JATROPHA OIL IN COMPRESSION IGNITION ENGINES

Effects on the engine, environment and Tanzania as supplying country

Graduation thesis

E.L.M. Rabé

Supervisor:
Dr.ir. L.M.T. Somers
Coordinator:
Prof.dr.ir. L.P.H. de Goey

Eindhoven University of Technology
Master Sustainable Energy Technology
Graduation department of Mechanical Engineering
Division Thermo Fluids Engineering

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Glossary

Additive
Material added in small amounts to finished fuel products to improve certain properties or characteristics

Air/fuel ratio
Mass ratio of air to fuel inducted by an engine.

Biodiesel
Plant oil, which has been chemically modified via a reaction with methanol or ethanol, called esterification. In other words biodiesels are Methyl esters of fatty acids meeting the requirements of ASTM specification.

Boiling range
The spread of temperature over which a fuel, or other mixture of compounds, distills

Cetane index
An approximation of cetane number based on an empirical relationship with density and volatility parameters such as the mid-boiling point. This approximation is not valid for biodiesel or biodiesel blends.

Cetane number
A measure of the ignition quality of diesel fuel based on ignition delay in an CI engine. The ignition delay is the time between the start of the injection and the start of the ignition. The higher the cetane number, the shorter the ignition delay and the better the ignition quality. More details are described in the introductive research report [34].

CI-engine
Compression Ignition engine, i.e. a Diesel engine.
It is an internal combustion engine in which ignition is caused by compression of the air-fuel mixture in the cylinder.

Cloud point
The temperature at which a sample of a fuel just shows a cloud or haze of wax (or in the case of biodiesel, methyl ester) crystals when it is cooled under standard test conditions, as defined in ASTM D2500

Compression ratio
The ratio of the volume between the piston and cylinder head before and after a compression.

EIA
Energy Information Administration, statistical agency of the U.S. Department of Energy.

Energy content of the fuel
The heat produced on combustion of a specified volume or mass of fuel, also known as heating value or heat of combustion

Flash point
The temperature to which the fuel has to be heated to produce a vapour/air mixture that will ignite when a source of ignition is present.

HDV
Heavy duty vehicles

Heating value
A distinction should be made between the Higher and Lower Heating Value (HHV and LHV):
HHV: The maximum potential energy released during complete oxidation of a unit of fuel. Includes the thermal energy recaptured by condensing and cooling all products of combustion.
LHV: The net energy released during oxidation of a unit of fuel excluding the heat required for vaporisation of the water in the fuel and the water produced from combustion of the fuel hydrogen. LHV= HHV- 21.998 (H) - 2.444 (W)

IEA
International Energy Agency, an intergovernmental body committed to advancing security of energy supply, economic growth and environmental sustainability through energy policy co-operation

Jatropha Methyl Esther (JME)
Biodiesel produced by esterification of Jatropha Oil

Jatropha Oil
PPO produced by pressing Jatropha seeds

LHV
Light duty vehicles

Octane number
The ratio of the volume of the combustion chamber at the beginning and that at the end of the compression stroke.

OECD
Organisation for Economic Co-operation and Development, a group of 30 member countries sharing a commitment to democratic government and the market economy. The governments work together to address the economic, social, environmental and governance challenges of the globalising world economy. OECD is best known for its publications and its statistics on economic and social issues from macroeconomics, to trade, education, development and science and innovation.

Pure Plant Oil (PPO)
PPO is just one name out of a range of names that is given to oil that can be annually renewed primarily by solar inputs, can be made for long term use in diesel engines and is liquid at atmospheric pressure in a temperature range of at least 0-100 degrees Celsius[4]. Other names are Renewable Oil, Bio-oil, Unmodified Vegetable Oil, Straight Vegetable Oil (SVO), Vegetable Oil, Fatty Acid Methyl Esther (FAME), Pure vegetable oil from oil plants (definition by the European Commission), Pflanzenöl (German).

SI-engine
Sprak Ignition engine, i.e. an Otto engine.
It is an internal combustion engine in which ignition is initiated by a spark.

Well-to-wheel analysis
Compares energy input, emissions and cost of the whole cycle of a fuel, from the fuel source (well) to vehicle kilometers in a car (wheel)

Abstract

Judging from the newspaper headlines, the problem of world energy supply is a hot topic at the moment. This is not surprising since research shows that the oil resources are declining and will become more difficult and expensive to recover. This leads to the development of renewable energy technologies.

Energy from biomass and more specific, biodiesel, is one of the opportunities that could cover the future energy demand. It should not be seen as the ultimate solution, but depending on climate characteristics, resources, geographical position and level of development as an appropriate option in a broader energy technology mix.

This thesis investigates the possibilities for biofuels produced from Jatropha Curcas, a plant that grows in countries around the equator, including Tanzania, on which this thesis focuses. The energy crop has several advantages; it grows on degraded, dry, wasted and even salty land, which can be re-cultivated afterwards; it is toxic, which makes it preferable to other energy crops, because it does not compete with food crops; it gives seeds already after one year and the life-span of the plant is more than 50 years; it is good for the economics and employment of the country; and so on.

The oil that was gained by pressing the Jatropha seeds and part of it has had a chemical treatment called esterification, which results in the less viscous Jatropha Methyl Ester, a biodiesel. The fuels were tested in an engine set-up and compared to two reference fuels; fossil diesel and the well-known biodiesel Rape Methyl Ester. The engine in the set-up was originally a 6-cylinder 11.6 DAF WS engine. It had been adjusted in order to make one measuring cylinder optically accessible. Hereby the combustion process could be filmed with a high speed camera. The experiment yielded the in-cylinder pressure as function of the crank angle, NO/NO_x measurements, a photo diode signal that represents the amount of soot produced and from the pressure also heat release and in-cylinder temperature could be computed.

The investigation of both the experiments and the broader literature study did not lead to any findings that could hamper the application of Jatropha oil or -Methyl Ester in Diesel engines. In the short term however, the use should be restricted to Tanzania. In the longer term there might be possibilities for export to Europe as well. This depends on if the European regulation still stimulates the use of bio-oil and bio-diesel by then.

Introduction

In this introduction the need for research in the field of alternatives for fossil transportation fuels will be explained. Based on problems rising from the world energy demand versus supply (paragraph 1.1), the need for renewable energy will be explained (paragraph 1.2). In paragraph 1.3 the meaning of renewable energy in the transport sector will be addressed. In the remaining paragraphs, the status quo of Jatropha Curcas is described and the research objective and thesis outline are presented.

1.1 *The problem of world energy supply*

World energy consumption has increased continuously for decades. With just a few periods like the oil crises in 1973 and 1979 in which the growth slowed down. Figure 2, the upper line, shows fairly steady increasing world consumption[1].

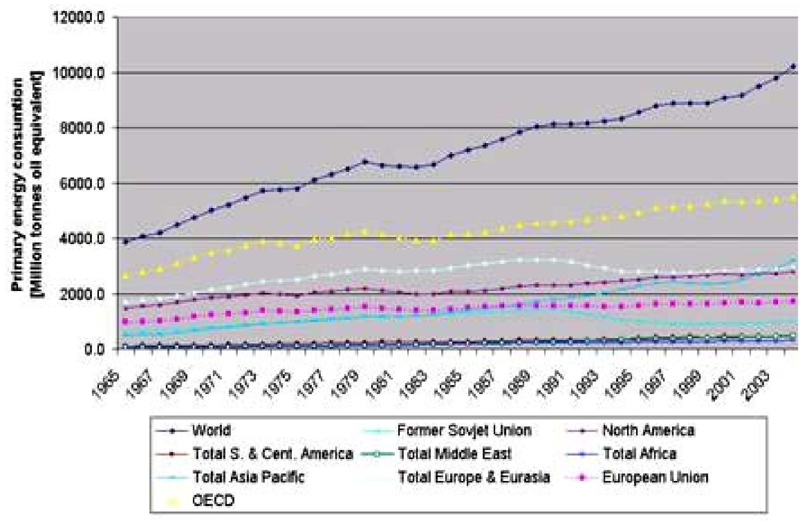


Figure 1: Primary Energy Consumption in million toe for the world, the continents and the EU and OECD (1965-2004)

According to the 'BP statistical review of world energy 2005' the world primary energy consumption in 2004 was 10224 million toe[2], which means a 4,3% growth compared to the year 2003. Energy consumption is not expected to decrease during this century, because the world population is still increasing and developing countries' economies are growing.

By contrast, the supply of primary energy recourses like oil and natural gas seem to decrease to a critical point. Although the exact date is debatable, most researchers

[1] Consumption only comprises commercially traded fuels. Excluded, therefore, are fuels such as wood, peat and animal waste which, though important in many countries, are unreliably documented in terms of consumption statistics.
[2] ´toe´ is ton oil equivalent, 1 toe= 41.868 GJ

agree that the production peak of oil and gas liquids is near. Some critics even say that we have already past it. The point of maximum production of oil is called the Hubbert Peak. At that point half of all the recoverable oil that ever existed on our planet has been used. There is still oil left, but it is much harder or much more expensive to recover it. Reaching the Hubbert peak means that production will decline in the future, while demand will continue to increase.

With the growing demand and decreasing supply, the issue of finding alternatives for finite resources is becoming more and more important. A third but not insignificant argument for alternative fuels is the carbon monoxide (CO_2) problem. The greenhouse effect is increased by greenhouse gasses like CO_2 that indirectly harm the environment by radiative forcing[3]. This effect has become common knowledge since the media started to pay attention to it.

Furthermore for many countries in the world the main drive to search for alternative fuels is to become independent of the oil exporting countries. By developing new energy technologies, the power of oil producing countries decreases and especially with the social unrest there, this is a priority to many countries.

1.2 Renewable energy as primary resource

One way to reduce the use of depleting primary energy sources, fossil fuels, is to develop renewable energy technologies. Renewable energy sources "capture their energy from existing flows of energy, from on-going natural processes, such as sunshine, wind, flowing water, biological processes, and geothermal heat flows" says the Wikipedia encyclopedia. Research areas follow directly from this definition. Technologies for using solar energy, wind energy, hydropower, energy from biomass and geothermal energy are some promising ones.

It is readily understood that there is no ultimate technique that can solve the problem; several techniques will have to exist in conjunction to each other. Some countries have distinguishing characteristics that make a certain technology more appropriate than another. Denmark for instance can gain advantages by focusing on wind energy since the country is very windy. Countries like Tanzania are most conveniently situated to use either solar power, or a derivative of that, biomass as primary energy source.

1.3 Biofuels

Transport covers one third of the Total Final Energy Consumption (TFEC), of which 80% is road transport [51]. The share of transport energy use has always been growing, especially since in other sectors people became aware of the need for increasing efficiency and diminishing consumption. This is the main reason for working on the development of biofuels.

[3] The generalised concept of radiative forcing in climate science is any change in the radiation (heat) entering the climate system or changes in radiatively active gases [49].

“A biofuel is any fuel that is derived from biomass - recently living organisms or their metabolic byproducts, such as manure from cows. It is a renewable energy, unlike other natural resources such as petroleum, coal and nuclear fuels...” is the definition the encyclopedia states[4]. Biofuels are called CO_2 neutral because the carbon in biofuels was recently extracted from atmospheric carbon dioxide by growing plants. This in contrast to fossil fuels that contains carbon that was encaptured millions of years ago. If fossil fuels are burned there is no CO_2 capture but only a lot of CO_2 emission. Burning biofuels does result in emmisions as well, but because approximately the same amount of CO_2 is used to grow the biomass, it does not result in a net increase of carbon dioxide in the Earth's atmosphere. CO_2 neutral fuels are therefore seen as a good way to reduce the amount of carbon dioxide released into the atmosphere by using them to replace non-renewable sources of energy.

One newly discovered biofuel is the oil that can be extracted from the seeds of a Jatropha plant. Jatropha Curcas, as the scientific name is, grows amongst others in Tanzania[5]. The characteristics of the cold pressed oil are similar to those of other more commonly known bio-oils like sunflower oil and rapeseed oil. This means that there are possibilities to use it in diesel engines as well.

1.4 Status quo and main gaps in current knowledge

Research on the use of bio-oil and biodiesel in diesel engines has shown that most emissions are lower than for conventional diesel. Just NO_x emissions are sometimes slightly higher and sometimes lower than for fossil diesel. For vegetable oil, it has turned out that the successful use of it is a function of the engine type; it cannot be safely used in an indirect injection, naturally aspirated and air-cooled engine for long periods of time [15]. This is related to the high viscosity of the oil, caused by the large molecular sizes of the components in the oil. The viscosity influences the flow properties of the fuel, such as spray atomization. High viscosity is normally coupled to a high boiling point, therefore vaporization and air/fuel mixing is worse. Because of that, high viscosity has an adverse effect on the combustion of bio-oils in the existing diesel engines [2]. Another problem associated with the use of bio-oils in diesel engines is the high reactivity of the unburned fuel, which could cause fouling of the injector nozzles and problems in the fuel pump and cylinder if deposits are formed. However, there is no unanimity about the suitability of bio-oils; there are numerous examples of well functioning cars on bio-oil and several research projects showed no problems at all[44].

Probably the functioning is dependent on the engine that is used. Older engines and bigger ones for trucks or ships tend to be more suitable for PPO, because the injectors are wider. Furthermore, the older engines are not as optimized for injection timing as modern engines. In order to clarify some of the contradictions found in previous investigations[6], some more long-term research projects will be examined and there will be done some engine tests on a HDV engine set-up situated at the Radboud Universiteit Nijmegen. The engine tests in this thesis will

[4] Wikipedia encyclopedia [50]
[5] More information is presented in the report of the preliminary investigation on this subject, [34].
[6] See the report of the preliminary investigation on this subject, [34].

show if the pure plant oil causes short term problems in a DAF six-cylinder HD engine of the type WS268L with a cylinder head of the type XF95.

The behavior of the fuel can be improved either by mixing it with conventional diesel or by esterification, as described in the introductory research report[34]. The product of esterification is called a methyl ester; depending on the kind of ester the name becomes for instance Rape Methyl Ester (RME, for rapeseed) or Jatropha Methyl Ester (JME, for Jatropha). The viscosity decreases in both cases and so will the problems with the application of it in the engine. Blends are already used in many countries and works well. The methyl esters have as disadvantage that the esterification process is a very energy consuming. In the preliminary investigation an energy balance is determined and it turned out that the total energy input for the production of biodiesel is twice as high as that of PPO.

1.5 Research objective

The aim of this research project is to investigate the described gaps in current knowledge. In order to do so, the inconsistent data of Jatropha will be examined critically and the ambiguities about the functioning of Jatropha Oil in diesel engines will be clarified. By means of running tests on an engine set-up on conventional diesel, Jatropha oil, JME and RME, experience is gained on this. The combination with literature research on the latest news on Jatropha is expected to make the investigation as complete as possible. Furthermore, the topic will be placed in a broader perspective; the possibilities for Jatropha Oil in Tanzania, the country where Jatropha is cultivated, will be investigated because it could stimulate local development and employment.

1.6 Outline of the thesis

This thesis is the result of a multi-disciplinary research, which means that the subject is not only technically investigated, but that the practical and cultural embedding is a focus point as well. The thesis starts with the broader part about Jatropha and Tanzania (Chapter 2-4), followed by a more technical chapter about emissions and other environmental impacts of burning fuels in CI-engines. The thesis continues with an in-depth investigation on the engine running on several fuel blends (Chapter 6 and 7). Finally, all gathered information will lead to specific information on the technical, social and environmental impact of the use of Jatropha oil in Tanzania.

The thesis addresses several research questions that are relevant to the research objective:

- What is the status in Tanzania with respect to the infrastructure of diesel fuel, the vehicles that are used, the amount of cars and trucks, the prices of fuels, the prices of cars and trucks and who can afford to use them, etc.? *(Chapter 4)*
- What are the possibilities for the use in Tanzania and possibly outside Tanzania? *(Chapter 4)*
- What emissions are produced by the use of diesel engines in cars and trucks with different fuels? *(Chapter 5)*

- What are the effects of these gases and how do they harm the environment? *(Chapter 5)*
- What emissions are produced by the use of Jatropha oil in the engine that will be used for practical investigation? *(Chapter 7)*
- Do problems occur with Jatropha oil in the diesel engine, and if so, what kind of problems are these? *(Chapter 7)*
- What differences are measured in the engine during the use of Jatropha oil compared to conventional fuels (pressure differences, temperature differences, amount of fuel needed, amount of air required, etc)? *(Chapter 7)*
- Can environmental damage caused by Jatropha oil use be further diminished or avoided and how? *(Chapter 8)*

Finally, Chapter 9 presents conclusions and recommendations including some future perspectives based on the results of the practical work and literature search.

2 Biomass as a source for alternative fuels

2.1 Introduction

In Chapter 1 the relevance of sustainable energy sources is explained briefly as an introduction. In this chapter the topic is pursued in greater depth and the focus will shift towards biomass as raw material for automotive fuels.

2.2 World energy need for automotive fuels

For calculations or even assessments of how much liters of biofuels are needed to cover a certain demand, assessments of the future development of the world energy supply are used. In these studies the future energy consumption and fuel mix are determined based on certain technical, economic, demographical, social, institutional and political parameters. A consistent way to study these issues is by means of scenarios [34]. After the first global energy scenario was constructed at the International Institute of Applied System Analysis, IIASA, during the late 1979s, many others were developed. Scenarios are not predictions, nor forecasts, but more like descriptions or images of what the world could look like in the future.

Two sorts of scenarios can be distinguished; normative and descriptive scenarios. Normative scenarios describe the future routes that can be taken in order to end up in a predefined status. Descriptive scenarios on the other hand, give insight in possible pathways for the future. Typical descriptive and well-known scenarios are the SRSS scenarios (Special Report on Emission Scenarios), which have been developed in the context of the Intergovernmental Panel on Climate Change (IPCC). The aim of these recently developed scenarios is to simulate the greenhouse gas emissions due to the combustion of fossil fuels for the time frame up to the year 2100. The IPCC publications have become standard works of reference and are widely used by policymakers, scientists and other experts. There are four storylines on which the IPPC scenarios are based, and they are situated along two axes, see Figure 2. The scenarios A1, A2, B1 and B2 differ in terms of participation in international trade and focus on economic, technological or sustainable (environmental) growth.

- The A1 scenario describes a future world of very rapid economic growth, global population that peaks around 2050 and declines thereafter, and the rapid introduction of new and more efficient technologies. Within the A1 scenario three groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)
- The A2 scenario assumes a more slowly changing world. Differences in culture will remain and production patterns will change very slowly. The result in continuously increasing global population. Economic development is very much regionally oriented, economic growth and technological changes are more fragmented and slower than in other scenarios.
- For B1, the population development is the same as in A1, but economic structures change very rapidly towards a service and information economy. B1 is oriented on sustainable development, which means reductions in material

intensity, introduction of clean and resource-efficient technologies, but without additional climate initiatives.

- The B2 scenario assumes a continuously increasing global population at a rate lower than in A2. Sustainability is just as in B1 an important objective, but the development is more locally. Economic development is at intermediate level; technological development is more diverse than in B1 and A1.

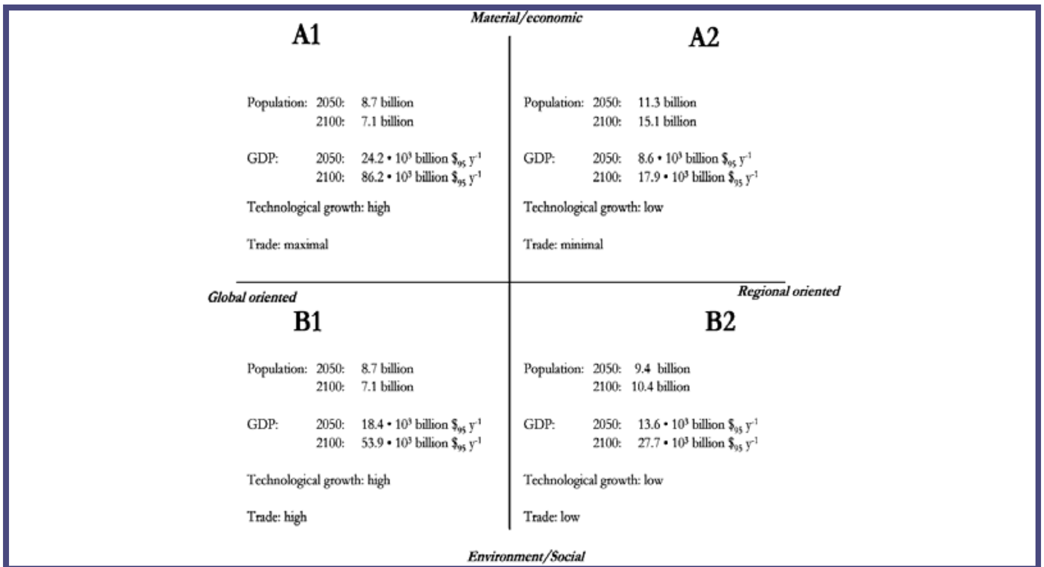


Figure 2: Schematic view of the four storylines on which IPCC scenarios are based

Quantifying these storylines leads to projections for the future on many aspects. In Figure 3 projections for CO_2 concentration, CO_2- and SO_2 emissions, temperature- and sea level rise are shown.

Based on scenarios like these, more specific outlooks can be made. In this thesis, it is interesting what the demand for transport fuels will be in the future. Based on the figures and data of the SRES/IPCC global energy scenarios, new scenarios were written for the transport sector specifically. Recently, the IEA has worked with the World Business Council for Sustainable Development (WBCSD) on a model based on global energy scenarios that gives an idea about how the transport sector is expected to develop the next couple of decades.

In April 2000 the Sustainable Mobility Project (SMP) was launched. Eight transport equipment producers, three fuel providers, a producer of light metals and the world's largest producer of tires for road vehicles joined together to create SMP. The collective view was to make both the increase of mobility and the decrease transport's impact attainable.

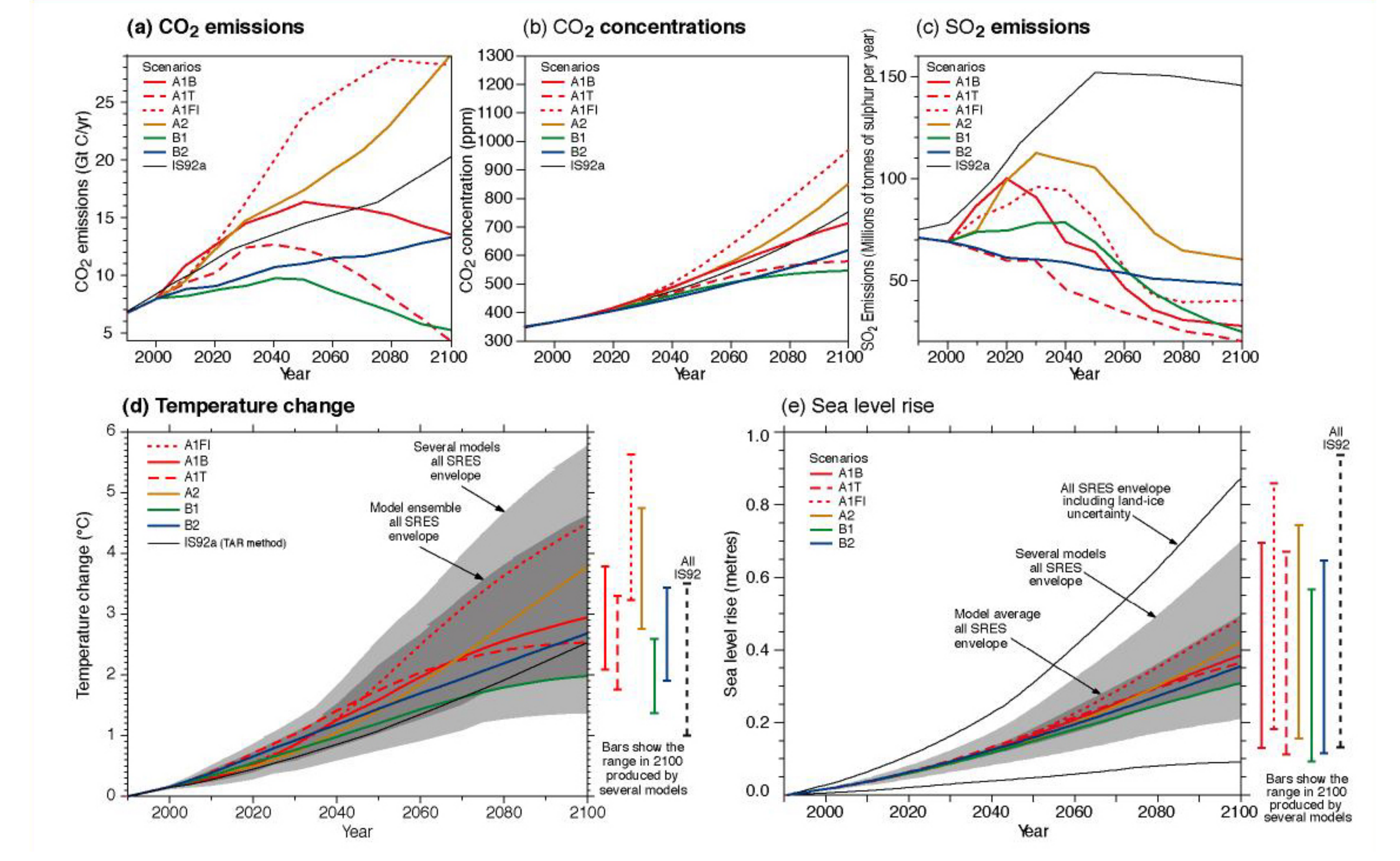


Figure 3: 'The global climate of the 21st century', [24]

From 2002 to 2004 IEA worked with the WBCSD's SMP to develop a global transport spreadsheet model that can serve in conducting projections and policy analysis. Based on recent trends in various important indicators and variables a reference case was defined. This reference case is used in the SMP's Final Report "Mobility 2030: Meeting the challenges to sustainability". It reflects the collective efforts of more than 200 experts from 12 industrial companies. Existing data from the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and WBCSD studies were used for this report. Based on this, the model and the report may be considered reliably.

Many sectors/modes, vehicle technologies/fuels, regions and variables are included in the spreadsheets of the SMP model, but not all technologies or variables are covered for all modes. The most detailed segment of the model covers light duty vehicles. Since nearly half of transport energy use is covered by LDV's[7] this will be the main focus in this thesis as well. Other modes, technologies, fuels, regions and variables that are important for this thesis are summarized in Table 1.

Table 1: Data from the SMP spreadsheet model that are used in this thesis

Sectors/Modes	Vehicle Technologies/Fuels	Regions	Variables
• LDV's (cars, minivans, SUV's) • Medium trucks • HDV's	• Internal Combustion Engine: ▪ Diesel ▪ Biodiesel	• OECD Europe • OECD North America • OECD Pacific (Japan, Korea, Australia, NZ) • Former Soviet Union (FSU) • Eastern Europe • Middle East • China • India • Other Asia • Latin America • Africa	• Passenger kilometers of travel • Fuel use • CO_2 emissions • Pollutant emissions (PM, NO_x, HC, CO)

The SMP model is benchmarked to the Reference Scenario published in the IEA's World Energy Outlook 2002 (WEO). "The reference case projects one possible set of future conditions, based on recent trends in various important indicators and other variables", is defined in the model documentation [17]. Adjustments are made for expected deviations from recent trends due to factors such as existing policies, population projections, income projections and expected availability of new technologies saturations in vehicle ownership, are all incorporated. Some assumptions are made as well:

- No major new policies are assumed to be implemented beyond those already implemented in 2003.
- No policy trajectory is evident for reduced LDV fuel consumption.
- After the year 2030 significant changes in trends are avoided. Trends in 2030 are assumed to exist until 2050 to see the net effects of actions and events years earlier in the year 2050 [17].

[7] LDV = Light duty vehicles, HDV = Heavy duty vehicles

In the reference case, global transportation fuel use increases by a factor of almost 2,5 between the year 2000 and 2050. It is striking that conventional fuels like gasoline, diesel and kerosene grows substantially while the share of other, sustainable fuels, remains very small.

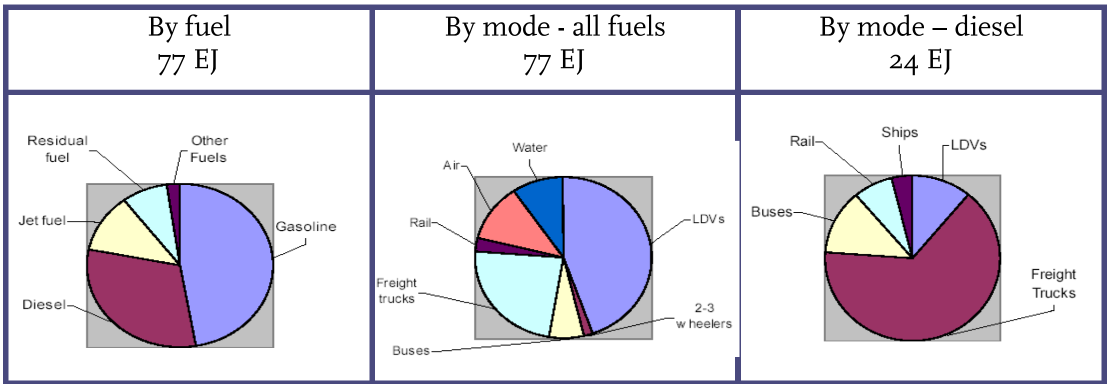


Figure 4: World transport energy use in 2000 [17]

In 2000 the world transport energy use equals 77 exajoules, from which 36 EJ gasoline and 24 EJ diesels, see Figure 4 and Table 2. In the year 2050 this would increase to 176 EJ (75 EJ gasoline and 56 EJ diesel) according to the reference scenario. The biggest growth occurs in the LDV's, HDV's and air travel. The model does also make a distinction between the regions mentioned in Table 2 and it is obvious that China is the biggest grower in this model. With an absolute increase of over 18 EJ, China will use more than five times as much in 2050 as in 2000. India has a relatively high growth as well, 440%, but in absolute numbers the 8,8 EJ increase is far less than China (see Table 2).

