

# Renewable Fuels for Cross Border Transportation

## ANNEX 4: Module sheets for vehicle technologies

### Overview:

Road Traffic (R)			
Piston Engine			
<b>C4R1</b>	Conventional	<b>C4R2</b>	Biodiesel
<b>C4R3</b>	Methanol	<b>C4R4</b>	Ethanol
<b>C4R5</b>	Methane gas	<b>C4R6</b>	Hydrogen
Other Combustion Engines			
<b>C4R7</b>	Gas turbine	<b>C4R8</b>	Steam engine
<b>C4R9</b>	Stirling engine		
Electric Propulsion			
<b>C4R10</b>	Battery	<b>C4R11</b>	GH <sub>2</sub> based fuel cell
<b>C4R12</b>	LH <sub>2</sub> based fuel cell	<b>C4R13</b>	Methanol based fuel cell
<b>C4R14</b>	Petrol based fuel cell		

Air Traffic (A)			
Jet Engine			
<b>C4A1</b>	Kerosene	<b>C4A2</b>	Hydrogen

Railway (T)			
Piston Engine			
<b>C4T1</b>	Conventional	<b>C4T2</b>	Biodiesel
<b>C4T3</b>	Methane Gas		
Other Combustion Engines			
<b>C4T4</b>	Gas Turbine		
Electric Propulsion			
<b>C4T5</b>	Fuel cell hydrogen	<b>C4T6</b>	Battery
<b>C4T7</b>	Fuel cell methanol		

Shipping (S)			
Piston Engine			
<b>C4S1</b>	Conventional	<b>C4S2</b>	Biodiesel
<b>C4S3</b>	Methane gas	<b>C4S4</b>	Hydrogen
Other Combustion Engines			
<b>C4S5</b>	Gas turbine		
Electric Propulsion			
<b>C4S6</b>	Fuel cell hydrogen	<b>C4S7</b>	Fuel cell methanol

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<b>No.:</b>	C4-R1	<b>Road Traffic - Piston Engine - Conventional</b>
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Class	4	Input from:	C3T5, C3P3
Category	Road Traffic	Output to:	-

**General description of the process**

All over the world, conventional combustion engines are mostly used in road traffic. This technology is standardized and well engineered. In general, there are two different types of drives in use: The petrol engine and the diesel engine. Most passenger cars run with petrol, but the use of diesel engines is growing. Long distance motorcycles have petrol engines with a similar engines but a rather low driving performance compared with cars. They are not considered in this study. Lorries and buses run with diesel all over Europe.

The reasons why these conventional engine concepts are so widely spread are the easy handling, the range, the supply guarantee, and the relatively low costs for the vehicles, the fuel and the infrastructure. The disadvantage of the conventional piston engines is its emission of pollutants. The emissions arise during the burning process in the spark-ignition engine. The main problem of these fossil fuels is the generation of the green-house gas carbon dioxide (CO<sub>2</sub>). Additionally, the following exhaust gases are generated:

- Carbon monoxide (CO), a toxic gas, is formed especially during idling, transforms into CO<sub>2</sub> in a short period of time
- Nitrogen monoxide (NO) reacts with the ambient air to form nitrogen dioxide (NO<sub>2</sub>). This gas produces irritations of the mucous membrane. These two substances are defined as nitrogen oxides (NO<sub>x</sub>).
- Hydrocarbons (HC) are part of the exhaust gas in a variety of forms beginning with small intermediate reaction productions to fuel components with a high molecular weight.
- Solid substances, particles.

To lower these emissions, the EU has initiated legal measures. Several norms for the limitation of exhaust fumes have been created, the so called "Euro norms". The present one is Euro 3. To decrease the emissions the catalytic converter was introduced which reduce CO, HC and NO<sub>x</sub>.

An other possibility to diminish emissions is to optimise the engine technology and the combustion process. There exists the trend to implement the technology of the direct injection into the spark-ignition engine, what will lead to synergies with respect to the engines running with conventional fuels.

**Regional specifications in the EU**

The basic technique and the exhaust fume norms are the same in all EU-countries. Indeed there are single climatic differences, which can have influence over the motor technology and the use of special fuels. Beyond it the vehicle armada regarding the age and the size is different in the particular countries.

### **Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Technologies reaching production now or within the next two decades, such as optimised and variable compression ratio, variable and optimised cooling rates at different operation conditions, variable valve timing or reduced mechanical friction losses, will enable the auto-industry to progressively improve the thermal efficiency for diesel and spark ignited engines over the next two decades.

Direct injection and downsizing will increase the efficiency of petrol engines and will lead to lower fuel consumption. Further developments are charge dilution and alternative load control strategies. The introduction of particle filter will decrease the emissions of particles from diesel engines.

From 2005 on the Euro 4 norm reduces the exhaust fumes limits for both automobiles and heavy vehicles, in 2008 Euro 5 enforces again the limits for the heavy vehicles.

For a long-term forecast there are only few data available. [DriWefa and Arthur D. Little: Future Powertrain Technologies; Lexington, Cambridge 2001] provides a forecast until the year 2020. Accordingly for cars the Euro 5 will reduce by 2012 the exhaust fumes limits for HC, CO and NO<sub>x</sub> to 50 % of Euro 4, and Euro 6 by 2018 will decrease the limits to 50 % of Euro 5. In 2008 a car will emit 120 g CO<sub>2</sub>/km, in 2012 90 g CO<sub>2</sub>/km. By 2010 0.013 g particles/km will be emitted, by 2015 the emission of particles will be 0.010 g/km. According to the technical progress the emission aims will surely be state of art for the whole vehicle armada in the year 2030.

