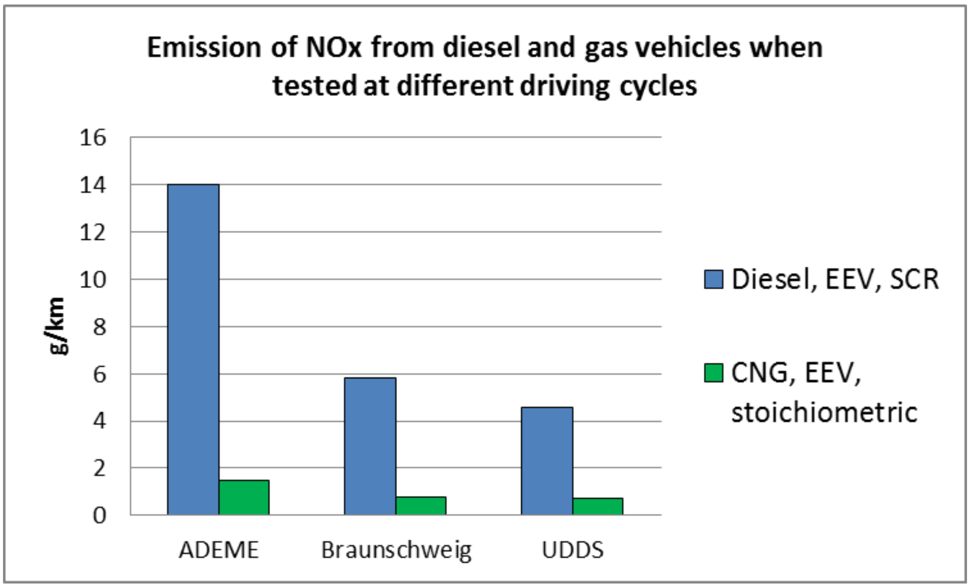

Figure 13: The effect on NOx emission when tested at different driving cycles – dieselbus with SCR and CNG bus, stoichiometric. [19]
(The original figure has been edited in order to focus on specific fuels).

The stoichiometric CNG vehicle consistently shows low emissions and little variation in emissions from cycle to cycle. The particle size distribution (12 stages between 0,02 and 10 microM) was also investigated (presented in *Figure 27*). The CNG buses had the lowest number in total, and in the smallest size class the CNG delivers almost two orders of magnitude lower numbers than the other technologies (including the diesel buses).

The NO_2 directly emitted by the stoichiometric CNG bus was very low. For the lean-burn CNG the emissions were much higher, even higher than for the diesel buses, see *Figure 14*.

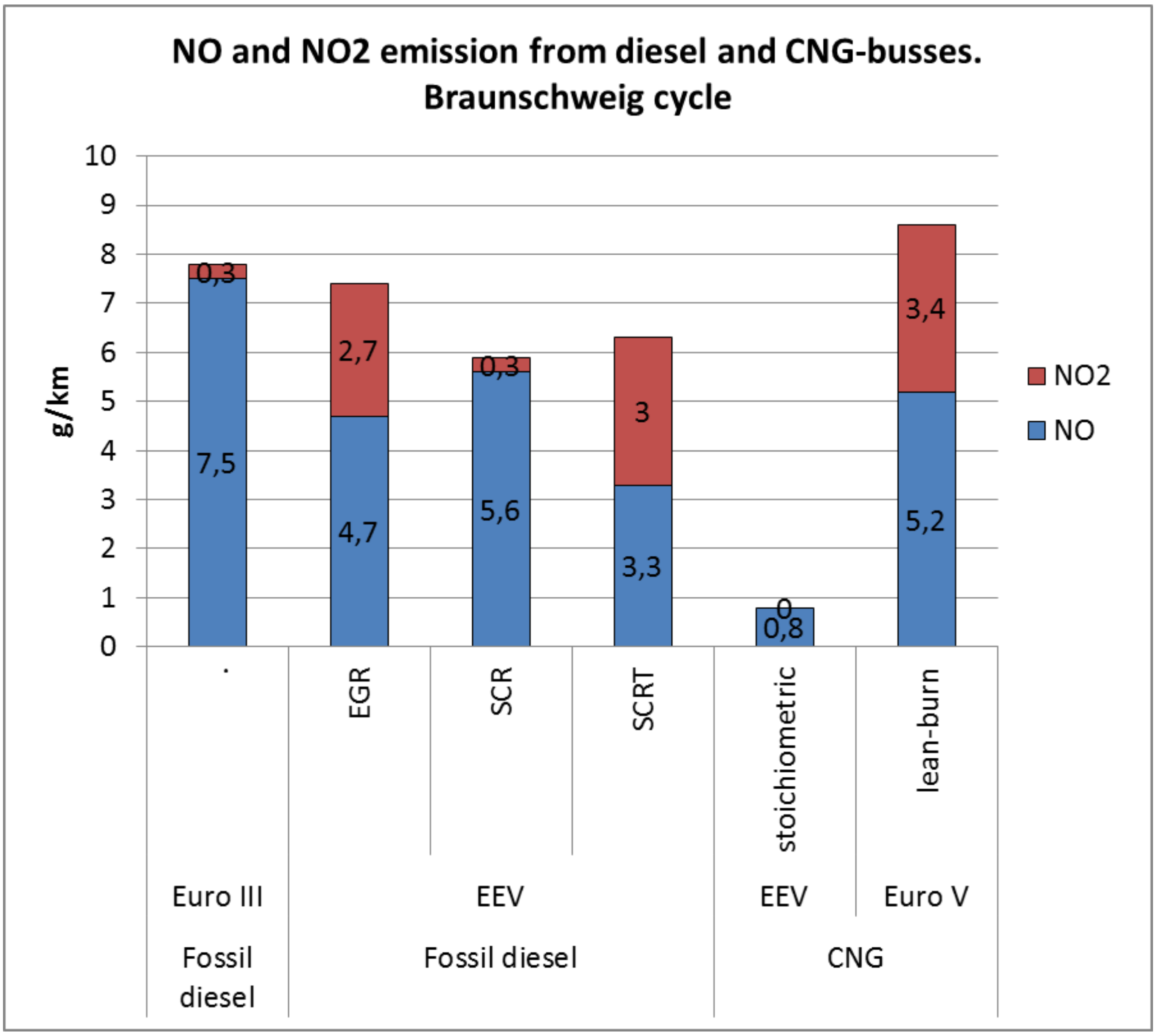

Figure 14: NO_2 and NO emissions for the tested buses – Braunschweig driving cycle. [19] *(The original figure has been edited in order to focus on specific fuels).*

Three vehicles were also tested on-road (Euro III diesel, EEV EGR diesel and stoichiometric CNG). The regulated emissions were analyzed with PEMS (Portable Emission Measurement System) equipment and the soot emissions were analyzed with an MSS (Micro soot sensor). The buses were driven on three bus routes in Helsinki. The results show that the NOx emissions from the CNG bus was much lower compared to the diesel buses, and the soot levels for the CNG bus were below detection limit. [19]

5.5.3.3 General conclusions - biogas

The summarized studies show that the emissions from gas vehicles are very dependent on the technology used.

Generally, when compared to conventional fuels, NMHC and CO emissions are low. For light duty vehicles, NOx emissions may be equal to or a little higher compared to gasoline-fuelled counterpart (for heavy duty vehicles the NOx emissions are dependent on the technology used, please see below). PM emissions are low (but might have stronger oxidative potency). Formaldehyde might be higher.
Test results – different technologies:

Stoichiometric: Low NOx emissions and low PM emissions. THC emissions (mainly CH_4) are also low. The test shows low NOx and PM emissions independent of driving cycle. Low particle number and much lower in the smallest size classes. NO_2 emitted directly was very low. Very low NOx emissions during real-life (on-road) testing.

Lean-burn: High NOx emissions (compared to diesel vehicle) and low PM emissions. High THC emissions (mainly CH4) compared to diesel and stoichiometric CNG bus. Low particle number and much lower in the smallest size classes. NO_2 emitted directly was high, even higher than diesel vehicles.

5.5.4 Biodiesel (FAME)

Biodiesel (FAME – Fatty Acid Methyl Ester) is together with bioethanol one of the most widely used renewable fuels. Biodiesel can be produced from triglycerids from many different feedstocks such as rapeseed oil, sunflower oil, palm oil, soybean oil, animal fat and used cooking oil. Biodiesel belongs to the first generation biofuels, with some exceptions (when produced from non-food crops or residues, such as used cooking oil or animal fats). Depending on the origin of the biodiesel, the properties of the fuel can vary. In northern Europe FAME from rapeseed oil has the most suitable properties and is therefore most commonly used, whereas in the USA FAME from soybean oil is the primary feedstock.

In the synthesis of the FAME, the triglycerids are transesterified into the corresponding methyl esters through a reaction including methanol and glycerol.

Both biodiesel (FAME) and "renewable diesel" (i.e. HVO) can be obtained from lipid feedstock.

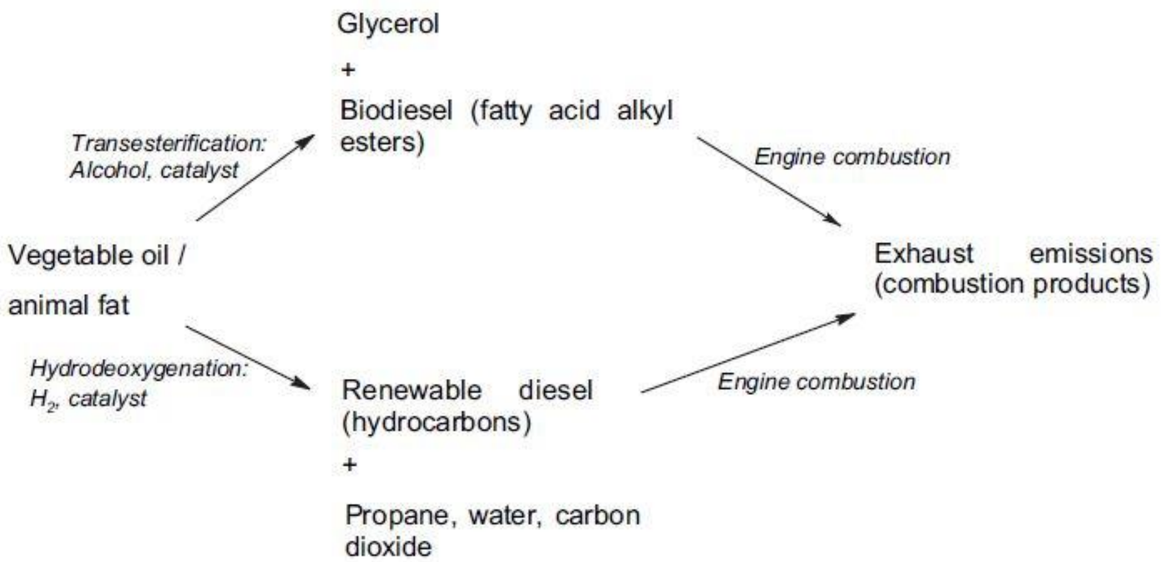

Figure 15: Flow chart for transformation of lipid materials (biodiesel and renewable diesel by hydrodeoxygenation) to products of engine combustion. [20]

Biodiesel is used both as neat fuel and in different blends together with conventional fossil diesel. When the biodiesel is used as neat fuel, B100, it should only be used in dedicated engines.

In Europe the fuel specification for fossil diesel (EN590) allows up to 7% of FAME to be blended in the fuel. In the USA, the use of diesel blend containing 20% of FAME, B20, is increasing.

5.5.4.1 Basic facts – Biodiesel

Raw material:
Oils from various origin, such as; rapeseed, sunflower, soybean, waste cooking oils, animal fat waste, jatropha, fish oil. The characteristics differ due to origin.

Applicable standard:
EN14214

Current use:
Available in small volumes all over the world. Oils of different origins are used in different parts of the world, due to specific characteristics.
Blends up to 7% in diesel (B7), according to specification EN590.
Blends up to 20% in diesel (B20) are used in some parts of Europe and in the USA.
High blends (more than 7%) can require hardware and software modifications.

Current limitations for increased usage:
The legislation for Euro VI will probably affect the use of high blends.
EU legislation (proposal) for limiting use of 1^{st} generation biofuels, and sustainability criteria.
High blends (>7%): Vehicle availability

Outlook for future use:
The legislation for Euro VI will probably affect the use of high blends.
EU legislation (proposal) for limiting use of 1^{st} generation biofuels, and sustainability criteria.

Vehicle application:
Heavy duty vehicles, CI engines –urban, haulage
Light duty vehicles, CI engines

Engine/vehicle conversion:
For high blends: Modifications of hardware and software. Fuel system (i.e. corrosive, sticky components can affect fuel pressure), engine control system. Often shorter service interval.

Highlighted emission components:
- NOx
- Mutagenic for some blends (inconclusive evidence)

Comments:
- Large variance between different feedstocks. At low temperatures (different between different feedstocks) the fuel will go semisolid and clog fuel injection parts and filters;
- Issues are known with bacteria cultures developing in fuel tanks;
- Hydroscopic;

- Deterioration of the fuel and engine oil.

5.5.4.2 Summary of studies on emissions and health effects - biodiesel

Comment regarding HC and biodiesel: Due to the chemical properties of FAME, the measurement principle for hydrocarbons described in test directives is not applicable. For this reason the THC emissions cannot be established correctly.

When comparing the regulated exhaust emission components between B0 and biodiesel blends, the biodiesel blends usually show a decrease for CO, HC and PM, and an increase for NOx. One explanation for this is presented in [21] where the authors attribute this to the presence of higher concentrations of oxygen in biodiesel which improves the combustion and reduces emissions, except for NOx which increases with higher oxygen content.

The emission effects of biodiesel have been studied and US EPA has published a summary of emissions data along with a regression model (US EPA 2002, 2010b) [22]. The data in *Table 7* show that biodiesel reduces emissions of PM, hydrocarbons, and CO and somewhat increases emissions of NOx. Predicted emission effects in heavy-duty diesels are shown for a 20% (volume) concentration of biodiesel, B20, in typical diesel fuel. Other studies have reported similar effects.