Table 2: Total transport energy use, absolute growth and relative growth by region[45]

	Total Energy Use (includng int'l shipping bunkers) Exajoules											Growth 2000-2050	
Region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	ABS	REL
OECD North America	28.6	30.4	32.8	35.1	37.2	38.8	40.4	41.8	43.3	44.8	46.3	17.7	0.6
OECD Europe	16.4	17.5	18.7	19.8	20.4	20.9	21.4	21.7	21.9	22.1	22.3	5.9	0.4
OECD Pacific	7.0	7.2	7.5	7.8	8.1	8.3	8.5	8.7	8.9	9.2	9.5	2.4	0.3
FSU	2.7	3.1	3.5	4.1	4.9	5.4	6.0	6.6	7.2	7.8	8.4	5.7	2.1
Eastern Europe	1.2	1.3	1.5	1.7	1.9	2.0	2.2	2.5	2.8	3.1	3.4	2.2	1.8
China	3.6	4.5	5.6	7.0	8.6	10.0	11.8	13.8	16.2	18.8	21.9	18.3	5.1
Other Asia	5.1	5.8	6.8	7.9	9.1	10.2	11.5	13.0	14.8	16.9	19.3	14.2	2.8
India	2.0	2.4	2.9	3.5	4.3	4.9	5.8	6.7	7.8	9.1	10.8	8.8	4.4
Middle East	3.1	3.4	3.7	4.1	4.6	5.1	5.6	6.0	6.4	6.8	7.3	4.2	1.4
Latin America	5.0	5.7	6.7	7.8	9.1	10.1	11.4	12.9	14.5	16.4	18.6	13.5	2.7
Africa	2.3	2.6	3.0	3.5	4.2	4.8	5.4	6.0	6.6	7.4	8.3	6.0	2.7
TOTAL - All Regions	77.0	83.9	92.8	102.4	112.2	120.7	129.9	139.6	150.4	162.4	176.0	99.0	1.3

Focusing on diesel fuel use now, it appears that especially the regions 'OECD North America' and ' OECD Europe' have used a lot of diesel fuel in 2000. The projections for the next couple of decades in the reference case are based on two considerations. The primary target was to stay close to the IEA/WEO 2002 projection and besides that it is assumed that average fuel consumption will become more and more similar across regions. Based on the IEA indicators database the average fuel consumption improvement over the past years is estimated at 0.4% per year in liters/100km. This is in absence of policies to promote improvement. One major exception is the US, where the improvement has been close to 0.0%. For the future projections policies have been taken into account and the improvement is projected from 0.2% for the US to up to 1.0% in the EU and Japan, where strong fuel consumption improvement policies are active.

Table 3: Total diesel fuel use for transport by region

	Total Diesel fuel Use (exajoules)										
Region	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
OECD North America	5.8	6.2	6.8	7.2	7.6	8.0	8.5	8.9	9.4	9.9	10.4
OECD Europe	6.2	6.9	7.7	8.7	9.1	9.3	9.4	9.5	9.5	9.5	9.6
OECD Pacific	2.0	2.0	2.1	2.1	2.2	2.3	2.4	2.6	2.7	2.8	2.9
FSU	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.7	1.9	2.1	2.3
Eastern Europe	0.4	0.4	0.5	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3
China	1.4	1.7	2.1	2.5	2.9	3.3	3.7	4.2	4.8	5.5	6.3
Other Asia	2.0	2.3	2.7	3.2	3.6	4.0	4.5	5.0	5.7	6.4	7.2
India	1.3	1.5	1.7	2.0	2.3	2.7	3.0	3.4	3.9	4.5	5.1
Middle East	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.3
Latin America	2.1	2.4	2.7	3.0	3.4	3.7	4.1	4.5	5.0	5.5	6.0
Africa	0.7	0.8	0.9	1.0	1.2	1.3	1.5	1.6	1.8	2.0	2.2
TOTAL - All Regions	23.6	26.2	29.5	32.8	35.8	38.4	41.3	44.4	47.7	51.5	55.6

This total diesel use for transportation is a summation of what is calculated for LDV diesels, LDV diesel hybrids, medium freight trucks, heavy freight trucks, freight rail, passenger rail, minibuses, buses and water-borne transport. The calculations for all separate transportation modes are similar and therefore the calculations for light duty vehicles will serve as an example for the others.

LDV total fuel consumption is calculated per region and per five years. For the year 2000 it is calculated with other numbers that are either assumed or calculated. For the year 2000, the calculations will be presented and explained below. Texts with the striped borders are considered as inputs (see also footnotes), the gray colored blocks are calculations and the first block with border is the output.

LDV Total fuel consumption = *[Billion liters gasoline equiv.]*	LDV vehicle travel * *[Billion km/year]*	Stock-average on-road fuel economy/100 *[Liter/100 km]*
LDV vehicle travel = *[Billion km/year]*	Total diesel LDV stock * *[Million]*	Average travel per vehicle *[Km/yr], placeholder assumption*
Total diesel LDV stock = *[Million]*	Reference case LDV stock * *[Million]*	Stock shares in (2000) *[-], Placeholder assumption*

Reference case LDV stock [8] = *[Million]*	LDV/1000 people * *[-], Forecast & assumption*[9]	Population / 1000 *[Millions], WEO 2002 and EIA forecast*

Stock-average on-road fuel ec. = *[Liter/100 km]*	Forecast on-road fuel ec. * *[Liter/100km], forecast*[10]	Ratio targets 2000 *[-], Placeholder assumption*[11]

Comparing consumption of energy use and more specifically diesel fuel use *per capita*, a remarkable difference between continents is observed (see appendix B). North American inhabitants obviously consume by far the most energy, almost 71 GJ per person per year, while the global average is around 13 GJ per person per year. And even although North Americans drive mostly on gasoline, their diesel consumption per capita is higher than any other region. This is a result of a high car ownership rate, high average travel per vehicle and low average number of persons per trip [17]. According to the reference case of the SMP model, the total diesel fuel use is going to rise to even higher levels. Both OECD Europe and OECD Pacific are developing in the direction of North America in the sense of the higher per capita energy use, as can be seen in the graphs of appendix B. According to this model also the regions FSU, Eastern Europe and Latin America will reach levels of around 30-40 GJ energy use per capita per year[45].

Table 4: Some important data from the SMP model reference case. More data, see appendix B

	Energy use per capita in 2005 [GJ]	Energy use per capita in 2050 [GJ]	Total Diesel use in 2050 [EJ]
OECD North America	71.3	79.3	10.4
OECD Europe	33.6	47.9	9.6
OECD Pacific	35.8	49.3	2.9
FSU	12.2	33.6	2.3
Eastern Europe	13.9	40.7	1.3
Latin America	12.9	28.1	6.0
Asia including China and India	-	-	18.6
World	13.1	18.9	55.6

For diesel fuels especially the three OECD regions and Eastern Europe will consume the most per capita. In absolute quantities however, especially Europe, North America, Latin America and Asia including India become very interesting in the future. In total these regions will consume almost 45 out of 55 EJ in 2050, which is almost a quarter of total global transport energy use at that time (see

[8] Reference Case, LDV Stock (millions) - Based on Car Ownership Rates. For non-OECD countries, this is developed as the product of car ownership rates (from the WEC) and population. This becomes the basis for the sales and scrappage forecasts in the reference case.
[9] For OECD North America and OECD Europe, IEA forecasts and assumptions and for the rest placeholder assumptions.
[10] Exogenous forecast of LDV stock average on-road fuel economy, sources: US EIA/AEO 2002, IEA indicators database, WEC 1999 (in some cases adjusted for fit, placeholder assumption)
[11] Ratios adjusted so that fuel economy for total stock hits target in 2000

appendix B). But even for the short term there is a big opportunity for diesel substitutes, since the worldwide diesel use is now approximately 26 EJ [45].

According to the SMP model however, the alternative fuels do not develop very rapidly. In fact, biodiesel use will remain insignificant everywhere. There is only a small increase in Europe; from 0.1% in 2000 it will grow to 1.0% in 2005 and to 4% in 2010 at which level it remains up until 2050. This is because the SMP reference case assumes no major new policies beyond those implemented in 2003. However, it could also be possible that alternative fuels become more and more important and the targets are set higher and higher. How much would this change the outcomes of the SMP reference model?

There is a feature added to the SMP model, which could give an indication of this. It offers the opportunity to change fields according to new policy measures, like the fact that policy makers all around the world try to stimulate the substitution of fossil fuels by biofuels. For instance, the following inputs, which are real numbers, probably give a totally different output.

- The European Union set a target for biofuels in 2010 at 5.75% of the total automotive fuel use.
- The US legislation focuses on ethanol, but has a target of 5% substitution of gasoline in 2010.
- India aims at 5% ethanol blending, eventually in the whole country.
- Latin America is focusing on expanding production for export purposes.

It would lead too far for this thesis to actually do the analyses again with these inputs, but it seems obvious that this would change the production of biofuels. In cases like this, the model generates the corresponding output. It is therefore not only a good policy making feature, but also a way to test how sensitive the model is to changes.

2.3 *Biomass availability and potential*

The main critic on biomass is its availability. Many argue that retrieving energy from biomass is no option, since there would not be enough land available for the amount of energy we need. In this paragraph land requirements and land availability for the production of biofuels are assessed.

A broad literature study led to the conclusion that statements on land scarcity are mostly based on wrong assumptions.

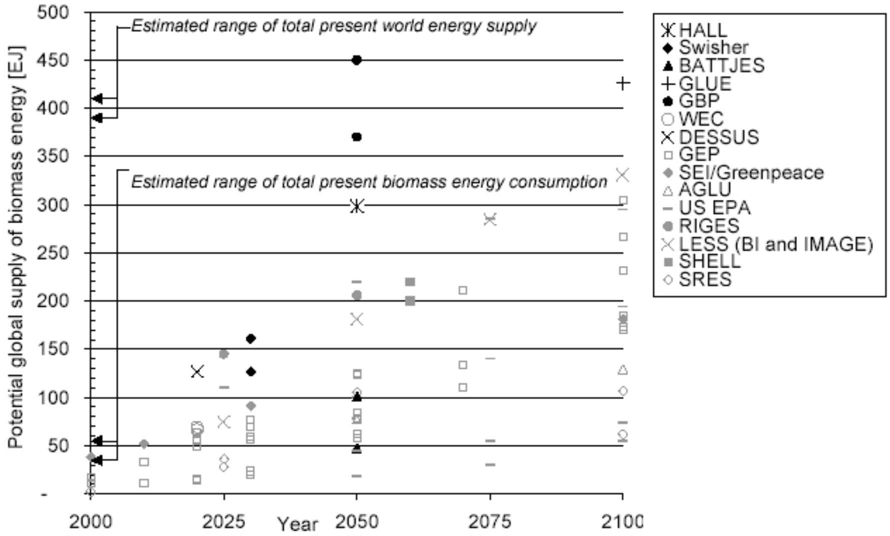
- First of all, the energy demand will not be totally covered by biomass. Several sustainable energy technologies will exist next to each other. Current developments show that already. Depending on climate characteristics, resources, geographical position and level of development, every region should find its own optimal energy technology or -mix.
- Besides that, not all biomass a country needs has to origin from its own land area; there are many possibilities in the international energy trade. Some world regions have a larger bioenergy production potential then others. Countries that have large land areas in combination with good crop production potential, low population density and extensive agricultural practices, may become suppliers of bioenergy in the future.

- And if the trade of biomass is desirable, there are more possibilities besides the trade of biofuels. In order to reduce the CO_2 production, it is necessary to use more renewable energy sources, in this case biomass. For the worldwide CO_2 problem, it does not matter where the substitution takes place. So the best way to do it is the most efficient way. Trading energy carriers such as electricity is a very good option from this point of view. The production can very easily be scaled up and optimized without any increased flexibility, demand or infrastructure. Trading of CO_2 credits is an already widely known concept. By trading emission credits, investors from other areas can be attracted. Countries that exceed the CO_2 emission limit that was set in the Kyoto Protocol, can buy emission allowances from other countries, so that the worldwide targets can be achieved.
- Moreover there is a discussion about the threat for the food production because some people think that energy crops will be competing with the food crops. In many cases however, this is not the case. Either because the crops are grown at uncultivated land or because the crops are grown in between rows of food crops, which can even improve the soil conditions.
- Further the total energy potential is often estimated too low, because the particularly high energy yield of the crops is not taken into account.
- Not only energy crops can be used to fulfill the demand of biomass, but also forests, woodland, permanent pastures and residues of the agriculture industry can be used.

Many investigations on the global availability of biomass energy have been done and the estimates on the future contribution of biomass energy to the energy supply vary widely. According to an exploration published in "Biomass and bioenergy" in 2003 the range of the global potential of primary biomass in approximately 50 years is quantified at 0-1135EJ/year [22]. This publication states that the crucial determining factors for the availability of biomass for energy are the following six.

1) The future demand for food, determined by the population growth and the future diet;
2) The type of food production systems that can be adopted world-wide over the next 50 years;
3) Productivity of forest and energy crops;
4) The (increased) use of bio-materials;
5) Availability of degraded land;
6) Competing land use types, e.g. surplus agricultural land used for reforestation[22].

This has been discussed in detail in the GRAIN study; a NOVEM-GAVE study published in 2000. In this study 17 different global bio-energy resource assessments were analyzed, from which 16 are shown in Figure 5. The black markers indicate studies that concentrated on the maximum physical biomass resource that may be available for energy purposes (" resource focused") and the gray markers indicate studies that looked from the demand side at the competitiveness of final energy carriers from biomass or estimated the amount if bio-energy needed for targets on sustainable energy supply ("demand driven").



Black markers are "resource focused" studies, whereas the gray markers are "demand driven"
Note: the total energy demand at 2025/2050 is estimated at: 120.7/176.0 EJ, see appendix B

Figure 5: Results of 16 studies that estimated the future potential contribution of biomass energy to world energy supply [8].

Biomass resources are actually the world's largest and most sustainable energy source. The annual primary energy production of biomass was about 4500 EJ in 1999[51]. But of course, not all the energy can be used as bioenergy; the annual bio-energy potential is about 2900 EJ, though only 270 EJ can be available on a sustainable basis and at competitive prices. The problem is not availability but the sustainable management and delivery of energy to those who need it [51].

Scenarios developed for the United States and the European Union indicate that substitution of up to 6% of fossil fuels by conventional biofuels is possible with the currently available amount of land. The European Union requires not more than 5% of available cropland to produce ethanol for a displacement of 5% gasoline and in the US 8% is required. Unfortunately, the numbers are considerably higher for diesel substitution, 15% and 13% respectively, because average yields in liters of final fuel per hectare of cropland are lower than for ethanol.

At higher displacement levels, the production of biofuels with current technologies and fuel crops, some problems with competition between fuel-, food- and fiber crops could occur. Especially the threat of losing land for food crops to the biofuel industry causes extreme political discussions. On the one hand it could raise the price of foodstuffs, but on the other hand it could also benefit farmers and rural communities.

But with other types of feedstock, this problem would be solved. There are already some possibilities in development, for instance celluloid crops and crop residues for which other conversion processes are developed. The oil plant discussed in this paper, Jatropha Curcas, is an even better solution. The plant is inedible and grows on very arid land, which solves the food versus energy discussion completely. It even delivers a new market in developing countries, because the land would not have been used otherwise. The multiple advantageous ‘Jatropha system’ could be one step forward in the economical development of countries like Tanzania.

For the long-term production of transportation fuels the perspective is still unsure. Many studies analysed this, but there are many factors influencing the potential of biofuels on the long run. Technically more than a third of the transportation fuels could be displaced by biofuels over the time frame of 2050-2100, even according to the more conservative estimations. However, these studies do not focus on the economical restrictions. The costs of displacing fossil fuels in the different outlooks are very uncertain.

One reliable study that has been done in the context of the FairBioTrade project is “A quickscan of global bio-energy potentials to 2050”. This work covers three parts and part B “Regional bioenergy potential and an assessment of underlying variables” gives some more detailed information on the technical global bioenergy production potential in 2050. The report shows that the agricultural land area could be reduced with approximately 70 % by the year 2050, just by producing more efficiently and optimizing the land use patterns. If this area would be used for bioenergy crop production, this would yield 215 EJy-1 to 1272 EJy-1. In Table 5 the regions with the highest potentials are summarized.

Table 5: Bioenergy potential for different regions produced on saved agricultural land area by efficient and optimized land use [43].

Region	Potential range [EJ/year]
South America & Caribbean	47-221
Sub-Saharan Africa	31-317
C.I.S. & Baltic States	45-199
Oceania	20-174
North America	38-102

Further “the bioenergy production potential of residues is limited to 71 to 94 EJy-1 globally. Surplus forest growth contributes up to 81 EJy-1 (technically), but this potential is very much dependant on the ecological and economical limitations included and the demand scenario.” concludes the report.

2.4 *Technical suitability of biomass for automotive fuels*

Biomass in all its forms can be used as a source for biofuels. However, not all biomass streams can be converted in every type of biofuel some can only be used for diesel-like biofuels and some only for gasoline substitutes. The most common biomass sources for ethanol, the generally excepted gasoline substitute, are sugar cane, sugar beets, corn, grains, wheat and maize. They are rich in sugar, starch or celluloid material.

For biodiesel, there are some well known sources as well. In Europe mainly rapeseed is used to produce biodiesel, but for instance in Africa palm oil is the favorite source. Other sources are sunflower seeds, soybeans and coconut oil. A disadvantage of the above mentioned sources is that they are also food crops, which means that biodiesel is seen as a food competitor. Jatropha oil does not have this disadvantage since Jatropha is not a food crop; it is toxic to both humans and animals.

Technically, there is little difference between the biodiesel produced from these sources. They all have similar characteristics as fossil diesel and can be used in CI engines without any problems. However, in Europe a biodiesel standard is developed to assure the quality to the customers. In chapter 8 the standards and regulations are discussed in detail. PPO on the other hand, does have some disadvantages that make the suitability questionable. Especially the fact that the viscosity is much higher than that of fossil diesel could lead to difficulties like cold start problems, bad atomization, ignition delay or formation of deposits on the injectors. However, this is already explained in a preliminary research report, so for more information, see [34].

2.5 Competing fuels

While the annual produced biomass in the world could in theory provide our total fuel demand, there are several reasons why not all produced biomass can be used as an energy source. In paragraph 2.3 some competing elements of the large-scale substitution of fossil fuels by biofuels were discussed. For instance the fuel- versus food crop discussion is an obstacle for the development of biofuels, but for Jatropha this is not the case, because Jatropha is non-edible. Another reason that biofuels would not be the one and only substitute for fossil fuels is that biomass is not only used for transport fuels, but also for other purposes. Besides all that, there are other fuels under development as well right now. In this paragraph the most promising competing fuels will be passed in review and at the end the possible options or threats for the development of Jatropha fuels will be discussed.

- Biodiesels or Methyl Esters are produced by esterification of plant oil. Jatropha Methyl Esther is the biodiesel made of Jatropha Oil. But other biodiesels are entering market already, like Rape Methyl Ester (from Rapeseed) and Sunflower Methyl Ester (from sunflower seeds). The properties of biodiesel are like those of fossil diesel and therefore can be used in most diesel engines without any or with little adjustments to the engine. It is also possible to use a blend of biodiesel and normal diesel, which is already very common in some countries. Esterification is a process in which methanol reacts with the plant oil, producing the oil methyl ester and the side-product glycerin. However, esterification is a very energy consuming process and in an overall energy balance is calculated that you only lose energy with it, see the introductory report [34]. This is why it is actually better to adjust the engine to PPO instead of adjusting the bio-oil to the engine.

- Bio-Ethanol is traditionally produced by fermentation of crops containing sugar or starch, like sugar beet, corn or grain. The biomass is converted by enzymes and bacteria at low temperature and pressure. A recent technology is to produce bio-ethanol from lignocellulosic biomass, which is woody and grassy material like poplar, eucalyptus and miscanthus. Bio-ethanol can be used in conventional or adapted Otto engines. Just as with biodiesels it can be used in blends with gasoline as well.

- Bio-Methanol is produced from the products of biomass gasification. The gas mixture is converted by means of methanol synthesis. Bio-methanol can be used as bioethanol or in certain fuel cells it can directly substitute hydrogen. The fuel cell produces electricity with which the engine is driven.

- Bio-DME (dimethylether) can be produced from the combination of gasification and DME-synthesis. This process is similar to that of methanol production. Another method is catalytic dehydratation of bio-methanol, which is a chemical process with catalysts. Bio-DME has approximately the same properties as natural gas and it can be used in conventional or adapted diesel engines.

- Bio-ETBE (ethyl tertiary butyl ether) is bio-ethanol that has reacted with isobutylene. It is added to gasoline in order to raise the oxygen content. The result is reduction of emissions and a higher octane number, which reduces the risk of knocking.

- Bio-MTBE (methyl tertiary butyl ether) is similar to bio-ETBE, but is produced from bio methanol instead of bio-ethanol. It has the same application as bio-ETBE.

- Biogas is the product of the fermentation of biomass. Fermentation is the degradation of wet biomass by microorganisms, at low temperature and without the presence of oxygen. In order to be used as a transport fuel, the biogas should be upgraded to a 98% methane content. If that is the case, it can be used in a gas engine.

- Fischer-Tropsch diesel can be produced by gasifying biomass and converting the gas mixture into a liquid by the so-called Fischer-Tropsch synthesis process. The products are long hydrocarbons called waxes, from which via hydro cracking diesel fractions can be produced. This can be used in conventional diesel engines, either in a blend or pure.

- SNG (Substitute Natural Gas) can be produced by several gasifying techniques, followed by a methanisation step, which increases the methane content in the gas. SNG is similar to natural gas and therefore can be used in normal gas engines.

- Biohydrogen is produced via gasifying or fermentation. The gasifying process is the same as for biomethanol, Fischer-Tropsch diesel and SNG. Fermentation is described in the biogas explanation. After one of these processes, the hydrogen content is increased by the steam-reforming step. Biohydrogen can be used either in fuel cells combined with an electric motor or in a combustion engine.

- HTU-diesel is diesel produced by the Hydro Thermal Upgrading process, which is developed only in The Netherlands. It is a conversion technique to convert wet biomass into a liquid similar to crude oil and is therefore called biocrude. By the process of HydroDeOxygenation (HDO) biocrude can be converted in a fuel like diesel.

In Figure 2 all options and processes are schematically shown. Between brackets is indicated in what kind of engine the product can be used.

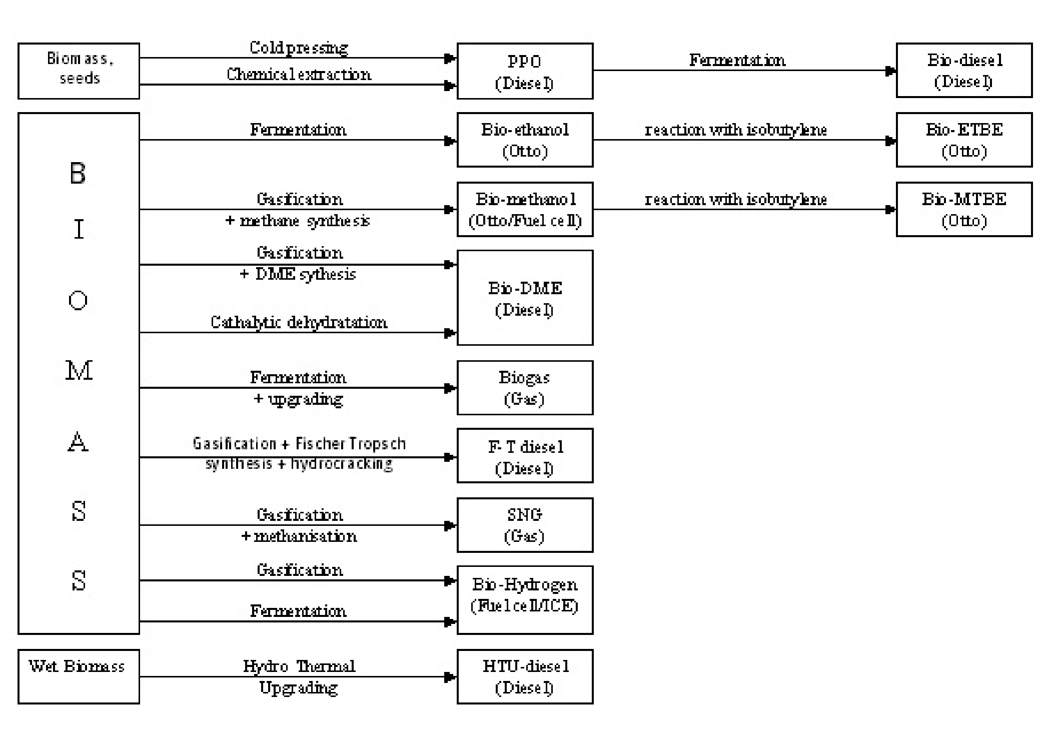


Figure 6: Schematic overview of the most common biomass conversion processes and their products.

In world-wide production Europe took the lead with more than 1,6 mill t Biodiesel produced in 2002 (at capacities of approx. 2,1 mill t), with Germany producing 580 000 t, France 400 000 t, Slovakia 120 000 t (in 2001) and the Czech Republic producing 70 000 t, while the USA were second to Europe with approx. 40 000 t production and Australia being in the phase of establishing 48 000 t production capacity. New initiatives in Brazil, Canada, Malaysia and the United Kingdom however, may change this situation quickly.

3 Jatropha Curcas; a promising energy crop

3.1 Introduction

In the research that has been done preliminary to this graduation work, some attention already has been spent on the plant Jatropha Curcas, so for more detailed information, see [34]. The Jatropha plants grow on degraded, dry, wasted and even salty land, which cannot be used for other purposes. But there are more reasons to call it a promising energy crop and these will be discussed in this chapter.

3.2 Important parameters for Jatropha Oil production

Since the preliminary research report [34] already focused on Jatropha Curcas in detail, this paragraph will only give a short over view of where Jatropha grows, how much can be cultivated per hectare, how the oil processing works and what the yield of the pressing is.

Jatropha grows in areas with a precipitation of between 250 and 1500 millimeter per year. The area where it is actually cultivated, see is much smaller. Figure 7B shows that only little of the suitable area of Africa is used for Jatropha.

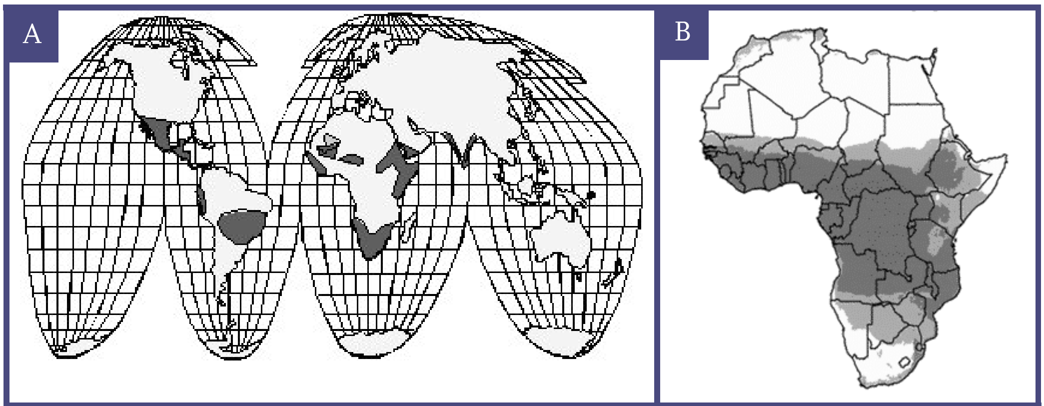


Figure 7: Jatropha distribution and possibilities.
A: The area on which Jatropha is cultivated.
B: The area in Africa that is suitable for Jatropha plantations.

Investigation of existing plantations shows that with about 600 mm rainfall per year the seed yield is 5 ton per hectare, which is quite high compared to other crops [20][27]. This yield can already be achieved in two years after plantation. Jatropha gives seeds from the first year on, but the estimated yield for one year old plantations is 2.5 ton per hectare.