### **Internal and external resources**

BERATERGRUPPE FÜR VERKEHR UND UMWELT GMBH (BVU); INSTITUT FÜR WIRTSCHAFTSFORSCHUNG (IFO); PLANCO; ITP: Traffic forecast 2015, by order of the Federal Ministry for Traffic, Construction and Housing, München; Freiburg; Essen, 2001

DRIWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

EWS: Empfehlung für Wirtschaftlichkeitsuntersuchungen an Straßen (Draft), Aktualisierung der RAS-W 86, 1997 – FORSCHUNGSGESELLSCHAFT FÜR STRAßEN- UND VERKEHRSWESEN (FGSV): Kommentar zu den Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen (Draft), Köln, 1997

INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG (IFEU): Emissions- und Immissionsprognosen für den Straßenverkehr in Deutschland – Welche Ziele werden erreicht?, (writer: Höpfner, Ulrich), Lecture „Technischer Kongress des VDA – IAA 2000“, Frankfurt, 2000

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris 1999

STATE INSTITUTE FOR ENVIRONMENTAL PROTECTION BADEN-WÜRTTEMBERG, Germany ([www.lfu.baden-wuerttemberg.de/lfu/abt3/luft/verkehr/abgasgrenzwerte/content.html](http://www.lfu.baden-wuerttemberg.de/lfu/abt3/luft/verkehr/abgasgrenzwerte/content.html))

### **Description of the calculation to obtain the quantitative figures**

#### **Economy figure:**

Costs per km are calculated after [EWS: Empfehlung für Wirtschaftlichkeitsuntersuchungen an Straßen (Entwurf), 1997]. No significant price changes are expected as the technology is well engineered.

#### **Ecology figure:**

The stricter exhaust gas limits given by legislation regularly will advance the motor technology.

For the future development of exhaust gas limits [DriWefa and Arthur D. Little: Future Powertrain Technologies, 2001] worked out scenarios for cars.

#### **Efficiency figure:**

The technological progress in the sector will most certainly lead to a further increase of the efficiency of all engines. The potential for improvements is higher for petrol powered engines than for diesel

engines.

Lorries show less potential than passenger cars because the commercial use of heavy duty vehicles has already led to a very high efficiency in the past.

The input energy is calculated from an average fuel consumption (LDV: petrol 7,5 l/100 km, diesel 6 l/100 km; HDV: diesel: 40 l/100 km) and the energy densities of the fuels.

The efficiency factor is limited through thermodynamic cycles. To obtain further progress the boundary conditions have to be optimised, e.g. an increase of the compression ratio and an increase of the boost pressure or the addition of fuel additives.

<b>Quantitative assessment of the module</b>																												
<b>Output unit:</b>	vehicle km																											
<b>Economy:</b>																												
Costs per output unit	0.10 – 0.15 €																											
<b>Ecology:</b>																												
CO <sub>2</sub> emissions	<p>Average of new passenger car fleet in 2001:            164g (European Manufacturers)            179g (Japanese Manufacturers)</p> <p>The car manufacturers committed with the European Commission to reduce the average CO<sub>2</sub> emissions of new cars to 140g by 2008 or 2009 respectively.</p> <p>CO<sub>2</sub> emissions of long distance lorries vary currently between 890 and 1200g.</p>																											
Emissions of other pollutants	<p>Mandatory tailpipe emission limits, <b>passenger cars</b>, Euro IV (2005):</p> <table border="1" style="margin-left: 40px;"> <thead> <tr> <th>[g/km]</th> <th>NO<sub>x</sub></th> <th>CO</th> <th>HC</th> <th>Particulates</th> </tr> </thead> <tbody> <tr> <td>Petrol</td> <td>0.08</td> <td>1.0</td> <td>0.1</td> <td>-</td> </tr> <tr> <td>Diesel</td> <td>0.3</td> <td>0.5</td> <td>0.1</td> <td>0.025</td> </tr> </tbody> </table> <p>Scenario assumptions from [Dri Wefa and Arthur D. Little: Future Powertrain Technologies, 2001]:            2012: 50 % of Euro IV            2018: 25 % of Euro IV</p> <p>In the future the petrol and diesel emission standards will converge.</p> <p>Mandatory tailpipe emission limits, <b>heavy duty vehicles</b>, Euro V, (2008):</p> <table border="1" style="margin-left: 40px;"> <thead> <tr> <th></th> <th>NO<sub>x</sub></th> <th>CO</th> <th>HC</th> <th>particulates</th> <th>smoke</th> </tr> </thead> <tbody> <tr> <td>[g/kWh]</td> <td>2.0</td> <td>1.5</td> <td>0.46</td> <td>0.02</td> <td>0.5 m<sup>-1</sup></td> </tr> </tbody> </table> <p>An average lowering of the specific fuel consumption from 2000 to 2020 by 1% per year is assumed.</p>	[g/km]	NO <sub>x</sub>	CO	HC	Particulates	Petrol	0.08	1.0	0.1	-	Diesel	0.3	0.5	0.1	0.025		NO <sub>x</sub>	CO	HC	particulates	smoke	[g/kWh]	2.0	1.5	0.46	0.02	0.5 m <sup>-1</sup>
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[g/kWh]	2.0	1.5	0.46	0.02	0.5 m <sup>-1</sup>																							
<b>Efficiency:</b>																												
Input energy (present state)	LDV Petrol: 241.2 MJ / 100 veh. km Diesel: 205.2 MJ / 100 veh. km HDV Diesel: 1411.2 MJ / 100 veh. km																											
Efficiency factor	From 30 % (petrol engine) to 43 % (diesel engine)																											

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants		x			
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market					x
Hazardousness			x		
Complexity of technique				x	
Standardisation					x

<b>No.:</b>	<b>C4-R2</b>	<b>Road Traffic – Piston Engine on Biodiesel</b>
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Class	4	Input from:	C3T3
Category	Road Traffic	Output to:	-

<b>General description of the process</b>
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Many diesel engines can be powered by biodiesel (e.g. RME = rape methylester, SME = sun flower methylester), provided that this biofuel complies with certain standards. The most common standard is DIN V51606. This standard complies to a great extent with the standards valid in Austria, France, Italy, Sweden, and the Czech Republic. Generally a mixed-fuel operation is also possible. However, if a fuel change is done from fossil diesel to biodiesel the fuel filter should be changed if it had been operating on fossil diesel for a longer period. The reason for this is, that biodiesel is working like a solvent in this case and cleans residues from the tank and from the lines carrying these residues into the filter where they generate congestions. In case of regular combined-fuel operation this measure is obsolete. The solubilizing effect of the biodiesel could lead to the swelling of hoses and seals. To avoid this effect a one-time re-equipment with parts made of fluorine rubber has to be carried out. If the engine had been running under low load for a longer period the motor oil could be thinned out. In this case an oil change would become necessary.

Almost all engine and vehicle manufacturers nowadays offer engines that can operate at least on a mixture containing 5 % RME. There exist flexible-fuel vehicles already that can operate both on biodiesel and on conventional diesel. However it is necessary to consult the lists of the manufacturers on biodiesel suitability as otherwise possible warranty claims would be terminated.