Table 7: Biodiesel (B20) emission compared to fossil diesel

Emissions	Percent Change
NOx	+2
PM	-16
HC	-14
CO	-14

Since conventional diesel fuel is highly paraffinic and biodiesel fuels contain esters, it is possible that unregulated emissions will be affected. Based on the particular feedstock used to produce the biodiesel fuel, emissions of formaldehyde and acetaldehyde may increase, as compared with a fossil diesel. More research in this area would be useful.

A review article [22], which includes studies performed prior to 30 April 2011, has analyzed and compared tests where diesel fuels with and without FAME have been used. The studies have included test results from heavy duty engines with emission standard Euro II (applicable from 1996) to Euro IV (applicable from 2005). In most cases, the regulated emission components HC, CO and PM shows a reduction when the fuel contains FAME. However, NOx emissions are increased. The raw material of the FAME has only a small impact on the regulated emissions.

The non-regulated components PAH and Nitro-PAH are generally lower in the exhaust from biodiesel compared to pure diesel fuel. For neat biodiesel, B100, significant decreases of PAH have been observed. For the blends, no consistent pattern can be distinguished, but there is a non-linear trend to lower emissions with increasing biofuel content for most PAH. The highest PAH emissions can be observed for B5 (except for the PAH compounds 2-nitroanthracene and 6-nitrobenzopyrene). When the B20 blend is used, the emissions contains lower amounts of PAH (except for the PAH compounds acenaphthene, fluorene, indeno[1,2,3-c,d]pyrene and 1-nitropyrene).

Some studies showed increased levels of aldehydes in the exhaust emissions from blends. The aldehyde levels in the exhausts were however well below occupational exposure limits. For aldehydes and other non-regulated components there is no consistent trend between diesel fuel and biodiesel blends. One of the conclusions from the authors is however that more recent studies, where more modern engines have been tested (i.e. preferably Euro IV engines), lower emissions are observed, most probably due to improved fuel quality and modern engine technology. [22]

In-vitro studies show indications for higher mutagenicity for the blends. The Ames' bio-assay test [23] was used, where bacterias (*Salmonella typhimurium*, strains TA100 and TA98) were exposed to particle extracts. The tests including blends from B5 up to B40 used in a Euro IV engine. The highest level of mutagenicity was found in B20. There is however a remark in the article regarding the storage of biodiesel blends, which can lead to deposits. This is particularly observed in B20.

Results from studies investigating the non-mutagenic effects, such as cytotoxicity, were also reviewed. The main conclusion was that the strongest effects could be observed for the blends. [22]

The elevated mutagenicity for B20 correlates with the results from engine tests using pure diesel and biodiesel blends up to 20% of RME [24]. In the study, three heavy duty engines were tested. One of the engines (Euro III) was tested with B0, B20 and B100. The regulated and non-regulated exhaust components were measured. For the regulated emissions, CO, HC and PM showed a tendency to decrease with higher biodiesel content, while the NOx emissions were slightly increased (2-4%). The mutagenic effects were determined using the Ames' bio-assay test [23], where the bacterias were exposed to particle extracts. The exposure was performed both with and without the addition of S9 (microsomal mixed-function oxidase systems, S9, extracted from rats – simulation of enzymatic activation). The highest mutagenicity was found at B20 without the addition of S9-mix, leading to the conclusion that the extracts are directly mutagenic and not depending on metabolic activation. The authors conclude that, based on these results, B20 must be considered as a critical blend. According to the authors, a possible explanation for this is that triglycerides boil under decomposition – and those products are usually considered as hazardous to human health. In one of the reference studies the authors had found a maximum of deposits

at B20 that could be oligomers from biodiesel, and the hypothesis is that this could cause the higher induced mutagenicity. [24]

Regulated and non-regulated exhaust emissions were measured from a commercial agriculture tractor [25]. Soybean oil based biodiesel was blended with fossil diesel and the engine was fuelled with blends containing B0, B50 and B100. The exhaust gases and particulate matter were analysed for carbonyls, Volatile Organic Compounds (VOCs) and PAH. The analysis was focused on emissions of organic compounds which are classified as air toxics by the US EPA [25] (i.e. 2,2,4-trimethylpentane, benzene, toluene, ethylbenzene, *m*-, *p*- and *o*-xylene, formaldehyde, acetaldehyde and methylethyl ketone). This study suggests that for the emission rates of the detected hazardous air pollutant, the amount of organic species in the exhaust emissions were reduced with increasing content of biodiesel in the fuel blends. [25]

Although the exhaust emissions from biodiesel blends show a general reduction of PM in total mass [26], the soluble organic fraction of the emitted particles is commonly a greater percentage of biodiesel exhaust emissions, whereas a smaller percentage of insoluble mass is present relative to fossil diesel soot. The smaller production of particles with a greater concentration of soluble organic fraction may impact the biologic effects and toxicity of biodiesel exhaust particles. A review article [26] summarizes some studies including mutagenic and cytotoxic effects of biodiesel. The mutagenic effects had been analyzed in-vitro through the Ames' bio-assay test and in rat hepatocytes. Both these in-vitro tests indicated a higher mutagenic activitiy for the fossil diesel, although more pronounced in the Ames' bio-assay test. One study had analyzed the cytotoxic effect comparing fossil diesel and biodiesel (RME) reporting higher effects from RME emissions. [26]

It is however worth noting that this review article is from 2007 (the latest articles included are from 2005), and both the engines and the production of fuels have changed since then. The authors stress the need to perform similar studies regarding exposure and human health effects as for fossil fuels. [26]

In one study, a Euro 4 light-duty vehicle was tested with different blends of biodiesel with different origins [27]. The regulated exhaust components were measured together with PAH. The blends used were B0, B10, B20 and B30 originating from soybean oil (SME), palm oil (PME), and rapeseed oil (RME) which was blended with limited amounts of sunflower oil and waste cooking oil. All of the FAME blends were examined according to the biodiesel standard EN14214; most of the physiochemical properties were found to agree with the standard, but with a few exceptions. The study found that there were minor differences connected to the biodiesel origin on the reduction of PM, HC and CO; the increased NOx emissions however seemed to be independent on the origin of the fuel. The results showed that the use of biodiesel resulted in increases of lighter PAH emissions when compared to B0. Larger PAHs

were found to decrease with biodiesel. PAH emissions were found to be affected by the average speed and load of the driving cycle, and also by cold-start conditions. In driving cycles simulating urban areas, some increases in PAH emissions were observed for all fuels.

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A test was carried out, where higher blends of FAME were investigated [28]. The light-duty vehicle (category N1) was tested and measurements of regulated components and PAH was performed. The vehicle was driven on a chassis dynamometer according to the NEDC (New European Driving Cycle) and the Artemis driving cycles (simulating urban, rural and motorway driving pattern). The biodiesel used was soy-based (SME), palm-based (PME) and an oxidized biodiesel obtained from used frying oils (UFOME). The diesel fuel used for reference and blendning were an ultra low sulfur diesel. The blends investigated were B30, B50 and B80 (by volume). The vehicle was equipped with a diesel oxidation catalyst and was tested with its original configuration.

The regulated emissions of NOx and PM are presented in *Figure 16*.

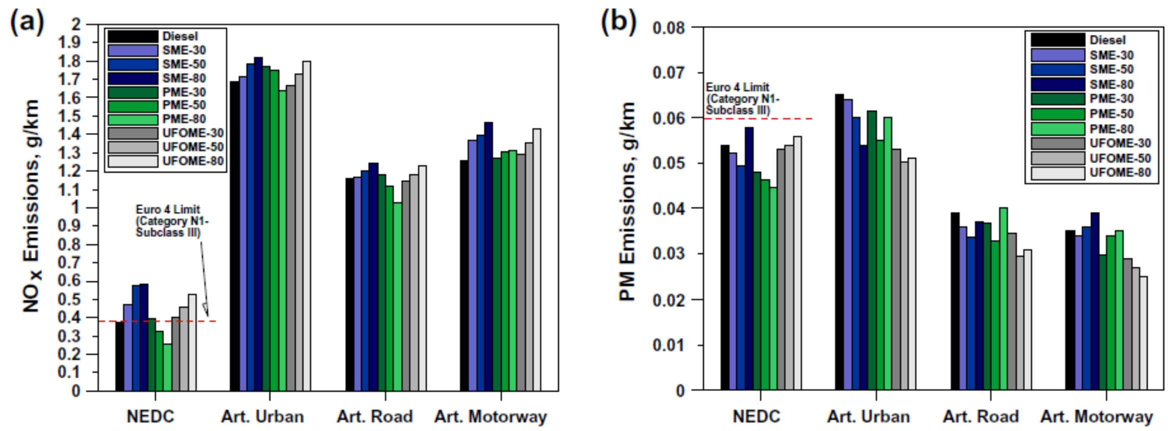
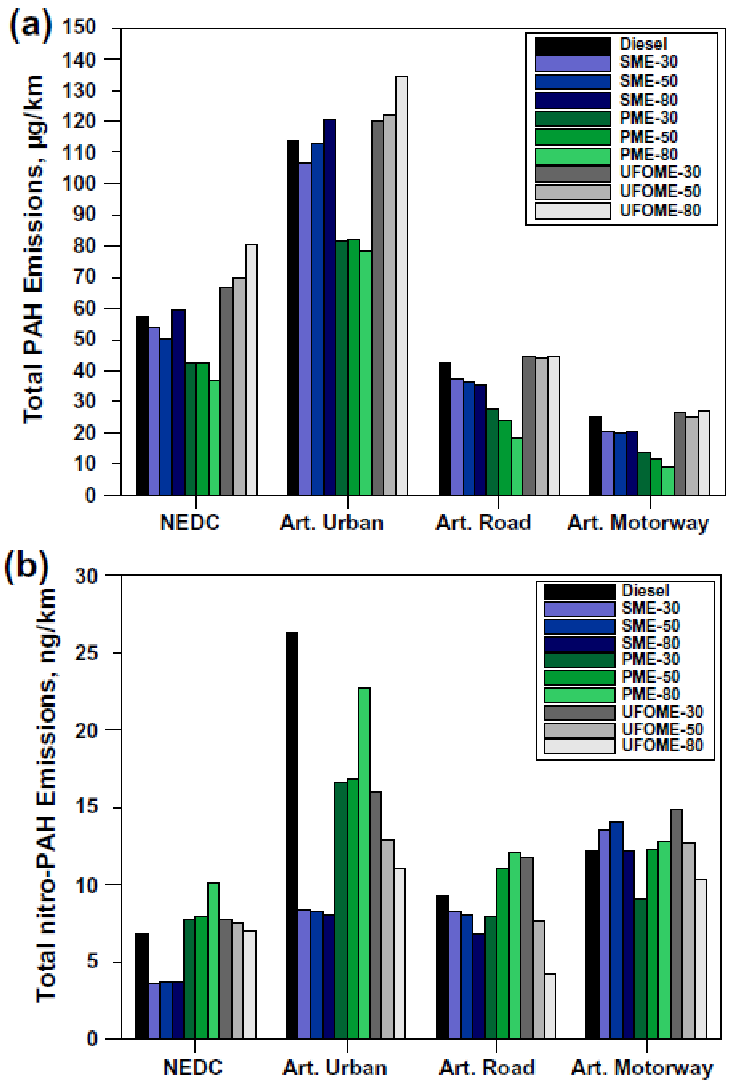


Figure 16: Regulated emissions of NOx and PM over the NEDC and the Artemis driving cycles. SME: Soybean oil Methyl Ester, PME: Palm oil Methyl Ester, UFOME: Used Frying Oil Methyl Esters. [28]

The effect of PAH emissions were also investigated. 12 PAH compounds were analyzed, and the result showed that low and medium molecular-weight PAHs (containing 3-5 aromatic rings) were the most predominant PAH compounds emitted from the vehicle. Phenanthrene, anthracene, fluoranthene and pyrene were the PAH compounds detected at high concentrations for all fuel/cycle combinations. The higher levels of light PAHs suggest that these compounds were pyrolysed from incomplete combustion of the fuel. Some heavier PAH compounds were also found in the exhaust, but in lower amounts than light PAHs. The results revealed that the addition of biodiesel led to some important increases in light PAH emissions. The use of UFOME and SME blends increased the formation of light PAHs, while the use of PME blends resulted in noticeable reductions. Most high molecular-weight PAH

compounds were found to decrease with biodiesel independent of its origin. The same observation holds for benzo[a]pyrene, benzo[a]anthracene and chrysene, which are known for their carcinogenic and teratogenic properties.
*Figure 17*a-c presents the total PAH, nitro-PAH and oxy-PAH emissions, which are the sum of the concentrations of the 12 PAH, 4 nitro-PAH and 6 oxy-PAH compounds, respectively.



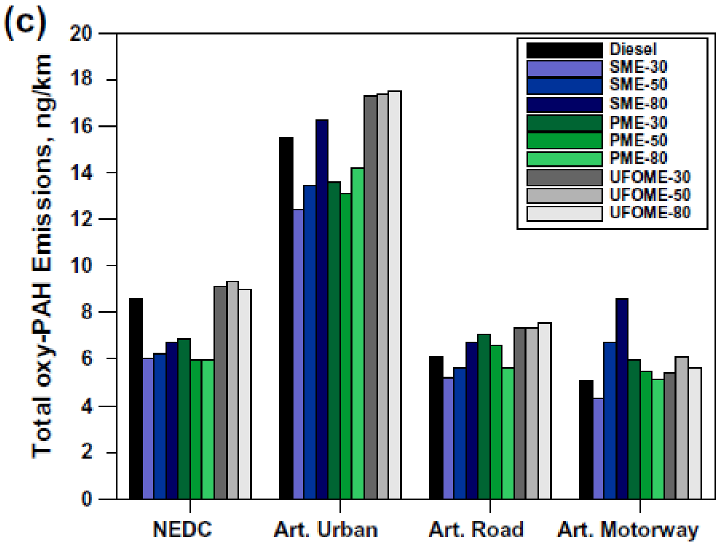


Figure 17: Emissions of total PAHs (a), total nitro-PAHs (b) and total oxy-PAHs (c) for the diesel fuels and biodiesel blends over all fuel/cycle combinations. SME: Soybean oil Methyl Ester, PME: Palm oil Methyl Ester, UFOME: Used Frying Oil Methyl Esters. [28]

The emitted PAHs were clearly influenced by the driving cycle under the present test conditions. The exhaust concentrations of all PAHs were quite low over Artemis Road and Motorway parts when compared to NEDC and Artemis Urban (i.e. simulating driving at low average speeds in urban areas). The observed reductions in PAH emissions can be attributed to the higher average speed and engine load during these driving conditions, which increases exhaust temperatures and performance of the oxidation catalyst.