New investigations show that there are different kinds of Jatropha. The seeds of the Jatropha Curcas L. species that exists in Tanzania, which have a length of 18 mm and a width of 10 mm and are presented in Figure 8, weigh 727 grams per 1000 seeds. In other words, one kilogram corresponds to approximately 1375 seeds, so the above mentioned yield of 5 ton per hectare corresponds to almost 7 million seeds per hectare. From this also the bulk density can be calculated, which is the weight per cubic meter of non-pressed seeds. This parameter is important if Jatropha oil will be produced on a large scale. The choice that has to be taken is namely if the seeds will be pressed centralized or decentralized. Decentralized has the advantage that less equipment is needed, but the disadvantage is that more transport is needed. In Tanzania, because of the low amount and bad quality of the roads, this is a very important choice in terms of economical feasibility. For detailed calculations on this, see [28].

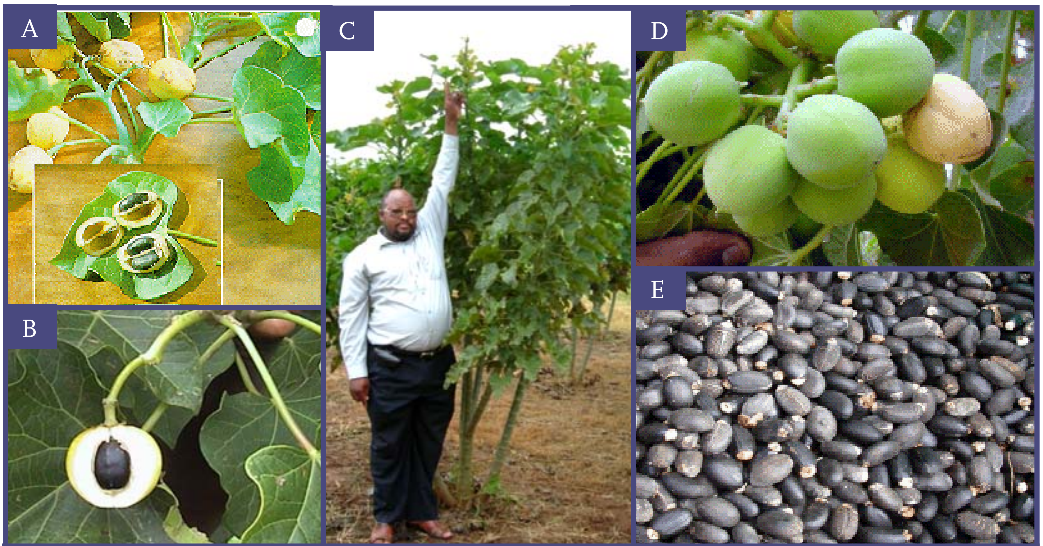


Figure 8: Pictures of Jatropha. A: Fruits with three seeds inside, B: Fruit close-up, C: A two year old plant, more than two meter high, D: Fruits from the second year, E: Only the seeds are pressed for oil.

An other important parameter for the production of jatropha oil is the oil yield that can be achieved with pressing. Jatropha seeds have an oil content of approximately 37 %, but when it is pressed the oil yield is about 25%. Other extraction methods are possible as well, but these methods cost energy and are too expensive for countries like Tanzania.

3.3 Previous research projects

The amount of research projects on Jatropha have increased significantly last year. At the time of writing the preliminary research report, projects in Mali, Nicaragua, India and Tanzania were known, now there are many more. In this paragraph the most important or well-known ones will be summarized.

Countries in which projects are situated are diverse; a short and certainly incomplete list will be given here. The list is based on several other existing lists[11][20][55].

- Australia: Jatropha Curcas has always been classified as a weed, but recently studies have shown that it is not. Since Australia is under pressure to discover alternative energy resources, the status of Jatropha has begun to change
- Benin: In the years around 1940 large amounts of Jatropha were exported to France, but since the 1990s, the director of CADER Attakora in Natitingou stimulates the dissemination of Jatropha hedges in the north of Benin.
- Brazil: Brazil, the number one on the production of bio-ethanol as a substitute for gasoline is now also focussing on biodiesel from Jatropha. About 20 million ha of degraded land is expected to be upgraded by Jatropha, also creating rural as well as city based employment.
- Cambodia: The Cambodian Agricultural Foundation has been investigating the potential of Jatropha. It was estimated that 150 tons per day could be delivered into the capital city
- Cuba: In the dry and saline province Guantánamo Jatropha was already used to produce soap. Now an initiative is underway to provide biodiesel for the fuel needs of the island.
- Egypt: In the desert near Luxor it has been proved that Jatropha can be cultivated on very poor ground by realising a 5,000 ha Jatropha plantation.

Figure 9: "Greening the desert", the evidence that Jatropha Curcas establishes in the desert robust, healthy and contamination free [33]

- Ghana: Anuanom Industrial Project Ltd is planning for 250,000 ha of Jatropha plantation. UNDP, which started "Mulitfunctional Energy Platforms" in Mali, wants to extend its project to Ghana.
- Guinea: Guinea has already a high density of Jatropha plants, but they are mostly used as hedges. There are no reports about projects there, but there is high potential
- Laos: The same holds for Laos; there are plenty Jatropha trees, but no projects have been established. The plans however exist and a government target of 9,000,000 ha by the year 2009 has been discussed.

- Indonesia: In Indonesia the first investigations by the government started in 1998 in which many institutions were involved. Now there is an established initiative of 9,000,000 ha in 2009.
- Madagascar: Already in 1940 Madagascar exported Jatropha to Marseille where they produced soap with it. Now there are still many plants there, but the seeds are not used at the moment. USAID supports the commercialisation of Jatropha and since more than 500,000 ha of cultivation is in place, this should be possible in the short term.
- Mali: The very first Jatropha project was situated in Mali and started already in 1987. The project was set up within the "Special Energy Program" of the German Agency for Technological Co-operation (GTZ). At the end of the GTZ projects in 1997, the population of Jatropha was estimated at around 10.000km of hedges, which corresponds to approximately 2.000 ton oil. Since 1993 UNDP finances new projects in the form of "Multifunctional Energy Platforms", which aim at lightening the workload of rural woman. About 70 units will be working on Jatropha oil. This program will also be extended to Senegal, Guinea, Cote dÍvoire and Ghana.
- Mexico: The university of Hohenheim is working on a Jatropha Gene Bank and studies especially the non-toxic varieties of Jatropha.
- Mozambique: The South African Oil & Gas Company 'Sasol Technology' built a gas pipeline from south Mozambique to Johannesburg and in the neighbourhood of the pipeline Jatropha plantations are created.
- Nepal: The cooperation organisation of the German protestant church finances the introduction of fuel from Jatropha in Nepal.
- Nicaragua: The Australian Agency for Cooperation finances a big project here to produce Jatropha Methyl Ester from the plant oil. At least 1,000 ha have been already planted.
- Senegal: In the region of Tiès, an American NGO 'Enterprise works' planted Jatropha to produce soap and bio-oil from it.
- South Africa: In South Africa at least three big projects are running. Emerald Oil Int. is initiating a plant that produces 100,000 tons of biodiesel per year. The aim is to import Jatropha for this from Zimbabwe, Malawi and Zambia. Further the college 'Owen Sithole College of Agriculture' has a test plantation in cooperation with 'Extention service, KwaZulu-Natal', which formed a Jatropha Task Team that promotes Jatropha south of Swaziland.
- Sudan: Research started here already in 1972. Jatropha has always been used as hedges, but now projects are rising. One project in North Darfur is set up in participation with the German Development Service.
- Tanzania: Since the focus in this thesis is on Tanzania as an example for other countries, the projects in Tanzania will be discussed a bit more detailed.
  - In Tanzania lots of projects have been and are initiated. One of them is the project of 'Diligent Energy Systems' on which the idea of this thesis was based. Diligent is "a Dutch company marketing transport fuels of biological origin in the Netherlands" as the website states [55]. Diligent is also represented in the FACT Foundation. "FACT (Fuels from Agriculture in Communal Technology) promotes, generates and disseminates knowledge about vegetable fuels in developing countries"[55]. Countries that are now involved in FACT are Colombia, India, Mali, Tanzania, Uganda and Denmark [54].
  - Another important project is that of the firm KAKUTE, which already produces soap from Jatropha. Now Kakute is introducing Jatropha in existing

    nurseries, so that local women can earn money selling seedlings. There is even a 2 ha. area planted with Jatropha seedlings. This plantation also functions as an example, where the population can be informed about the advantages of Jatropha and where field days are organised.
  - Other examples are a women's group in Mto Wa Mbu, the village of Engaruka and the project Vyaumu Trust. For more information about these projects, consult [20]
- Thailand: In Thailand about 30 academic institutions and private industry groups are involved with Jatropha. The government initiated a national alternative energy platform and upgraded the role of Jatropha.
- Zambia: In 1999 twenty farmers from Zambia visited the BUN project in Zimbabwe. They were very enthusiastic and 2 years later a study mentioned that over 100 farmers started to plant Jatropha.
- Zimbabwe: The BUN project mentioned above, is located in Makosa and was set up in 1996. The project is funded by the Rockefeller Foundation, the Australian Agency for International Development and the Royal Dutch Embassy. The aim is to produce oil as a fuel, use it for soap making or lighting and use the press cake as fertilizer. Similar projects in Zimbabwe are Binga Trees Project and projects by Environment of Africa and Plant Oil Producers Association. For more information about these projects, consult [20].

Based on detailed analysis of these and other previous projects, some conclusions can be drawn. In the first place there are many advantages of the production of Jatropha Oil as a biofuel:

- As has been stated before, Jatropha Curcas can grow on very poor grounds for which no other purpose can be found.
- Depleted land can be re-cultivated.
- This fact and the fact that Jatropha is toxic, make it preferable to other energy crops, because it does not compete with food crops, which is a very big issue at the moment.
- Jatropha oil cannot only become an export product, but it can also be a cheap alternative for Tanzanian's own market.
- The production of Jatropha oil will create employment for poor people.
- The cultivation of jatropha will enrich the soil and also other products can grow on it again, this makes it very suitable for intercropping[12] as well.
- The plant gives seeds already after one year and the life-span of the plant is more than 50 years.
- Since Jatropha Oil use leads to a reduction of carbon dioxide emissions, carbon credits can be obtained and even sold again on the international market.
- European countries like the Netherlands will not be able to fulfill the European directives for the use of alternative fuels by using their own land capacity and the development of Jatropha and the import of Jatropha oil could be a solution for them.
- Tanzania itself will become less dependent on OPEC countries.
- The dramatically increasing diesel price will lead to better opportunities for alternative fuels like Jatropha oil.

[12] Intercropping means that one plant is planted between rows of other plants and that this has good influence on both species, see also section 2.3.

There are some disadvantages as well, like the fact that the viscosity of Jatropha oil is much higher than fossil diesel and the fact that import of the fuel is not profitable on a small scale, but they are not difficult to solve.

Further it turned out that three varieties of Jatropha are known so far. The *Cape Verde variety* is found in almost all countries of the world except in Central America. It produces small seeds, about 16.8 mm long. The *Nicaragua variety* has fewer, but longer seeds of about 20.3 mm. The plant itself has larger leafs with a more rounded form. The yield of both is approximately the same. The third variety is a non-toxic one that exists in Mexico and can be eaten after roasting. This thesis only focuses on the Cape Verde variety, since that is the one that grows in Tanzania.

3.4 Environmental and social benefits for both developing countries and European countries

With energy crops there is another environmental effect that is often used as an argument against their cultivation. Especially in countries with either little land left for cultivation land or few food resources, the discussion about food crops versus energy crops is critical.

The core element of the discussion is whether cultivation of energy crops is a threat for food crop cultivation. In Europe for instance and especially in a densely populated country such as The Netherlands the amount of cultivation land is already very scarce. Critics are of the opinion that the widespread rapeseed fields are illegitimate if food crops and rapeseed become competitors. The fact that Europe will have great difficulty to become self-sufficient of biomass for energy, together with the above described competition, gives the success of Jatropha as energy supply in a number of developing countries a positive impulse.

Jatropha is, since it grows on dry, semi-arid land and food crops don't a perfect solution for uncultivated land. The fact that it grows best around the equator is positive for developing countries in that region as well as for densely populated countries in Europe. In developing countries Jatropha is particularly attractive for agricultural applications, especially since the fuel can be produced decentralized in rural areas, near the consumption.

3.5 Jatropha Fuel specifications compared to conventional fuels

In this master thesis some experiments will be done on a heavy duty compression ignition engine in order to investigate the differences between operation on Jatropha originated fuels and other more commonly known fuels. In fact four test fuels will be used, namely:

- pure cold-pressed Jatropha Oil,
- Jatropha Methyl Ester, the esterificated form of Jatropha oil, a biodiesel,
- Rape Methyl Ester, in order to compare JME with a well known and extensively investigated biodiesel and
- Conventional diesel, since this is the fuels aimed to substitute by Jatropha fuels.

In this section the differences between PPO and biodiesels that are described in literature will be investigated in order to use this information for the experiments.

In general PPO has a higher viscosity than diesel and is esterificated in order to get a less viscous fuel, biodiesel. Viscosity is in fact the main difference between the two. A description of the process can be found in the research project preliminary to this thesis. The transesterification reaction can be seen in Figure 10.

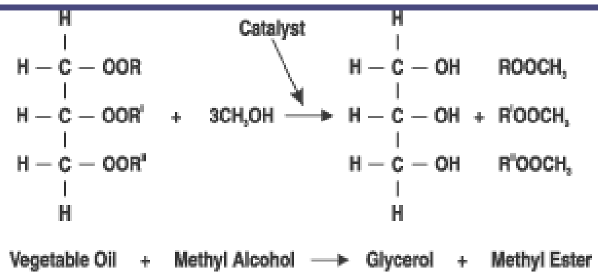


Figure 10: Transesterification reaction

The reaction shows why the viscosity of PPO is higher than that of biodiesel. The large molecules of PPO are split into smaller molecules; those of the methyl ester. About the molecules in Jatropha oil and Jatropha Methyl Ester only little is known. From the fuels used for the experiments, samples have been analyzed and the characteristics of Jatropha oil are compared to those of other pure plant oils see Table 6. The results in Table 6 and Table 7 show that the viscosity of Jatropha oil is indeed higher than those of the biodiesels, namely 72 mm^2/s compared to around 5 mm^2/s. the viscosity is the same as that of rapeseed, but higher than those of the other pure plant oils. The density of PPO in general is higher than that of biodiesel and also the flashpoint is higher, which makes it a safer fuel. The last important result shown here is the solidification point, which is much higher for Jatropha oil than for the (bio)diesels, which could give rise to problems in cold climates.

Table 6: Characteristics of several kinds of PPO. Source: adjusted from [82]

Characteristic		Jatropha	Rapeseed	Soy	Sunflower	Palm
Heat of combustion	(MJ/kg)	39.2	37.6	39.6	39.5	36.9
	(MJ/l)	36.0	34.4	36.2	36.3	33.8
Viscosity at 20 °C	(mm^2/s)	78.2	78	61	58	60
Viscosity at 27 °C	(mm^2/s)		39.2	65.4	58.5	
Cetane number	(-)	37.8	37.6	38	37.1	39
Density at 15 °C	(g/cm^3)	0.919	0.914	0.914	0.918	0.915
Solidification point	(°C)	2	-11	-4	-5	31
Flashpoint	(°C)	236 *	285	330	316	280

* Flashpoint Jatropha after degumming = 197 °C

Table 7: Characteristics of RME and JME. Source: adjusted from [82]				
Characteristic		**Fossil diesel**	**Rape Methyl Ester (RME)**	**Jatropha Methyl Ester (JME)**
Viscosity at 40 °C	(mm^2/s)	2.07 – 3.2	6	4.2
Cetane number	(-)	43.2 – 52	46 - 54	51
Density at 15 °C	(g/cm^3)	0.815 – 0.859	0.882	0.879
Solidification point	(°C)	-9 – -24	-2	-
Flashpoint	(°C)	52 – 102	84	191

4 Possibilities of Jatropha oil in Tanzania

4.1 *Introduction*

Based on the examinations described in the previous chapters, the possible use of Jatropha Oil in Tanzania itself will be investigated and described in this chapter. Most western companies involved in projects like this would like to transport the Jatropha Oil to for instance Europe in order to put it on the European Market and optimize profitability. On the one hand this is understandable, because those companies have invested in the project. On the other hand it is not conform sustainable development. Therefore in this chapter the main goal is to search for a solution in which both the investor and the local community gain a profit.

4.2 *Economic situation*

In order to see the situation in Tanzania in the right perspective, the economic situation should be investigated. This has been done via literature research and a visit of a month to the area where the first Jatropha projects were set up at the moment of writing. Further there are other students that have done investigations on Jatropha in Tanzania in the more social and logistic sphere and also their findings will be used [13][28].

The Gross Domestic Product, PPP [13] of Tanzania in 2002 was 20,381 million current international dollars compared to 47,822,815 million for the world. With a population of approximately 35 million the GDP PPP per capita was 579 international dollars in 2002. This is not only far below the world's GDP per capita of 7880, but also far below the Sub-Saharan Africa GDP PPP per capita of 1779. Tanzania is, based on the GDP PPP per capita, the second poorest country in the Sub-Saharan Region [12]. Almost 20 percent lives on less than one dollar a day and 60% on less than two dollars a day [49].

Agriculture is very important to Tanzania; more than 45% of the GDP in Tanzania in 2000 was generated by agriculture [49]. This is positive for the introduction of Jatropha as an energy crop; especially intercropping is a preferable option, because no extra work is involved. Farmers already have to water their food crops, for Jatropha this is not necessary, but the little water it will get in this situation, will increase the yield. Besides, topography and climate conditions limit the cultivation of crops to only 4% of the land area [52]. This can be approved by Jatropha cultivation, since it has a soil enriching effect.

At the moment of visit, the Diesel price varied between 980 and 1090 Tanzanian shilling (Tsh), which is between 0.73 and 0.81 euro. For a country where almost 60% of the population lives on less than 2 dollars a day[14], this is very costly. Since

[13] Gross Domestic Product (GDP), PPP is gross domestic product converted to international dollars using Purchasing Power Parity (PPP) rates. An international dollar has the same purchasing power in a given country as a United States Dollar in the United States. In other words, it buys an equivalent amount of goods or services in that country. Data has not been adjusted to a constant year.

[14] This was in 2000 and at that times 2 US dollars was about 2,15 Euro.

the diesel price is very high by Tanzanian standards, it should be possible to bring Jatropha oil into the market for a lower price, even in the startup phase [1].

4.3 Diesel infrastructure

This section was meant to give many data on the current diesel infrastructure in Tanzania, like the amount of (diesel)cars and fuels stations, import data and fuel consumption. Unfortunately not all data were traceable, because most numbers are not on the internet and someone would have to go to numerous institutions to retrieve the information needed. Since this would be a time and money consuming operation, it was decided not to do this. Some numbers however have been found.

Section 4.2 already stated that the diesel price in May 2005 was between 980 and 1090 Tsh. Compared to the average income of the Tanzanian population of 64,000 Tsh. this is an enormous amount. Taxi drivers even limit the amount of fuel in their tank to the amount they drive in one time because otherwise it will be stolen.

Tanzania is in state of development, but the diesel infrastructure is totally different from what we are used to here. There is 88,200 kilometer of roadways, from which 3704 kilometer is paved. That is only 4.2% compared to 90% in the Netherlands. If the total length of roadway is scaled to the total land area, it turns out that there is less than 100 meter of roadway per square kilometer. In the Netherlands this is 3500 meter. Further there are very little petrol stations compared to the Netherlands, even that little, that every petrol station in the country of 886,037 km^2, 26 times The Netherlands, is on the map.

Of course this leads to much less oil consumption we are used to, 0.1 liter per person a day instead of 8.92 in The Netherlands. However, still 3498000 liters of oil are consumed in Tanzania. In order to substitute all of this by Jatropha oil, 7380 km^2 of land is needed[15], which is 0.8 percent of the total land area, see Table 8 as well.

Table 8: Important data about diesel infrastructure of Tanzania. Source: adjusted from [52].

	Tanzania	The Netherlands	World
Population	36,766,356	16,407,491	6,446,131,400
Total land area [km^2]	886,037	33,883	148,940,000
Oil consumption [liter/day]	3,498,000	146,280,000	12,735,900,000
Oil consumption per person [liter/day]	0.10	8.92	1.98
Roadways [km]	88,200	116,500	19,403,061
from which paved [km]	3,704 (4.2%)	104,850 (90%)	12,942,104 (66.7%)
Roadways [km/km^2 land area]	<0.10	3.4	0.13

[15] 3,498,000 l/d*365 d/y =1,276,770,000 l/y, the annual yield is 1730 l/ha(calculated with numbers from [28]), so 738,017 ha is needed, 100 ha equals 1 km^2, so this is 7380 km^2.

4.4 *Inland use vs. export*

Based on the findings of sections 4.1-4.3 it seems reasonable to conclude that production of Jatropha is beneficial for the soil, agriculture in general, employment, the national economic situation and for becoming less independent of oil producing countries. However, in the short term it is not beneficial to export the seeds or even the oil to Europe and therefore it seems better to use it for inland use first.

Maybe in the longer term, there are also possibilities for Jatropha as an export product for Europe. This does not only depend on the scale effect on profitability, but on other issues as well. In Europe there are stricter norms than in Tanzania and in order to export it to Europe, Jatropha oil or diesel should comply with these norms. Therefore the results of the experiments in this thesis will be compared to the current regulation and to fuels that are already permitted in Europe.

Another question is if there are no other environmental issues that could prevent exporting from being a success. Also this question needs further investigation. The next chapters are aimed on answering these questions.

5 Environmental issues

5.1 *Introduction*

The main advantage of biofuels is of course that it is CO_2 neutral, which is explained in paragraph 1.3. But CO_2 is not the only issue, other gasses are important as well. This chapter is devoted to these other emissions emitted by combustion of biodiesel. Also the other ways in which the production of biodiesel could harm the environment are discussed. Paragraph 5.2 answers the question which gasses are emitted by the use of different fuels and blends in Compression Ignition Engines in cars or trucks. In paragraph 5.3 the effects of these emissions are explained and it is examined how they harm the environment.

5.2 *Emissions from biodiesel combustion in a CI engine*[16]

Research shows that biodiesel generally produces less carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM) and sulphur dioxide (SO_2) than diesel. Even blends can already lower these emissions. For nitric oxide (NO_x) this is not always the case. Depending on fuel system designs, engine calibrations and manufacturers approach towards the NO_x /PM trade-off[17], NO_x emissions are either slightly higher or slightly lower than for fossil fuels. In order to examine the emissions of biodiesel in greater detail the emissions will be divided into two groups: emissions from complete and incomplete combustion.

5.2.1 Emissions from complete combustion

Emissions from complete combustion are those emitted to the atmosphere with combustion, these are carbon dioxide (CO_2), nitric oxides (NO_x), nitrous oxide (N2O), Sulphur oxides (SO_x), hydrogen chloride (HCl) and heavy metals (HM). The CO_2 neutrality of biofuels has already been explained, but besides CO_2 there are other harmful emissions to take into account.

NO_x

The Environmental Protection Agency (EPA) recently published a review of all biodiesel emission data published for heavy duty engines. Figure 5 shows the results for NO_x, PM, CO and HC.

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[16] Answering the question What emissions are produced by the use of diesel engines in cars and trucks with different fuels?

[17] Generally measures to reduce NO_x lead to an increase in soot and vice versa for a given technological status. Manufacturers choose their own approach towards optimizing both; this is what is meant by NOx/PM trade-off.

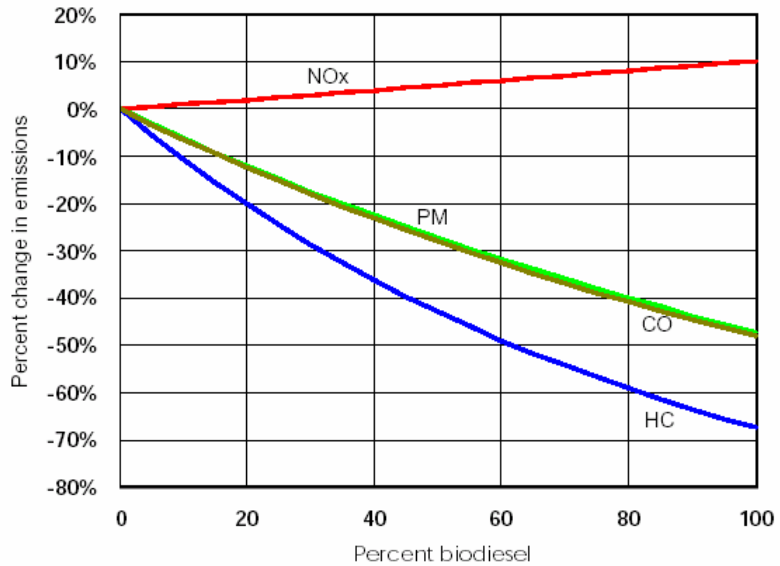


Figure 11: Summary of US Environmental Protection Agency evaluation of biodiesel effects on pollutant emissions for heavy duty engines. **NO_x**, nitrogen oxides, PM particle matter, CO carbon monoxide, HC, hydrocarbon. Source: EPA.

On average the emissions of CO, PM and HC are substantially lower than for fossil diesel. However, the data also show an increase in emissions of NO_x. Other sources show a reduction of NO_x emissions with the use of biodiesel, approximately by the same percentages. This is due to differences in several conditions. First of all, without any changes in engine management like timing and course of injection, NO_x emissions increase by using RME, but software was developed to optimize diesel engines on RME, which resulted in a reduction of NO_x emissions [26]. Further, according to ´The biodiesel handbook´ [26], a number of factors can cause a difference in any emission compared to the average numbers assessed by the EPA. For instance different fuel system designs and engine calibrations can lead to emission differences of biodiesel. Also similar engines of other manufacturers could have different emissions measured. This is because greater particle matter reduction leads to a larger increase in NO_x emissions, manufacturers choose for different approaches towards optimizing the NO_x /PM trade-off. Even the type of fuel injection system, unit injectors or a common rail system, can cause differences. Finally also the source material for biodiesel can influence the amount of NO_x emitted with combustion. Test results show that NO_x emissions vary with the iodine number of the fuel that was tested. The iodine number is a measure of the degree of saturation, which is the number of carbon-carbon double bonds in the biodiesel fatty acid chain [26]. The higher the saturation rate (or iodine number) the lower the NO_x emissions are. Research in this field is very important because in areas that exceed ozone air qualities, limitations in the market could occur for fuels that produce NO_x.

N2O

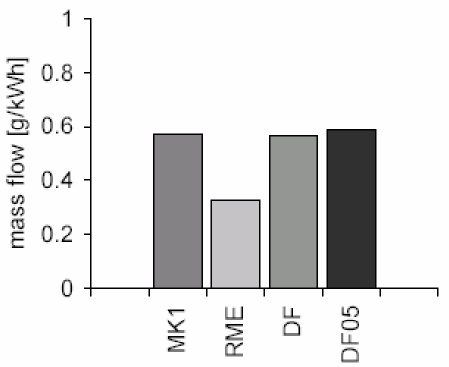
Complete oxidation of fuel nitrogen produces nitrous oxide. Emission levels of N2O are very low for combustion of biomass.

SO_x, HCl, HM
Other emissions from complete combustion like heavy metals and SO_x are very low compared to those of fossil diesel, which is self-evident, because biofuels don't contain as much Sulphur as fossil fuels and no heavy metals at all. Hydrogen chloride is produced if the biomass source contains chloride. This is only the case for miscanthus, grass and straw, so for biodiesel production this is no important issue.

5.2.2 Emissions from incomplete combustion

Incomplete combustion occurs if the amount of oxygen is too low, or by inadequate air/fuel mixing. Also low combustion temperatures, short resident times and low radical concentration can result in incomplete combustion. Emissions from incomplete combustion are carbon monoxide (CO), methane (CH_4), non-methane volatile organic components (NMVOC), particle matter (PM), polychlorinated dioxins and furans (PCDD/F), ammonia (NH3) and ozone (O3).

CO
In the biomass handbook an evaluation of emissions of biodiesel versus fossil diesel is described. To evaluate the emissions of biodiesel versus fossil diesel on a broad basis, four different fuels were investigated, namely standard fossil diesel (DF), Swedish low Sulphur diesel (MK1), a low/Sulphur DF with a high concentration of aromatics and a flatter boiling curve[18] (DF05) and German Rape Methyl Ester (RME). The biodiesel investigated complies with the European standard EN14214, see appendix C. For all fuels the emissions were clearly below the limit stated in the Euro II norm valid for the test-engine. RME turned out to emit the smallest amount of CO, which could be due to the oxygen bonded in the ester bonds of the biodiesel chain, which allows more CO to be oxidized to CO_2. In figure 6 the results are presented.



DF is standard fossil diesel, MK1 is Swedish low Sulphur diesel, DF05 is a low/Sulphur DF with a high concentration of aromatics and a flatter boiling curve and RME is German Rape Methyl Ester.