Due to additives the operation temperature during the cold season lies at about –22 ° Celsius.

Biodiesel can be degraded up to 98 during a period of 28 days and is listed in water pollution class 0. Diesel oil is listed in water pollution class 2. For this reason any measures to avoid the leakage of fuel into the environment needn't be as restrictive and cost-intense as it is the case with conventional fuels.

<b>Regional specifications in the EU</b>
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In Austria, Sweden and Germany vehicles run with pure biodiesel, in France biodiesel is added to normal fuel from 5 to 30 % and in Italy normal fuel is blended with 5 % biodiesel.

<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
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Like diesel engine.

<b>Internal and external resources</b>
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DRIWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

EUROPEAN COMMISSION, DIRECTORATE-GENERAL FOR ENERGY, Limited: A Technical Study on Fuels Technology related to the Auto-Oil II Programme – Final Report Volume II: Alternative Fuels, (writer: Arcoumanis; Bechtel), 2000

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris, 1999

EUROPEAN UNION (ED.): Proposal for a Council Directive amending Directive 92/81/EEC with regard to the possibility of applying a reduced rate of excise duty on certain mineral oils containing biofuels and on biofuels', COM 2001, 547 final, in: Official Journal of the European Communities, C149/7

KRÜGER; LIEBSCHER; FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

Information from web pages:

OEHLMÜHLE LEER CONNEMANN GMBH & CO (<http://www.biodiesel.de/schad2.htm>)

BRITISH ASSOCIATION FOR BIO FUELS AND OILS (BABFO) (<http://www.biodiesel.co.uk>)

**Description of the calculation to obtain the quantitative figures**

**Economy figure:**

Most new-built diesel vehicles can operate on biodiesel today without any special equipment. As the costs are comparable to those of conventional diesel engines the data of conventional piston engine can be used.

**Ecology figure:**

Numbers for the present state from [International Energy Agency IEA: Automotive Fuels for the Future – The Search for Alternatives, 1999]

While the emissions of NO<sub>x</sub> increase by approx. 12 % for **direct injection engines** and by 8 % for **chamber-engines**, the emissions of CO decrease by 10 respectively 12 %, the emissions of hydrocarbons by 10 respectively 35 % and for PM by 24 respectively 36 % and for soot by 52 respectively 50 %. This is a result of the fact that the biodiesel molecule contains 11 % of bounded oxygen. This oxygen can also be used for combustion along with the oxygen in the air.

Biodiesel has to fulfil the Euro exhaust gas limits. For the future development of exhaust gas limits [Dri Wefa and Arthur D. Little: Future Powertrain Technologies, 2001] made scenarios for cars.

**Efficiency figure:**

Operating an engine on biodiesel might lead to an increase of the fuel consumption by up to 15 %.

**Quantitative assessment of the module for the present state**

<b>Output unit:</b>													
<b>Economy:</b>													
Costs (€) per output unit	Same as piston engine on diesel												
<b>Ecology:</b>													
Emission of CO <sub>2</sub> (g/km)	LDV: 80 – 280 (156) HDV: 1020 – 1060 (1040)												
Emissions of other pollutants (g/km)	<table border="1"> <thead> <tr> <th></th> <th>NO<sub>x</sub></th> <th>CO</th> <th>HC</th> </tr> </thead> <tbody> <tr> <td>LDV</td> <td>1.10</td> <td>0.75</td> <td>0.23</td> </tr> <tr> <td>HDV</td> <td>15.9 – 17.3</td> <td>1.6 – 2.4</td> <td>0.36 – 0.43</td> </tr> </tbody> </table> <p>Particles: LDV 0.17 HDV 0.74</p> <p>The biodiesel vehicles have to fulfil the emission limits. So the emissions will decrease.</p>		NO <sub>x</sub>	CO	HC	LDV	1.10	0.75	0.23	HDV	15.9 – 17.3	1.6 – 2.4	0.36 – 0.43
	NO <sub>x</sub>	CO	HC										
LDV	1.10	0.75	0.23										
HDV	15.9 – 17.3	1.6 – 2.4	0.36 – 0.43										
<b>Efficiency:</b>													
Input energy	LDV: 223.2MJ / 100 veh. km HDV: 1489.0 MJ / 100 veh. km												
Efficiency factor	from 35 % to 43 %												

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants		x			
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market					x
Hazardousness				x	
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	<b>C4-R3</b>	<b>Road Traffic – Piston Engine on Methanol</b>
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Class	4	Input from:	C3T1
Category	Road Traffic	Output to:	-

**General description of the process**

The most common alcohol to be used as a fuel in Europe is methanol. There are two ways to obtain methanol: It can be easily extracted from fossil energy carriers with intermediate or long-term availability such as coal and natural gas and it can also be produced from wood or waste. Although methanol is a toxic substance the hazard level is the same as for petrol. The calorific value of methanol of 20 MJ/kg is about half the calorific value of conventional fuels. If the considerably higher pre-ignition resistance is used to increase the compression ratio this disadvantage can be turned over into an advantage with respect to the performance of the engine in comparison to the one of a spark-ignition engine powered by petrol.

Because of the strong corrosive effect of methanol, improvements must be made with respect to materials on spark-ignition engines used by now. There exist already vehicles that are running on a petrol-methanol blend of M0 to M85 (Mx: M means share of methanol, x = percentual value). Blend rates of M15 to M90 are prospected. By using solubilizers for diesel engines the blends could contain even 30 % of methanol. If the percentage of methanol is higher, a striking aid must be added to keep the auto-ignition going. This way the performance of the diesel engines will be reduced as well as the efficiency, but on the other hand the release of emissions decreases.

In order to be able to use fuels with a higher percentage of methanol the suction pipe initiation and the pilot ignition procedure have been developed. The pilot injection procedure brought good results so far. The methanol is injected into the piston shortly before the maximum compression is achieved. Vehicles powered by petrol have considerably higher emissions of NO<sub>x</sub>, CO und VOC than vehicles operating on methanol. In addition methanol engines generate only a small quantity of aromatic compounds. This is leading to a reduction of the impact of the ozone. A negative aspect is that methanol powered engines release large quantities of formaldehyde during a cold start. This problem can be avoided by using cold start catalysts.