Diesel particulate matter toxicity can also be assessed by determining the carcinogenic effect of each individual PAH by means of a conversion factor (their toxic equivalent factor, TEF). TEFs were used to estimate human health risk associated with inhalatory exposure to PAHs. *Figure 18* shows the general toxicity of the tested fuels over the different driving cycles. As can be observed there is a clear reduction in the overall toxicity for all biodiesel blends compared to diesel fuel, with the exception of UFOME blends which provided a slight increase in PM toxicity during Motorway operation. This result suggests that the use of an oxidized biodiesel obtained from used frying oils eliminates the benefits of the biofuel with respect to the soy- and palm-based biodiesels. [28]

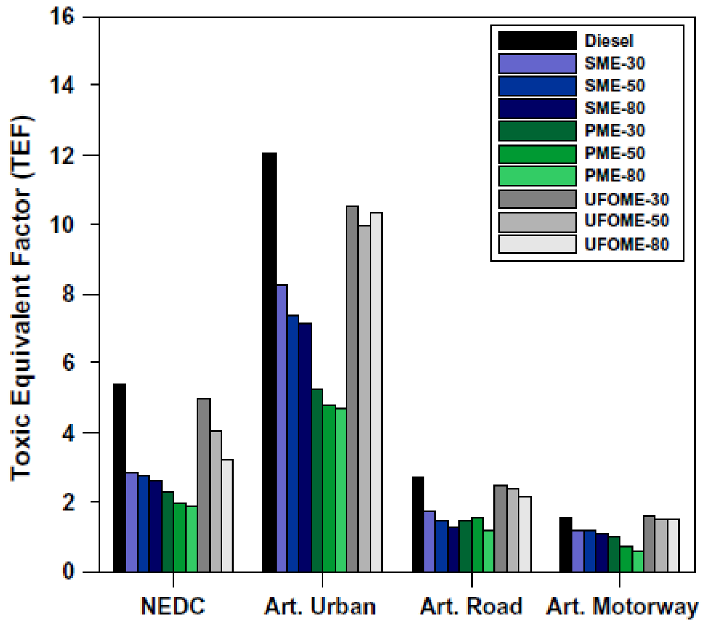


Figure 18: Toxicity equivalent factors (TEFs) for diesel fuel and its blends with biodiesel. SME: Soybean oil Methyl Ester, PME: Palm oil Methyl Ester, UFOME: Used Frying Oil Methyl Esters. [28]

The authors concludes that the experimental results showed that the use of biodiesel led to increases in light PAH emissions as compared to diesel fuel, which were the dominant PAH compounds in the test matrix. However, larger PAHs and those compounds which are known for their carcinogenic properties were found to decrease with biodiesel. [28]

5.5.4.3 General conclusions - biodiesel

Please observe, regarding HC and biodiesel: Due to the chemical properties of FAME, the measurement principle for hydrocarbons described in test directives is not applicable. For this reason the THC emissions cannot be established correctly.

The effect on the exhaust when adding biodiesel to fossil diesel is dependent on the concentration of the blend, as well as operating conditions (urban driving vs motorway).

For both light duty and heavy duty vehicles the regulated emissions of **CO, HC and PM** are generally **reduced** when biodiesel is blended into fossil diesel.

Emissions of **NOx** are generally **increased** with biodiesel blends.

B20 blends seem to induce higher levels of mutagenicity in the Ames' bio-assay test. In one study, the highest mutagenicity was found in B20 without the addition of S9-mix (the compounds are directly mutagenic and are not dependent on metabolic activation).There

are however contradictive results regarding mutagenicity and cytotoxicity for biodiesel.
There is a need for further research in this area.
The problem of deposits seems to be particularly observed in B20.

Aldehydes can be elevated by biodiesel.

There does not seem to be consistent evidence for major emission differences depending on the origin of the biodiesel, with the exception of used frying oils (UFOME). Blends with used frying oil **increased** the **total PAH emissions**.

Different blends affect PAH emissions differently. There are some evidence of a non-linear trend to **lower total PAH emissions** with increasing biofuel content.

There is a tendency for increase of lighter PAH emissions, whereas larger PAH compounds are reduced, compared to fossil diesel.

5.5.5 Hydrogenated Vegetable Oil (HVO)

Like biodiesel (FAME), HVO can be obtained from lipid feedstock (see *Figure 15*). The HVO is produced from fat or oil by a hydrodeoxygenation reaction at elevated temperature and pressure in the presence of a catalyst.

The HVO fuel is fully paraffinic and contains no aromatics, sulfur and oxygen.

The hydrocarbons in HVO (Hydrogenated Vegetable Oils) are identical to hydrocarbons in fossil petrol and diesel; and HVO is sometimes referred to as a "drop-in" fuel because it can be used in unmodified engines in all blends [28]. Today, it is primarily used as blending component in fossil diesel.

The density of HVO is typically 780 kg/m3. A blend of fossil diesel fuel and 30% HVO fulfils all EN590 requirements. [29]

5.5.5.1 Basic facts – HVO

Raw material:
Vegetable oils, algae, wood and animal fat.

Applicable standard:
EN590 (diesel) / EN228 (petrol)

Current use:
Used as blending component in fossil diesel.

Current limitations for increased usage:
Limited access – high investment cost for producers.

Outlook for future use:
The legislation for Euro VI will probably affect the use of high blends.
EU legislation (proposal) for limiting use of 1st generation biofuels, and sustainability criteria.

Vehicle application:
Petrol / HVO: All SI engines.
Diesel / HVO: All CI engines.

Engine/vehicle conversion:
None if final product (neat or blend) complies with EN590 / EN228.

Highlighted emission components:

- NOx for CI engines

Comments:

- The hydrocarbons in HVO are identical to hydrocarbons in fossil petrol and diesel;
- Many types of vegetable oils can be used as feedstock for HVO without problems with properties of the final product [30]

5.5.5.2 Summary of studies on emissions and health effects - HVO

In a review article [22], studies regarding bio-derived versus petroleum-derived diesel fuels have been investigated. The HVO fuel shows tendencies of reducing the regulated emissions and causing weaker toxic effects compared to fossil diesel.

Usually, the HVO is blended with fossil diesel fuel and no engine adjustments are performed. The effects on emissions from an optimized engine were described in [31], where the difference regarding chemical and physical properties for the HVO fuel were taken into account. The HVO fuel used in the study fulfilled the EN590 except for lower density (780 kg/m3). The regulated emissions were measured, and the results indicate that both the PM and NOx emissions can be reduced after optimization of the engine. In this study, the baseline was the original engine and the differences are related to optimization of the engine. No fossil diesel fuel was used as reference.

An extensive field test was performed in Helsinki, Finland [29] – the OPTIBIO project. The test campaign included an HVO fuel that was used in city buses, and the project involved 300 buses totally. The fuels used in the study were 30% HVO blend and 100% HVO (10 buses). The reference fossil diesel was B0 fulfilling the EN590 standard. In connection to the field test, a research program investigating the exhaust emissions were performed. The buses were of emission standards between Euro II and EEV (Enhanced Environmentally Friendly Vehicle). All in all, 17 buses representing different emission standard were tested regarding regulated emissions, whereas 3 buses were chosen for unregulated emission measurements. The measured unregulated components consisted of PAH compounds, lighter aromatics, aldehydes and carbonyls.

On average the regulated emission components were reduced with neat HVO. The most consistent reductions could be observed for the older vehicles, Euro II and III. For the newer buses the fuel effect was difficult to distinguish due to variations in fuel injection equipment and aftertreatment systems.

In more detail, emissions of CO, THC and PM were reduced compared to fossil diesel. Generally, the reduction was in accordance with the concentration of the blend, where more

HVO content in the fuel gave stronger reductions. The effect on NOx is however more complex. The results show that neat HVO has a potential to reduce aggregated NOx and PM emissions, but this is dependent on optimization of the engine for the specific fuel.
The unregulated emission components were measured from 3 buses with different emission standard (Euro III, Euro IV and EEV). The fuels used were fossil diesel (B0) and neat HVO. In gaseous phase, light hydrocarbons, aldehydes and ammonia were measured. In the particulate phase, the particle size distribution was measured and PAH compounds were analyzed. Among the PAH compounds analyzed, the "priority PAH" compounds from the US EPA list of Mobile Source Air Toxics [32], were included: benz(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, chrysene, 7,12-dimethylbenz(a)anthracene, indeno(1,2,3-cd)pyrene.

From the unregulated measurements, the main conclusion is that paraffinic HVO reduces the harmfulness of exhaust significantly. Substantial emission reductions of the analyzed PAH compounds were observed, as was reductions of lighter aromatics (such as benzene and toluene). The aldehyde emissions consisted mainly of formaldehyde and acetaldehyde. The Euro III vehicle showed increased aldehyde emissions for the HVO fuel compared to fossil diesel. For the Euro IV and EEV vehicles there was no difference in aldehyde emissions between HVO and fossil diesel. Emissions of ammonia were low and no difference could be observed between the two fuels.

The particle size distribution was also measured. For the Euro IV and EEV vehicles the HVO reduced the particle number evenly and no significant effect on the distribution profile could be observed.
The study concludes that switching to paraffinic HVO fuel is a viable way of reducing the harmfulness of exhaust gases, in particular from older vehicles. According to the authors, it is worth noting that improved diesel technology and exhaust aftertreatment also deliver significant reductions (including emissions of PAH, aldehydes and PM). The bus engines tested in this study were not optimized for HVO fuel. Since especially NOx and PM emissions are dependent on the fuel injection systems as well as the exhaust control strategies, such an optimization could lead to even more significant reductions of especially NOx and PM.

In addition to the bus test, low-temperature emissions were investigated in the project [29]. Two light-duty vehicles (Euro 4) were tested at three different temperatures, +23°C, -7°C and -20°C. The test fuels were winter grade diesel fuel, 100% HVO (with adequate cold flow properties) and a blend with 30% HVO in winter grade diesel. The results showed that the HVO fuel, both as neat and blend, lowered CO and THC emissions at all temperatures, at the most 70-90% for neat HVO. The PM emissions were also lower with HVO compared to fossil diesel. The fuel effects on NOx were small and no obvious trend could be seen. [29]

A comprehensive project studying urban buses was carried out in cooperation with IEA's Implementing Agreements on Alternative Motor Fuels and Bioenergy [19]. The project comprised life-cycle analysis of different fuels suitable for urban buses. In the Tank-to-Wheel

part of the study, 4 buses were tested with respect to emission measurement. The tested buses were of emission standard Euro II, Euro III, EEV (EGR) and EEV (SCR). The fuel effects concerning regulated emissions measured on the EEV vehicles are presented in *Figure 19* (EEV EGR) and *Figure 20* (EEV SCR).

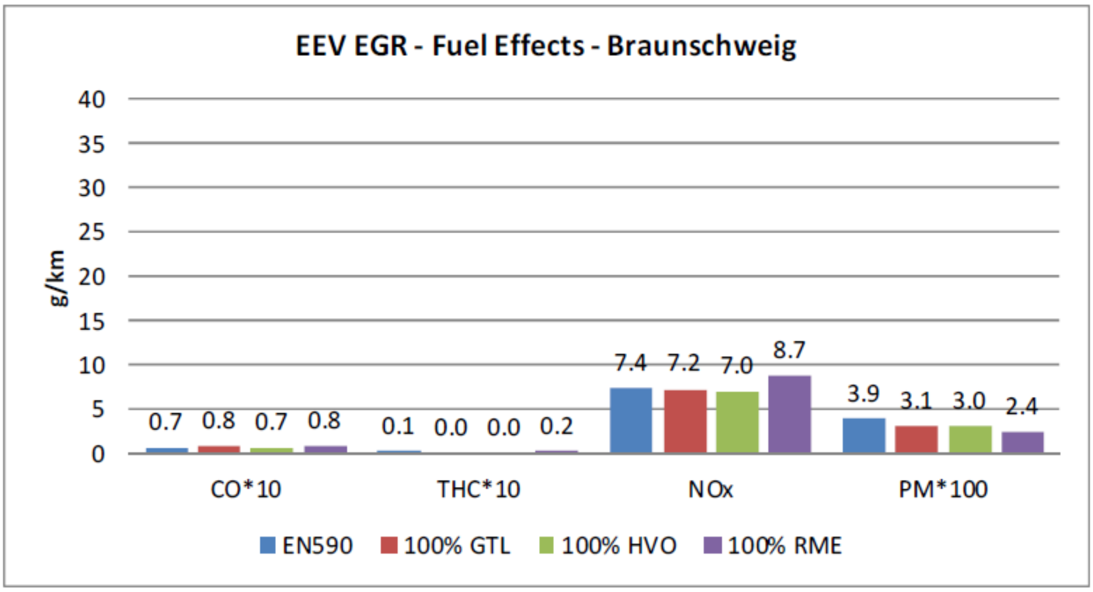


Figure 19: Fuel effects on regulated emissions. Diesel vehicle equipped with EGR, emission standard EEV. EN590: fossil diesel, GTL: Gas To Liquid diesel, HVO: Hydrogenated Vegetable Oil, RME: Rapeseed Methyl Ester. [19]