Figure 12: Specific CO emission rates. Source: [26]

[18] A boiling curve is

NMVOC

About other emissions there is not very much to find. In a SAE paper [42] a study about the transient emissions from three modern heavy duty engines is described. All engines are direct injected, turbo charged and intercooled. Three test fuels were used, pure biodiesel (B100), pure fossil diesel (B0) and a blend with 20 percent biodiesel and 80% fossil diesel (B20). The results were positive for biodiesel: "The use of biodiesel resulted in lower emissions of unburned hydrocarbons, carbon monoxide, and particulate matter, with some increase in emissions of oxides of nitrogen on some engines. Biodiesel also appeared to enhance the ability of the catalytic converters to reduce particulate emissions." [28]. In this test also the volatile organic fraction was measured. In the first engine, a Cummins N14 from now on called engine A, the VOF was higher for biodiesel than for fossil diesel, 0.050 g/hp-hr compared to 0.035 g/hp-hr. In the second engine DDC series 50, engine B, the difference between the two was less significant, 0.032 compared to 0.029 g/hp-hr. If an oxidation catalyst was added, the VOC emission of biodiesel was even below that of fossil diesel (0.015 vs. 0.020 g/hp-hr). The third engine, a Cummins B5.9 showed similar results.

Table 9: Overview of the volatile organic fraction emitted by biodiesel compared to diesel measured for three engines.

	Engine	Displacement volume [l]	Power [kW]	VOF [g/hp-hr]	
				diesel	biodiesel
A	Cummins N14	8.4	300	0.035	0.050
B	DDC series 50	8.5	205	0.032	0.029
C	Cummins B5.9	5.9	265		

Based on these results, the emission of VOC is not necessarily a problem for the implementation of biodiesel.

PM

Diesel engines have high emissions of fine particles. The legal limit is met by RME as well as diesel where the RME emissions are approximately one third lower. However, PM in general is not as important as the size distribution, but is not considered in legislation. The ultra fine particles are regarded as being much more relevant, at least in toxicological terms. The examination described in the biodiesel handbook, shows that RME leads to more particles in the 10-40 nm range and less with larger diameters compared to fossil diesel.

CH_4, PCDD/F, NH_3, O_3

In most studies on biodiesel and its emissions in diesel engines not all emissions are mentioned. Even SAE papers do not give any information about this. Some papers are on PCDD/F emissions, but not in combination with biodiesel. Therefore no information can be given on this and of course this leads to the recommendation for further investigation.

5.3 *Effects of emissions on the environment*

All emissions mentioned above are harmful, but the effect that these emissions have on the environment and on human health is not always known. Not all emissions from vehicles are greenhouse gases, but unfortunately they have other serious consequences. In this paragraph the environmental and health effects caused by traffic emissions will be examined. Hereby the practical positive effects of the use of biodiesel will become clear.

Greenhouse gases

The main greenhouse gas is evidently CO_2, but also CH_4 and N2O cause an increased greenhouse effect. However the contribution of the sector 'traffic and transportation' to CH_4 and N2O is marginal compared to agriculture, waste removal and the energy sector respectively agriculture and industry. On the other hand, approximately % of the total CO_2 emission in the Netherlands in 2002 is originating from traffic [37].

Under the Kyoto protocol the European Union as a whole (EU-15) has undertaken to reduce the emission of greenhouse gases with on average 8% in the time period 2008-2012 compared to the reference year[19]. For the Netherlands the target is a reduction of 6% compared to 1990/1995.

Acidification

Acidification is caused by emissions of NH3, NO_x, SO_2, PM and NMVOC. These gases are converted in acids and cause acid deposits, which can damage soil, vegetation, fresh water, buildings and coastal ecosystems. The contribution of traffic to the total NH3 emission is very small, but on emissions of especially NO_x, PM and NMVOC it is substantial, as can be seen in Table 5.

Table 10: Acidificating emissions in the Netherlands caused by the traffic sector and the share of the total emissions for 2002 .
Source: adjusted from [37].

	Emissions from traffic in kton					*share of total*
	1990	**1995**	**2000**	**2001**	**2002**	***2002***
NH3	1	2	3	3	3	*2.2%*
NO_x	372	325	290	282	273	*66%*
SO_2	28	28	21	19	19	*24%*
PM	25	21	19	18	18	*40%*
NMVOC	197	145	110	104	98	*44%*

The trend of concentrations and emissions of NO_x and SO_x in The Netherlands matches that of Northwestern Europe quite well. Also the trend for particle matter is comparable to that of Northwestern Europe, but decreases less rapid. In other words major trends are similar to those found locally in the Netherlands [37].

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[19] Reference year according to Kyoto is defined as (1990/1995): sum of CO_2-, and CH4- and N2O-emissions in 1990 plus F-gas emissions (HFK's, PFK's en SF6) in 1995 (without temperature corrections for CO_2).The base emissions (1990/1995) are calculated at 210 Mton CO_2-equivalent.

Eutrophication
Eutrophication occurs when the amount of nutrients for plants in the soil are that high that normal ecological processes are being disordered. It is caused by external addition of organic or inorganic fertilizers or by a decreased groundwater level due to dehydratation. The most important fertilizers are nitrogen (N), phosphor (P) and potassium (K). The fact that these compounds are found in the environment is not only because of deposition from the air, but to a much larger extent by drainage of waste water and use of fertilizers. However, awareness of the problems caused by these compounds is helping to prevent great harm [33].

Soil contamination
Emissions of diesels are seen as an important cause of soil contamination. Air pollutants form deposits and end up in the groundwater. Besides traffic, agriculture and industry are contributors to soil contamination. Especially heavy metals, PAHs and VOCs are seen as contaminators. Measures like making unleaded gasoline compulsory, has lead to some improvement, but concentrations of other metals like cadmium (Cd), zinc (Zn) and copper (Cu) are still quite high.

Smog
There are two types of smog; photochemical smog and sulfurous smog [7]. Sulfurous smog is also called industrial smog since it is produced primarily by burning coal or oil at large power plants. Under certain conditions[20] the sulfur oxides (mostly sulfur dioxide) that are produced at these power plants combine with particulates to concentrated sulfurous smog.
Photochemical smog results in a more brown instead of gray air. The production of photochemical smog is directly related to automobile use. Nitrogen oxides and organic compounds (hydrocarbons) react under solar radiation via complex reactions into photochemical smog. Since NO_x is emitted by CI engines and driving on biodiesel may increase the amount of emitted substance, this is a point of particular interest for the development of Jatropha oil or –diesel.

Health effects
Besides effects on the environment in general, there are effects of pollutants that are very specifically harmful for animals and humans. Almost every part of the human body is affected by one pollutant or another. In general, chemicals affect the same organ systems in all people who are exposed. However, the seriousness of the effects may vary from person to person due to differences in heredity, health, previous exposure to chemicals including medicines, and smoking or drinking habits. Some toxins have far reaching effects, for example dioxins are stored in fat cells of the body, but they cause damage to the entire organism through disease, damaged skin or birth defects [7].

Focusing now on the pollutants emitted by traffic, especially CO, SO_x, HM and PM cause severe health problems. CO is an odorless, colorless and tasteless gas, but it can cause fatal poisoning. Exposure to low levels of carbon monoxide can produce symptoms like a throbbing headache, dizziness, fatigue and shortness of breath. At higher levels it can cause severe headaches, weakness, dizziness and nausea, irregular heartbeat and unconsciousness. Very high levels of carbon monoxide can

[20] These conditions are: "stable air with sufficient relative humidity, cloud cover and formation of inversion layer and thick fog, lasting several days" [7].

lead to seizures, coma, respiratory failure, and death. Besides CO, also SO_x, HM, PM can cause lung problems.

Table 6 summarizes the abovementioned environmental effects in the left column and the emissions from traffic that cause the problems, in the right column.

Table 11: Environmental effects and the emissions that cause it.
Source: adjusted from [9].

Environmental effects	**Emissions**
Increased greenhouse effect	CO_2, CH_4, N2O
Acidification	SO_2, NO_x, NH3
Eutrophication	N and P compounds
Soil contamination	HM, PAHs, VOC
Smog	HM, PAHs, VOC, PM, CO, SO_2, NO_x
Health effects	**Emissions**
Human toxicity	CO
Lung problems	CO, SO_x, HM, PM

6 Engine set up for experimental measurements

6.1 Introduction

In previous chapters some questions about the use of pure plant oil in compression ignition engines are answered by means of literature research. In the next few chapters, the engine experiments that were done for this thesis in conjunction with the University of Nijmegen, The Netherlands, will be explained. This chapter describes the experimental set-up and explains how and why certain measurements methods are used.

6.2 Engine set-up

The engine used in the set-up is originally a 6-cylinder 11.6 liter DAF WS engine. The first cylinder is the measuring cylinder and is adjusted for this by replacing the original combustion chamber by a XF 95 DAF combustion chamber [5]. It is intended that the combustion process can be filmed with a high speed camera. In order to make this possible, the combustion chamber has been moved up about 40 cm by elongating the piston and cylinder. The second and third combustion chambers are removed and adjusted in order to maintain the engine balanced. The other three cylinders, number 4, 5 and 6, operate under normal conditions using the standard inlet and outlet manifolds and drive the measurement cylinder. Figure 13 gives a schematic overview of the adjusted engine.

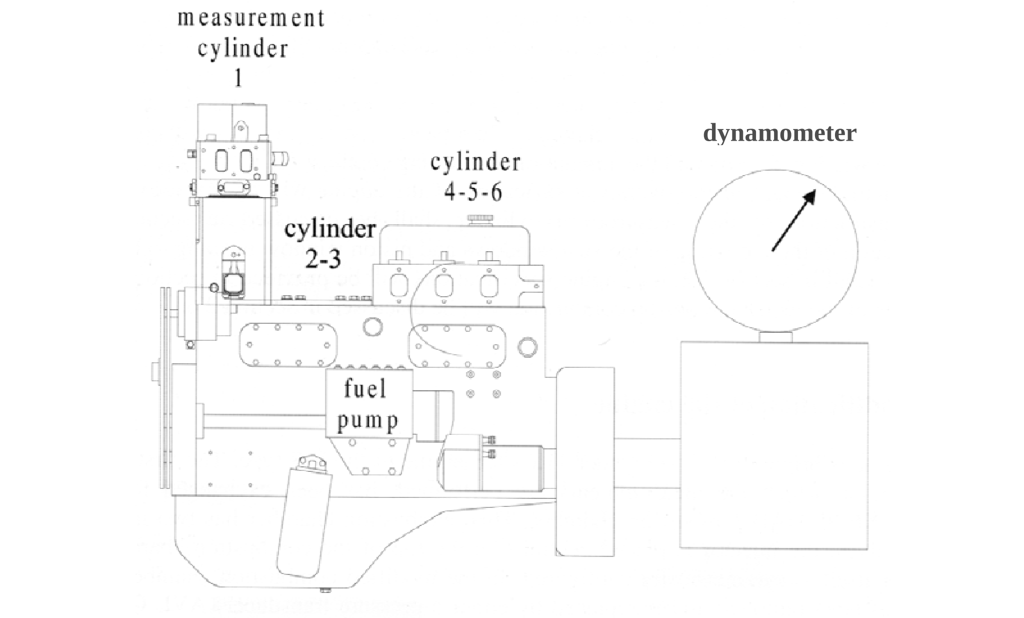
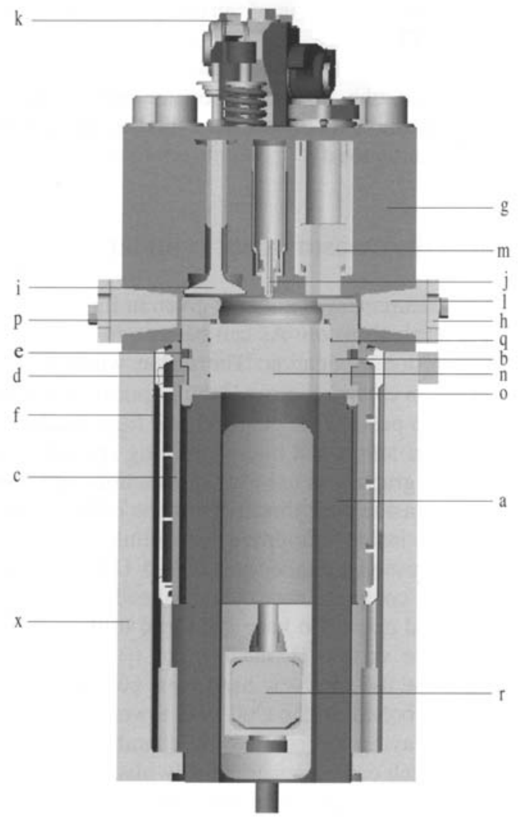


Figure 13: Schematic overview of the adjusted engine. Source: [5]

The measurement cylinder must be able to operate independently of the rest of the engine and therefore it has its own compressor, air inlet system and injection system, which can be controlled at distance.

The engine is used to study combustion using laser diagnostics and therefore the measuring cylinder has been made optically accessible. Figure 14 shows how this is done. The character 'n' indicates the piston window; a quartz window mounted on top of the piston elongation with a piston crown. The letter 'r' indicates the mirror via which the camera can see through the window into the combustion chamber. There are side windows as well through which emissions are detected with a camera via a spectrograph.



a - *piston elongation*
b - *piston crown*
c - *liner*
d - *rider ring*
e - *piston ring*
f - *cylinder*
g - *cylinder head*
h - *side window holder*
i - *valve*
j - *injector*
k - *rocker*
l - *side window*
m - *top window*
n - *piston window*
o - *copper ring*
p - *graphite rings*
q - *rubber ring*
r - *mirror*
x - *tower*

Figure 14: The measurement cylinder. Source: [5]

6.3 *Measurements*

During the experiments on the engine, NO_x emissions and soot emissions are measured. Before analyzing the influence of several parameters on NO_x and soot emission, the Diesel Dilemma should be explained. This dilemma means that there is a trade-off between NO_x, soot and efficiency.

For a given fuel holds that a high temperature or a high amount of oxygen results in a good oxidation of fuel as well as of soot and nitrogen. Good oxidation of the fuel leads to a high thermal efficiency, good oxidation of soot leads to low soot emissions, but good oxidation of nitrogen leads to high NO_x emissions. In other words, adjusting the temperature to an optimum for efficiency has higher NO_x emissions as a result. Of course, decreasing NO_x emission will result in an increased soot emission, and so on.

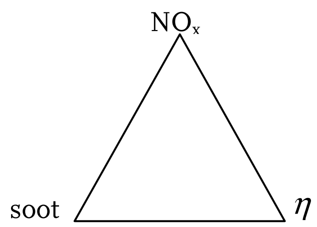


Figure 15: "The Diesel Dilemma"

Parameters

Many parameters can be changed in an engine. However, due to limited time, only the effect of injection timing and oxygen percentage were used to move around in the NO_x/soot map. This was done for all fuels studied in this thesis and were compared to RME and standard Diesel.

Injection timing is the moment at which the fuel is being injected into the cylinder, generally expressed in crank angles before top dead center (bTDC). Top dead center is the moment at which the piston reaches the highest point in the cylinder at the end of the compression stroke and the cylinder volume is at minimum. Changes in injection timing can lead to differences in ignition delay, which is the time between injection and auto-ignition. This can be explained by focusing on the two phases that occur during a combustion process. Because of the high cylinder temperature and -pressure at the moment of injection, the fuel vaporizes. At some time after injection, the gas ignites. First there is a so-called *premixed combustion* of the already injected fuel mass and after that a *diffusive part* controlled by the mixing rate of fuel and air at the fuel jet periphery.

With early injection both pressure and temperature are relatively low. This causes a longer ignition delay. For a given fuel, the longer the ignition delay, the more *premixed combustion* occurs. This leads to a high heat release peak, fast combustion, generally more NO_x because of a higher temperature, generally less soot because of a higher temperature inherent to more premixed combustion. *Diffusive combustion* is exactly the opposite.

During all experiments, the measurements were done at three different injection times, namely 3, 8 and 13 degrees bTDC.

The entrained ***oxygen percentage*** is changed in order to simulate Exhaust Gas Recirculation, EGR. Normally EGR is applied on engines by recirculating part of the gas at the outlet to the inlet and with this, non-combusted elements can be combusted during the second combustion. By recirculation of exhaust gases, the concentration of oxygen in the incoming gas is lower and that of water and carbon dioxide is higher than in air. Since the c_p[21] of water and carbon dioxide is higher than that of oxygen and nitrogen, the amount of energy absorbed is higher and therefore the temperature is lower. This combined with the low oxygen percentage leads to slower oxidation with typically lower efficiency, lower nitrogen oxides (NO_x) and higher hydrocarbons (HC), carbon monoxide (CO) and soot emissions as a result.

In the set-up, EGR is simulated by using gas from a tank with only 15% oxygen instead of 21% the rest is replaced by nitrogen (N_2). This means that in this case the effect of higher c_p of the EGR inlet gas is not present, but that of low oxygen percentage is[22].

EGR is especially aimed on reducing NO_x, since the norms for NO_x have become stricter. Based on this assumption, one would expect that the EGR simulation – decreasing the amount of oxygen- leads to less NO_x than operation under normal conditions. This is why the oxygen percentage in the incoming gas is a parameter in this experiment.

Finally the ***fuel*** composition is changed. This is done to investigate if biofuels made of Jatropha lead to improvement on emissions, since that is the main objective of the experiments. There are four fuels, Diesel as a well known reference fuel on which all regulation is administered, Jatropha Methyl Ester (JME) and Jatropha Oil (JO) as subjects of investigation and Rape Methyl Ester (RME) as reference for biofuels for which special norms have been made.

6.4 Methods

During all engine tests, several measurements were done with sensors and camera's and recorded with help of oscilloscopes and computers. This is used to determine the influence of injection timing, the amount of oxygen in inlet air and the kind of fuel on NO_x emission, and soot production. In this section the methods

[21] c_p is the specific heat capacity at constant pressure in $J \cdot kg^{-1} \cdot K^{-1}$, which is the amount of energy required to raise the temperature of one kilogram of the substance by one Kelvin. Substances with high specific heat, in this case water and carbon monoxide, require much more energy to increase their temperature and preserve their temperature better.

[22] This is because the specific heat of oxygen is similar to that of nitrogen: $c_{p,\, O_2}$=0.92 kJ/kgK ≈ $c_{p,\, N_2}$=1,04 kJ/kgK, whereas $c_{p,\, CO_2}$=0.82 kJ/kgK and $c_{p,\, H_2O}$=2.0 kJ/kgK, all at T=273 K

used for the measurement of NO_x emission and soot production will be explained. But before that two ways to determine the ignition delay will be described.

High speed visualization

The high speed camera described in section 6.2 is used to film the process in the combustion chamber. The movies contain interesting information as well. However, how to analyze the movies was not sure yet at the moment of writing. It needs some more discussion and time. Therefore the movies are only used to derive the ignition delay.

Ignition delay can influence emissions. Therefore it is important to determine it for every case in order to make sure that detected differences in emissions are not simply a result of the ignition delay.

Injection and ignition can be detected in the movies if the frames can be viewed separately. With the software package Vision, the movie can be played at any speed and frames can be viewed separately. Time of injection and first detectable light, i.e. auto-ignition, are easily retrievable in this way. The difference is a good approximation of the injection delay.

Figure 16 shows a picture in which the movie frames are depicted next to each other. Frame A shows the start of injection and B the start of ignition, i.e. the first detected light.

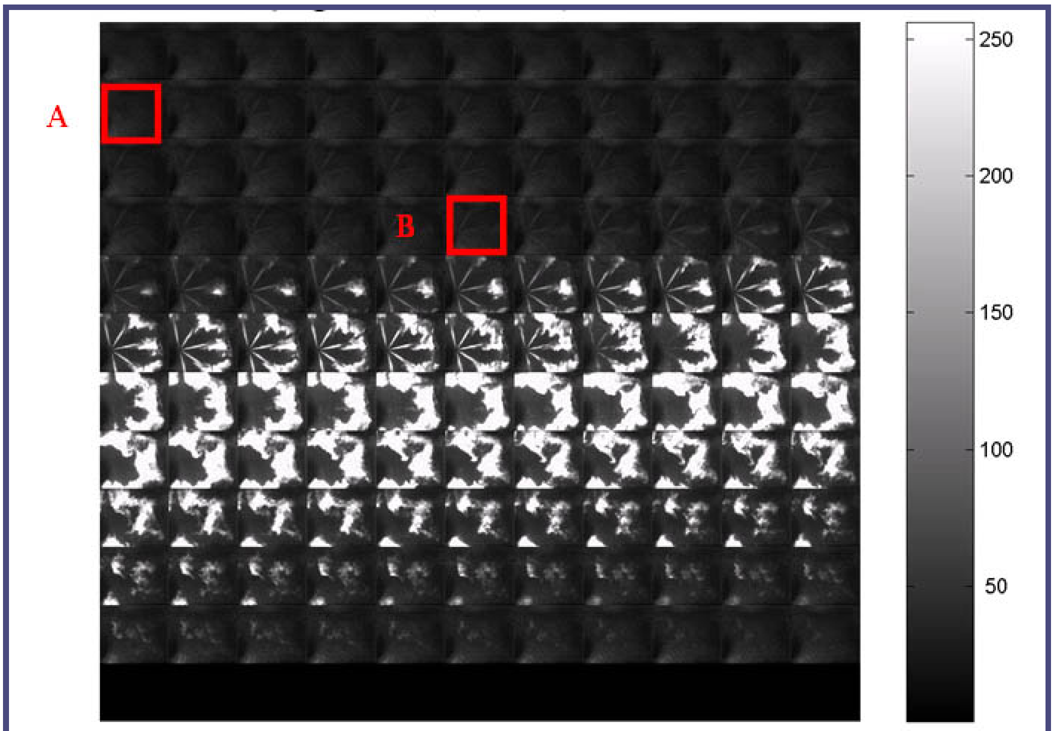


Figure 16: Frames of the movie P4a, RME, frames 0-120, 121 frames @ 30,000Hz. True elapsed time 4.172 ms, movie intensity [545 4095], rescaled to 8 bit.

Heat release

Ignition delay can also be determined from the heat release curve. The heat release is derived from the measured pressure based on the first law of thermodynamics.

The first law of thermodynamics says:

$$dU = pdV - dQ_{env} \tag{1}$$

with U the internal energy [J], p the in-cylinder pressure [Pa], V the cylinder volume [m^3] and Q_{env} the heat exchange with the environment [J]. In combusting systems the internal energy can be written as:

$$\begin{aligned} dU &= d\left(\sum_i m_i u_i\right) \\ &= \sum_i m_i du_i + \sum_i u_i dm_i \\ &= \sum_i m_i c_{vi} dT + \sum_i u_i dm_i \\ &= mc_v dT + dQ_{comb} \end{aligned} \tag{2}$$

Here m_i is the mass of component i in the mixture and u_i its specific internal energy [J/kg]. Now introducing $dQ=dQ_{comb} + dQ_{env}$ and substitute eq. (2) in eq. (1) gives:

$$dQ = pdV - mc_v dT \ ,$$

with m the total mass in the cylinder [kg], c_v the specific heat of the mixture [$Jkg^{-1}K^{-1}$] and T the in-cylinder temperature [K]. Generally this equation is expressed in the known quantities, p and V. This can be done simply by substituting T for p and V using the equation of state $pV=mR_g T$.

$$dQ = \frac{\gamma}{\gamma - 1} pdV + \frac{1}{\gamma - 1} Vdp \tag{3}$$

with γ the ratio of specific heats (c_p/c_v)

This can be transformed again to:

$$\frac{dQ}{d\alpha} = p\frac{dV}{d\alpha} - V\frac{dp}{d\alpha}$$

with α the crank angle [degrees].

Since both volume and pressure are known as a function of the crank angle, the heat release curve can be calculated.

Time line
An important issue for comparing these two is that the time line is the same for both. Since for the heat release, the start of injection is not easy to determine from the graph, the start of injector current (SoIc) is used instead of the start of injection (SOI). The SoIc is the activation of the injector, which in these experiments are 3, 8 or 13 degrees bTDC. The time delay between this trigger and the actual start of injection is mainly caused by the time needed for building up the magnetic field by the coil in the injector used for lifting the needle. This time delay is almost independent of the rail pressure and is typical 775 microseconds for a BOSCH Diesel injector of a common rail system[40].

So, for both measurements the start of injector current will be used to mark the start of injection and the results of the high speed visualization can be compared to the heat release curve without any problems. With the high speed visualization this time delay can also be seen. The first frame of the movie is approximately at the SoIc. Not exactly, because the pictures are made every 0.3 crank angle degrees, sometimes the frames are not exactly the frame of SoIc or of ignition, but the maximum fault is one frame, in other words 0.3 degrees. The first detected light of the liquid spray is typically around 10 frames later than SoIc. This corresponds to ten times the interval between the frames, which is around 400 microseconds. Note that this is different from the reported value for the BOSCH injector but is in the same order of magnitude.

The moment of ignition is derived with the two methods as well. In the high speed visualization this is the moment of first detected light, which is frame B in Figure 16. In the heat release analysis, the moment of ignition is derived by extrapolating the steep slope of the increasing heat release peak to the horizontal axes as depicted in Figure 17.

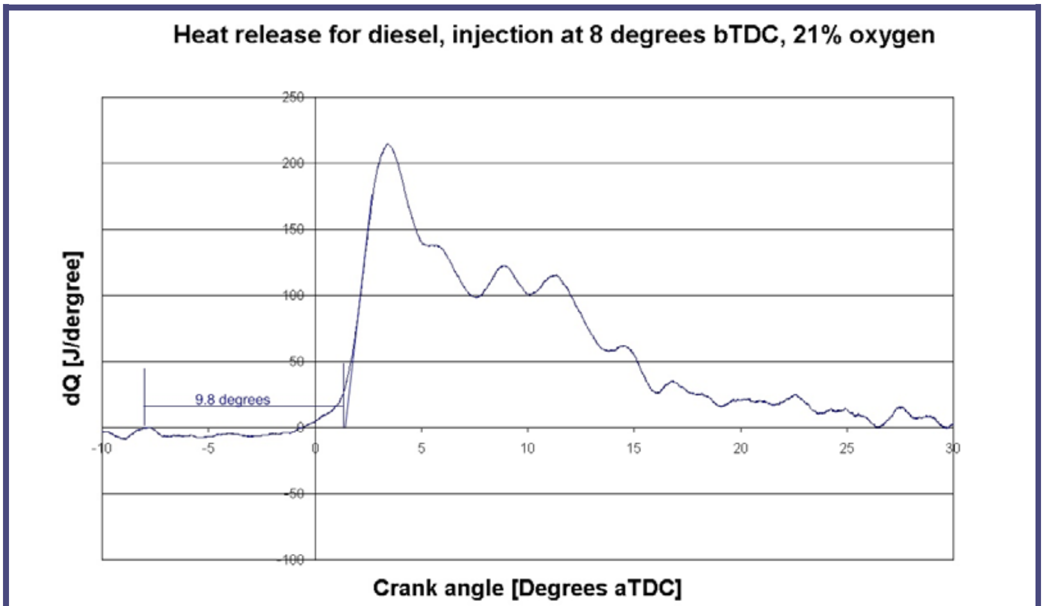


Figure 17: Method to derive the ignition delay from the heat release curve

One could also see the start of the increasing line as the start of ignition, but where this exactly is, would be disputable. The margin of error is the same for all measurements and around 2 degrees.

NO_x measurements

NO and NO_x measurements are done by a chemiluminescency nitrogen oxides analyzer. The chemiluminescency method is based on the chemilnuminescent gas phase reaction between ozone and nitric oxide.

$$NO + O_3 \rightarrow NO_2 + O_2 + \textit{ Photon emission}$$

As the reaction equation shows, photons are emitted, or in other words light is visible. This is because ten percent of the nitrogen dioxide produced is in electronic excited state. That state will transit to normal state, the molecule loses energy and this gives rise to light emission. The light intensity is measured by means of a photomultiplier tube. Since only nitric oxide can be detected by chemiluminescence, a converter is incorporated to convert NO_2 into NO. In the NO_x mode, the gas is led through the converter and in the NO mode not. In this way the analyzer measures the amount of NO or NO_x in the exhaust and gives quantitative data that can be compared to each other very easily.

Besides this, the NO concentration inside the cylinder was measured by means of laser-induced fluorescence (LIF). With LIF a laser beam is directed through the cylinder. The wavelength of the tunable laser is set such that it corresponds to a unique electronic state transition of a molecule, here NO. The molecules will fall back to their ground state, emitting light in a specific wavelength that can be isolated from all other light using a small band pass filter. The fluorescence signal is detected through the nearest side window by the CCD camera that records the signal that comes via the spectrograph and detects the HC and NO radicals. The analysis of the LIF signals is extremely difficult and time consuming. Within the scope of this thesis it was not possible.

Soot measurements

According to the Diesel dilemma, for a given fuel, soot emission decreases if NO_x increases. This is logical, because if injection is early, the temperature and pressure are low, this causes a long ignition delay and therefore premixed combustion is dominant. The heat release curve will than show a high peak, combustion is fast and generally less soot is produced due to the high temperature and better premixing. However, if the injection is too early, the pressure is not high enough for immediate vaporization and the injection spray will still be liquid when it hits the walls of the combustion chamber. Wall-wetting, as this is called, leads to decreased NO_x emissions, low thermal efficiency and increased CO, HC and soot emissions.