If methanol is produced from biomass the CO<sub>2</sub>-balance is a fairly good one. The balance depends on what kinds of energies are used for distillation and for the transport to the end-user. If CO<sub>2</sub>-neutral energy carriers are used, the CO<sub>2</sub>-balance will be good. The same quantity of CO<sub>2</sub> that is released during combustion will be converted into O<sub>2</sub> during plant growth (C is stored in the plant).

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

The disadvantages of methanol's cost of infrastructure will continue to be show-stoppers through the 2008 to 2020 period, except for the niche reciprocation engine vehicle markets. Almost the whole methanol is produced from natural gas and will probably continue to be for the next 20 years. Only when the oil price raise to the point where natural gas-derived methanol is competitive with oil, methanol will be a serious option for passenger cars.

With respect to the long-term development of engines running on methanol it can be expected that the problems that occur currently will be solved and that the emission limits will be kept.

### Internal and external resources

DRIWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris 1999

EUROPEAN COMMISSION, DIRECTORATE-GENERAL FOR ENERGY, Limited: A Technical Study on Fuels Technology related to the Auto-Oil II Programme – Final Report Volume II: Alternative Fuels, (writer: Arcoumanis; Bechtel), 2000

EUROPEAN UNION (ED.): Proposal for a Council Directive amending Directive 92/81/EEC with regard to the possibility of applying a reduced rate of excise duty on certain mineral oils containing biofuels and on biofuels', COM 2001, 547 final, in: Official Journal of the European Communities, C149/7

KRÜGER; LIEBSCHER; FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

ORGANIZATION FOR PROMOTION OF LOW EMISSION VEHICLES ([www.levo.or.jp](http://www.levo.or.jp))

METHANEX ([www.methanex.com](http://www.methanex.com))

### Description of the calculation to obtain the quantitative figures

**Economy figure:** Running on methanol the engine needs some modifications, because methanol is more corrosive than petrol. All materials that contact methanol have to be more corrosion resistant than those materials in normal spark ignition engines.

**Ecology figure:** The emissions of NO<sub>x</sub>, CO and VOC are lower than for a petrol engine. Data from [International Energy Agency IEA: Automotive Fuels for the Future – The Search for Alternatives, 1999].

**Efficiency figure:** Methanol has a lower energy density than petrol or ethanol, but a higher pre-ignition resistance.

### Quantitative assessment of the module for the present state

<b>Output unit:</b>	vehicle km				
<b>Economy:</b>					
Costs per output unit (€)	0.24				
<b>Ecology:</b>					
Emission of CO <sub>2</sub> (g)	LDV: 177 HDV: 810 – 960				
Emissions of other pollutants (g/km)			NO <sub>x</sub>	CO	HC
	Methanol	LDV	0.24 – 0.30	2.87 – 4.15	0.36 – 0.65
		HDV	6.5 – 7.5	1.94 – 9.60	0.27 – 2.76
	Particles: HDV: 0.21				
<b>Efficiency:</b>					
Input energy	LDV: 233 MJ / 100 veh. km				
Efficiency factor	approx. 31 %				

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption		x			
Release CO <sub>2</sub>		x			
Emissions of other pollutants				x	
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market				x	
Hazardousness			x		
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	<b>C4-R4</b>	<b>Road Traffic – Piston Engine on Ethanol</b>
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Class	4	Input from:	C3T2
Category	Road Traffic	Output to:	-

**General description of the process**

The properties of ethanol are quite similar to methanol. Ethanol is usually made of biomass, crop, starch or cellulose material.

Today ethanol in vehicles is mainly used in Brazil. It covers a considerable share of the fuel demand. Another big consumer of ethanol are the USA. Ethanol can be used pure or as a blend. From a certain share of ethanol (about 25 %) a modification of the vehicle is required. Popular is the blend of 90 % petrol and 10 % ethanol which is called “E10”. Higher blends are possible as well, e.g. E85. As another positive impact of ethanol is that ethanol adds additional oxygen to the petrol, which helps for a better combustion. This leads to lower emissions.

The energy density of ethanol is higher than that of methanol, but it is lower compared with petrol or diesel. Therefore on-board storage of ethanol needs a larger and thus heavier tank to provide an amount of energy equivalent to petrol.

Ethanol can also be used in modified diesel engines of heavy duty vehicles. Compared to a conventional diesel vehicle the emissions of HC can be reduced up to 40%. But thereby the motor capacity decreases.

The amount of space for fuel crops in Europe is limited. This means that only a small part of the conventional fuel can be replaced by bioethanol.

**Regional specifications in the EU**

Because of volatilisation the use of pure ethanol is problematic in the warm regions in southern Europe.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Ethanol will always have a place in niche markets close to biomass production and where social incentives exist, but its disadvantages will continue to outweigh its advantages for widespread usage, and ethanol will only make moderate gains in market share in the 2008 to 2020 timeframe.

As there do not occur any crucial technical problems with ethanol for piston engines today, it can be assumed that for the long-term perspective the technical feasibility is given to keep all emission limits.

**Internal and external resources**

THE OIL COMPANIES’ EUROPEAN ORGANIZATION FOR ENVIRONMENT, HEALTH AND SAFETY (CONCAWE): Energy and Greenhouse Gas Balance of Biofuels for Europe – an Update, Brussels, 2002

DRIFWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

EUROPEAN COMMISSION, DIRECTORATE-GENERAL FOR ENERGY, Limited: A Technical Study on Fuels Technology related to the Auto-Oil II Programme – Final Report Volume II: Alternative Fuels, (writer: Arcoumanis; Bechtel), 2000

EUROPEAN PARLIAMENT: Bioethanolbeimengung zu Kraftstoff, (writer: Oestling, A.; Chambers, G.) Themepaper No. 07/2001, Luxembourg, Brussels, 2001

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris, 1999

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KRÜGER; LIEBSCHER; FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

U.S. DEPARTMENT OF ENERGY: Guidebook for Handling, Storing & Dispensing Fuel Ethanol, Arlington

THE EUROPEAN ASSOCIATION FOR RENEWABLE ENERGIES E.V. (www.eurosolar.org)

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

A spark ignition engine operating with a blend of ethanol and petrol is state of the art.

#### **Ecology figure:**

The emissions of NO<sub>x</sub>, CO and VOC are lower than in a petrol engine. (Data from [INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris, 1999])

#### **Efficiency figure:**

1500 l of ethanol are needed to substitute 1000 l petrol [www.eurosolar.org]. With the energy density an input energy can be calculated. Running a diesel bus on ethanol/petrol mixture decreases the efficiency factor.