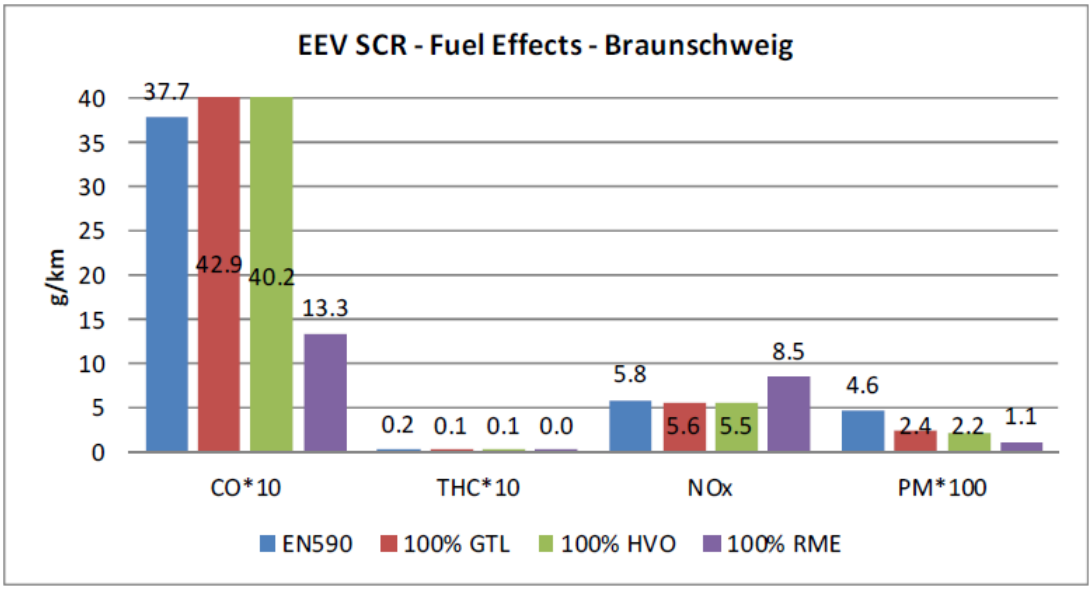


Figure 20: Fuel effects on regulated emissions. Diesel vehicle equipped with SCR, emission standard EEV. EN590: fossil diesel, GTL: Gas To Liquid diesel, HVO: Hydrogenated Vegetable Oil, RME: Rapeseed Methyl Ester. [19]

Engine dynamometer tests were performed using a Euro III engine. The engine was not equipped with any exhaust aftertreatment devices. The results showed that HVO reduced NOx emissions by 15% relative to fossil diesel fuel, whereas the PM was reduced by 8%. The particle extracts were used to perform Ames' bio-assay test, using the strains TA100 and TA98, both of the strains were exposed with and without metabolic activation (i.e. S9-mix). The results showed that HVO delivered significantly lower mutagenicity compared to fossil diesel fuel. HVO also produced the lowest PAH emissions. [19]

5.5.5.3 General conclusions - HVO

The results indicate that emissions of **CO, THC and PM** can be **reduced** by replacing fossil diesel with neat HVO. The effect is most consistent for older vehicles (i.e. Euro II and III). For newer vehicles the fuel effect is more difficult to distinguish due to engine technology and aftertreatment systems. The reduction persists at cold ambient temperatures.

The effect on NOx seems to be more complex, probably depending on the engine calibration regarding NOx/PM emissions.

Neat HVO reduces the emissions of PAH compounds selected in the study [29]. There was also a reduction in lighter aromatics (such as benzene and toluene).

There are contradictive results for aldehydes (which mainly consists of formaldehyde and acetaldehyde).

Particle size distribution measurement showed decreases of particle number for all size stages.

Ames' bioassay test showed significantly lower mutagenicity for HVO compared to fossil diesel.

The HVO diesel is a so called "drop-in" fuel and can be used without engine adjustments. However, one study showed that engine optimization can reduce NOx and PM emissions to a larger extent.

5.5.6 Ethanol

Production of bioethanol

Sugar- and starch-based ethanol
In the sugar-to-ethanol process, sucrose is obtained from sugar crops such as sugar cane, sugar beet and sweet sorghum, and is subsequently fermented to ethanol. The ethanol is then recovered and concentrated by a variety of processes.The conversion process of starch crops requires an additional step, the hydrolysis of starch into glucose, which requires more energy than the sugar-to-ethanol route.
The costs of production from sugar and starch are very sensitive to feedstock prices. Efficiency could be improved and costs lowered through use of more effective amylase enzymes, decreased ethanol concentration costs and enhanced use of co-products. [33]

Cellulosic ethanol
Bioethanol can be produced from ligno-cellulosic feedstocks through the biochemical conversion of the cellulose and hemicellulose components of biomass feedstocks into fermentable sugars. The sugars are then fermented to ethanol, following the same conversion steps as sugar- and starch-based ethanol. [33]

Use of bioethanol

Evaporative emissions
The addition of ethanol to gasoline affects the volatility of gasoline and can increase evaporative emissions. Between 0% and 10% ethanol, there are significant increases in evaporative emissions (including permeation) [34]. However, in most countries this is compensated by a lower vapor pressure in the gasoline.

Aldehyde emissions
Aldehydes are formed in an oxidation reaction of primary alcohols, such as methanol and ethanol. In the exhausts from a vehicle using ethanol the exhausts contains unburned ethanol, aldehydes and acetic acid. The aldehyde emissions are higher for ethanol fuelled vehicles compared to fossil gasoline or diesel vehicles. The aldehydes in the exhausts consist primarily of acetaldehyde, but also elevated levels of formaldehyde. Formaldehyde is a known carcinogen, whereas acetaldehyde is considered a "probable" carcinogen [15].

5.5.6.1 Basic facts – Ethanol

Raw material:
Crops/biomass with sugar and/or starch content.

Applicable standard:

Ethanol (blended in petrol):	EN15376, ASTM D 4806, EN228
E85:	SS155480, ASTM D 5798, CVA15293, DIN51625, prEN15293
ED95:	SS155437

Current use:

Ethanol (blended in petrol):	EU, USA, South America, Southeast Asia, China
E85:	EU, USA, China and Brazil (E100)
ED95:	Norway, Sweden, Finland, France, Holland, Poland, Spain, South Africa, Brazil, Thailand, Australia

Current limitations for increased usage:

General:	Access to raw material.
Ethanol (blended in petrol):	Blending of >10% require vehicle modifications.
E85:	Vehicle availability.
ED95:	Vehicle availability (ED95 only for dedicated vehicles).

Outlook for future use:
Current EU ILUC proposal suggests max 5% of 1st generation ethanol.
For ED95: Questions for Euro VI usage.

Vehicle application:

Ethanol (blended in petrol):	Light duty vehicles, SI engines.
E85:	Light duty vehicles, flexible fuel SI engines.
ED95:	Heavy duty vehicles – urban, CI engines.

Engine/vehicle conversion:
Ethanol (blended in petrol): None for blends of 0-10% in petrol [35].
For higher blends / E85 / ED95:

- Parts in direct contact with the fuel need to be chosen appropriately (due to more aggressive fuel);
- Worse lubrication properties require upgrades of fuel injectors, valves and valve seats;
- Fuel pumps and injectors may need to be upgraded due to higher fuel flow;
- Engine control system needs to be adapted;
- Some applications use a fuel sensor to determine petrol/ethanol mixture at additional cost;
- Engine heater is recommended when used at lower temperatures than +5°C.

Additional requirements for ED95:
- High compression pistons need to be used;
- Shorter service intervals.

Highlighted emission components:
- Aldehydes (primarily acetaldehyde)
- ED95: ultrafine particles

Comments:
E85 / ED95:
- Common issue of fuel injector deposits;
- Engine oil dilution can cause both deterioration of oil properties, as well as issues with boiling off effects;
- Hydroscopic.

E85:
- Safety issues: Flammable, rapid burn, visible flame, wide range of air-fuel mix is combustible (wider than petrol-air). Standard fire extinguisher foam will not work;
- Efficiency potential of approximately 40% compared to petrol engines.

ED95:
- Safety issues: Flammable, rapid burn, partly visible flame, wide range of air-fuel mix is combustible (wider than diesel-air). Standard fire extinguisher foam will not work.

5.5.6.2 Summary of studies on health effects and emissions - Ethanol blends in petrol

A study presented at the SAE Powertrain & Energy conference in Gothenburg September 2012 [36] has investigated the emission effects from different ethanol blends. One flex-fuel light-duty vehicle was tested at three different temperatures: +24°C, +10°C and -7°C (test temperatures during certification according to US EPA and CARB). The fuels used were E0, E10, E20 and E85. Regulated emissions were measured, as well as ethanol, methane and totally 13 different carbonyl compounds (including formaldehyde and acetaldehyde).

The results at +24°C showed a decrease for all emissions with elevated ethanol content in the fuel; except for emissions of ethanol and carbonyls which increased with higher ethanol content. Of total carbonyls, tests using E85 produced 72% acetaldehyde and 7% formlaldehyde (i.e. approximately eight times more acetaldehyde compared to formaldehyde). For E20 the ratio between acetaldehyde and formaldehyde were 2.35:1, and for E10 the ratio was 2 to 1. Most of the aldehydes were emitted during the first phase of the FTP75 driving cycle. [36]

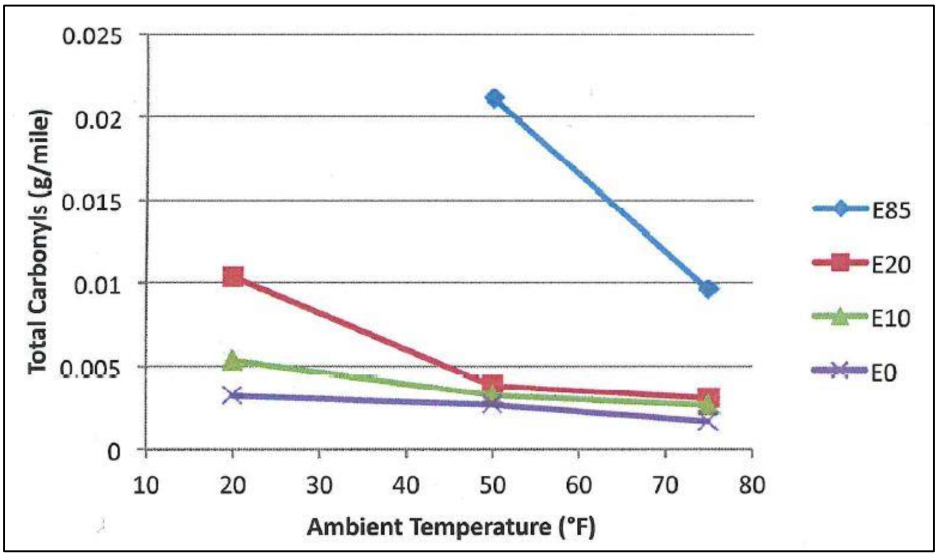


Figure 21: Total carbonyl emissions with E0, E10, E20 and E85 at different ambient temperatures (20°F=7°C; 50°F=10°C; 75°F=24°C). [36]

At colder ambient temperatures, a larger quantity of fuel is injected – especially with ethanol fuels. [*Comment from author: The startability of a flex-fuel engine is much dependent upon the presence of the petrol part of the ethanol fuel. In order to improve the start, extra fuel is injected during the start-up phase and thereby allowing more petrol to take part in the combustion.*] Due to this, high levels of unburned ethanol are present in the exhaust during start-up. This especially occurs during cold start and before the catalyst is heated up. The results show that all exhaust components increased as the ambient temperature dropped from +24°C to -7°C. [36]

Regulated and unregulated emissions from different ethanol blends were measured from a Flex-fuel vehicle [37]. The study comprised vehicles of model years between 1984 and 2007. This summary will however only include results for the newest vehicle – a Flex-fuelled vehicle of model year 2007. The test fuels used were CARB phase 2 certification fuel (fossil gasoline, containing 11% MTBE (Methyl Tert-Butyl Ether)), CARB phase 3 certification fuel (containing 5.7% ethanol), E10, E20, E50 and E85. CARB 2 was considered to be the reference fuel, and CARB 3 was used as the base fuel for creating the ethanol blends. The measured unregulated emissions were 13 different carbonyl compounds (such as aldehydes and ketones), 1,3-butadiene and BTEX (benzene, toluene, ethylbenzene and xylen).

The CO and NOx emissions did not show significant differences between the CARB 2 fuel and the different fuel blends. The THC and NMHC emissions increased for E85, but not for the lower fuel blends.

For the carbonyls, significant increases in formaldehyde and acetaldehyde were observed when using E85 fuel. The blends of E10, E20 and E50 resulted in reductions of formaldehyde compared to the reference fuel, CARB 2. For carbonyl results, see Figure 22.

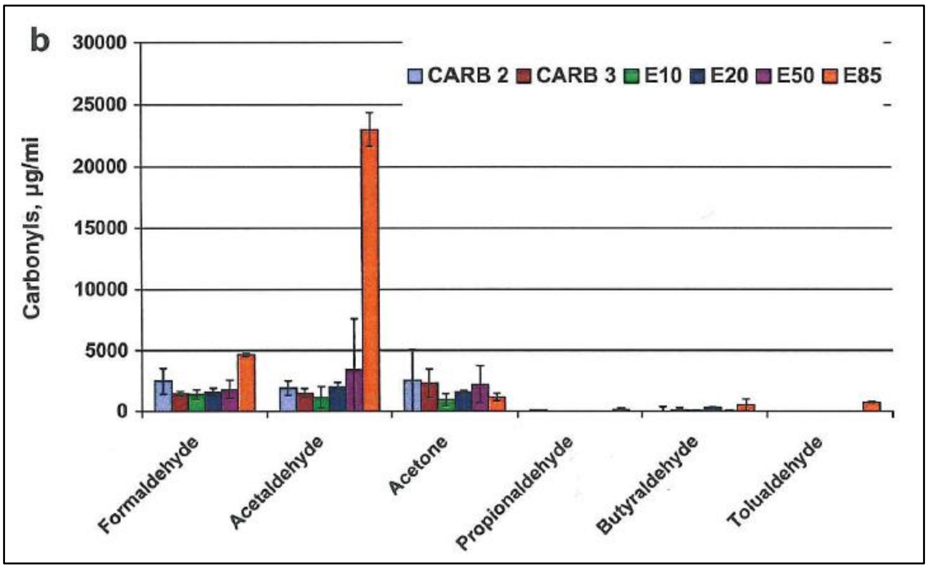


Figure 22: Carbonyl compounds measured over FTP driving cycle. [37]

The largest contribution to total carbonyls was emitted during the first phase of the driving cycle. [33]

The emissions of 1,3-butadiene showed a decreasing trend with higher ethanol blends. The E85 fuel gave consistently low emissions of BTEX (benzene, toluene, ethylbenzene and xylene), see Figure 23.