For the soot measurements, a photo diode is used. The photo diode measures the total amount of light produced by combustion. A general accepted rule says that a high negative peak in the photo diode signal indicates a high level of soot radiation. Since the luminescence is proportional to the amount of soot and T_{soot}^4, this should be taken into account. Therefore a high intensity can be caused by a high amount of soot, a high temperature (T), or both.

Unfortunately, the measurements won't yield quantitative results, but qualitatively much will become clear.

7 Results

In this section, the results of the engine tests will be discussed. This chapter is divided into two main sections, one in which the reference fuel, fossil Diesel is analyzed and one in which the other fuels will be investigated. In each section, the same sub-divisions are made. The first sub-section deals with the thermodynamic analysis and the second shows the NOx and soot results and discusses if this correlates with the qualitative thermodynamic dependencies or not. Based on this, conclusions can be drawn on the differences between fuels.

7.1 Reference fuel, fossil Diesel

The reference fuel used in the experiment is fossil Diesel, since this is the fuel that is currently used most in Diesel engines. In order to find out if Jatropha fuels could substitute Diesel, this is the most natural comparison. The actual Diesel fuel used in the experiment is TOTAL low-sulphur Diesel, the specifications can be found in appendix H.

Thermodynamic analysis
The thermodynamic history of a fuel in a certain operation point includes in-cylinder pressure and derived from that in-cylinder temperature, heat release and efficiency.

In Figure 18, the ***pressure*** curves of three measurements of the combustion of fossil Diesel in the combustion engine are shown in one figure. As it shows, injection timing influences the peak pressure of combustion; the cylinder pressure is different for the three times of injection, 3, 8 and 13 bTDC. For injection at 13 degrees bTDC, in other words relatively early injection, the peak pressure is highest and for injection at 3 degrees bTDC, late injection, it is lowest.

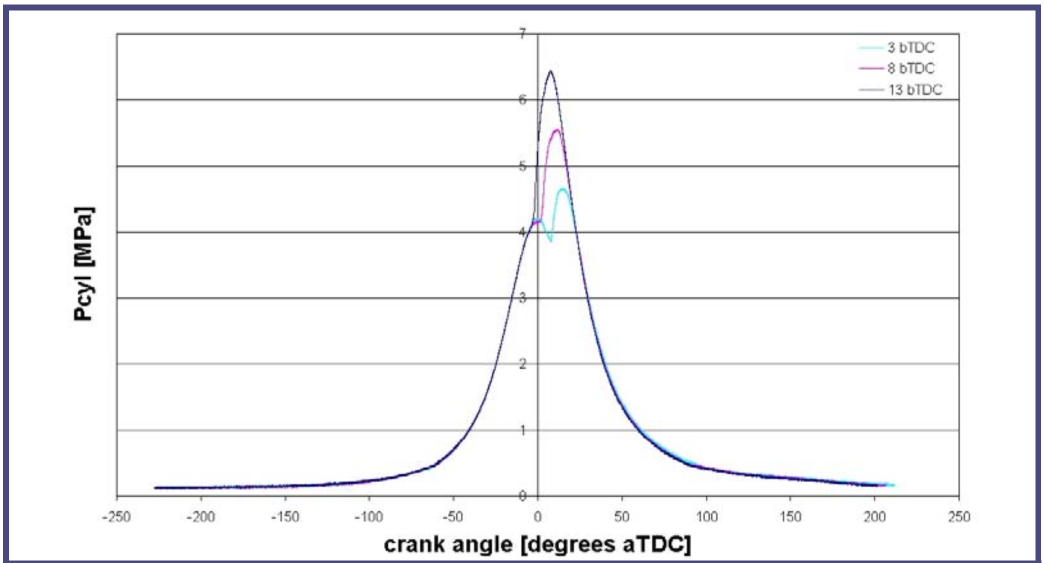


Figure 18: Pressure curve, Diesel, 21% oxygen, different injection timings

>>The earlier the injection, the higher the peak of cylinder pressure. But if injection is too early, incomplete combustion will occur and the peak temperature and peak pressure will be lower. This condition, however, is with the current set of injection timings not met.

Figure 19 shows the same, but than for two different oxygen percentages, 21% and 15%, representing normal operation on air and operation on a mixture of 15% oxygen and 85% nitrogen respectively. The measurements with 15% oxygen simulate, as explained in section 6.3, exhaust gas recirculation. As the figure shows also the amount of oxygen in the incoming gas influences the peak pressure.

>>A low oxygen percentage leads to a lower peak cylinder pressure than that of normal operation.

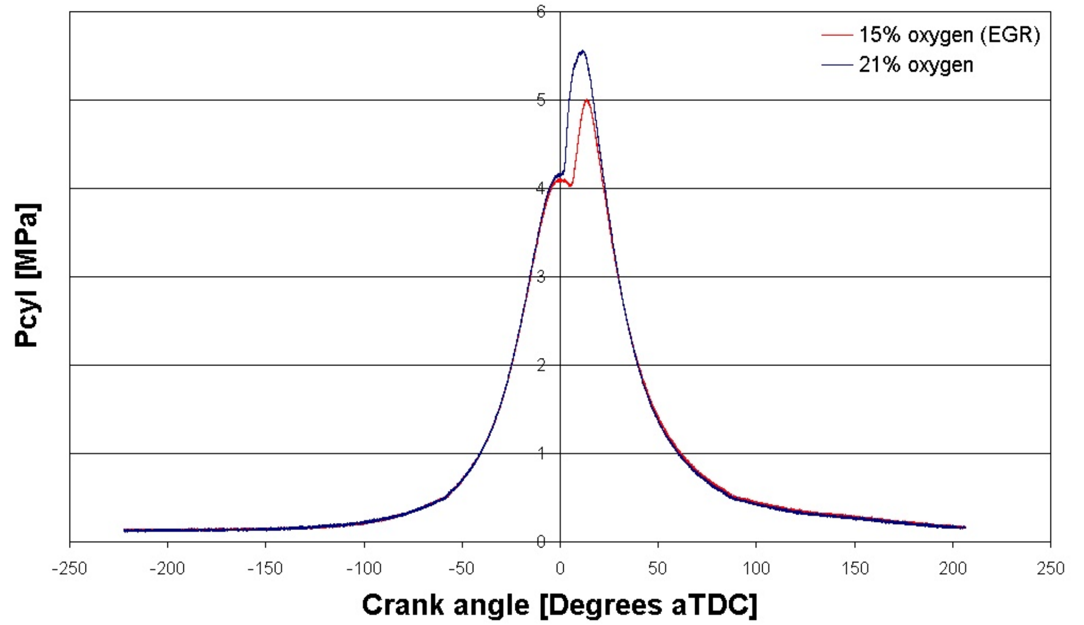


Figure 19: In-cylinder pressure curve, Diesel, 8bTDC, for different oxygen percentages in the incoming gas

From the in-cylinder pressure, an indirect qualitative measurement of NO can be obtained. The in-cylinder pressure is a measure for an ‘average’ in-cylinder gas temperature:

$$p \cdot V = n \cdot R \cdot T$$

with p pressure [Pa=Nm^{-2}], V volume [m^3], n the amount of moles [mol], R de universal gas constant (8.31 J/mol K) and T temperature [K].

So at a given volume, a higher pressure means a higher average temperature if the amount of moles is constant.

$$\frac{p_0}{T_0} = \frac{p}{T}$$

From the Zeldovich mechanism [19], it is known that:

$$NO \propto e^{\frac{-E_a}{R \cdot T}}$$

with E_a the activation energy [J/mol], R de universal gas constant (8.31 J/mol K) and T temperature [K].

>> In other words, normally a higher pressure peak correlates to a better oxidation of fuel, N_2 and soot, which leads to higher efficiency, lower soot and higher NO_x.

When analyzing the results, this dependency should be taken into account.

Since the other thermodynamic properties are derived from the measured in-cylinder pressure, it is obvious that these should show different values as well. Indeed the results show this for instance for temperature and heat release.

Higher ***heat release*** peaks generally correspond to higher NO_x emissions. Figure 20 shows that the peak for injection timing at 13 degrees bTDC is highest.

>>So according to these results, early injection gives a high peak in heat release and thus high NO_x production.

This corresponds to the conclusion that is drawn from the pressure curve.

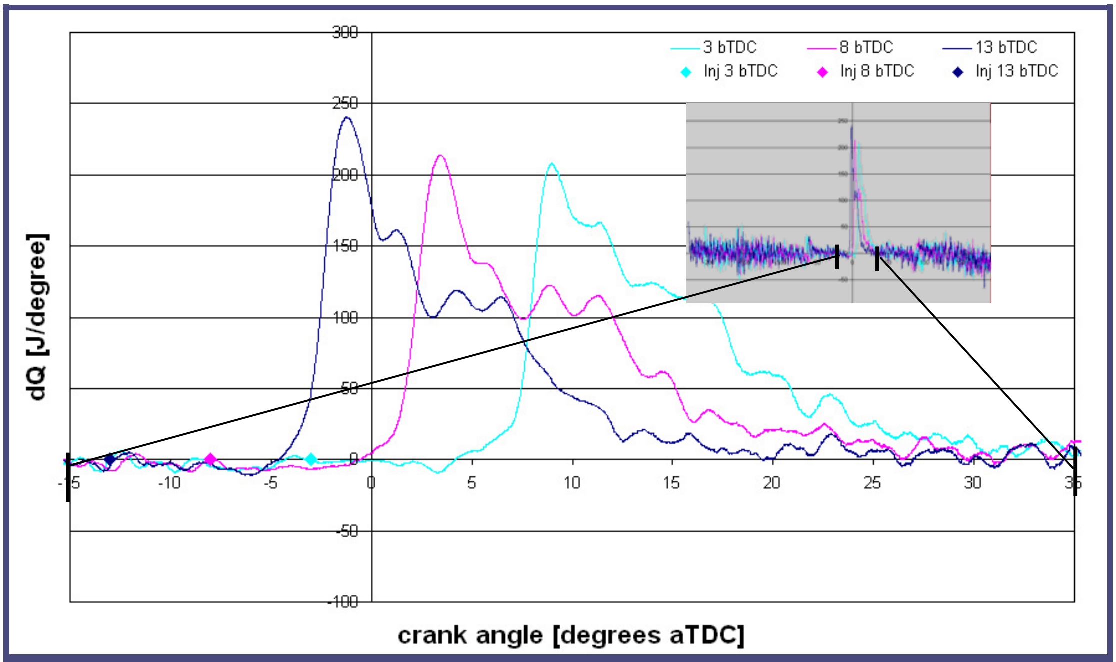


Figure 20: Heat release, Diesel, 21% oxygen, different injection timings. The insert shows the heat release over a larger span in crank angles.

For ***temperature*** holds that a higher peak temperature generally leads to more NO_x. If the temperature curve on the left is consulted, it can be seen that the highest peak temperature is found for ignition at 13 degrees bTDC. The other two do not differ significantly. In the right temperature curve can be seen that the temperature curve for 21% oxygen has the highest peak.

>>Based on temperature, the results could show more NO_x for early injection compared to late injection and for 21% oxygen compared to 15%.

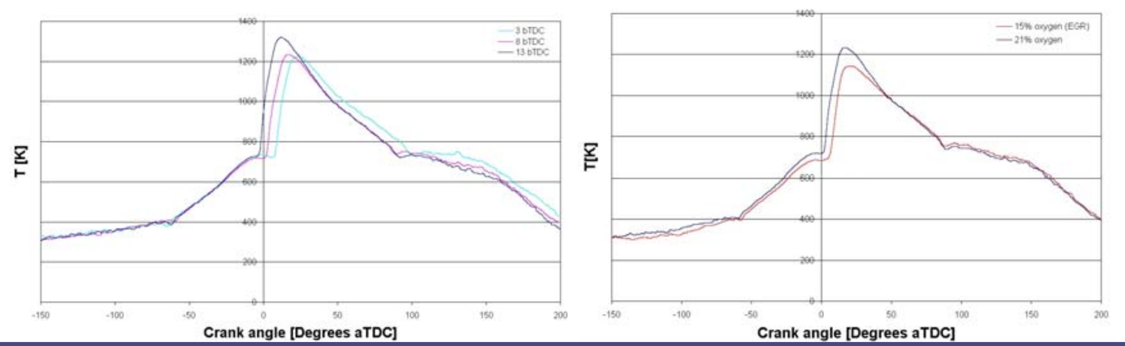


Figure 21: Computed in-cylinder temperature at different injection timings with 21%oxygen in the inlet gas (left) and for different oxygen percentages with injection at 8bTDC (right).

Looking at the left graph it seems surprising that the maximum temperature for injection at 3 and 8 degrees bTDC are approximately the same while the peak pressures are quite different from each other. The explanation can be found in the volume, which changes fast near top dead center. The ideal gas law shows:

$$\frac{p_{8bTDC}}{p_{3bTDC}} \cdot \frac{V_{8bTDC}}{V_{3bTDC}} \propto \frac{T_{8bTDC}}{T_{3bTDC}}$$

$$\frac{5.569Mpa}{4.667Mpa} \cdot \frac{1.587mm^3}{1.716mm^3} = 1.10 \propto \frac{T_{8bTDC}}{T_{3bTDC}} = \frac{1168K}{1094K} = 1.07$$

This shows that the small differences in temperature, while the differences in pressure are substantial, can be explained by the difference in volume at that time.

Also the ***ignition delay*** of a certain fuel in a certain operation point influences the NO_x and soot emission. In the figure below the results of the high speed camera images and the heat release curve are represented. Both indicate that ignition delay is for all injection timings approximately the same. For the high speed visualization of the late injection (3 bTDC) it seems higher, but this is probably due to the fact that no movie is made with laser illumination and that the spray is not visible as good as with the other movies. But because the SoIc is used, this difference is not seen in the results. The results of the high speed camera are 11.1, 10.8 and 10.8 degrees for 3, 8 and 13 bTDC respectively, those derived from the heat release curve are 10, 9.8 and 10 degrees; see also Figure 22 and Figure 23.

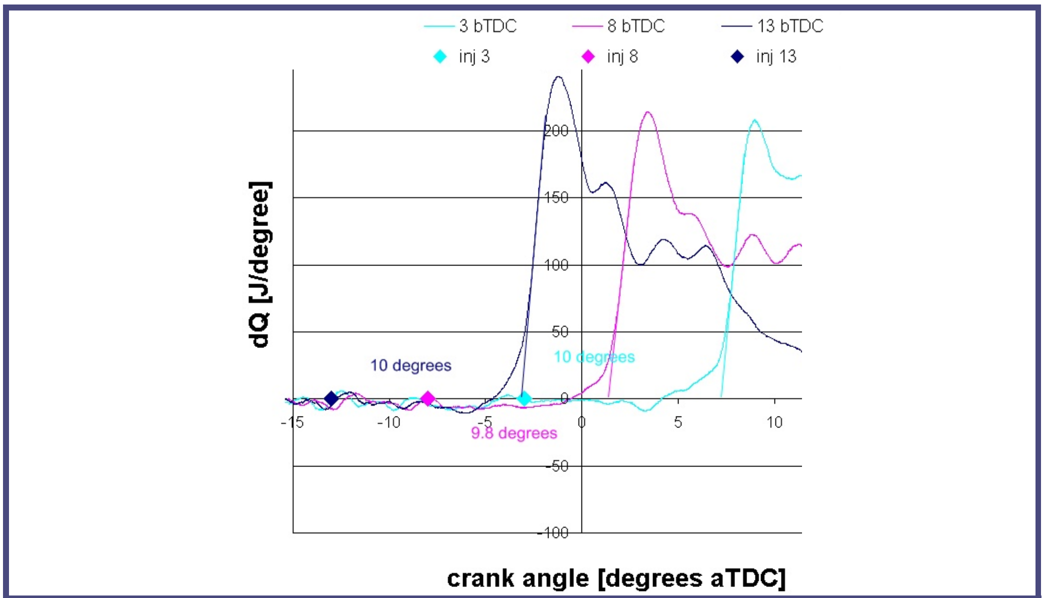


Figure 22: Results of the heat release curve for ignition delay at different injection timings.

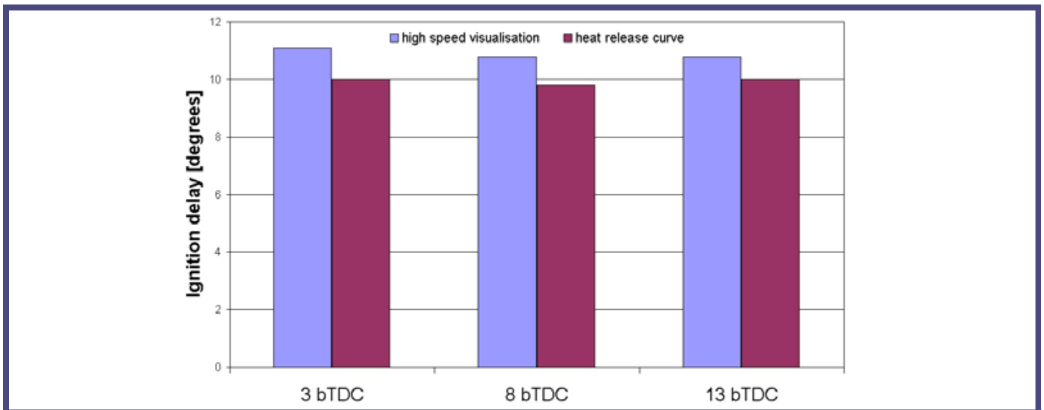


Figure 23: Results of the high speed visualization and the heat release curve for ignition delay at different injection timings.

The results of ignition delay for 15% oxygen compared to 21% oxygen are presented below. Here the ignition delay is not the same; the measurement with less oxygen had a longer ignition delay. This is not surprising, because the combustion is less explosive due to a lower oxygen percentage. This results in a lower heat release curve and a lower combustion temperature and a longer ignition delay.

The results of the high speed camera are 10.8 and 13.5 degrees for 21% and 15% oxygen respectively, those derived from the heat release curve are 9.5 and 12.5 degrees; see also Figure 24 and Figure 25.

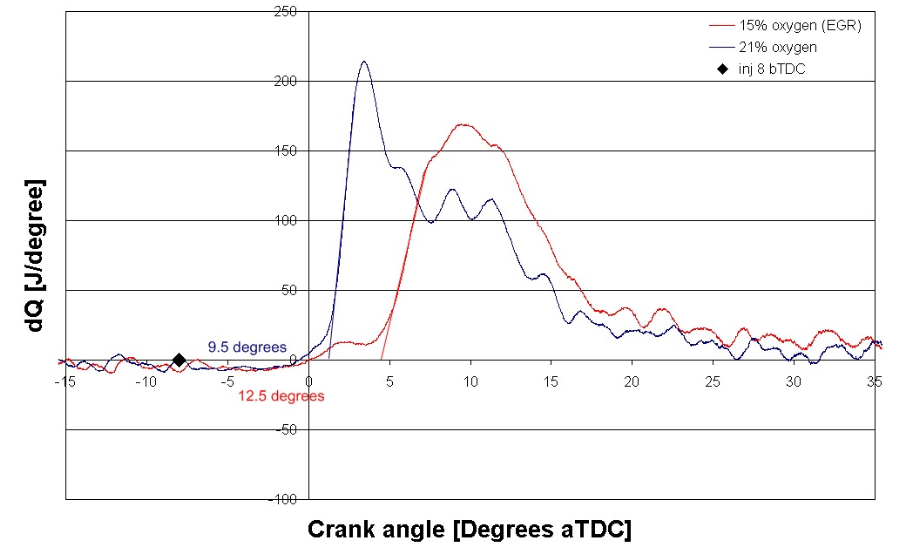


Figure 24: Results of the heat release curve of ignition delay for different percentages of oxygen in the incoming air.

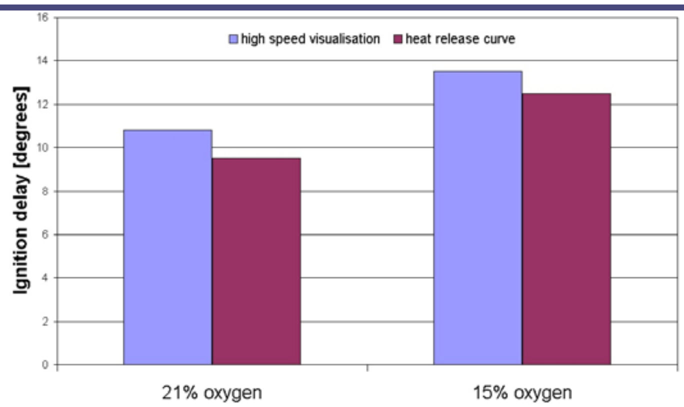


Figure 25: Results of the high speed visualization and the heat release curve of ignition delay for different percentages of oxygen in the incoming air.

In Figure 23 as well as Figure 25, the ignition delay derived from the camera is for all cases around one degree higher. The reason for this is not clear, but probably the pressure (from which the heat release is derived) has already grown before light can be detected.

The last issue for the thermodynamic analysis is the ***thermal efficiency***. For the thermal efficiency, the most important measure is the calculated indicated mean effective pressure, IMEP. IMEP is the average effective pressure inside a cylinder during one complete combustion cycle (intake, compression, power, exhaust), which when multiplied by the cylinder swept volume would produce the same power output as the real pressure does.

$$\text{IMEP}=\frac{W_i}{V_d}=\int_0^{720} p(x)dV$$

with IMEP the indicated mean effective pressure [Pa], W_i the indicative energy [J], V_d the displacement volume [m^3] and p the pressure [Pa].

Thus the IMEP is calculated from the area below the pressure-volume curve. The higher the IMEP in a given engine operation point with constant inlet conditions, the higher the engine efficiency. In an ideal situation, where the IMEP is maximum, the combustion is exactly at top dead center. In this case, the pressure boost that occurs pushes the piston down as it goes down. If combustion takes place just before top dead center (TDC), then the pressure boost pushes the piston down while it is still moving upwards and energy gets lost. Does the combustion occur too late, than not all energy out of the fuel is converted into useful work and some energy disappears with the exhaust gases as heat or pressure.

Efficiency is defined as:

$$\eta_i = \frac{W_i}{m_f Q_{LHV}}$$

with η_i the efficiency, m_f the fuel mass and Q_{LHV} the lower heating value of the fuel. Since $m_f = \int \dot{m}_f dt$ and $\dot{m}_f \propto \sqrt{\rho}$, the efficiencies can be compared:

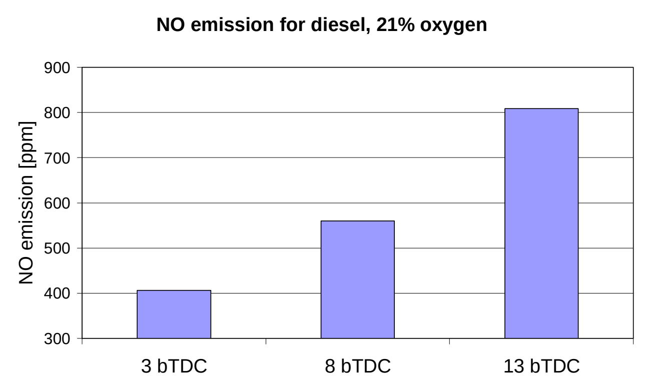
$$\frac{\eta_i^F}{\eta_i^D} = \frac{W_i^F}{W_i^D} \cdot \frac{\sqrt{\rho^D}}{\sqrt{\rho^F}} \cdot \frac{Q_{LHV}{}^D}{Q_{LHV}{}^F} \qquad (4)$$

the superscript ^{F} stands for the investigated fuel; this can be JME, JO or RME and with the superscript ^{D} is referred to Diesel, the reference fuel.

Measurements

NO_x measurements

Now the results of the measurements of Diesel can be analyzed. For Diesel the quantitative measurements in the exhaust were only done for NO and not for all NO_x. Unfortunately, the NO_x data are not available for Diesel. However, it is generally the case for direct injection Diesel engines that emissions of nitric oxide are much higher than those of nitrogen dioxide, so nitric oxide emissions are a good measure for the total nitrogen oxide emission [6]. The results show 406 particles per minute (ppm) NO for injection at 3 bTDC, 560 ppm for 8 bTDC and 809 ppm for 13 bTDC, see the overview below.



Injection [degrees bTDC]	NO [ppm]
3	406
8	560
13	809

Figure 26: NO emissions, Diesel, 21% oxygen

The results show that with early injection (13 degrees bTDC), the NO emission is much higher than for late injection (3 bTDC). Before any conclusions can be drawn based on these numbers, first it should be checked if this correlates to the thermodynamic history of these three cases.

Summarizing the results and the thermodynamic analysis:

Results show that	*early injection*	→			*high NO*
Pressure curve:	early injection	→	high peak pressure	→	high NO
Heat release curve:	early injection	→	high heat release peak	→	high NO
Ignition delay:	no influence	→	no influence	→	no influence

>>>In other words, the results correlate with the thermodynamic history and the differences could be caused simply by that. No conclusions on differences in NO_x production due to changing injection timing can be drawn from the result.

Soot measurements

For soot the same analysis will be performed. First the results will be summarized, then the thermodynamic history will be analyzed and correlations will be searched for.

In section 6.4 it was already explained that there are no quantitative results for soot emission or production. The photo diode signal will therefore be used solely as a qualitatively measure.

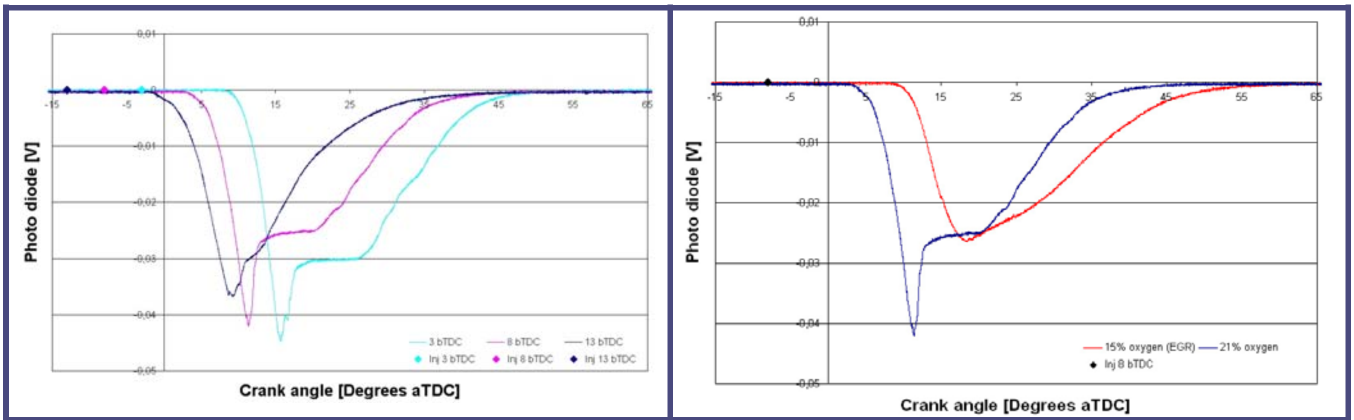


**Figure 27: Photo diode signal as function of the crank angle.
Left: for three injection timings, right for different oxygen percentages**

As has been said before, according to the Diesel dilemma, soot emission tends to lower at higher NO_x levels. In other words, for soot the results will probably be the other way round.

The photo diode results for the various injection timings are depicted in the left graph of Figure 27. It shows that for early injection (13 bTDC), the peak is lower than for 8 and 3 bTDC. The results for different percentages of oxygen in the incoming gas constitute the right graph in Figure 27. It shows that, with less oxygen, the negative peak is lower than for normal operation.

The photo diode measures the total luminosity of the combustion. Soot emits radiation that can be detected by a photo diode. The light yield is however not only dependent on the soot mass, but also on the soot temperature. The law of Stefan-Boltzmann learns that the energy flux emitted from a black body, in this case soot, is dependent on the temperature of the body. The law states:

$$\Phi = \frac{\sigma}{T^4},$$

where Φ is the energy flux [W/m^{-2}], σ the Stefan-Boltzmann constant ($5.670 \cdot 10^{-8}$ Wm^{-2}K^{-4}) and T the temperature [K] of the black body. So the energy emitted is a function of T to the power four and the photo diode signal should first be corrected by this factor.

The temperature derived from the pressure curve is the in-cylinder temperature and not the temperature of the soot particles. But as an indicator it is better to take this temperature than to ignore the influence. Therefore a factor (T_{max}, fuel/T_{max}, Diesel) is taken into account. The equation this is:

$$soot \triangleq \int Pd(\alpha)/T(\alpha)^4 \, d\alpha = \sum Pd_i / T_i^4 \, d\alpha \text{, which will be called } Pd_{Tcorr,\,i}$$

with $Pd(\alpha)$ the photo diode signal for as a function of the crank angle and $T(\alpha)$ the temperature as a function of the crank angle. However, with the available data it is

only possible to calculate the summation, the right hand side of the equal sign. For a certain fuel Pd_i *is* the photo diode signal and T_i the temperature.
Now scaling the signal is very simple:

$$\frac{Pd_{Tcorr,i}}{Pd_{Tcorr,ref}}$$

Table 12: Calculation of the temperature corrected photo diode signal (injection timing)		
Injection Timing	$\sum \frac{Pd_i}{T_i^4} d\alpha$	**Set 8bTDC at 1**
8 bTDC	5.03 e -12	1
3 bTDC	1.13 e -12	0.22
13 bTDC	6.36 e -12	1.27

Table 13: Calculation of the temperature corrected photo diode signal (oxygen percentage)		
Oxygen percentage	$\sum \frac{Pd_i}{T_i^4} d\alpha$	**Set 21% at 1**
21% O_2	5.03 e -12	1
15% O_2	2.61 e -12	0.52

Both results have to be checked on correlations with influence of pressure, heat release and ignition delay.