### Quantitative assessment of the module for the present state

<b>Output unit:</b>	vehicle km				
<b>Economy:</b>					
Costs per output unit (€)	0.23				
<b>Ecology:</b>					
Emission of CO <sub>2</sub> (g)	LDV: 200 HDV: 830 – 1000				
Emissions of other pollutants (g/km)			NO <sub>x</sub>	CO	HC
	Ethanol	LDV	0.10	1.66	0.45
		HDV	12.2 – 13.5	2.57 – 9.60	0.63 – 0.65
	Particles: HDV 0.21				
<b>Efficiency:</b>					
Input energy (MJ)	LDV: 240.5 per 100 veh. km				

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption		x			
Release CO <sub>2</sub>		x			
Emissions of other pollutants			x		
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market				x	
Hazardousness			x		
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	<b>C4-R5</b>	<b>Road Traffic – Piston Engine on Methane Gas</b>
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Class	4	Input from:	C3T4, C3P2
Category	Road Traffic	Output to:	-

**General description of the process**

A vehicle running on natural gas (over 80 % CH<sub>4</sub>) reaches performances comparable to those of a vehicle running on conventional fuels. Natural gas is stored in two states of aggregation: in liquid form (LNG = Liquefied Natural Gas), or as a gas under a pressure of 200 bar (CNG = Compressed Natural Gas). At present the CNG is the preferred storage alternative in Europe. For this reason the range of the vehicles running CNG is considerably reduced although they are invested with high-volume tanks. Replacing the commonly used pure steel gas cylinders under pressure by composite cylinders can diminish this disadvantage. The weight of these composite cylinders is about 50 % the weight of the pure steel cylinders. In unary operation buses equipped with a volume of 560 l CNG achieved ranges between 280 and 320 km. A passenger car equipped with 80 l CNG covers distances between 200 and 260 km.

The limited range and also the fact that the dimension of the network of filling stations for natural gas is far away from the dimension of the network for conventional fuels lead to the bivalent operation. For this kind of operation the vehicle is equipped with two kinds of storage devices and the engine can run alternatively both on natural gas and petrol. As natural gas has a very high pre-ignition resistance the operation on natural gas requires a spark-ignition engine as the ignition has to be done externally.

As a result of the high pre-ignition resistance of methane in unary operation on natural gas the efficiency of the engine could be considerably improved by increasing the compression ratio. In this case the option for an operation on a second kind of fuel would foil any kind of advantages with respect to consumption and emissions.

For this reason the unary operation is the appropriate option. As the gas supplier adds different doses of liquid gas in dependence of the season an engine running on natural gas must be invested with the capacity to automatically adjust its operation with respect to the control of ignition timing, pre-ignition control, load and air ratio. Vehicles running on natural gas emit 20 % less specific CO<sub>2</sub> emissions than vehicles running on diesel. Utility vehicles don't profit from this advantage as the energetic demand is by 20 to 25 % higher due to the higher weight of the tank, a reduction of the efficiency in the part-load sector and a reduction of the compression ratio.

Natural gas is a suitable fuel for power generation, on-site power, and residential uses. These applications do not have the inherent hurdles that CNG faces for passenger car usage, namely the lack of infrastructure and reduced range.

**Regional specifications in the EU**

The gas vehicles have not yet been introduced in every country of the EU. Italy has with 400,000 vehicles the most gas vehicles in the EU. For comparison in Germany there drive only 13,000 gas vehicles. The development is dependent on the number of refilling stations.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Absent major oil price hikes, however, for the period between 2008 and 2020, CNG is expected to continue in its niche fleet applications, because the driving forces to overcome the expensive infrastructure challenges will not have materialized. If oil prices rose sufficiently, CNG would experience significant LDV growth, mainly in fleet vehicles (perhaps 1 to 3 % of vehicle sales).

### Internal and external resources

DRI WEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris, 1999

KRÜGER, LIEBSCHER, FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

AKADEMIE FÜR TECHNIKFOLGENABSCHÄTZUNG IN BADEN-WÜRTTEMBERG (ED.): Art und Menge von stofflichen Emissionen aus dem Verkehrsbereich, (writer: Wiedmann, T.; Kersten, J.; Ballschmitter, K.), Arbeitsbericht Nr. 146, , Stuttgart, 2000

BUNDESVERBAND DER DEUTSCHEN GAS- UND WASSERWIRTSCHAFT  
([http://www.bundesverband-gas-und-wasser.de/publik/aktuelles/erdgas\\_auto3.htm](http://www.bundesverband-gas-und-wasser.de/publik/aktuelles/erdgas_auto3.htm))

ADAM OPEL AG (<http://www.opel.de/showroom/zafira>)

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

Additional costs of CNG-vehicles compared with petrol car and diesel bus

	2005	2010
CNG-car	1000 €	750 €
CNG-bus	17500 €	12500 €

#### **Ecology figure:**

A CNG-vehicle has up to 90% lower NMVOC emissions but high NO<sub>x</sub> emissions. Also possible is an emission of unburnt methane. But several studies documented that for the climate protection CNG-vehicles are better than conventional petrol or diesel vehicles.

Data form [DRI WEFA and Arthur D Little: Future Powertrain Technologies, Lexington; Cambridge, 2001]

#### **Efficiency figure:**

Natural gas has a higher knock resistance than conventional fuel what leads to a higher motor efficiency factor.

Quantitative assessment of the module for the present state													
<b>Output unit:</b>	vehicle km												
<b>Economy:</b>													
Costs per output unit	n/a												
<b>Ecology:</b>													
Emission of CO <sub>2</sub> (g/km)	LDV: 64 – 224 (151) HDV: 870 – 1030 (950)												
Emissions of other pollutants (g/km)	<table border="1"> <thead> <tr> <th></th> <th>NO<sub>x</sub></th> <th>CO</th> <th>HC</th> </tr> </thead> <tbody> <tr> <td>LDV</td> <td>0.2 – 0.3</td> <td>0.95 – 1.04</td> <td>0.34 – 0.58</td> </tr> <tr> <td>HDV</td> <td>2.3 – 5.1</td> <td>2.4 – 14.9</td> <td>0.68 – 2.91</td> </tr> </tbody> </table> Particles: HDV 0.17		NO <sub>x</sub>	CO	HC	LDV	0.2 – 0.3	0.95 – 1.04	0.34 – 0.58	HDV	2.3 – 5.1	2.4 – 14.9	0.68 – 2.91
	NO <sub>x</sub>	CO	HC										
LDV	0.2 – 0.3	0.95 – 1.04	0.34 – 0.58										
HDV	2.3 – 5.1	2.4 – 14.9	0.68 – 2.91										
<b>Efficiency:</b>													
Input energy	7.2 MJ/l												
Efficiency factor	Stoichiometric combustion: 34-36% Lean fuel-air ratio combustion: 37-41%												