Exhaust emissions of benzene originate either from unburned fuel or is formed during combustion. The 1,3-butadiene is a product of fuel fragmentation [33].

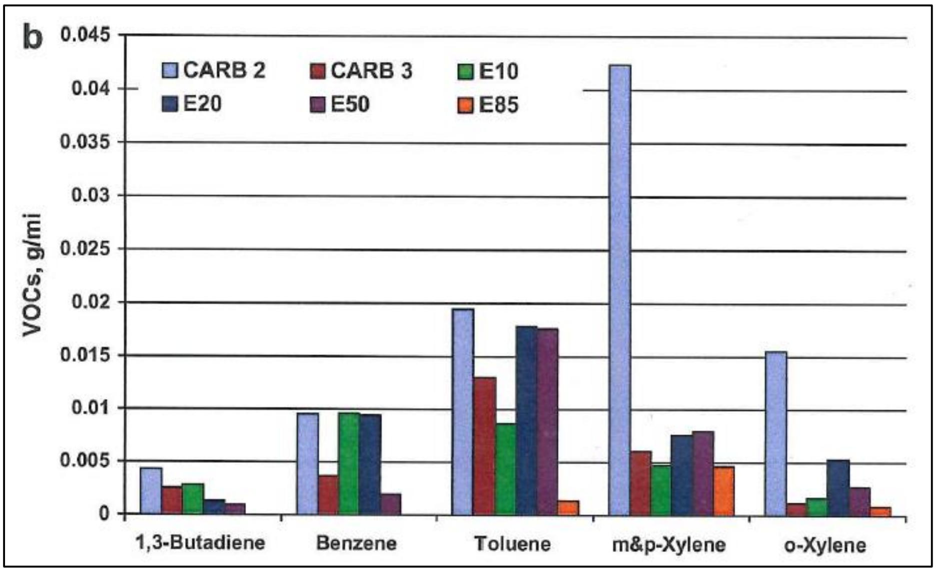


Figure 23: 1,3-butadiene and BTEX emissions from the Flex-fuelled vehicle, FTP driving cycle. [37]

5.5.6.3 General conclusions – ethanol blends in petrol

Compared to fossil petrol the effects on CO and NOx are contradictive, probably due to engine calibration. The emission levels are dependent on ambient temperature, where cold temperature results in increased levels.

The THC and NMHC increases for E85 blend. The emissions consist mainly of unburnt ethanol.

Significant increases of aldehydes (mainly acetaldehyde) were observed for E85, whereas lower blends showed decreases of formaldehyde.
Ethanol is the main precursor of acetaldehyde in vehicle emissions. Acetaldehyde is considered a probable carcinogen, and formaldehyde is carcinogenic [15].

The emissions of 1,3-butadiene showed a decreasing trend with higher ethanol blends, and the E85 fuel gave consistently low emissions of BTEX.
Both 1,3-butadiene and Benzene are carcinogenic [15].

5.5.7 ED95

ED95 consists of 95% ethanol and 5% ignition enhancers. The fuel is suitable for fuel optimized heavy duty compression engines. The fuel is most often used in captive fleets, such as city buses.

5.5.7.1 Summary of studies on health effects and emissions – ED95

VTT in Finland performed a study where different bus technologies and fuels were tested [19]. In this comparison, two diesel buses and one bus fuelled with additive treated ethanol were included. The diesel buses were of emission standard EEV, one equipped with EGR and one with SCR exhaust aftertreatment. The ethanol fuelled bus was certified as an EEV.

The regulated emissions from the ethanol bus are presented in *Figure 24*.

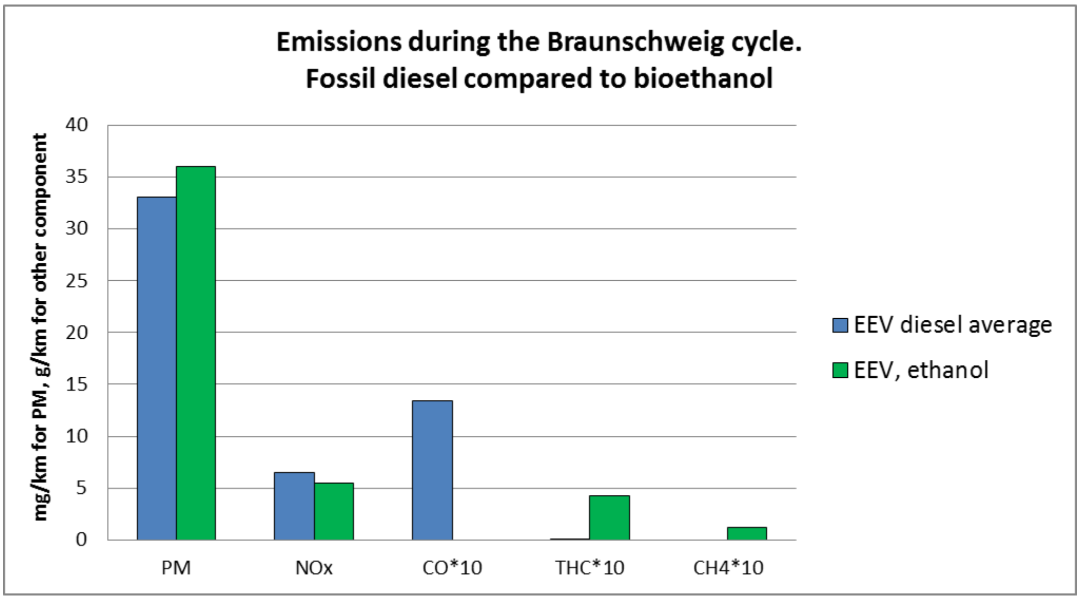


Figure 24: Regulated emissions for diesel vehicle and ethanol vehicle. Tests performed with the Braunschweig driving cycle. [19]
(The original figure has been edited in order to focus on specific fuels).

The ethanol fuelled bus emits lower NOx compared to the average emissions from the diesel buses, whereas the PM emissions are higher.

The effect of different driving patterns was also investigated. Six different driving cycles were used – NYBUS, ADEME, Braunschweig (simulating urban bus driving); JE05, UDDS and WHVC (simulating truck operation). The results from the diesel with EGR and the ethanol bus are included, in *Figure 25* and *Figure 26*, for comparison.

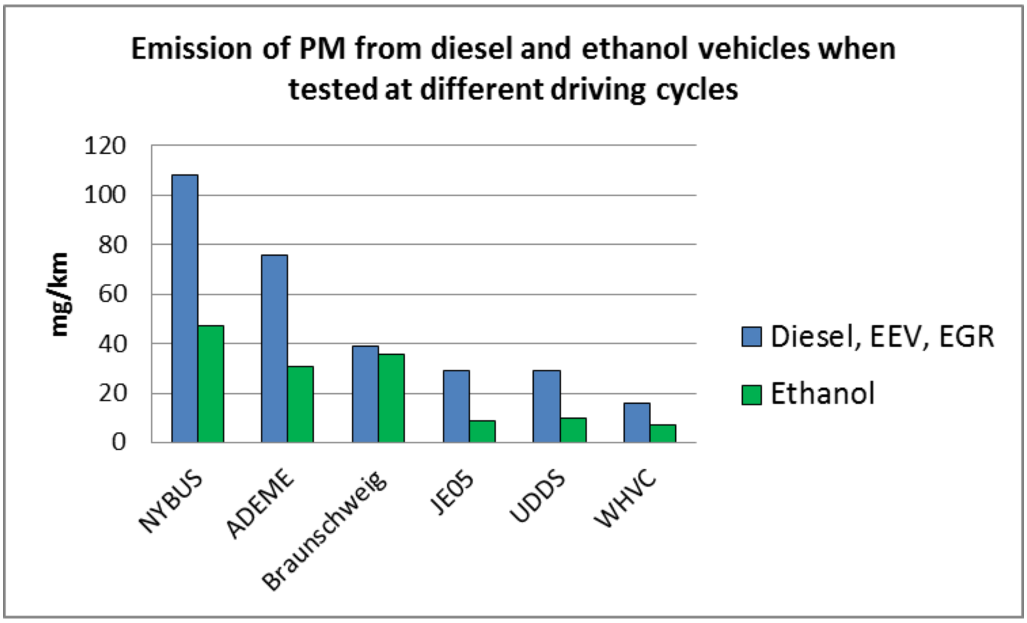


Figure 25: The effect on PM emissions when tested at different driving cycles – diesel bus and ethanol fuelled bus. [19]
(The original figure has been edited in order to focus on specific fuels).

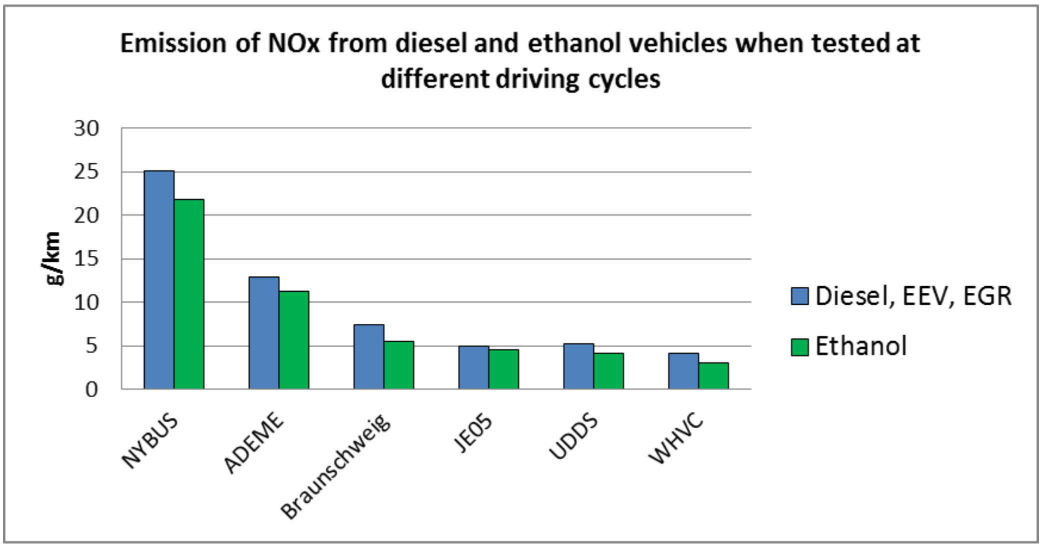


Figure 26: The effect on NOx emissions when tested at different driving cycles – diesel and ethanol fuelled bus. [19]
(The original figure has been edited in order to focus on specific fuels).

The NOx emissions are decreased to some extent for the ethanol fuelled bus, and the PM emissions are lower or much lower for all driving cycles.

The particle size distribution (12 stages between 0,02 and 10 microM) was also investigated. The ethanol fuelled bus emitted highest levels of the smallest particles (i.e. 0,02-

0,05 microM). The size distribution for the diesel and ethanol fuelled vehicles can be compared in *Figure 27*.

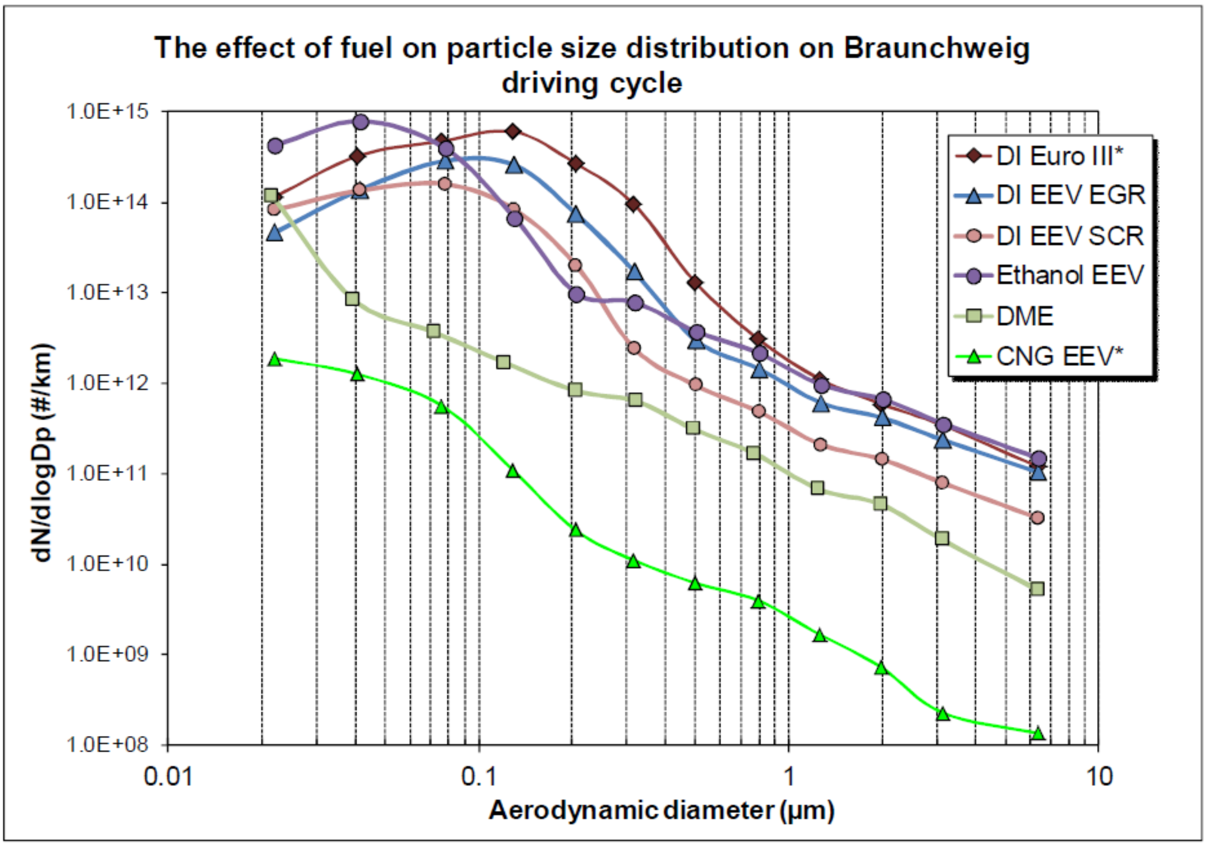


Figure 27: Particle number and size distribution – Braunschweig driving cycle. [19]

The NO2 was analyzed directly. For the ethanol fuelled bus, the NOx emission as well as the ratio between NO/NO2 were of the same magnitude as for the diesel bus equipped with SCR.