Injection timing

- Early injection shows a higher peak pressure, which generally corresponds to less soot, since the soot oxidation is good because of more premix and higher temperatures.
- The heat release curve shows a higher peak for early injection and generally this leads to less soot due to a higher temperature and also better premix.
- Ignition delay is approximately the same and therefore no influence of this parameter could be identified.

Oxygen percentage

- Less oxygen in the incoming gas shows a lower peak in-cylinder pressure. A smaller peak pressure generally leads to more soot because of poorer soot oxidation due to the lower temperature.
- The heat-release peak is also lower when operating on a lower oxygen percentage. This normally indicates that more soot is formed as well due to poorer oxidation of fuel, soot and hydrocarbons.
- Ignition delay however is longer, which allows more premix. This manifests in a more rapid combustion typically leading to less soot.

Summarizing these results:

for injection timing:

Results show that:	*Early injection*	→	*Higher photo diode signal*	→	*Less soot*
Pressure curve shows:	Early injection	→	Higher peak pressure	→	Less soot
Heat release curve shows:	Early injection	→	Higher heat release peak	→	Less soot
Ignition delay shows:	No influence	→	No influence	→	No influence

for oxygen percentage:

Results show:	*Less oxygen*	→	*Smaller photo diode signal*	→	*Less soot*
Pressure curve shows:	Less oxygen	→	Smaller peak pressure	→	More soot
Heat release curve shows:	Less oxygen	→	Smaller heat release peak	→	More soot
Ignition delay shows:	Less oxygen	→	Longer ignition delay	→	Less soot

This shows that for early injection the results correlate with the thermodynamic parameters, but that for a smaller oxygen percentage the photo diode signal does not correlate with all thermodynamic parameters. So apparently:
>>the effect of oxygen percentage on oxidation has a bigger influence than its effect on the premix fraction with respect to soot radiation.

7.2 *Investigated fuels*

Taking into account the findings for Diesel, the differences between the fuels can be investigated. For this section the injection timing was kept constant at 8 degrees bTDC and the amount of oxygen was kept normal, at 21% oxygen. This eliminates the effect of injection timing and oxygen percentage for these measurements. As mentioned in section 6.3, there are four fuels: Diesel as a well-known reference fuel, Jatropha Methyl Ester (JME) and Jatropha Oil (JO) as subjects of investigation and Rape Methyl Ester (RME) as reference for biofuels for which special norms have been made. Again this section is divided into two parts; the thermodynamic analysis and the measurements.

Thermodynamic analysis

In the ***pressure curve*** below one can see that the data of the four fuels do not differ too much from each other. The peak in the pressure curve is lowest for Jatropha Oil. In the table and figure below the values are summarized.

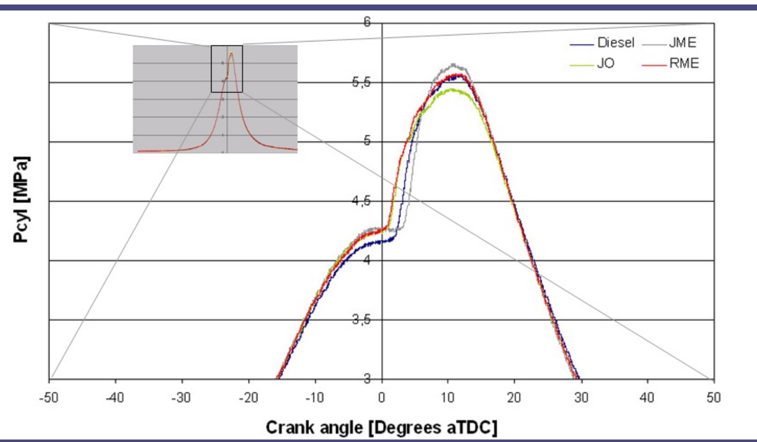
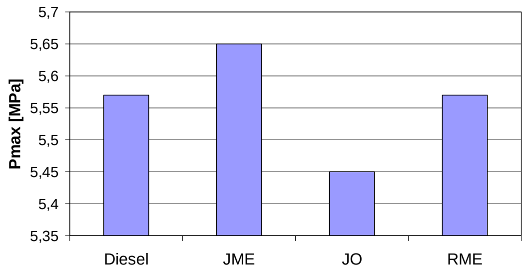


Figure 28: Pressure curve for the four investigated fuels. Injection 8 bTDC, oxygen percentage 21%.



Fuel	P_{max} [MPa]
Diesel	5,57
JME	5,65
JO	5,45
RME	5,57

Figure 29: Peak pressure, 8 bTDC, 21% oxygen

The question however, is if this correlates with the amount of energy input, which is probably different for all cases, since the injector flow was always 12 degrees long and the density and energy content is not the same. Table 14 shows the characteristics of the four tested fuels, which already have been discussed in chapter 2.

Table 14: Characteristics of Diesel, Jatropha Oil, Rape Methyl Ester and Jatropha Methyl Ester. Source: adjusted from [28]

Characteristic		Diesel	JME	JO	RME
Heating value **	(MJ/kg)	42*	36.5	39.2	37.3
Viscosity at 40 °C	(mm^2/s)	2.00 – 4.50*	4.2	43 ***	6
Cetane number	(-)	51.0*	51	37.8	46-54
Density at 15 °C	(g/cm^3)	0.820 – 0.845*	0.879	0.919	0.882
Solidification point	(°C)	-9 – -24	-	2	-2
Flashpoint	(°C)	56*	191	236	84

* Values are for the diesel used during the experiments, namely total low-sulphur diesel [47].
**Lower heating values. Other source, namely [46][29]
*** Approximation, see Figure 30

- The density shows small differences, but even though they are small, it could make some differences in the amount of injected fuel. Higher density, as for Jatropha oil, generally leads to more injected mass.

- The heating values of the biofuels are all somewhat lower than that of diesel and the differences amongst each other are minor.

These two can be captured by comparing the efficiencies of the investigated fuels with the reference fuel, Diesel.

This has been done by means of equation (4) explained in section 7.1.

$$\frac{\eta_i^{\ F}}{\eta_i^{\ D}} = \frac{W_i^{\ F}}{W_i^{\ D}} \cdot \frac{\sqrt{\rho^D}}{\sqrt{\rho^F}} \cdot \frac{Q_{LHV}^{\ \ D}}{Q_{LHV}^{\ \ F}}$$

In the table below the calculation has been worked out.

Table 15: Calculation of the efficiency of the investigated fuels compared with Diesel. Injection at 8bTDC, oxygen percentage 21%.

Fuel	IMEP [MPa]	ρ^F	$\sqrt{\rho^F}$	$Q_{LHV}^{\ \ F}$	$\frac{W_i^{\ F}}{W_i^{\ D}}$	$\frac{\sqrt{\rho^D}}{\sqrt{\rho^F}}$	$\frac{Q_{LHV}^{\ \ D}}{Q_{LHV}^{\ \ F}}$	$\frac{\eta_i^{\ F}}{\eta_i^{\ D}}$
Diesel	0.48969	0.8325 ±0.0125	0.91241	42	1	1	1	1
JME	0.44917	0.879	0.93755	36.5	0.91726	0.97319 ± 0.0073	1.15068	**1.02718 ±0.0077**
JO	0.4654	0.919	0.95864	39.2	0.9504	0.95178 ± 0.0071	1.07143	**0.92692 ±0.0072**
RME	0.45946	0.882	0.93915	37.3	0.93826	0.97153 ± 0.0073	1.12601	**1.02641 ±0.0077**

In other words, the efficiencies of JME and RME are higher than that of diesel in this specific operation point. That of JO is only slightly lower than that of Diesel and it turned out that with data from other sources the efficiency is higher than that of Diesel as well, so a real hard conclusion is difficult to make.

There is a third characteristic that might have influence and that is the viscosity of the fuels during the testing.

- The viscosities were mentioned in chapter 2 but unfortunately the viscosity for JO was only given for 20 °C. Since the viscosity of JO is much higher than for the (bio)diesels, it is important to find out what the viscosity was during the experiments. Figure 30 shows that the viscosity drops with increasing temperature therefore it is important to know what the temperature was during the experiments. Jatropha was heated to 34 °C before it was used in the engine. This means that the viscosity was about 49 centistokes (cSt, 1 cSt=1 mm^2/s), which is still much higher than that of the viscosity of about 5 cSt of the (bio)diesels.

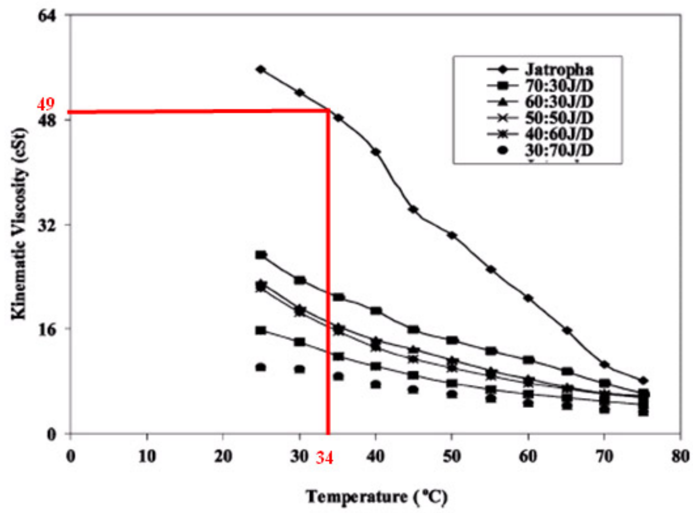


Figure 30: Effect on temperature on the viscosity of Jatropha Oil and blends with fossil Diesel in different J/D-ratios. Error! Reference source not found.

> Small increases of viscosity don't have any influence on the behavior of the injector according to literature [41]. But in this case the viscosity of Jatropha oil is around ten times higher than that of Diesel. What the influence is of that is not sure. Probably the injected mass is lower at the same rail pressure.

Because of this high viscosity, the comparison of the efficiency of JO with that of Diesel is probably not valid. More research on the effect of a tenfold increase of viscosity is needed, before any conclusion can be drawn about this.

So based on these data, only for JME and RME can be concluded that the efficiency in this specific operation point is higher than for Diesel.

Heat release

The heat release graph shows that the peak is lowest for Jatropha oil. Lower heat release peaks generally correspond to lower NO_x emissions. So according to these results, the NO emission measurements should show that Jatropha oil has lowest NO emission and JME the highest. The raw data of the peaks in heat release are summarized in the table below.

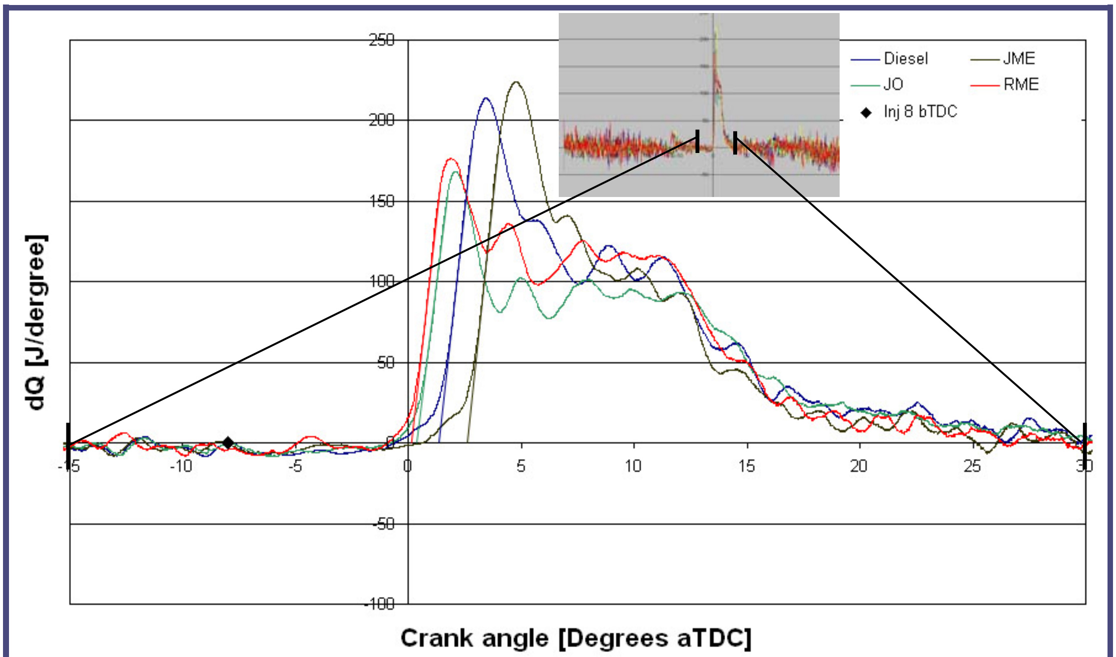
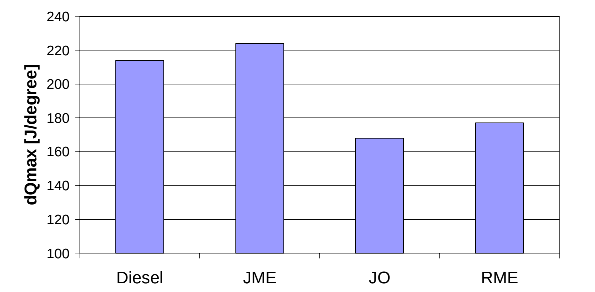


Figure 31: Heat release curve for the four investigated fuels. Injection 8 bTDC, oxygen percentage 21%.



Fuel	dQ_{max} [J/degree]
Diesel	214
JME	224
JO	168
RME	177

Figure 32: Heat release peak, 8 bTDC, 21% oxygen

Ignition delay

Ignition delay is again derived in two ways; with the high speed camera and by analyzing the heat release curves. Now the two measurement methods do not show a difference. Depending on the measurement method, Jatropha oil or RME has the shortest ignition delay.

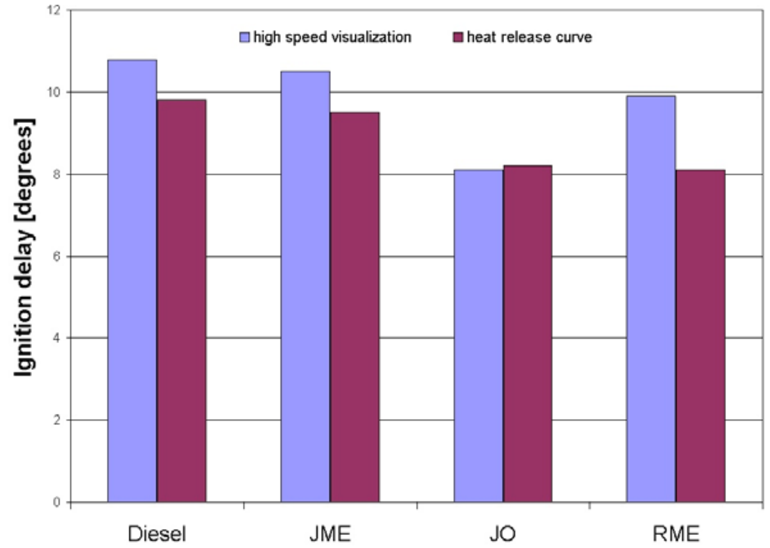


Figure 33: Ignition delay for the four investigated fuels, measured with high speed visualization. Injection 8 bTDC, oxygen percentage 21%.

It is surprising that the ignition delay of Jatropha oil is low, because due to the high viscosity one would expect that the atomization is not as good as for the other fuels and that it auto-ignites later instead of earlier. An explanation could be found in other fuel characteristics, like the surface tension, vapor tension or chemical composition of Jatropha oil [40]. Further investigation on this is recommended.

As was noticed before, the results for Diesel showed similar differences in ignition delay between the high speed visualization and the heat release measurements, namely approximately one crank angle degree. The question rises if this is the case for every fuel and engine setting. All movies and heat release curves were examined and Table 16 and appendix I show the results.

Table 16: Differences in the two measurement methods for ignition delay.

	Diesel			JME			JO			RME		
	HSV	dQ	**Diff.**	HSV	dQ	**Diff.**	HSV	dQ	**Diff.**	HSV	dQ	**Diff.**
3 bTDC	11.1	10	**1.10**	12.0	6.7	**5.3**	7.5	4.0	**3.5**	11.1	-	**-**
8 bTDC	10.8	9.8	**1.00**	10.5	9.5	**1.0**	8.1	8.2	**-0.1**	9.9	8.1	**1.8**
13 bTDC	10.8	10	**0.80**	10.8	15.7	**-4.9**	8.7	13.9	**-5.2**	10.2	13.6	**-3.4**

It turned out that for other fuels, the difference between the ignition delay derived from the high speed visualization and from the heat release curve is not consistent. So no conclusion can be drawn.

Measurements

NO_x measurements

In the figure below the quantitative NO data that were obtained from the measurements in the exhaust are summarized. Unfortunately, the NO_x data are not available due to unsuccessful measurements. However, as mentioned earlier, it is generally the case for direct injection Diesel engines that emissions of nitric oxide are much higher than those of nitrogen dioxide, so nitric oxide emissions are a good measure for the total nitrogen oxide emission. The data show that the emission of NO for the investigated biofuels is lower than that of Diesel.

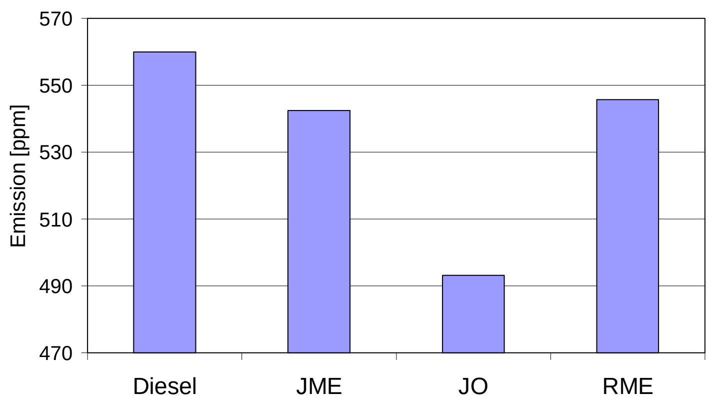


Figure 34: NO emissions for the four investigated fuels. Injection 8 bTDC, oxygen percentage 21%.

Now the results can be compared with the thermodynamic history for every fuel and correlation can be sought. The results of the investigated fuels, JO and JME will be compared to Diesel as the reference fuel.

- JME shows the highest peak pressure, which generally corresponds to more NO, since the soot oxidation is good because of more premix and higher temperatures. JO on the other hand has the lowest peak pressure, so less NO can be expected based on the pressure peak.
- The heat release curve shows a higher peak for JME and generally this leads to more NO due to a higher temperature and also better premix. Again, for JO this is the opposite
- Ignition delay is lowest for JO. Generally this leads to less NO, because of less premix and a slower combustion.

Results show that	*JO*	→			*less NO than Diesel*
Pressure curve:	JO	→	lower peak pressure	→	less NO
Heat release curve:	JO	→	lower heat release peak	→	less NO
Ignition delay:	JO	→	shorter ignition delay	→	less NO

Results show that	*JME*	→			*less NO than Diesel*
Pressure curve:	JME	→	higher peak pressure	→	more NO
Heat release curve:	JME	→	higher heat release peak	→	more NO
Ignition delay:	JME	→	no influence	→	no influence

The results of the NO measurements for Jatropha oil show less NO, as can be expected from the thermodynamics, so no conclusions can be drawn. JME however, shows less NO emissions, while the thermodynamics would lead to more NO. So apparently:

➢ the effect of JME instead of Diesel on the premix fraction has a bigger influence than the effect on oxidation with respect to NO production.

Soot measurements

If the fuels are compared with each other, the curve of the photo diode in combination with the heat release curve and the temperature curve can be used. How this works is already explained for Diesel, therefore here only the results will be presented. In the table below the calculation is worked out; the last column gives the relative Pd_{corr} for JME, JO and RME compared to Diesel.

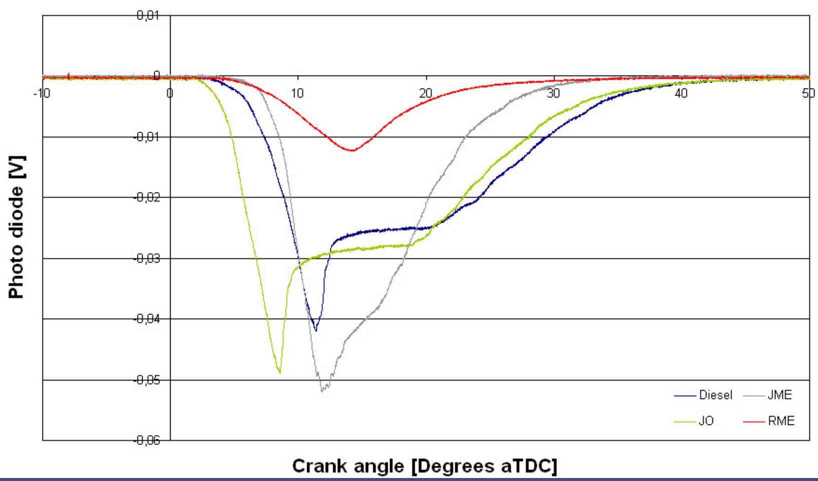


Figure 35: Photo diode signal for the four investigated fuels. Injection 8 bTDC, oxygen percentage 21%.

Table 17: Calculation of the temperature corrected photo diode signal (injection timing)

Injection Timing	$\sum \frac{Pd_i}{T_i^4} d\alpha$	**Set Diesel at 1**
Diesel	5.02 e -12	1
JME	-9.24 e -15	-0.01
JO	7.30 e -12	1.45
RME	3.44 e -12	0.68

Fuels for which the photo diode signal after correction is higher then one, produce more soot than Diesel does. So, from these numbers can be concluded that based on these measurements only Jatropha oil produces more soot than Diesel and the others don't. But the thermodynamic analysis should be taken into account.

- JME shows the highest peak pressure, which generally corresponds to less soot, since the soot oxidation is good because of more premix and higher temperatures. JO on the other hand has the lowest peak pressure, so more soot can be expected base on the pressure peak.
- The heat release curve shows a higher peak for JME and generally this leads to less soot due to a higher temperature and also better premix. Again, for JO this is the opposite
- Ignition delay is lowest for JO. Generally this leads to moor soot, because of less premix and a slower combustion.

Results show that	***JO***	→			***more soot than Diesel***
Pressure curve:	JO	→	lower peak pressure	→	more soot
Heat release curve:	JO	→	lower heat release peak	→	more soot
Ignition delay:	JO	→	shorter ignition delay	→	more soot

Results show that	***JME***	→			***same amount of soot as Diesel***
Pressure curve:	JME	→	higher peak pressure	→	less soot
Heat release curve:	JME	→	higher heat release peak	→	less soot
Ignition delay:	JME	→	no influence	→	no influence

This shows that the results for Jatropha oil, derived from the photo diode signal, correlate perfectly with the thermodynamics, which could mean that the result of low soot is only due to the thermodynamic history and not due to the chemical characteristics of JO itself.
For JME the results do not correlate with all thermodynamic parameters. So it could be that:
>>the effect of the use of JME instead of Diesel on oxidation has a smaller influence than the effect on the premix fraction with respect to soot radiation.
But because of many uncertainties due to this indirect measurement, no hard conclusions can be drawn.

7.3 *Conclusions*

Summarizing the experiments, several conclusions can be drawn. First of all the reference fuel, Diesel, is analyzed on the effect of injection timing and oxygen percentage in the inlet gas on NO and soot emissions. The results show that:

- NO emission is higher for early injection
- Soot emission is lower for early injection
- Soot emission is lower if less oxygen is in the inlet gas.

The NO measurements for operation with less oxygen in the inlet gas failed; therefore no results can be discussed.

The results were checked on correlations with the prevailing thermodynamic conditions. It turned out that the NO results correlate with the thermodynamic history and the differences could be caused simply by that. In other words no conclusions can be drawn. The soot emissions for the measurements with less oxygen however, were independent of the thermodynamic conditions, so apparently:

➢ the effect of oxygen percentage on oxidation has a bigger influence than its effect on the premix fraction with respect to soot radiation.

Based on this the other fuels were investigated. The operation conditions remain constant; injection is at 8 degrees before top dead center and the inlet gas is normal air with an oxygen percentage of 21%. It turned out that all biofuels emitted both less NO and soot:

- NO emission is lower for JO than for Diesel
- NO emission is lower for JME than for Diesel
- Soot emission is higher for JO than for Diesel
- Soot emission is the same for JME as for Diesel

Jatropha oil resulted in less NO, as could be expected from the thermodynamics, so no conclusions can be drawn. JME however, showed less NO emissions, while the thermodynamics would lead to more NO. So apparently:

➢ the effect of JME instead of Diesel on the premix fraction has a bigger influence than the effect on oxidation with respect to NO production.

JO resulted in more soot, as could be expected from the thermodynamics, so no conclusions can be drawn. JME however, showed a similar amount of soot as Diesel did, while the thermodynamics would lead to less soot. So it could be that:

➢ the effect of the use of JO instead of Diesel on oxidation has a smaller influence than the effect on the premix fraction with respect to soot radiation.

But because of many uncertainties due to this indirect measurement, no hard conclusions can be drawn.

8 Meeting the standards and regulation

We have seen that it is possible to produce Jatropha oil in Tanzania even during the startup period of the production of Jatropha. If Jatropha is produced on large scale there may be economically viable possibilities for Europe as well [28]. Therefore this chapter summarizes investigations that have been done to find out whether Jatropha Oil and JMA meet the current standards and requirements of the European Union.

8.1 Different kind of regulations

Within the European legislation there are several kinds of policy measures on biofuels. The relationship between European and national policy is depending on the kind of measure used. The "Treaty establishing the European community", article 249 in chapter 2 "Provisions common to several institutions" defines the four policy measures used by the European Commission and the Council.

- A regulation shall have general application. It shall be binding in its entirety and directly applicable in all Member States.
- A directive shall be binding, as to the result to be achieved, upon each Member State to which it is addressed, but shall leave to the national authorities the choice of form and methods.
- A decision shall be binding in its entirety upon those to whom it is addressed.
- Recommendations and opinions shall have no binding force." [34].

The directive is the most commonly used instrument of harmonization of European member states and also in the field of biofuels a directive is in force, namely the European Directive on the promotion of biofuels[23]. It encourages the wider use of biofuels and other renewable transport fuels in order to help Europe meet its strategy and commitments on reducing greenhouse gas emissions, improving the security of energy supplies and increasing the use of renewable energy sources [33]. This directive sets a European target of 5,75% substitution of fossil fuels with biofuels by the end of 2010 and an interim target of 2% by the end of 2005, which was not met. Since each member state has a different situation with respect to climate, land use and biomass use for other purposes, the directive is flexible and offers the member states to set their own individual targets. Where the national targets depart from the content of the European directive, the Member State should justify this with reasons.

8.2 Fuel specifications

Besides a directive on the use of biofuels, there is also a standard on the quality of biofuels. In principle, biofuels should meet the fossil fuel quality standards. For bioethanol, which is never used in pure form but is always mixed with gasoline, this is still the case. For biodiesel on the other hand, there is a special standard for biodiesel developed, namely EN 14214:2003[24]. In this European standard maximum and minimum requirements are defined for all Fatty Acid Methyl Esters

[23] Directive 2003/30/EC of 8 May 2003 of the European Parliament and the Council on the promotion of the use of biofuels or other renewable fuels for transport (OJ L 123, 17.5.2003, p. 42)

[24] NEN-EN 14214:2003 means that the European standard EN 14214:2003 is implemented by the Dutch standardization institute NEN, just like in Germany exists the DIN-EN 14214:2003 (DIN=Deutsches Institut für Normierung).

that will be used in diesel engines. The five most important suppliers of injection nozzles and accompanying equipment have declared that this standard is the only guarantee against premature failure of the equipment and with that of the diesel engine. This certified biodiesel should however be mixed with fossil diesel of likewise standardized quality (EN 590:2004 "Automotive fuels - Diesel - Requirements and test methods").

Table 7 shows that Jatropha diesel, JME, complies with the European norm EN14214. Jatropha oil does not and can't be used as a diesel fuel in Europe under the current legislation. It seems to be definite since the papers tell that Europe is not planning to stimulate PPO, but only biodiesel. For the use outside Tanzania, which is only a feasible option on the long term as has been concluded in chapter 4, only JME could be used if the legislation remains unadjusted. Preliminary research [34] showed that the use of esterificated fuels is in energetic perspective not a very efficient option, but in case of using PPO the engine needs some small modifications and a transition into this direction is not very likely in Europe according to the newspapers. The only possibility for PPO is using it in a blend with fossil diesel, or maybe even with biodiesel -notwithstanding the fact that this is not approved yet-. The Kwame Nkrumah University of Science and Technology in Ghana published an article with physical properties of diesel/jatropha oil blends. The results for the 80% diesel/20%jatropha oil blend and that of the 97.4/2.6 one, are in Table 7 as well. Since there is no PPO standard, the blend of Jatropha oil with diesel will have to comply with the diesel norm EN 590. As can be concluded from these numbers, the blends do neither comply with EN590 nor with EN14214. In other words not even blends of oil with diesel are an option for Europe under the current standards and legislation.