Qualitative assessment of the module for the present state					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>			x		
Emissions of other pollutants				x	
Emissions of noise				x	
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure				x	
<b>Other indicators</b>					
Readiness for market					x
Hazardousness			x		
Complexity of technique				x	
Standardisation					x

<b>No.:</b>	<b>C4-R6</b>	<b>Road Traffic – Piston Engine on Hydrogen</b>
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Class	4	Input from:	C3P1, C3P2
Category	Road Traffic	Output to:	-

**General description of the process**

Advanced spark-ignition engines can be powered also by hydrogen after small modifications (ignition system, new combustion device). There exist two versions of the combustion.

In case of the simpler alternative the mixture is formed outside the combustion chamber. The problems generated by this version are the backfires into the suction pipe, a high speed of the flame front as well as advanced ignitions and misfires. The problem of the advanced ignitions and misfires can be eliminated by injecting H<sub>2</sub>O into the initial mixture.

The more sophisticated version is to inject the hydrogen directly into the combustion chamber. For this procedure liquid hydrogen is required. The hydrogen is vaporized and the cold gas is transported under high pressure into the combustion chamber. The low temperatures and the poor lubrication features of the liquid fuel are also problematic. As at this temperatures any kind of material is very brittle and every common lubricant is only available in solid the expenditures necessary to activate the liquid hydrogen feed pump and the injection elements are rather high.

Despite of this there exists an interest in engines with internal carburation as they offer an increased performance and a higher engine efficiency.

In 2000 BMW presented the first H<sub>2</sub> prototype, the BMW 750 hL with a 140-litre kyro tank which stores liquid hydrogen at -250°C. Additionally it has a petrol tank to guarantee the fuel supply.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Today some components for the hydrogen piston engine are quite expensive, also the production of hydrogen. Mass-produced vehicles will presumably be available at the earliest by 2004 in a small scale.

For the 2008 to 2020 timeframe, the transition to a hydrogen economy with a complete pipeline infrastructure will not be performed. A change-over into the hydrogen-industry is possible within the next 30 to 50 years when the entire infrastructure is provided.

**Internal and external resources**

DRIWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

INTERNATIONAL ENERGY AGENCY (IEA): Automotive Fuels for the Future – The Search for Alternatives, Paris, 1999

KRÜGER; LIEBSCHER; FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

Information from web pages:

BMW GROUP ([www.bmw.com](http://www.bmw.com))

HYDROGEIT, Der Wasserstoff-Guide ([www.hydrogeit.de](http://www.hydrogeit.de))

KATALYSE E.V; OEKOSERVE GMBH ([www.umweltlexikon-online.de](http://www.umweltlexikon-online.de))

Description of the calculation to obtain the quantitative figures
<p><b><u>Economy figure:</u></b></p> <p>Additional costs for LH<sub>2</sub>-vehicles compared with conventional ones are estimated to 1500 € for cars and for 25000 € for a busses in 2010.</p> <p><b><u>Ecology figure:</u></b></p> <p>A vehicle with a hydrogen piston engine operates CO<sub>2</sub>-free. Therefore only the energy chain leading to the hydrogen is important for the CO<sub>2</sub>-emissions.</p> <p><b><u>Efficiency figure:</u></b></p> <p>Due to an extremely lean hydrogen / air mix a low fuel consumption is possible.</p>

Quantitative assessment of the module for the long term perspective	
<b>Output unit:</b>	vehicle km
<b>Economy:</b>	
Costs per output unit	0.29 € – 0.45 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> (g/km)	0
Emissions of other pollutants (g/km)	NO <sub>x</sub> : 0.038g    H <sub>2</sub> O: 100.6g
<b>Efficiency:</b>	
Input energy	115 MJ / 100 km
Efficiency factor	40 %

Qualitative assessment of the module for the long term perspective					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>					x
Emissions of other pollutants				x	
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market			x		
Hazardousness			x		
Complexity of technique			x		
Standardisation		x			

<b>No.:</b>	C4-R7	<b>Road Traffic – Gas Turbine</b>
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Class	4	Input from:	all C3T and C3P
Category	Road Traffic	Output to:	-

**General description of the process**

The gas turbine is an internal combustion engine like the piston engine but the functional principle is a different one. The basic difference lies in the fact that the ignition of the combustion is not done via an explosion but in a continuous mode. Gas turbines are already used in many applications that require a low unit weight. The implementation of this engine in passenger cars and trucks would lead to reduced emission of pollutants, a more favourable torque, a reduced unit weight. The main advantage against the background of the introduction of renewable fuels is the multifuel performance of this engine which allows using all liquid or gaseous burnable substances like petrol, diesel, methanol/ethanol, natural gas or hydrogen.

The gas turbine operates according to the following technical principle: The compressor heats the air intake and compresses it to 5 bar. In a second step this air is used to burn the fuel in the gas turbine combustor. The high temperature that is generated by this process leads to the expansion of the mixture and this way the gas turbine is actuated. The thermal energy is converted into mechanical energy. The efficiency achieved by this transformation is fairly high, between 40 to 50 %. A positive aspect of the continuous combustion is the low emission of pollutants (especially CO, HC und NO<sub>x</sub>).

Several technical difficulties have kept the gas turbine from being implemented on a broad basis into road vehicles by now. The high operating temperatures put enormous stress on the implemented components, reducing the life span of the entire device and leading to a very costly series production. Besides the efficiency of 30 % that is state of the art by now is also rather low. In case of part load operation the efficiency falls down to 10 to 15 %. Further disadvantages are the high noise generation and a delayed reaction behaviour in comparison with the piston engine.

Numerous research and development activities are aimed at eliminating the disadvantages of the gas turbine. Special attention is given to the research on new materials (ceramics) and improved components like heat exchangers and compressors. Especially at the beginning of the nineties numerous research projects were engaged in the improvement of the gas turbine as a drive of vehicles, although no large scale field tests have been carried out.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Due to the state of the art the gas turbine is not likely to play an important role with respect to the usage of renewable energies in traffic. For this reason it is left out from further considerations.