5.5.7.2 General conclusions – ED95

The NOx emissions are reduced, compared to diesel, independent on driving cycle.

The PM emissions are reduced, compared to diesel equipped with EGR, independent on driving cycle.

The ED95 bus emitted highest levels of the smallest particles compared to diesel and gas fuelled heavy duty vehicles (in one study, i.e. inconsistent evidence). Generally, ultrafine particles have negative effect on health.

5.5.8 Dimethyl ether (DME)

DME is a gas fuel suitable for dedicated heavy duty vehicles. The fuel is in liquid form in the pressurized tank, but is transformed to gas phase under atmospheric pressure.

For the time being, DME is primarily used in Asia and some plants are being built in China and Japan [34]. However, the interest is increasing in European countries. Coal and natural gas are the primary feedstocks for DME production. DME can also be produced from the thermochemical conversion of biomass to produce synthesis gas, which is then followed by the catalytic conversion of the synthesis gas to DME. Unlike any other synthetic diesel fuel, DME virtually eliminates soot emissions and the need for Diesel Particulate Filters (DPF). According to [19], DME has progressed from the laboratory environment into the field testing phase.

5.5.8.1 Basic facts - DME

Raw material:
Natural gas, coal biomass, pulp and paper mill waste.

Applicable standard:
None

Current use:
Not commercially available in Europe. Ongoing fleet studies.

Current limitations for increased usage:

- Production capacity;
- Vehicle availability;
- Infrastructure.

Outlook for future use:
Global interest due to availability of raw material, relative low carbon emissions and renewable sources.

Vehicle application:
Heavy duty vehicles , CI (gas) engines – urban

Engine/vehicle conversion:
Fuel system, engine control system and possibly valve mechanism.

Highlighted emission components:

- Methane

Comments:

- Exhaust emissions are almost smokeless;
- Good climate behaviour;
- Low NOx emissions compared to diesel.

5.5.8.2 Summary of studies on health effects and emissions - DME

In an IEA study, VTT in Finland tested and coordinated a study including alternative fuels for buses [19]. Among the tested vehicles, there were two diesel fuelled buses certified to emission standard EEV (one equipped with SCR, one with EGR exhaust aftertreatment), and one DME fuelled vehicle. It should however be noted that the DME fuelled vehicle was a prototype heavy duty truck simulated as a bus, and the results for the DME vehicle should be considered as indicative. According to the manufacturer, the DME vehicle was compatible to emission standard Euro V.

The regulated emissions for the diesel buses and the DME prototype vehicle are presented in
Figure 28.

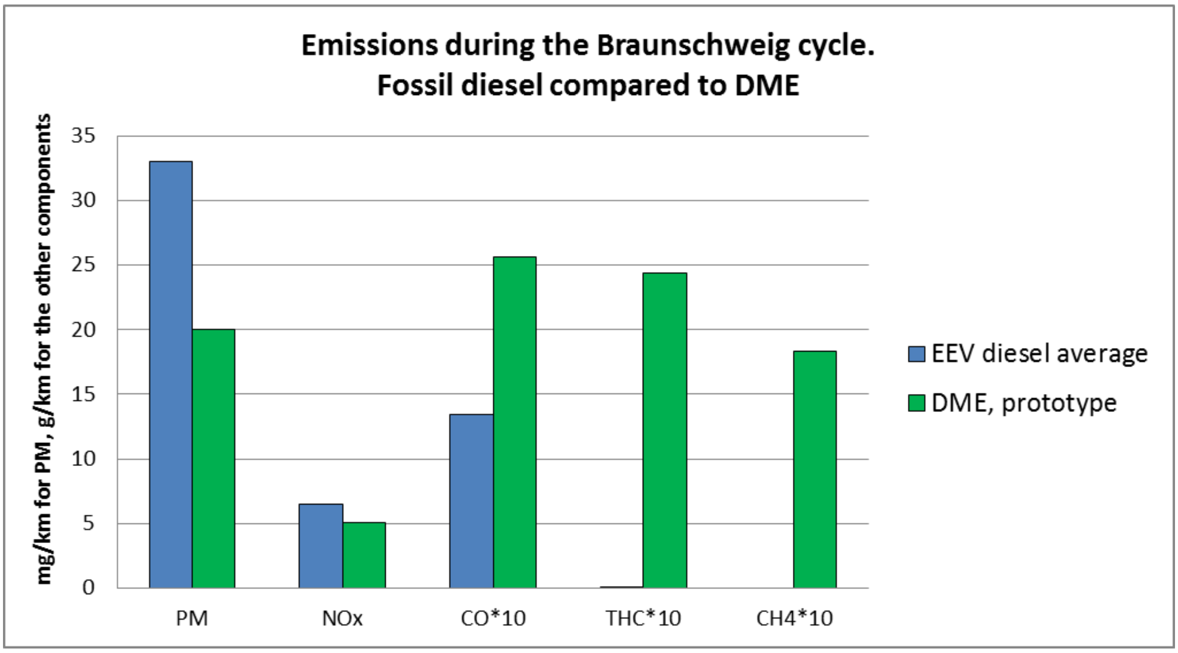


Figure 28: Regulated emissions for diesel vehicle and DME fueled vehicle (DME prototype). Tests performed with the Braunschweig driving cycle. [19]
(The original figure has been edited in order to focus on specific fuels).

Both the NOx and PM emissions are lower for the DME vehicle compared to the diesel fuelled buses (average values for the buses equipped with EGR and SCR). The high THC emissions from DME consist mainly of CH_4.

According to the authors, the very high CO emissions in combination with the high THC value is an indication that transient control was not yet fully optimized for the prototype vehicle. The particle size distribution (12 stages between 0,02 and 10 microM) was also investigated (*Figure 27*). When compared to the diesel buses, the DME vehicle had lower emissions at all stages except for the smallest particles, where it was at the same level.

5.5.8.3 General conclusions - DME

(Please note that the conclusions are based on tests performed on a prototype heavy duty truck).

The NOx and PM emissions were reduced compared to fossil diesel.

DME lead to high THC emissions, consisting mainly of CH_4.

Very high CO and THC emissions indicate that the transient control was not yet fully optimized.

Particle size distribution showed lower emissions for all stages except for the smallest particles (same level as diesel vehicles).

5.5.9 Synthetic diesel (Fischer-Tropsch diesel)

In this summary, emission effects of Fischer-Tropsch (F-T) based fuels are described. Various feeds may be used to produce F-T diesel – natural gas, coal, shale, and biomass. Fuel that has properties similar to F-T diesel may also be produced by processing vegetable oil in a refinery; the end result is commonly called hydrogenated vegetable oil.

F-T diesel produced from biomass is called BTL, while F-T diesel produced from natural gas is called GTL. When coal is used as the input, the resulting fuel is called CTL.

F-T diesel is produced generally by a process consisting of two steps. The process for BTL produced from biomass is described in Figure 29. First, a feedstock is thermally treated to produce a synthesis gas consisting primarily of CO and hydrogen. In the second step, the synthesis gas is reacted catalytically to produce a mixture of hydrocarbons, the composition of which may be adjusted by choosing reactor design and reaction conditions. Most commercial processes produce either diesel fuel or lubricant base stocks. Raw F-T fuel is usually upgraded to improve quality by hydrocracking and hydro-isomerization creating isoparaffins from normal paraffins and/or removing waxy materials to improve cold flow performance. The resulting fuel is similar to petroleum diesel in molecular weight range (C8-C24), although the distributions may not match exactly. [34]

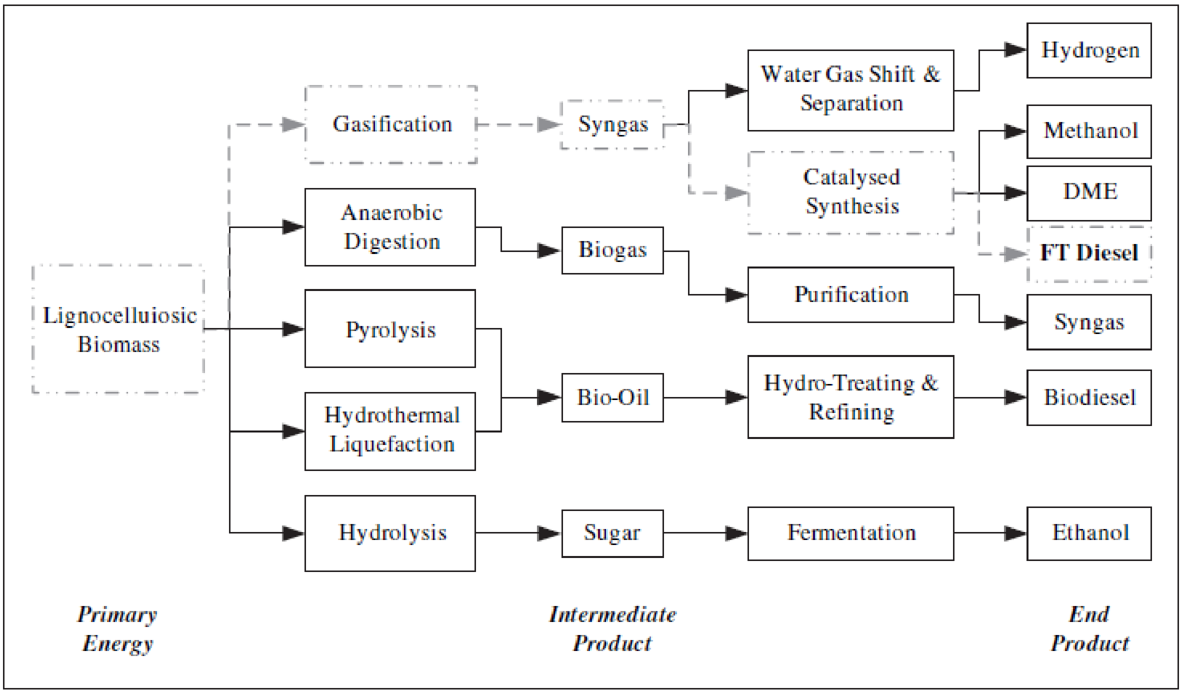


Figure 29: Conversion processes for lignocellulosic biomass. [38]

The most likely use of F-T diesel will be as blendstocks in standard diesel fuel. Use of F-T diesel as blendstocks allows fuel manufacturers to increase diesel production without the

expense of marketing a totally new fuel. If engine manufacturers develop new engine technology that takes advantage of the special properties of F-T diesel, then a separate grade of fuel would have to be produced, distributed and marketed.

5.5.9.1 Basic facts – Synthetic diesel (Fischer-Tropsch diesel) from biomass (BTL)

Please observe that the basic facts only include synthetic diesel with biomass origin.

Raw material:
Any kind of biomass.

Applicable standard:
EN228 (petrol) /EN590 (diesel)

Current use:
Not yet commercially available.

Current limitations for increased usage:
Not yet commercially available.

Outlook for future use:
Global interest due to availability of raw material.

Vehicle application:
Heavy duty vehicles – haulage, urban
Light duty vehicles

Engine/vehicle conversion:
None if compliant with EN228 / EN590.

Highlighted emission components:
-

Comments:
BTL fuels may be produced from almost any type of biomass, residues or organic wastes, such as; short rotation trees, perennial grases, straw, forest thinning's, bark from paper-pulp production, bagasse, waste paper, and reclaimed wood or fiber based-composities [39].