Jatropha Methyl Ester does meet the fuel specifications of Europe and on the longer term, if it is economically feasible, introduction of this fuel in Europe seems possible.

Table 18: Physical properties of Diesel, Jatropha Oil (JO) and Jatropha Methyl Ester (JME) compared to the European biodiesel norm EN14214 [35][3].

Properties	Diesel	JO	D/JO 80/20	D/JO 97.4/2.6	EN 590	JME	EN 14214
Density (kg/m^3)	840	918	876.9	868.4	**820-845**	880	**860-900**
Viscosity at 40°C (cSt)	4.59	49.9	8.2*	5.9*	**2-4.5**	5.65	**3.5-5.0**
Calorific value (MJ/kg)	42.4	39.8	44.2	45.2	**-**	38.5	**-**
Flashpoint (°C)	75	240	90	88	**>55**	170	**>120**
Cetane number (-)	45-55	45	-	-	**>51**	50	**>51**
Carbon residue % (m/m)	0.1	0.44	-	-	**<0.3**	N.A.	**<0.03**

*These viscosities are measured at 37.8°C (cSt)
Note that the density does not linearly change with the percentages JO and Diesel. This is plausible [31]

8.3 Emissions

Although the use of biodiesel reduces the net CO_2 emissions, other emissions such as NO_x and soot are important as well and therefore these two measured in this thesis as well. Road transport contributes to air quality problems through vehicle emissions. To preserve air quality, vehicles in Europe must meet certain standards for emissions before they can be approved for sale in the European Union. These standards were initiated in 1993 in the EU and are called 'EURO' emission standards.

EURO 4 standards are in force since the first of January 2005 and the European Commission opened a consultation process on the new car limits, EURO 5, on July 15th 2005. If the proposal is both approved by the Parliament and the Council is can be adopted. If approved, the EURO 5 standards will become effective by 2010 at the latest.

The aim of the Euro 5 standard is to reduce emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and particulate matters (PM), which are considered harmful to human health. In Table 2 an overview of the requirements that should be met is shown for Euro 2, 3 and 4 plus the predictions for the Euro 5 standard.

Table 19: Overview of emission measures in place since 1996. [53]

Emissions Standard	Particulate matters (PM) [mg/km]		Oxides of nitrogen (NO_x) [g/km]		Hydrocarbons (HC) [g/km]		Carbon monoxide (CO) [g/km]	
	Diesel	*Petrol*	*Diesel*	*Petrol*	*Diesel*	*Petrol*	*Diesel*	*Petrol*
Euro 2 (1996)	80-100	-	-	-	-	-	0.7/0.9	0.5
Euro 3 (2000)	50	-	0.5	0.15	-	0.2	0.56	-
Euro 4 (2005)	25	-	0.25	0.08	-	0.1	0.3	-
Fiscal incentives guidance document (2005)	5	-	-	-	-	-	-	-
Euro 5* (2010)	5	5	0.2	0.06	-	0.075	-	-

* *The values shown here are tentative and subject to the consultation process opened July 2005*

Besides these requirements for the vehicles to be sold in the EU, there is a directive, namely directive 2001/100/EC amending Council Directive 70/220/EEC 'on the approximation of the laws of the Member States on measures to be taken against air pollution by emissions from motor vehicles'. This is the directive for light duty vehicles and similar for heavy duty vehicles is directive 1999/96/EC amending Council Directive 88/77/EEC 'on the approximation of the laws of the Member States relating to measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emission of gaseous pollutants from ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles'.

A complete list of air quality directives as well as directives belonging to the other paragraphs can be found on the website of the European Union[25].

8.4 *Reducing environmental damage*

Control of nitrogen oxides from automobile exhausts is accomplished by exhaust gas recirculating (EGR), which is used is both diesel and gasoline engines. With EGR 5-10% of the engine's exhaust gas is recirculated to the engine cylinders. As a result of the intermixing of the recirculated exhaust gas and the incoming air, the oxygen percentage is smaller. Combustion slows down, which lowers the peak temperature. Since NO_x formation increases with temperature, EGR can limit the generation of NO_x. At low rpm however, the inert gas from EGR would not provide enough power to keep the engine running, so the EGR valves remain closed in this case.

Normally, recirculation gases are led through pipes to the inlet manifold (external EGR) or exhaust gas is trapped in the cylinder by not fully expelling the exhaust stroke (internal EGR). In the engine set-up used in this thesis, EGR is simulated by simply running the engine on gas with a oxygen percentage of 15% instead of 21%. Unfortunately, the measurements were unsuccessful because of malfunctioning of the measurement instruments and no results can be discussed here.

There is a drawback to EGR as well; EGR reduces the engine's fuel efficiency, and thereby increasing production of carbon dioxide gas.

[25] The url of the website that is meant here is: http://66.102.9.104/search?q=cache:yLIvemYnN9gJ:europa.eu.int/comm/environment/air/legis.htm+amending+Council+%22Directive+98/69/EC%22&hl=nl

9 Conclusions and recommendations

The thesis answered all research questions that were defined at the beginning of the thesis work.

- What is the status in Tanzania with respect to the infrastructure of diesel fuel, the vehicles that are used, the amount of cars and trucks, the prices of fuels, the prices of cars and trucks and who can afford to use them, etc.? *(Chapter 4)*
- What are the possibilities for the use in Tanzania and possibly outside Tanzania? *(Chapter 4)*
- What emissions are produced by the use of diesel engines in cars and trucks with different fuels? *(Chapter 5)*
- What are the effects of these gases and how do they harm the environment? *(Chapter 5)*
- What emissions are produced by the use of Jatropha oil in the engine that will be used for practical investigation? *(Chapter 7)*
- Do problems occur with Jatropha oil in the diesel engine, and if so, what kind of problems are these? *(Chapter 7)*
- What differences are measured in the engine during the use of Jatropha oil compared to conventional fuels (pressure differences, temperature differences, amount of fuel needed, amount of air required, etc)? *(Chapter 7)*
- Can environmental damage caused by Jatropha oil use be further diminished or avoided and how? *(Chapter 8)*

The thesis was both broad and in-depth oriented. Chapter 6 and 7 describe the experiments and the results and the conclusions from the experimental research were already presented in section 7.3. The data showed differences for Jatropha Oil and Jatropha Methyl Esther compared to Diesel. Especially on the production of NO conclusions can be drawn. The soot results are disputable and therefore no hard conclusions can be drawn.

Both JME and JO produced less NO than Diesel. Especially JO showed a significant difference. The thermodynamic history could be the reason for the difference of JO, but not of that of JME. Chemical properties could be the cause of the better performance on NO emissions.

For soot this is the other way around; the lower soot emission from JME correlates with the thermodynamic history and therefore no conclusions about the effect of the chemical properties of the fuel on soot emissions can be drawn. JO on the other hand, does show less soot emission while the thermodynamics would expect different. However, since the influence of the very high viscosity of JO compared to the other fuels is unknown, no hard conclusions can be drawn either. More research on the effect of ten times higher viscosity is recommended.

Further it is recommended to do the experiments again for more engine settings. Because there are only three injection timings examined, some trends might not show. Besides that, it would be better to measure the temperature in the combustion chamber instead of calculating it from the in-cylinder pressure, but this is very hard, more research is necessary to develop a way to do this. Finally, one more recommendation is mentioned here, namely that it is better to measure the soot emission in the exhaust by means of a dilution tunnel, which measures the mass of soot or by means of smoke capacity that measures the light reflection.

The overall conclusion is that the investigation of both the experiments and the broader literature study did not lead to any findings that could hamper the application of Jatropha oil or -Methyl Ester in Diesel engines. In the short term however, the use should be restricted to Tanzania. In the longer term there might be possibilities for export to Europe as well. This depends on if the European regulation still stimulates the use of bio-oil and bio-diesel by then.

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Appendix A: European standards for biodiesel and fossil Diesel

EN14214:2003 standards and test methods [35] [26] for biodiesel

Property	Unit	Limits Minimum	Limits Maximum	Test method [a]
Ester content [a]	% (*m/m*)	96,5 [b]		prEN 14103
Density at 15 °C [c]	kg/m^3	860	900	EN ISO 3675 EN ISO 12185
Viscosity at 40 °C [d]	mm^2/s	3,50	5,00	EN ISO 3104
Flash point	°C	120	–	ISO/DIS 3679 [e]
Sulfur content	mg/kg	–	10,0	prEN ISO 20846 prEN-ISO 20884
Carbon residue (on 10 % distillation residue) [f]	% (m/m)	–	0,30	EN ISO 10370
Cetane number [g]		51,0		EN ISO 5165
Sulfated ash content	% (m/m)	–	0,02	ISO 3987
Water content	mg/kg	–	500	EN ISO 12937
Total contamination [h]	mg/kg	–	24	EN 12662
Copper strip corrosion (3 h at 50 °C)	Rating	Class 1		EN ISO 2160
Oxidation stability, 110 °C	Hours	6,0	–	prEN 14112
Acid value	mg KOH/g		0,50	prEN 14104
Iodine value			120	prEN 14111
Linolenic acid methyl ester	% (m/m)		12,0	prEN 14103
Polyunsaturated (>= 4 double bonds) methyl esters [i]	% (m/m)		1	
Methanol content	% (m/m		0,20	prEN 14110
Monoglyceride content	% (m/m)		0,80	prEN 14105
Diglyceride content	% (m/m)		0,20	prEN 14105
Triglyceride content [j]	% (m/m)		0,20	prEN 14105
Free glycerol [j]	% (m/m)		0,02	prEN 14105 prEN 14106
Total glycerol	% (m/m)		0,25	prEN 14105
Group I metals (Na+K) [k]	mg/kg		5,0	prEN 14108 prEN 14109
Group II metals (Ca+Mg) [l]	mg/kg		5,0	prEN 14538
Phosphorus content	mg/kg		10,0	prEN 14107

- [a] See 5.5.1
- [b] The addition of non-FAME components other than additives is not allowed, see 5.2.
- [c] Density may be measured by EN ISO 3675 over a range of temperatures from 20 °C to 60 °C. Temperature correction shall be made according to the formula given in Annex C. See also 5.5.2
- [d] If CFPP is –20 °C or lower, the viscosity measured at -20 °C shall not exceed 48 mm^2/s. In this case, EN ISO 3104 is applicable without the precision data owing to non-Newtonian behaviour in a two-phase system.
- [e] A 2 ml sample and apparatus equipped with a thermal detection device shall be used
- [f] ASTM D 1160 shall be used to obtain the 10% distillation residue.
- [g] See 5.5.3.
- [h] See 5.5.1. An improved method is under development by CEN/TC 19.
- [i] Suitable test method to be developed
- [j] See also 5.5.1.
- [k] Method under development. See Annex A for precision data for sum of Na + K
- [l] See 5.5.1. Method under development. See Annex A for precision data for sum of Ca + Mg.

[26] The source is from the final draft since this is the version I own and other versions should be bought from CEN. The numbers are the same.

EN590:2003 standards and test methods [35] [27] for fossil diesel

Property	Unit	Limits		Test method [a]
		minimum	maximum	(See 2. Normative references)
Cetane number [b]		**51,0**	–	EN ISO 5165
Cetane index		46,0	–	EN ISO 4264
Density at 15 °C [c]	**kg/m^3**	820	**845**	EN ISO 3675 EN ISO 12185
Polycyclic aromatic hydrocarbons [d, e]	**% (*m/m*)**	–	**11**	EN 12916
Sulfur content [f]	**mg/kg**	–	**350** (until 2004-12-31) or **50,0**	EN ISO 20846 EN ISO 20847 EN ISO 20884
			10,0	EN ISO 20846 EN ISO 20884
Flash point	°C	Above 55	–	EN ISO 2719
Carbon residue [g] (on 10 % distillation residue)	% (*m/m*)	–	0,30	EN ISO 10370
Ash content	% (*m/m*)	–	0,01	EN ISO 6245
Water content	mg/kg	–	200	EN ISO 12937
Total contamination	mg/kg	–	24	EN 12662
Copper strip corrosion (3 h at 50 °C)	rating	class 1		EN ISO 2160
Oxidation stability	g/m^3	–	25	EN ISO 12205
Lubricity, corrected wear scar diameter (wsd 1,4) at 60 °C	µm	–	460	EN ISO 12156-1
Viscosity at 40 °C	mm^2/s	2,00	4,50	EN ISO 3104
Distillation [h, i] % (*V/V*) recovered at 250 °C % (*V/V*) recovered at 350 °C **95 % (*V/V*) recovered at**	 % (*V/V*) % (*V/V*) **°C**	 85 	 < 65 **360**	EN ISO 3405
Fatty acid methyl ester (FAME) content [k]	% (*V/V*)	-	5	EN 14078

NOTE Requirements in bold refer to the European Fuels Directive 98/70/EC [1], including Amendment 2003/17/EC [2]

[a] See also 5.6.1

[b] See also 5.6.4

[c] See also 5.6.2

[d] For the purposes of this European Standard, polycyclic aromatic hydrocarbons are defined as the total aromatic hydrocarbon content less the mono-aromatic hydrocarbon content, both as determined by EN 12916.

[e] EN 12916 is not able to distinguish between polycyclic aromatic hydrocarbons and fatty acid methyl esters (FAME). FAME, if present in diesel fuels, will overestimate the value for polycyclic aromatic hydrocarbons. An improved method for the determination of polycyclic aromatic hydrocarbons is under development by CEN/TC 19.

[f] See also 5.6.3

[g] See also 5.4.2

[h] For the calculation of the cetane index the 10 %, 50 % and 90 % (*V/V*) recovery points are also needed.

[i] The limits for distillation at 250 °C and 350 °C are included for diesel fuel in line with EU Common Customs tariff.

[k] FAME shall meet the requirements of EN 14214

[27] The source is from the final draft since this is the version I own and other versions should be bought from CEN. The numbers are the same.

Appendix B: Data from the SMP model reference case

Total gasoline fuel use (exajoules)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	18.0	18.7	19.7	21.1	22.2	22.9	23.4	23.8	24.2	24.6	24.9
OECD Europe	5.8	5.7	5.2	4.9	4.6	4.5	4.4	4.4	4.3	4.2	4.2
OECD Pacific	3.0	3.0	3.1	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.0
FSU	1.6	1.8	2.1	2.5	3.0	3.3	3.7	4.1	4.4	4.6	4.8
Eastern Europe	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.9
China	1.4	1.8	2.3	3.1	4.0	4.8	5.8	7.0	8.3	9.9	11.6
Other Asia	1.5	1.8	2.1	2.5	3.0	3.4	3.9	4.5	5.3	6.2	7.2
India	0.6	0.7	0.9	1.1	1.4	1.7	2.0	2.4	2.8	3.4	4.2
Middle East	1.3	1.5	1.6	1.8	2.1	2.3	2.5	2.7	3.0	3.2	3.4
Latin America	1.7	2.0	2.4	2.8	3.4	3.7	4.1	4.6	5.2	5.9	6.6
Africa	1.0	1.2	1.4	1.7	2.1	2.5	2.8	3.0	3.3	3.7	4.1
TOTAL - All Regions	36.4	38.7	41.6	45.5	49.8	53.1	56.6	60.4	64.7	69.5	74.9

Total diesel fuel use (exajoules)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	5.8	6.2	6.8	7.2	7.6	8.0	8.5	8.9	9.4	9.9	10.4
OECD Europe	6.2	6.9	7.7	8.7	9.1	9.3	9.4	9.5	9.5	9.5	9.6
OECD Pacific	2.0	2.0	2.1	2.1	2.2	2.3	2.4	2.6	2.7	2.8	2.9
FSU	0.8	0.9	1.0	1.1	1.3	1.4	1.5	1.7	1.9	2.1	2.3
Eastern Europe	0.4	0.4	0.5	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3
China	1.4	1.7	2.1	2.5	2.9	3.3	3.7	4.2	4.8	5.5	6.3
Other Asia	2.0	2.3	2.7	3.2	3.6	4.0	4.5	5.0	5.7	6.4	7.2
India	1.3	1.5	1.7	2.0	2.3	2.7	3.0	3.4	3.9	4.5	5.1
Middle East	1.0	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.3
Latin America	2.1	2.4	2.7	3.0	3.4	3.7	4.1	4.5	5.0	5.5	6.0
Africa	0.7	0.8	0.9	1.0	1.2	1.3	1.5	1.6	1.8	2.0	2.2
TOTAL - All Regions	23.6	26.2	29.5	32.8	35.8	38.4	41.3	44.4	47.7	51.5	55.6

Total energy use (exajoules)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	28.6	30.4	32.8	35.1	37.2	38.8	40.4	41.8	43.3	44.8	46.3
OECD Europe	16.4	17.5	18.7	19.8	20.4	20.9	21.4	21.7	21.9	22.1	22.3
OECD Pacific	7.0	7.2	7.5	7.8	8.1	8.3	8.5	8.7	8.9	9.2	9.5
FSU	2.7	3.1	3.5	4.1	4.9	5.4	6.0	6.6	7.2	7.8	8.4
Eastern Europe	1.2	1.3	1.5	1.7	1.9	2.0	2.2	2.5	2.8	3.1	3.4
China	3.6	4.5	5.6	7.0	8.6	10.0	11.8	13.8	16.2	18.8	21.9
Other Asia	5.1	5.8	6.8	7.9	9.1	10.2	11.5	13.0	14.8	16.9	19.3
India	2.0	2.4	2.9	3.5	4.3	4.9	5.8	6.7	7.8	9.1	10.8
Middle East	3.1	3.4	3.7	4.1	4.6	5.1	5.6	6.0	6.4	6.8	7.3
Latin America	5.0	5.7	6.7	7.8	9.1	10.1	11.4	12.9	14.5	16.4	18.6
Africa	2.3	2.6	3.0	3.5	4.2	4.8	5.4	6.0	6.6	7.4	8.3
TOTAL - All Regions	77.0	83.9	92.8	102.4	112.2	120.7	129.9	139.6	150.4	162.4	176.0

Population (millions)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	405.3	426.4	446.5	466.3	485.9	504.5	521.4	537.1	552.8	568.5	584.1
OECD Europe	513.9	519.7	523.0	524.8	525.8	525.6	523.6	509.1	494.7	480.3	465.9
OECD Pacific	197.2	200.8	203.4	204.7	204.8	204.2	202.9	200.1	197.3	194.5	191.7
FSU	254.0	252.0	250.9	250.5	249.9	248.3	245.9	246.5	247.1	247.7	248.4
Eastern Europe	99.5	96.4	93.4	90.5	87.6	84.5	81.4	82.2	83.0	83.9	84.7
China	1271.7	1317.8	1362.5	1406.4	1442.2	1466.9	1480.9	1478.7	1476.6	1474.4	1472.2
Other Asia	891.3	967.4	1042.9	1118.8	1193.6	1265.1	1330.3	1400.5	1470.8	1541.0	1611.2
India	1013.9	1088.6	1164.0	1230.5	1291.3	1351.8	1408.9	1449.7	1490.5	1531.3	1572.1
Middle East	167.5	192.1	218.1	245.0	271.7	299.5	327.3	353.3	379.3	405.3	431.2
Latin America	415.2	446.1	476.6	506.1	534.2	560.2	584.2	603.1	622.0	640.9	659.8
Africa	793.6	891.7	997.0	1110.0	1231.0	1358.1	1488.9	1616.9	1744.9	1872.8	2000.8
Total	6023.1	6398.9	6778.2	7153.7	7518.0	7868.8	8195.8	8477.4	8759.0	9040.6	9322.2

Total gasoline fuel use per capita (gigajoules)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	44.3	43.9	44.2	45.2	45.7	45.4	44.9	44.4	43.8	43.2	42.6
OECD Europe	11.3	10.9	10.0	9.3	8.8	8.6	8.5	8.6	8.7	8.8	8.9
OECD Pacific	15.2	15.1	15.4	15.7	15.7	15.6	15.5	15.5	15.6	15.7	15.8
FSU	6.1	7.1	8.4	9.9	11.9	13.3	15.0	16.5	17.7	18.7	19.5
Eastern Europe	5.9	6.6	7.5	8.4	9.3	9.5	9.7	9.6	9.6	9.9	10.2
China	1.1	1.3	1.7	2.2	2.8	3.3	3.9	4.7	5.6	6.7	7.9
Other Asia	1.7	1.8	2.0	2.2	2.5	2.7	2.9	3.2	3.6	4.0	4.5
India	0.5	0.6	0.7	0.9	1.1	1.2	1.4	1.6	1.9	2.2	2.7
Middle East	7.9	7.6	7.5	7.5	7.7	7.7	7.7	7.8	7.8	7.8	7.8
Latin America	4.1	4.5	5.0	5.6	6.3	6.6	7.0	7.7	8.4	9.2	10.0
Africa	1.3	1.3	1.4	1.5	1.7	1.8	1.9	1.9	1.9	2.0	2.1
TOTAL - All Regions	6.1	6.1	6.1	6.4	6.6	6.7	6.9	7.1	7.4	7.7	8.0

Total diesel fuel use per capita (gigajoules)

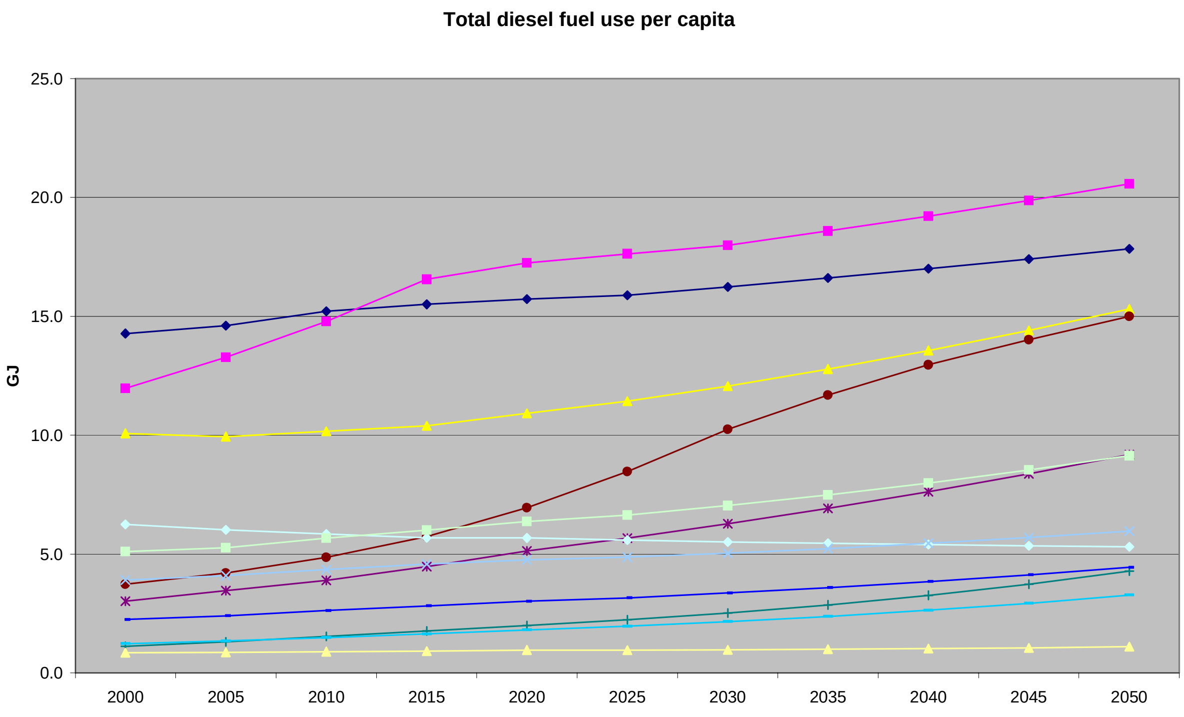
	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	14.3	14.6	15.2	15.5	15.7	15.9	16.2	16.6	17.0	17.4	17.8
OECD Europe	12.0	13.3	14.8	16.6	17.2	17.6	18.0	18.6	19.2	19.9	20.6
OECD Pacific	10.1	9.9	10.2	10.4	10.9	11.4	12.1	12.8	13.6	14.4	15.3
FSU	3.0	3.5	3.9	4.5	5.1	5.7	6.3	6.9	7.6	8.4	9.2
Eastern Europe	3.7	4.2	4.9	5.7	7.0	8.5	10.2	11.7	13.0	14.0	15.0
China	1.1	1.3	1.5	1.8	2.0	2.2	2.5	2.9	3.3	3.7	4.3
Other Asia	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.1	4.4
India	1.2	1.3	1.5	1.6	1.8	2.0	2.2	2.4	2.6	2.9	3.3
Middle East	6.2	6.0	5.8	5.7	5.7	5.6	5.5	5.4	5.4	5.4	5.3
Latin America	5.1	5.3	5.7	6.0	6.4	6.6	7.0	7.5	8.0	8.5	9.1
Africa	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.1
TOTAL - All Regions	3.9	4.1	4.3	4.6	4.8	4.9	5.0	5.2	5.5	5.7	6.0

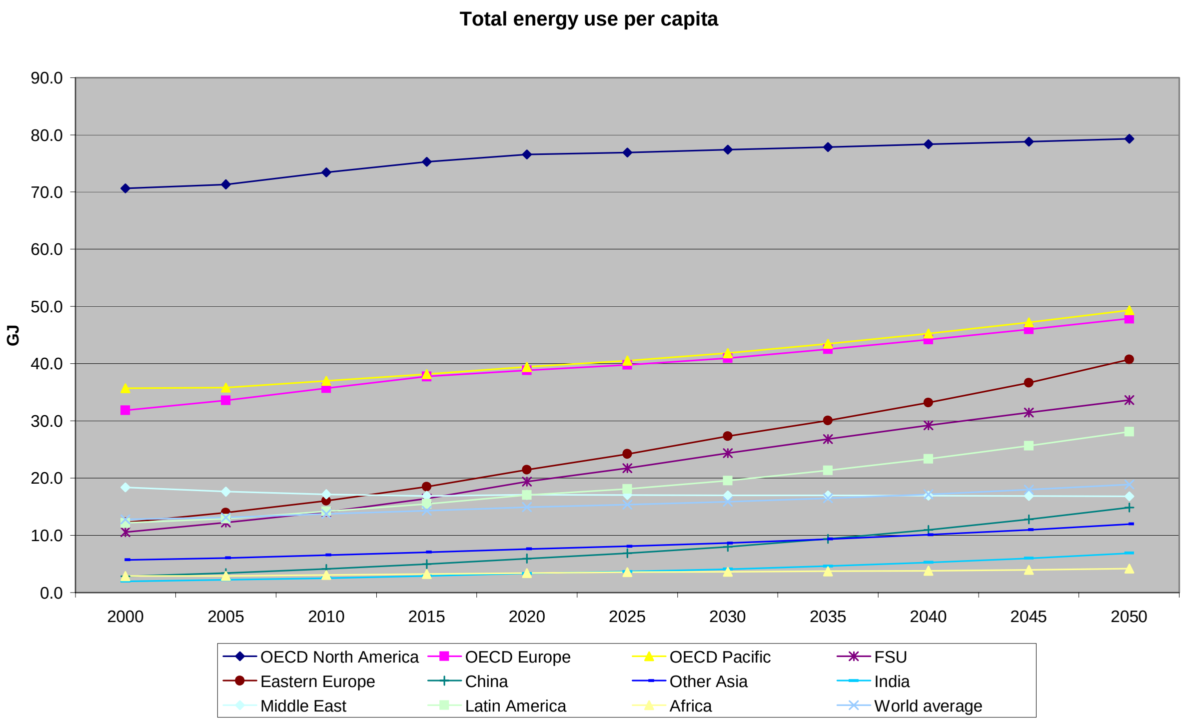
Total energy use per capita (gigajoules)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	70.6	71.3	73.4	75.3	76.6	76.9	77.4	77.9	78.3	78.8	79.3
OECD Europe	31.9	33.6	35.7	37.7	38.8	39.8	41.0	42.5	44.2	46.0	47.9
OECD Pacific	35.7	35.8	37.0	38.2	39.4	40.5	41.8	43.5	45.3	47.2	49.3
FSU	10.6	12.2	14.1	16.4	19.4	21.7	24.3	26.8	29.2	31.4	33.6
Eastern Europe	12.3	13.9	16.0	18.5	21.5	24.2	27.3	30.1	33.2	36.7	40.7
China	2.8	3.4	4.1	5.0	5.9	6.8	8.0	9.4	11.0	12.8	14.9
Other Asia	5.7	6.0	6.5	7.0	7.6	8.1	8.6	9.3	10.1	11.0	12.0
India	2.0	2.2	2.5	2.9	3.3	3.7	4.1	4.6	5.2	6.0	6.9
Middle East	18.4	17.6	17.2	16.9	17.1	17.0	17.0	16.9	16.9	16.9	16.8
Latin America	12.1	12.9	14.2	15.5	17.0	18.1	19.5	21.3	23.4	25.6	28.1
Africa	2.8	2.9	3.0	3.2	3.4	3.5	3.6	3.7	3.8	3.9	4.1
TOTAL - All Regions	12.8	13.1	13.7	14.3	14.9	15.3	15.9	16.5	17.2	18.0	18.9