**Internal and external resources**

BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000

BOSCH GROUP: Kraftfahrtechnisches Taschenbuch, 23. Ed., Vieweg Publishing House, Braunschweig, 1999

KRÜGER; LIEBSCHER; FAHL: Alternative Kraftstoffe, Landsberg/Lech, 1997

ATTAP Project (advanced turbine technology application project) of the USA; Research Project

AGATA (advanced gas turbine for the automobile) of European manufacturers, Ceramic Gas turbine program (CGT), Japan

MITSUBISHI MOTORS COOPERATION (<http://www.mitsubishi-motors.co.jp>)

BC RESEARCH, ALTERNATIVE TRANSPORTATION FUELS DATABASE, Advanced Gas Turbine (AGT) 100 project (<http://catf.bcresearch.com/>)

### Description of the calculation to obtain the quantitative figures

**Economy figure:**

As the gas turbine is still under development it is not possible to make any reliable statements on costs in case of regular operation. It is possible that at mass production prices will adapt to that of conventional piston engines.

**Ecology figure:**

The release of CO<sub>2</sub> depends on the used fuel and on the preceding production chain. The use of hydrogen from renewable sources results in a CO<sub>2</sub>-free operation. A problem which has not been answered yet, is the rather low efficiency. The use of petrol or diesel as a fuel would lead to a higher consumption compared to the piston engine and an increased release of CO<sub>2</sub>. It can be assumed that the reduced efficiency will apply accordingly for other fuels like natural gas, ethanol, methanol or biodiesel.

**Efficiency figure:**

All evidences show that the efficiency is worse in comparison to the conventional piston engine. If there occurred remarkable improvements, this would be different.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption	x				
Release CO <sub>2</sub>	dependent on fuel				
Emissions of other pollutants					x
Emissions of noise		x			
<b>Vehicle aspects</b>					
Performance				x	
Range			x		
Refuelling procedure	dependent on fuel				
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness	dependent on fuel				
Complexity of technique		x			
Standardisation	x				

<b>No.:</b>	C4-R8	<b>Road Traffic – Steam Engine</b>
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Class	4	Input from:	all C3T and C3P
Category	Road Traffic	Output to:	-

<b>General description of the process</b>
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Based upon the idea of burners with a very low rate of pollution at the beginning of the 1990s the idea was born to develop a completely new drive technology. Due to a series of favourable features the concept of the steam engine was selected as a basis for the start of this development. The research is based upon first projects initiated in the seventies on steam engines in road vehicles aimed towards a reduction of the emission of pollutants. Within the framework of the research on regenerative energies in transportation this concept is of importance as it features the multifuel capability.

Potentially steam engines can operate at a very high efficiency. Test constructions lead to engines with an efficiency almost as high as the efficiency of diesel engines. To put these engines into practice a series of technical difficulties have to be overcome. For instance at present the construction volume is rather high, that means that the performance density is rather low. Further development will lead to the reduction of the construction volume. As the concept of the steam engine is still in an initial stage of development a considerable improvement potential can be expected.

<b>Regional specifications in the EU</b>
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For the operation of the steam engine pure water is used, that in case of temperatures falling below zero would freeze and destroy the engine. In colder climatic regions this fact could generate problems. However this problem could be eliminated by using heating or by eliminating the water from the engine cycle, when switching off the engine.

<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
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The ENGINION company plans to launch a steam engine on the market in 2004 as an additional device for electricity production in parked trucks. At present there are no large scale research projects towards the application as a power unit for the drive of vehicles. If research projects were started in the near future, it would be possible to bring this engine type onto the market ahead of 2010.

<b>Internal and external resources</b>
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Information from web pages:

ENGINEER ASSOCIATION CAR AND TRAFFIC (IAV) ([www.iav.de](http://www.iav.de))

ENGINION AG ([www.enginion.com](http://www.enginion.com))

### Description of the calculation to obtain the qualitative figures

**Economy figure:**

As the concept is still in the research state no statements on this issue can be made. Due to the fact that the construction more or less resembles the construction of a conventional piston engine the cost structure could also be comparable to the one of this engine.

**Ecology figure:**

As with all multifuel capability engine concepts the CO<sub>2</sub> generation depends on the fuel used. With hydrogen as fuel zero carbon emission is achieved. If hydrocarbons are used (gaseous or liquid) there occur different rates of CO<sub>2</sub>-generation. In its present state of development the steam engine has an efficiency that lies only slightly below the one of highly optimised petrol or diesel engines. A further optimisation would lead to an efficiency at the level of the diesel engine operating with direct injection.

**Efficiency figure:**

At the actual stage of development the efficiency is worse in comparison to the conventional piston engine. An efficiency comparable to conventional engines seems to be achievable.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	dependent on fuel				
Emissions of other pollutants					x
Emissions of noise				x	
<b>Vehicle aspects</b>					
Performance				x	
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness	dependent on fuel				
Complexity of technique			x		
Standardisation	x				

<b>No.:</b>	C4-R9	<b>Road Traffic – Stirling-Engine</b>
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class	4	input from:	all C3T and C3P
category	Road Traffic	output to:	-

**General description of the process**

Like the gas turbine the Stirling-engine is operating on a drive concept based upon continuous combustion. In addition this engine type features a multifuel capability. Since the invention of this engine almost 200 years ago the concept did not ever have any real success on the market so far despite of the repeated approaches to improve its technology.

Technical principle: In contradiction to the piston engine the combustion of the fuel doesn't take place in but outside the cylinder (external combustion). The combustion leads to a temperature gradient between the inside and the outside of the cylinder and an inner mechanism converts this temperature gradient via cyclic compression and expansion into mechanical energy. In the cylinder no gas exchange between new and consumed gas takes place as it is the case in the piston engine. Major advantages of the engine construction are the continuous combustion leading to a very low emission of pollutants, to reduced noise generation and to the multifuel capability. Decisive disadvantages are the conceptual and technical difficulties at the implementation of this principle into a vehicle engine. As the major part of the thermal energy is conveyed to the cooling water a big energetic loss occurs here and as a result the efficiency of the engine is low. Via a so-called regenerator with a high heat accumulation capability part of the energy is recuperated. The further development of this device will be of major importance for the future performance of this engine.