5.5.9.2 Summary of studies on health effects and emissions - Synthetic diesel (Fischer-Tropsch diesel)

F-T diesel has been shown to reduce emissions from diesel engines significantly. In one study of a heavy-duty diesel engine, emissions relative to petroleum diesel were reduced by 40% for PM, 20% for NOx, 41% for HC and 30% for CO [40]. These reductions are consistent with the properties and composition of F-T diesel. In a test of a European light-duty diesel passenger car, a 50/50 mixture of conventional and F-T diesel reduced emissions of HC and CO by about 45% and PM emissions by 22%. NOx emissions were not affected. The benefits for reducing emissions of hydrocarbons, CO and NOx suggest a nonlinear benefit for the mixtures. More emissions data in heavy-duty diesels with modern aftertreatment devices would be useful. [40]

A study by VTT investigates the emission performance from diesel buses from different emission standards where GTL-diesel from natural gas was used [19]. Among the tested vehicles, there were two with emission standard EEV – one equipped with SCR and one with EGR exhaust aftertreatment systems. The regulated emissions were investigated, and the vehicles were driven according to the Braunschweig driving cycle which simulates urban bus driving. When comparing the emissions from the EN590 diesel and the GTL, the most dominant effect is the reduction of PM. The NOx emissions are reduced by a few percent. [19]

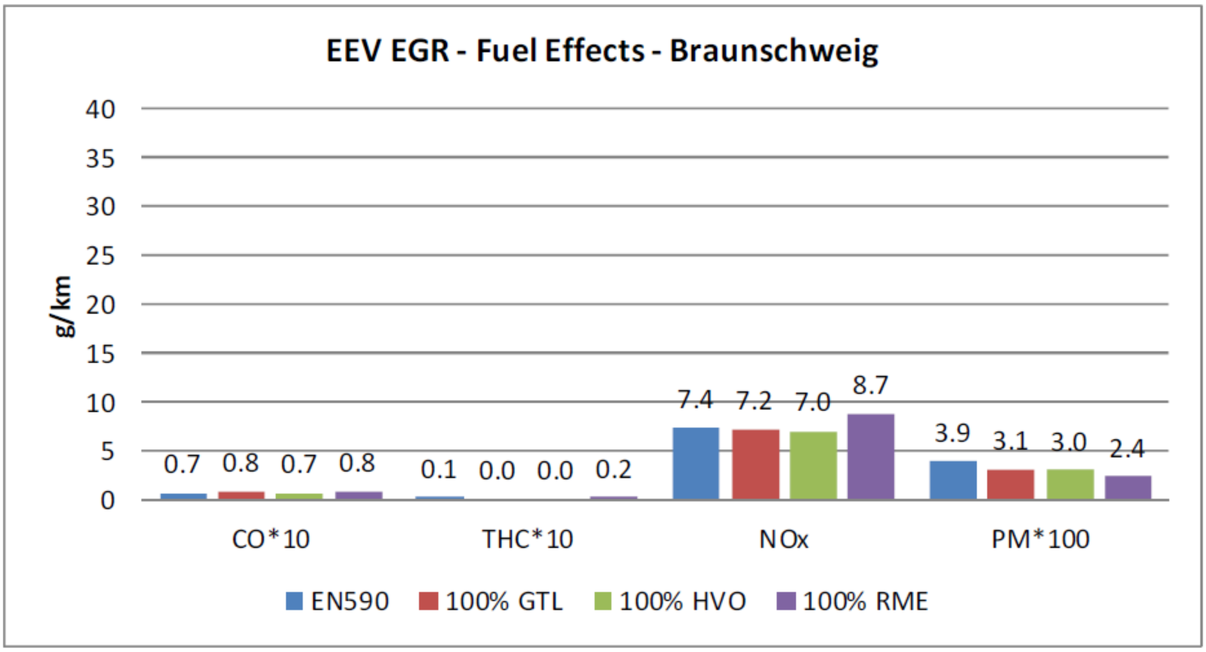


Figure 30: Fuel effects on CO, THC, NOx and PM emissions – EEV EGR bus. [19]

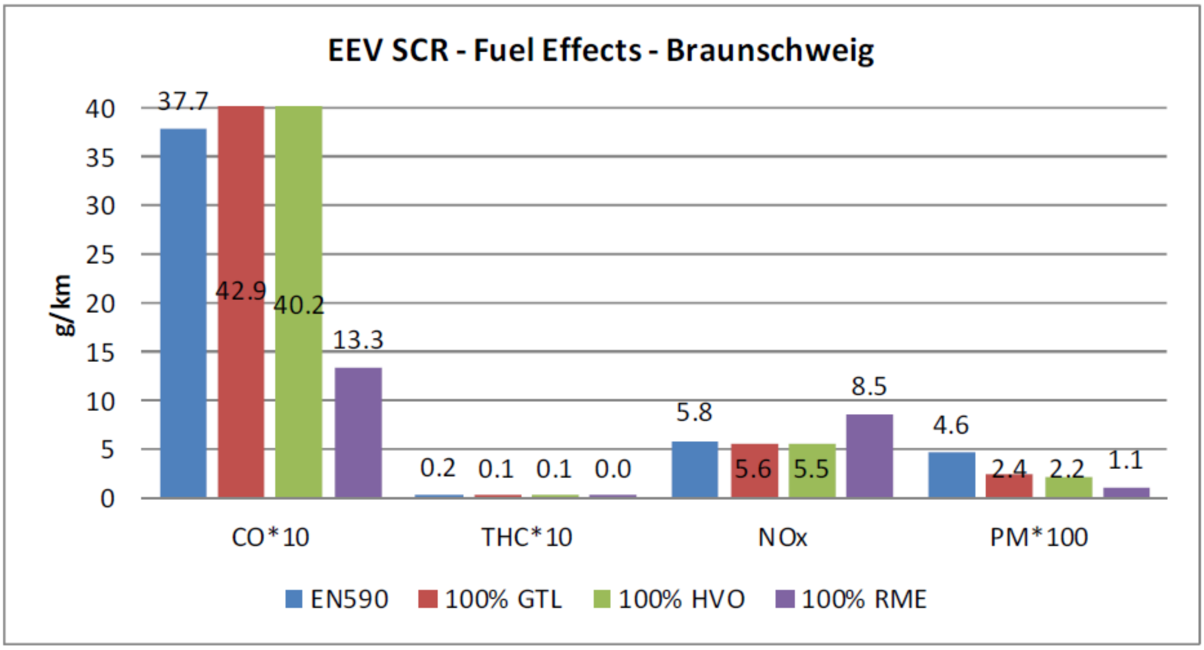


Figure 31: Fuel effects on CO, THC, NOx and PM emissions – EEV SCR bus. [19]

5.5.9.3 General conclusions – Fischer-Tropsch diesel

Different studies show different results regarding the effect of F-T diesel on exhaust emissions. This shows that more research is needed in this field.

There seems to be a tendency towards **decreased emissions** of the regulated emissions **CO, THC and PM** when replacing fossil diesel with F-T diesel.

No clear trend can be seen for NOx emissions. Further testing is needed in this area.

5.5.10 Methanol

Methanol is mainly synthesized from natural gas, but also from coal. Biomass can be converted to methanol via thermochemical and biotechnological pathways as shown in *Figure 32*.

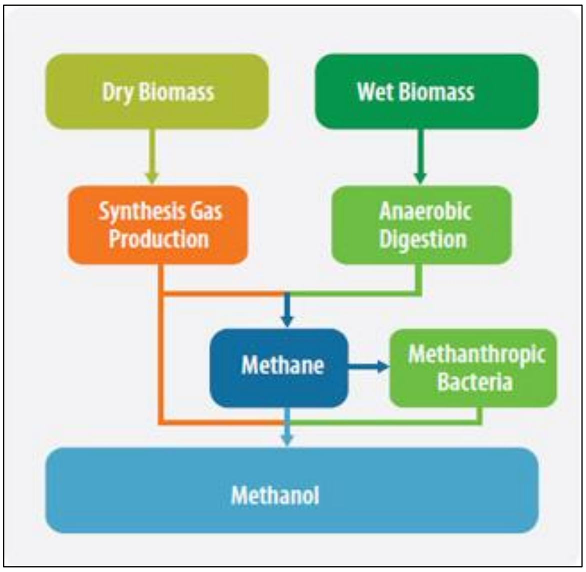


Figure 32: Pathways for methanol production. [41]

The use of methanol-gasoline mixtures in spark-ignition vehicles has a number of technical challenges. Methanol has even lower energy density than ethanol. It is not particularly miscible with gasoline and is prone to phase separation in the presence of small amounts of water – more so than ethanol. High levels of methanol in gasoline require specially designed cars. Methanol itself is well known for its neurotoxicity, and methanol use as a fuel can result in high emissions of formaldehyde, a toxic pollutant. [34]

Methanol is usually made from natural gas or, in China, from coal. China is now the world leader in methanol production and a significant amount of methanol finds its way into the gasoline pool. The probability of increased use of methanol is low in the US, Europe and Japan, and medium in other parts of the world such as China and India. It should also be noted that, in addition to its direct use as transportation fuel, methanol is used in the production of other fuels; for example, in the production of biodiesel and possibly as a source of hydrogen for fuel cells. [34]

5.5.10.1 Basic facts - Methanol

Raw material:
Natural gas, biogas, steam reformed coal, woody biomass.

Applicable standard:
For blends in petrol: EN228 (up to 3% methanol is allowed according to current EU standard)

Current use:
Limited use (mainly in China), blended in petrol and diesel.

Current limitations for increased usage:
- Highly toxic;
- Corrosive properties;
- Production capacity for biomethanol;
- Vehicle availability.

Outlook for future use:
- Major engine modifications required;
- Investment in fuelling equipment and infrastructure;
- Safety and health concerns.

Vehicle application:
-

Engine/vehicle conversion:
- Fuel system, engine control system, intake system, valve mechanism, change of elastomers and plastics;
- Light metals, such as aluminium, should not come in contact with fuel;
- Engine heater recommended below +5°C.

Highlighted emission components:
Aldehydes, mainly formaldehyde

Comments:
- Safety issues:
    - Toxic fuel;
    - Flammable with a wide range of mixtures;
    - Non-visible flame.
- Corrosive for vehicles and fuelling equipment prohibiting use of light metals.

5.5.11 Butanol

Butanol is an alcohol that can be used as a transport fuel. Biobutanol can be produced from cereal crops, sugar cane, sugar beet, etc, but can also be produced from cellulosic raw materials.

According to the Health Effects Institute [34], research is being conducted to develop manufacturing processes to produce alcohols of higher molecular weight, such as tertiary-butanol and n-butanol from renewable resources, most likely through fermentation. These alcohols are more compatible with gasoline than ethanol, and it is possible that they will be approved for use at higher concentrations than ethanol. Significant research must be carried out before these alcohols are commercially viable. [34]

Some basic information for butanol can be found in [42]: Butanol is a four carbon alcohol that exists in four different isomers as n-butanol (l-butanol), sec-Butanol, tert-Butanol and iso-Butanol. Butanol is particularly interesting compared to ethanol because ethanol is highly water soluble, making it incompatible with normal transportation processes (pipelines and other bulk delivery containers). [42]

5.5.11.1 Basic facts - Butanol

Raw material:
Biomass (cereal crops, sugar cane, sugar beet, cellulosic raw materials etc) or fossil hydrocarbons.

Applicable standard:
For blends in petrol: EN228

Current use:
Not yet commercially available. Used as blending component in fleet studies in USA.

Current limitations for increased usage:
Butanol is currently not allowed as blending component in diesel fuel.
For blends in petrol:

- EN228 allow up to 15% butanol;
- Butanol has other commercial applications with higher price tolerance.

Outlook for future use:
If the production cost can be made competitive, and the production meets EU's sustainability critera, it can be interesting.

Vehicle application:

Low blend in petrol: Light duty vehicles (SI engines)
Engine/vehicle conversion:
None if compliant with EN228.

Highlighted emission components:
Probably aldehydes.

Comments:
Currently, the major source of Butanol is fossil raw materials.

5.5.11.2 Summary of studies on health effects and emissions - Butanol

There is little data on emissions from these alcohols in current and future vehicles. [34]

Regulated and non-regulated gas components were investigated when using different alcohol components in gasoline [42]. The engine was a modern direct-injected spark ignition gasoline engine. Ethanol, n-butanol and iso-butanol were used as blending agents. To allow for a realistic comparison of fuels, blends of gasoline and butanol were selected at identical levels of mass-specific oxygen content in the fuel. The resulting concentrations equivalent in mass-specific oxygen content to E10 and E50 were 16 Vol-% and 83 Vol-% respectively for the butanol blends.

Addition of alcohol to the fuel mix resulted in a consistent reduction of NOx emissions regardless of operation point. The emissions consisted also of unburnt fuel as well as formaldehyde and acetaldehyde. Both formaldehyde and acetaldehyde emissions increase with addition of butanol to the fuel blend. Propene, 1,3-butadiene and acetylene emissions, which are required for carbon growth processes leading to benzene, also increased with addition of butanol. [42]

5.5.11.3 General conclusions - butanol

Butanol seems to have the potential to reduce NOx emissions.

In THC emissions, residues of unburnt butanol could be found. Increase of aldehyde emissions, mainly formaldehyde and acetaldehyde.

One study showed an increase of 1,3-butadien, propene and acetylene in the exhaust emissions with addition of butanol.

5.6 Prices on fuels

When looking at bio-fuels, it is difficult to get accurate data on current production costs. The official information from fuel producers is limited and costs vary constantly based on availability of feedstock and type of feedstock, as well as demand. There are also different types of production processes that generate different operating costs which makes the comparison of fuels more complex [43]. Many fuel producers also benefit from government subsidizing creating an even more complex price comparison.

5.7 Future expectations

Based on historical data, it is assumed that the trend with political subventions for producing renewable fuels will continue. The possibility of vehicles running on more than one fuel can increase the flexibility on the fuel market.

5.7.1 Bi-fuels

For vehicles capable of running on more than one fuel there are different systems:

- Flexible-fuel vehicles
- Bi-fuel vehicles (primarily light duty vehicles)
- DualFuel (primarily heavy duty vehicles)

Flexible-fuel vehicles
The two fuels are mixed together in the same tank and the resulting blend is burned in the combustion chamber.

Bi-fuel vehicles (light duty vehicles)
Bi-fuel vehicles are vehicles with multifuel engines capable of running on two fuels, i.e. conventional fossil fuel and an alternate such as gas. The two fuels are stored in separate tanks and fuel systems and the engine runs on one fuel at a time, with the capability to switch back and forth between the two fuels (manually or automatically).

The installation of a bi-fuel system is a major adjustment because of two complete separate fuel systems. The installation is space consuming with two tanks and will also increase the weight of the car. The most common bi-fuel combination today is petrol with gas.

The goal is to drive on gas as much as possible and use petrol to start the engine due to inadequate start characteristics for the gas. The petrol will also work as a range extender, due to the gas storage limitations and low kilometer range for gas.

Another possible benefit with bi-fuel is that the car can be driven in areas with extended environment legislations, for example in city traffic, and the conventional fossil fuel can be used as a range extender during highway driving.

Dual-fuel vehicles (heavy duty vehicles)
In the DualFuel vehicle the fuels are stored in separate tanks and mixed during the combustion process.