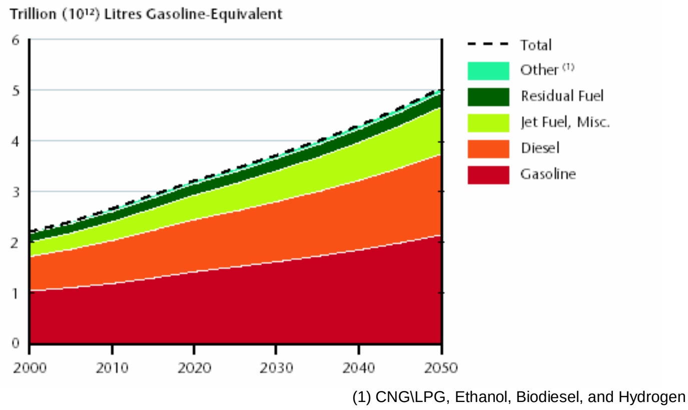
Population (millions)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	405.3	426.4	446.5	466.3	485.9	504.5	521.4	537.1	552.8	568.5	584.1
OECD Europe	513.9	519.7	523.0	524.8	525.8	525.6	523.6	509.1	494.7	480.3	465.9
OECD Pacific	197.2	200.8	203.4	204.7	204.8	204.2	202.9	200.1	197.3	194.5	191.7
FSU	254.0	252.0	250.9	250.5	249.9	248.3	245.9	246.5	247.1	247.7	248.4
Eastern Europe	99.5	96.4	93.4	90.5	87.6	84.5	81.4	82.2	83.0	83.9	84.7
China	1271.7	1317.8	1362.5	1406.4	1442.2	1466.9	1480.9	1478.7	1476.6	1474.4	1472.2
Other Asia	891.3	967.4	1042.9	1118.8	1193.6	1265.1	1330.3	1400.5	1470.8	1541.0	1611.2
India	1013.9	1088.6	1164.0	1230.5	1291.3	1351.8	1408.9	1449.7	1490.5	1531.3	1572.1
Middle East	167.5	192.1	218.1	245.0	271.7	299.5	327.3	353.3	379.3	405.3	431.2
Latin America	415.2	446.1	476.6	506.1	534.2	560.2	584.2	603.1	622.0	640.9	659.8
Africa	793.6	891.7	997.0	1110.0	1231.0	1358.1	1488.9	1616.9	1744.9	1872.8	2000.8
Total	6023.1	6398.9	6778.2	7153.7	7518.0	7868.8	8195.8	8477.4	8759.0	9040.6	9322.2

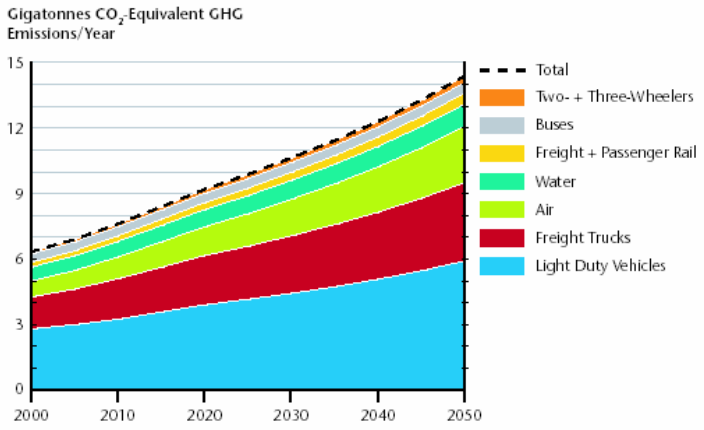

Total diesel fuel use per capita
GJ
25.0
20.0
15.0
10.0
5.0
0.0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050


Total energy use per capita
GJ
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
OECD North America
OECD Europe
OECD Pacific
FSU
Eastern Europe
China
Other Asia
India
Middle East
Latin America
Africa
World average

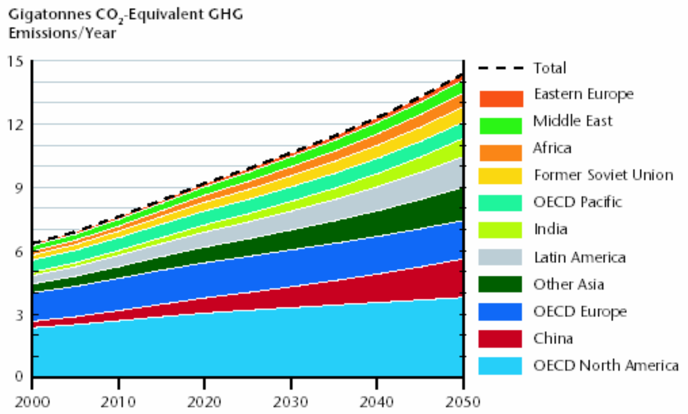
Appendix C: Global projections for transport fuels and emissions [25].



Worldwide transport-related fuel use – all transport modes.

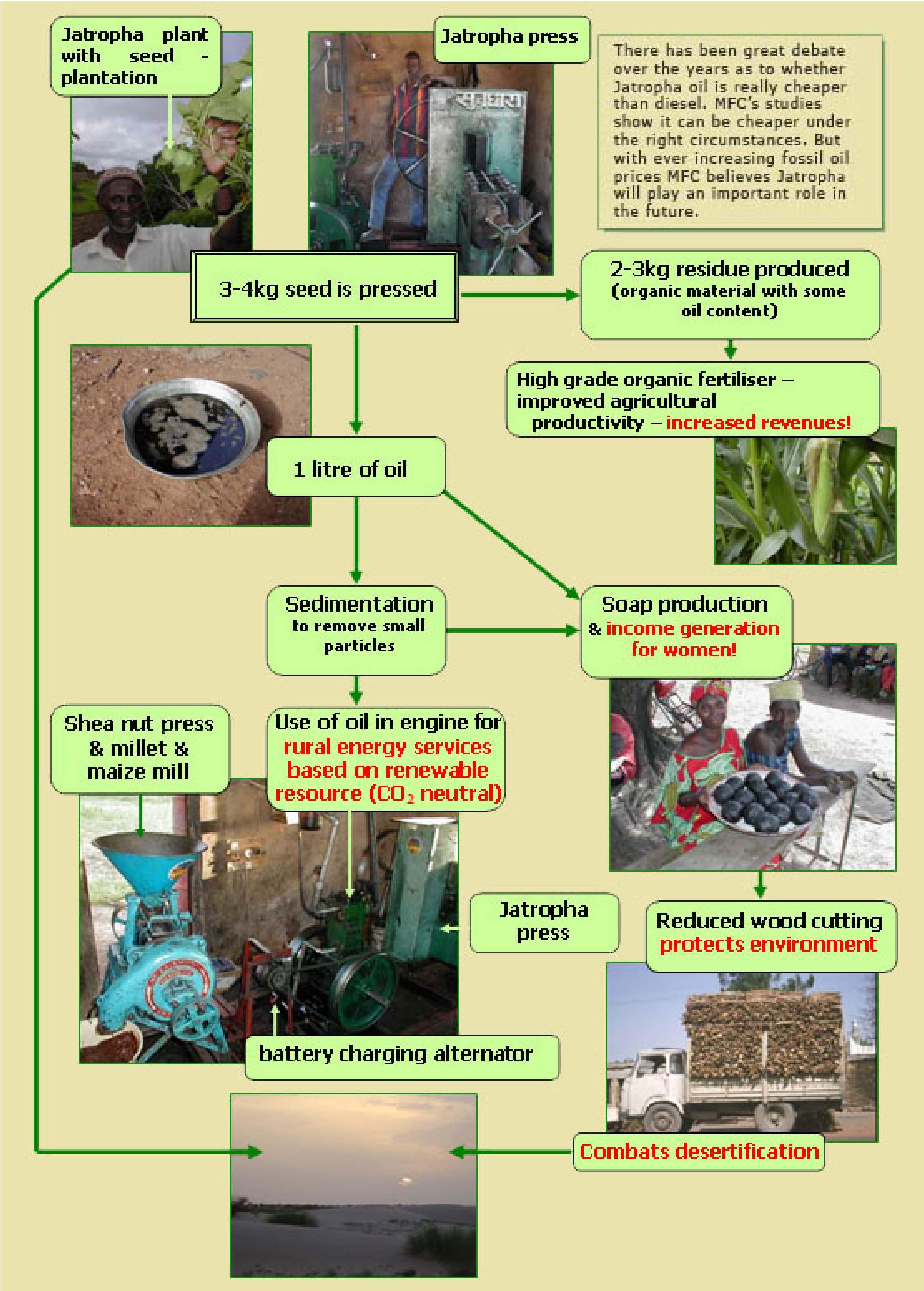


Transport-related Well-To-Wheels CO_2 emissions by mode



Transport-related Well-To-Wheels CO_2 emissions by region

Appendix D: Jatropha pressing scheme (Source: Malifolkecenter)



Appendix E: Jatropha oil analysis results

Title:	Jatropha oil
Archive Number:	D1278F

Analyse	Result
Acid value (mg KOH / gram).	1.8
Saponification value (mg KOH / gram).	192
Iodine value (g I / 100gram)	105
Water content (%)	0.11
Phosphor (mg/kg)	9
Lecithine (mg/kg)	9

Fatty acid composition (GC)

	RESULT
C14	0.1
C16	14.9
C16:1	1.0
C17	0.1
C18	5.8
C18:1	37.6
C18:2	39.6
C18:3	0.2
C20	0.2
C20:1	0.1
>C22	0.3

	RESULT
jg	107.5

Appendix F: Synthesis method of Jatropha Methyl Ester from Jatropha Oil

Requirements:
For 5 liters of biodiesel , approximately 8 liter of Jatropha Oil is needed.
2 liters of methanol in which 80 grams of NaOH is dissolved.

1. Make a solution of 40 grams per liter NaOH in methanol. Make sure you solute it slowly, since heat is released with the process.

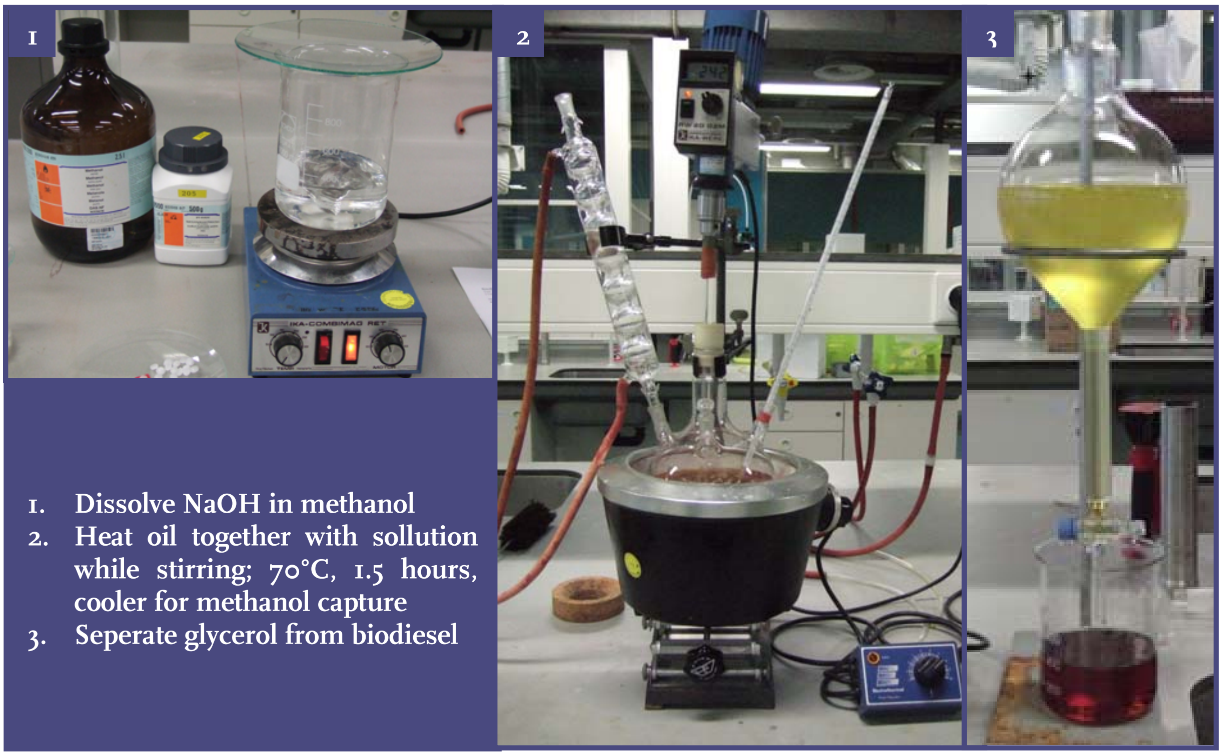
2. Make a reflux set-up with a flask of 2 liter in a heating mantle.

   Add 1 liter of Jatropha-oil in the flask and 260 ml methanol with soluted in it the NaOH.
   Add a stirring rod and place everything at the bottom of the mantle.
   Place the cooler and turn it on.
   Stir strongly and heat the substance up till 70˚C.
   Let the unit react for 90 minutes at 70˚C

3. Remove the cooler and let the content of the flask cool outside the mantle. Pore everything into the disperce funnel and leave it some time until two layers appear. Then draw the glycerin layer off.

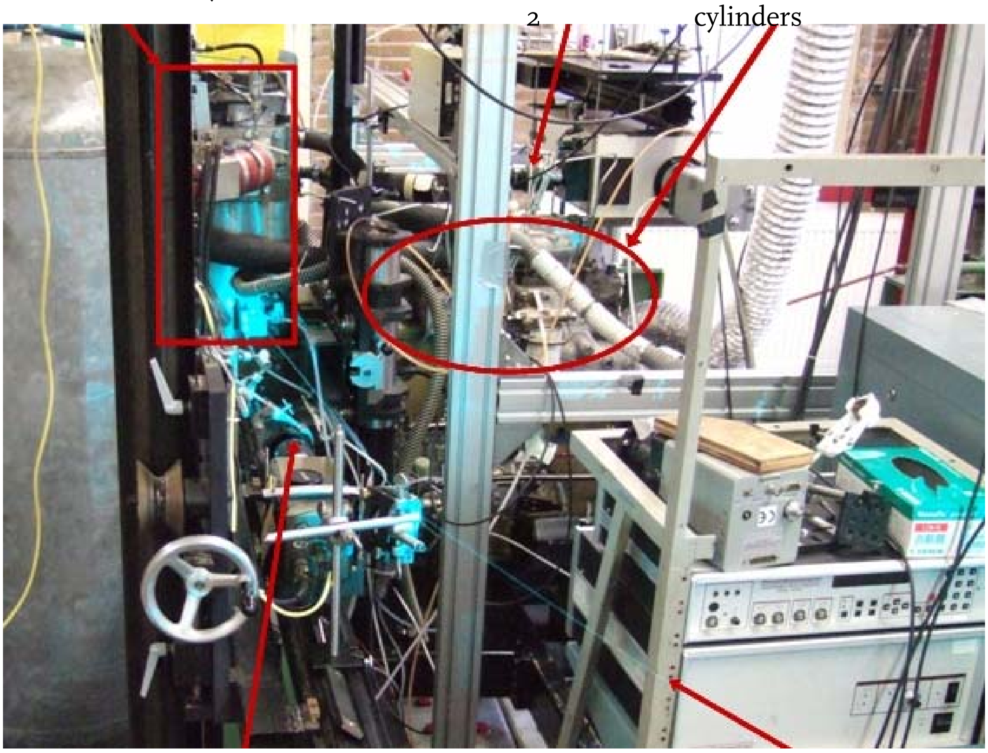
Picture of the esterification set-up

Graphics of the proces steps



Appendix G Engine set-up

Measurement cylinder
Camera 2
Three cylinders
unmodified



Camera 1
Laser beam

Appendix H: Specifications of TOTAL diesel 2005

This Diesel is used as reference diesel during the experiments.

TOTAL DIESEL 2005 LAAGZWAVELIG

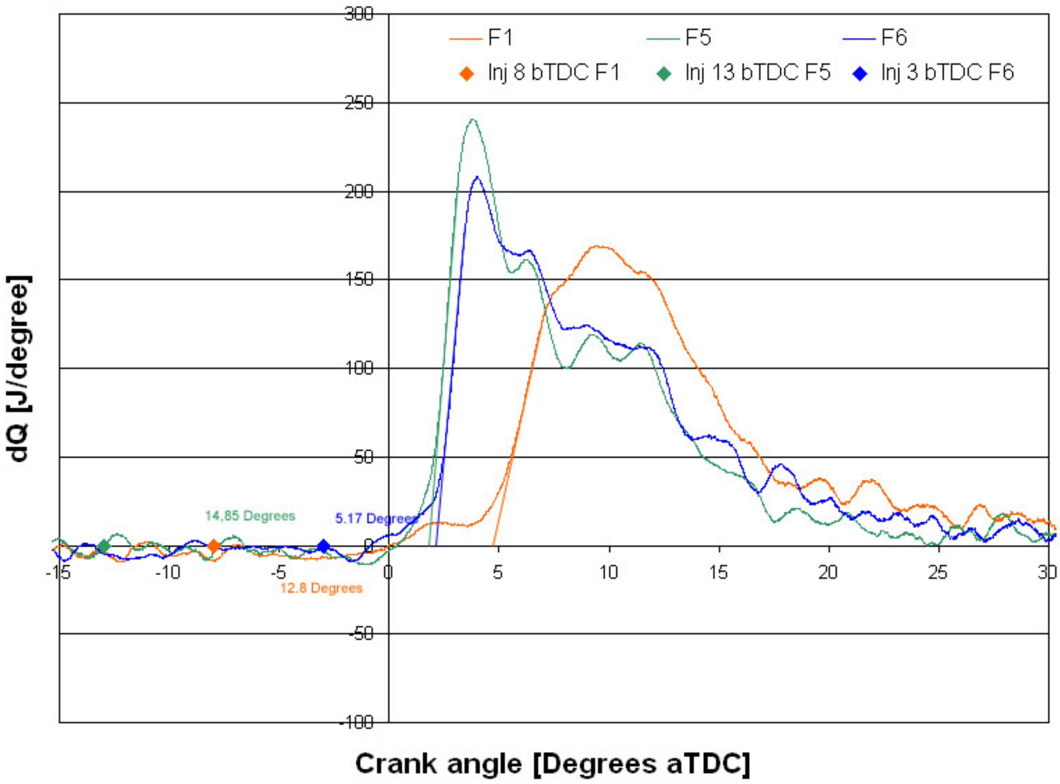
Productspecificatieblad

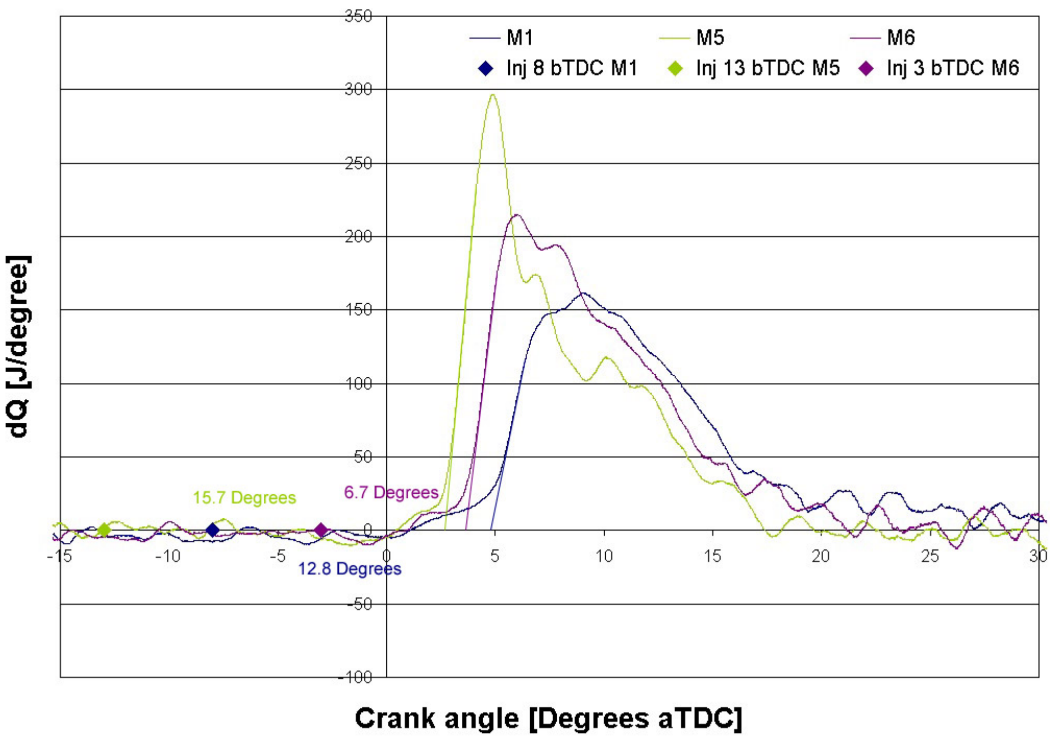
TOTAL

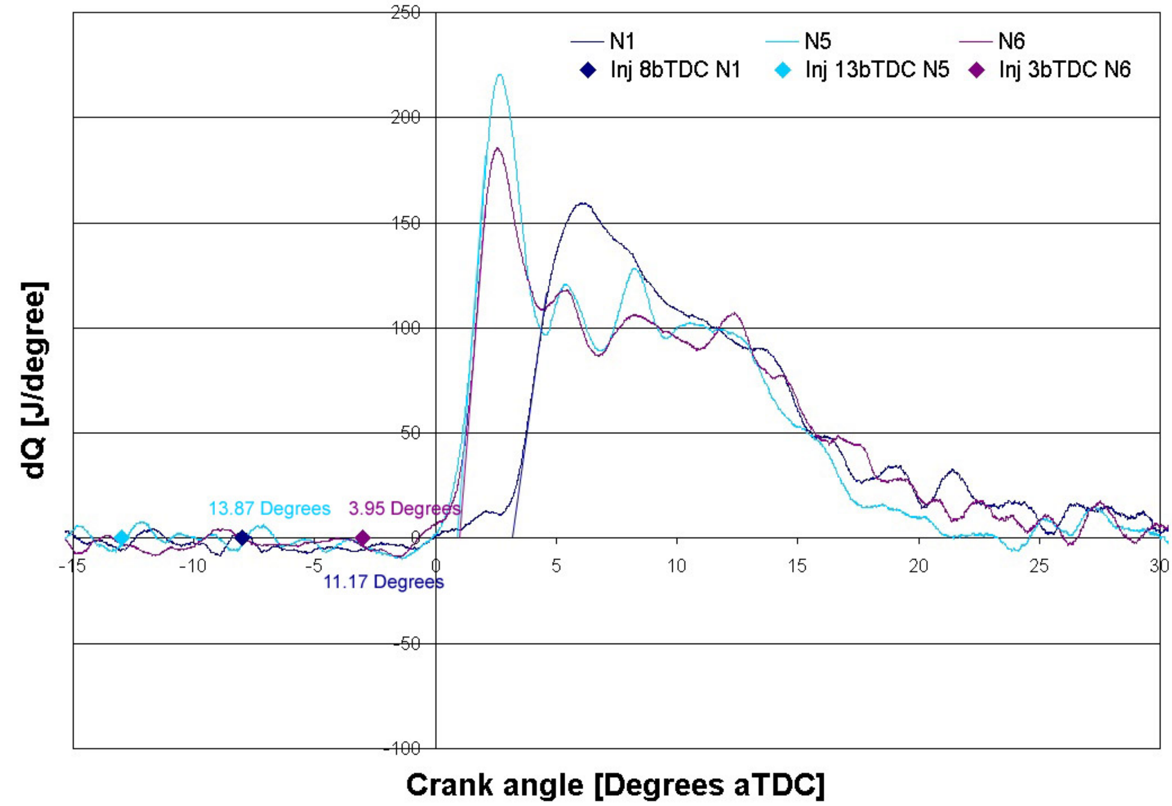
Diesel

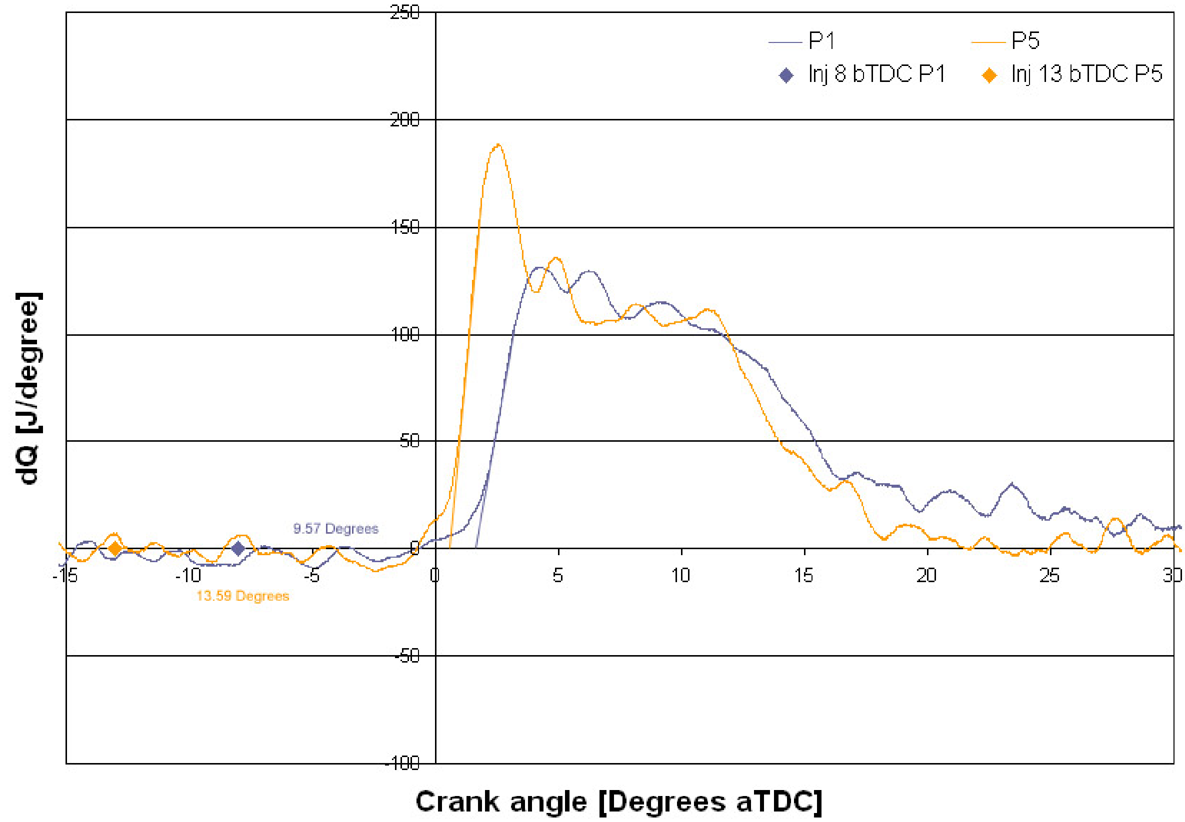
ANALYSECIJFERS	Testmethode	Eenheid	Minimum		Maximum
Uiterlijk	Visueel			Helder en doorzichtig	
Dichtheid bij 15 °C	EN 12185	kg/m^3	820		845
Troebelpunt (cloudpoint)	ASTM D 5771				
Zomerkwaliteit		°C			+2
Intermediate		°C			0
Winterkwaliteit		°C			-7
Temperatuurgrens voor filtreerbaarheid (C.F.P.P. = Cold Filter Plugging Point)	EN 116				
Zomerkwaliteit		°C			-6
Intermediate		°C			-11
Winterkwaliteit		°C			-20
Cetaanindex	EN 4264		48.0		
Cetaangetal	EN 5165		51,0		
Vlampunt Pensky Martens	EN 22719	°C	56		
Kin. viscositeit bij 40 °C	ISO 3104		2,00		4,50
Corrosie test	ASTM D 130				1b
Watergehalte	ASTM D 6304	mg/kg			200
Zwavelgehalte	ASTM D 2622	ppm gew.			50
Destillatie	pr EN 3405				
Verdampt bij 250 °C		% vol.			64
Verdampt bij 350 °C		% vol.	85		
Verdampt bij 360 °C		% vol.	95		
Wear Scar	ISO12156-1	μm			460

Appendix I: Ignition delay from heat release curves for all engine settings






N1
N5
N6
Inj 8bTDC N1
Inj 13bTDC N5
Inj 3bTDC N6
13.87 Degrees
3.95 Degrees
11.17 Degrees
dQ [J/degree]
Crank angle [Degrees aTDC]


P1
P5
Inj 8 bTDC P1
Inj 13 bTDC P5
9.57 Degrees
13.59 Degrees
dQ [J/degree]
Crank angle [Degrees aTDC]