For heavy duty vehicles the DualFuel technology is under development. In existing vehicles, the diesel engine has been complemented with a gas tank (with either compressed or liquified gas). There are several suppliers performing the retrofit installation, and different concepts are used. Tests performed so far show that the regulated emissions from the retrofitted vehicles will need to be reduced by exhaust aftertreatment systems to comply with the legislation. [44]

6 Conclusion

The future directives involving the transport sector will lead to increased development regarding engine and vehicle technology and exhaust aftertreatment. The use of biofuels will increase and it is of importance to understand the effects these fuels can have on issues regarding environment and health.

The exhaust emissions from different biofuels and blends including biofuels have to be studied more thoroughly, including both regulated and unregulated compounds. In this literature study, scientific reports involving biofuels have been summarized. However, the different methods for sampling and analyzing the unregulated compounds make comparison difficult.

The exhaust emissions generated during testing should be further evaluated regarding health effects. One of the objectives in this study was to evaluate the health effect influence from biofuels, based on published reports and scientific articles. One general conclusion is that there is very limited material in this field. In combination with this fact, the methodologies often used differ too much to enable a fair comparison. Some researchers apply theoretical factors for the analyzed compounds, which assume an additive and linear effect. The complex processes in a human cell can however lead to different influences for different compounds; where they can have synergistic, antagonistic or even additive effect. The health effects can also be studied in-vivo (through animal exposure) or in-vitro (i.e. cell cultures, Ames' bio-assay test). With the limited material available it is even more important that the studies can be compared, both in regard of the test results and between the fuels.

The fuel qualities provided on the national market is an important factor for improving local air pollution and health effects from exhaust emissions. The future emission legislation will lead to more extensive use of exhaust aftertreatment systems (such as SCR and diesel particulate filters). The major benefit when improving the fuel quality is that this factor affects emissions from all vehicles (including also non-road mobile machinery), whereas the legislation can affect emissions in the future.

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8 Appendix

Fact sheets for respective fuel are presented in Appendix, in the following order:

- Fossil Petrol (SI)
- Fossil Diesel (CI)
- BioMethane (upgraded Biogas) (CI/SI)
- Biodiesel – FAME (CI)
- HVO (CI/SI)
- ED95 (CI)
- E85 (SI)
- DME (CI)
- Synthetic diesel (Fischer-Tropsch diesel) with biomass origin (BTL) (CI)
- Methanol (SI)
- Butanol (SI)
- Biodiesel (FAME) – as blending component in diesel (CI)
- Ethanol – as blending component in petrol (SI)
- Butanol – as blending component in petrol (SI)

Fossil Petrol	
Raw material used:	Crude oil
Applicable standard:	EN228
Current use:	All over the world in SI applications, potential to blend with different biofuels.
Current limitations for incresed usage:	Increased demand from emerging markets. Possibly less use due to European legislation [8]* to increase use of renewable fuels.
Outlook for future use:	Limited amount (reserves can run out). Probably further legislation for the use of renewable fuels. Continued use as blending component in ethanol.
OEM modification to vehicle:	-
Used vehicle conversion:	-
Highlighted emission components:	-
Comment:	

[8]*Source: EU Renewable Energy Directive (RED): DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Dirctives 2001/77/EC and 2003/30/EC

Fossil Diesel (CI)

Raw material used:	Crude oil
Applicable standard:	EN590
Current use:	All over the world in CI applications. Potential to blend with different biofuels.
Current limitations for incresed usage:	Increased demand from emerging markets. Possibly less use due to European legislation [8]* to increase use of renewable fuels.
Outlook for future use:	Limited amount (reserves can run out). Probably further legislation for the use of renewable fuels. Continued use as blending component in biofuels.
OEM modification to vehicle:	-
Used vehicle conversion:	-
Highlighted emission components:	Aromats, PAH, NOx, Particles.
Comment:	

[8]*Source: EU Renewable Energy Directive (RED): DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Dirctives 2001/77/EC and 2003/30/EC

BioMethane (upgraded Biogas) (CI/SI)	
Raw material used:	Biomass, waste water sludge
Applicable standard:	Swedish standard SS155438, European standard under development
Current use:	Available in small volumes all over the world. SI applications.
Current limitations for increased usage:	Fuel availability, vehicle availability. Infrastructure for high-pressure gas delivery >200 Bar. Non-lubricating fuel with possible additional wear on engines.
Outlook for future use:	Access to raw material. Production capacity. High investment costs in infrastructure and fuelling equipment.
OEM modification to vehicle:	Pressurized fuel system, engine control system, intake system, valve mechanism.
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	Methane
Comment:	Biogas needs to be upgraded to be able to use as vehicle fuel. Risk for methane slip (methane is a much worse greenhouse gas than CO_2). Possible to mix with compressed natural gas (CNG).

BioDiesel – FAME (Fatty acid Methyl Esters) (CI)	
Raw material used:	Rapeseed, sunflower, soybean, waste cooking oils, animal fat waste, jatropha and fish oil
Applicable standard:	EN14214
Current use:	All over the world in small quantities. CI applications
Current limitations for increased usage:	Vehicle availabilty
Outlook for future use:	Questions for EuroVI usage. EU legislation proposal for limiting use of 1st generation biofuels. Question mark for ability to meet EU's next step in sustainability criteria.
OEM modification to vehicle:	Fuel system, engine control system, often shorter service intervals
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	NOx, mutagenic for some blends (inconclusive evidence).
Comment:	Large variance between different feedstocks. At low temperatures (different between different stocks) the fuel will go semi solid and clog fuel injection parts and filters. Issues are known with bacteria cultures developing in fuel tanks. Hydroscopic. Deterioration of the fuel and engine oil.

BioDiesel (FAME) - as blending component in diesel	
Raw material used:	Rapeseed, sunflower, soybean, waste cooking oils, jathropha and animal fat
Applicable standard:	EN14214 and EN590
Current use:	As blending component up to 7%
Current limitations for increased usage:	None up to 7% blending. Exceeding 7%, hardware and software modifications are in some cases required.
Outlook for future use:	All over the world (in CI applications). EU legislation proposal for limiting use of 1st generation biofuels. Question mark for ability to meet EU's next step in sustainability criteria.
OEM modification to vehicle:	None, when complying to EN14214/EN590
Used vehicle conversion:	None, when complying to EN14214/EN590
Highlighted emission components:	NOx, mutagenic for some blends (inconclusive evidence)
Comment:	Large variance between different feedstock. At low temperatures (different between different stocks) the fuel will go semi solid and clog fuel injection parts and filters. Issues are known with bacteria cultures developing in fuel tanks. Hydroscopic. Deterioration of fuel and engine oil.

HVO, Hydrogenated Vegetable Oil (CI/SI)	
Raw material used:	Vegetable oils, algae, wood and animal fat
Applicable standard:	EN228/EN590
Current use:	Used in CI applications as blending component
Current limitations for increased usage:	Higher investment for producers compared to FAME
Outlook for future use:	For CI and SI applications as fuel or blending component
OEM modification to vehicle:	Non, if final product is compliant with EN228/EN590
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	NOx for CI applications
Comment:	The hydrocarbons in HVO are identical to hydrocarbons in fossil petrol and diesel. Many types of vegetable oils can be used as feedstock for HVO without problems with properties of the final product [30].

ED95 ethanol fuel (CI)	
Raw material used:	Crops/biomass with sugar and/or starch content
Applicable standard:	SS155437
Current use:	Norway, Sweden, Finland, France, Holland, Poland, Spain, South Africa, Brazil, Thailand, Australia
Current limitations for increased usage:	Access to raw material. Vehicle availability (ED95 requires dedicated vehicles).
Outlook for future use:	Questions for Euro VI usage. EU legislation proposal for limiting use of 1st gen biofuels. Most current production are able to meet EU's next step in sustainability criteria
OEM modification to vehicle:	Due to more aggressive fuel, parts in direct contact with the fuel need to be chosen appropriately. Worse lubrication properties require upgrades to fuel injectors, valves and valve seats. Fuel pumps and injectors may need to be upgraded due to higher fuel flow. New high compression pistons need to be used. A common issue is fuel injector deposits. Engine oil dilution can cause both deterioration of oil properties as well as issues with boiling off effects. Engine control system needs to be adapted. Engine heater is recommended when used at lower temp than +5°C. Shorter service intervals.
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	Aldehydes, ultrafine particles
Comment:	Flammable, rapid burn, partly visible flame, wide range of air-fuel mix is combustible (wider than diesel-air), standard fire extinguisher foam will not work. Hydroscopic. Efficiency potential of approximately 40% compared to diesel fuel.

E85 ethanol fuel (SI)

Raw material used:	Crops/biomass with sugar and/or starch content
Applicable standard:	SS155480, ASTM D5798, CVA15293, DIN51625, prEN15293
Current use:	EU, USA, China and Brazil (E100)
Current limitations for increased usage:	Vehicle availability, access to raw material.
Outlook for future use:	Questions for Euro VI usage. EU legislation proposal for limiting use of 1st generation biofuels. Most current production are able to meet EU's next step in sustainability criteria
OEM modification to vehicle:	Due to more aggressive fuel, parts in direct contact with the fuel need to be chosen appropriately. Worse lubrication properties usually mean the valves and valve seats need to be upgraded. Fuel pumps and injectors may need to be upgraded due to higher fuel flow. A common issue is fuel injector deposits. Engine oil dilution can cause both deterioration of oil properties as well as issues with boiling off effects. Engine control system needs to be adapted. Some applications use a fuel sensor to determine petrol/ ethanol mixture at additional cost. Engine heater is recommended when used at lower temp than +5°C.
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	Aldehydes
Comment:	Flammable, rapid burn, visible flame, wide range of air-fuel mix is combustible (wider than petrol-air), standard fire extinguisher foam will not work. Hydroscopic. Usage of SI direct injection together with turbo show efficiency potential of approximately 40% compared to petrol fuel. Cold start issues can be solved.

Ethanol – as blending component in petrol	
Raw material used:	Crops/ biomass with sugar and/or starch content
Applicable standard:	EN15376, ASTM D 4806, EN228
Current use:	EU, USA, South America, Southeast Asia and China.
Current limitations for increased usage:	Access to raw material. Blending >10% require vehicle modifications.
Outlook for future use:	Current EU ILUC proposal suggests max 5% 1st generation ethanol. Most current production are able to meet EU's next step in sustainability criteria
OEM modification to vehicle:	None for 0-10% [35]* mixture in petrol
Used vehicle conversion:	None for 0-10% [35]* mixture in petrol
Highlighted emission components:	Aldehydes
Comment:	Flammable, rapid burn, visible flame.

[35]*Source: List of approved vehicles found under http://www.bilsweden.se/publikationer/aktuellt/vilka-bilar-kan-koras-pa-e10

DME, Dimethyl Ether Fuel (CI)	
Raw material used:	Natural gas, coal, biomass, pulp and paper mill waste
Applicable standard:	None
Current use:	Not commercially available, fleet test ongoing.
Current limitations for increased usage:	Production capacity, vehicle availability and infrastructure
Outlook for future use:	Global interest due to availability of raw material, relativily low carbon emissions and renewable sources.
OEM modification to vehicle:	Fuel system, engine control system and possibly valve mechanism
Used vehicle conversion:	Same requirements as for OEM
Highlighted emission components:	Methane
Comment:	Exhaust emissions are almost smokeless with quieter combustion, low NOx emissions compared with diesel. Good cold climate behavior.

Synthetic diesel (Fischer-Tropsch diesel) – from biomass origin (BTL) (CI)	
Raw material used:	Any kind of biomass
Applicable standard:	EN228, EN590
Current use:	Not available
Current limitations for increased usage:	Not yet commercially available
Outlook for future use:	Global interest due to available raw material.
OEM modification to vehicle:	-
Used vehicle conversion:	-
Highlighted emission components:	-
Comment:	BTL fuels may be produced from almost any type of biomass, residues or organic wastes such as short rotation trees, perennial grasses, straw, forest thinning's, bark from paper-pulp production, bagasse, waste paper or reclaimed wood or fiber based-composites. [39]

Methanol Fuel (SI)	
Raw material used:	Natural gas, biogas, steam reformed coal, woody biomass
Applicable standard:	For blends in petrol: EN228 (up to 3% methanol is allowed according to current EU standard)
Current use:	Some provinces in China use M15 and M85 (blends with petrol).
Current limitations for increased usage:	Highly toxic. Corrosive properties. Production capacity for biomethanol. Vehicle availability.
Outlook for future use:	Major engine modifications required, as well as investment in fuelling equipment and infrastructure. Safety and health concern.
OEM modification to vehicle:	Fuel system, engine control system, intake system, valve mechanism, change of elastomers and plastics. No use of light metals such as aluminum in contact with fuel. Engine heater recommended below +5°C
Used vehicle conversion:	Same as OEM, questionable if financially viable.
Highlighted emission components:	Aldehydes
Comment:	Toxic fuel that is flammable in a wide range of mixtures, flameless burn (non visible). Corrosive for vehicles and fuelling equipment prohibits use of light metals.

Butanol fuel (SI)	
Raw material used:	Biomass or fossil hydrocarbons
Applicable standard:	None
Current use:	Not commercially available, OEM´s currently conducting screening tests.
Current limitations for increased usage:	Vehicle availability. Butanol has other commercial applications with higher price tolerance.
Outlook for future use:	If the production cost can be made to be competitive and meet EU's sustainability criteria it will be interesting.
OEM modification to vehicle:	Fuel system, engine control system, but needs to be investigated further.
Used vehicle conversion:	Same requirements as for OEM.
Highlighted emission components:	Aldehydes
Comment:	Currently the major source of Butanol is fossil raw materials.

Butanol – as blending component in petrol	
Raw material used:	Biomass or fossil fuels.
Applicable standard:	EN228
Current use:	Currently being investigated
Current limitations for increased usage:	EN228 allow up to 15% butanol in petrol. Butanol has other commercial applications with higher price tolerance. Butanol is currently not allowed as blending component in diesel fuel.
Outlook for future use:	If the production cost can be made to be competitive and meet EU's sustainability criteria it will be interesting.
OEM modification to vehicle:	None if complying with EN228.
Used vehicle conversion:	Same requirements as for OEM.
Highlighted emission components:	Aldehydes
Comment:	Currently the major source of Butanol is fossil raw materials.