Despite a series of efforts in the research sector in the eighties this did not mean any breakthrough for the concept of the Stirling-engine. There exist some typical disadvantages that could not be overcome so far, for example the sealing of the pistons.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

A large scale technical application of the Stirling engine in vehicle technology is not to be expected in the foreseeable future. It is more plausible that this concept will be used for stationary operation in the sector of the cogeneration or in the sector of the solar energy.

**Internal and external resources**

BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000

BOSCH GROUP: Kraftfahrtechnisches Taschenbuch, 23. Ed., Vieweg Publishing House, Braunschweig, 1999

DRI WEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

E. SCHMIDT, STIRLINGMOTOR.COM (<http://www.stirlingmotor.com/>)

**Description of the calculation to obtain the qualitative figures**

**Economy figure:**

As the stirling-engine is still under development it isn't possible to make any reliable statements on costs in case of regular operation. It is possible that at mass production prices will adapt to that of conventional piston engines.

**Ecology figure:**

The CO<sub>2</sub> generation depends on the fuel used and on the preceding production chain. With hydrogen produced from renewable sources a fuel zero carbon emission is achieved. Due to the problem of the low efficiency for which there hadn't been found any solution so far in case of using petrol and diesel as fuels both fuel consumption and CO<sub>2</sub> generation would increase compared with the conventional piston engine. It can be expected that the low efficiency will be valid for other fuels like natural gas, ethanol, methanol and biodiesel too.

**Efficiency figure:**

There is some evidence that the efficiency is below that of a conventional piston engine.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	dependent on fuel				
Emissions of other pollutants					x
Emissions of noise				x	
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness	dependent on fuel				
Complexity of technique		x			
Standardisation	x				

<b>No.:</b>	<b>C4-R10</b>	<b>Road Traffic – Electric Drive by Battery</b>
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Class	4	Input from:	-
Category	Road Traffic	Output to:	-

### General description of the process

Electric drives do not generate any direct pollutants and they operate at a very low noise level. Therefore this type of drive is potentially extremely suitable to solve the environmental problems of road traffic. Efforts to implement battery operated vehicles into road traffic have been made since the very early stages of the automobile history. But because of the difficulties of storing electrical energy by battery this drive is used only for niche market applications so far. The main obstacles are given by the low specific energy of batteries in connection with a high weight, big volume and high costs. Besides the production and the disposal or the recycling of the batteries cause some major environmental problems due to the chemistry of the batteries.

The following table describes the characteristics of the four major battery types:

Type	Advantages	Disadvantages	Energy density [Wh/kg]
Lead/acid	Established, low-cost, maintenance-free	Low specific energy, cycle life < 500, poor low-temperature performance	35 - 50
Nickel/cadmium	Established, long cycle life	Moderate specific energy, poor high-temp. performance, toxic, high costs	40 - 60
Sodium/sulphur	High specific energy, low-cost materials	High operating temperature, corrosion, safety problems (fire)	150 - 240
Lithium-ion	High specific energy, long cycle life	Early stage of development, high cost	80 - 130

Research is under way on many other battery technologies. All battery types suffer from a low specific energy and furthermore from other disadvantages with respect to charging time, efficiency, the energy losses during parked time, the limitation of the charging cycles and a specific hazard potential for the environment. All in all these factors limit the range of electrically driven vehicles using a battery to approximately 100 km up to now.

A major difficulty is the charging time of batteries. In contradiction to the refuelling with liquid or gaseous fuels the time period needed in this case, leaving out of consideration the sophisticated replacement of a battery, is rather long. Even the so-called fast charge lasts approximately one hour and the normal charge takes 8 hours. On the other hand there is the advantage of the simple infrastructure needed for charging. Electricity is available everywhere and is easy to handle.

#### Description of some state-of-the-art battery powered vehicles:

Automaker	Model	Description
Peugeot/Citroen	106/Saxo électrique	4 seat passenger car, nickel/cadmium, top speed 95 km/h
Fiat	600 elettrica	4 seat passenger car, nickel/cadmium, top speed 100 km/h
Kewet (Oslo)	Kewet el Jet	2 seat passenger car, lead-acid or nickel/cadmium battery, top speed 85 km/h, range 40 – 100 km/h
Commuter Cars Coop. (USA)	Tango	2 seat passenger car of minimal size, high performance (0-100 km/h: 4s, top speed 170 km/h), modified lead-acid battery, range 150 km

### **Regional specifications in the EU**

All battery types - especially lead/acid batteries - are subject to capacity losses at low temperatures. In case of temperatures lying considerably below zero degrees only a share of the battery capacity can be used. This means that especially in Northern countries only a limited operation during winter time would be possible. Another possibility would be to implement devices for the heating of the batteries.

As the electricity network in the EU is area-wide developed problems occurring due to the lack of disposability of electric energy can be excluded. There are differences between the sockets systems and the voltages creating problems to cross-border traffic. A standardisation would be reasonable but not essentially necessary for cross-border traffic as there exist potential transformers.

### **Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Despite the great efforts in research that were made during the eighties and the nineties a quantitative step with respect to the increase of the specific energy of batteries was not possible. Therefore it is rather difficult to estimate the development chances of battery technologies in the stage of research. However steep development leaps are not probable.

Since it seems that during the next ten years battery technology will go only through a rather small development with respect to performance and cost reduction the applications for the battery drive will remain limited to a few niche applications due to the range problem. The implementation of batteries in noise and pollution sensitive inner city areas and on short distances is conceivable as here the possibility of frequent recharge is given. Electric rollers for short distances are also a conceivable alternative.

An application in the long-distance traffic is not conceivable, not even for the long-term scenario.

### **Internal and external resources**

RAND, D.A.J.; WOODS, R.; DELL R.M.: Batteries for Electric Vehicles, Research Studies Press Ltd., Taunton, Somerset, 1998

ROLLER D. (ED.): Clean Power Sources and Fuels, 31st ISATA conference, Düsseldorf, 1998

#### Information from web pages:

ELECTRIC VEHICLE ASSOCIATION OF THE AMERICAS (EVAA) ([www.evaa.org](http://www.evaa.org))

NETHERLANDS AGENCY FOR ENERGY AND THE ENVIRONMENT: Program on Electric Vehicles in Europe, Research funded by the Commission of the European Communities (CEU) in the framework of the JOULE II – Programme ([www.ecn.nl/unit\\_bs/ev/joule/](http://www.ecn.nl/unit_bs/ev/joule/))

INFOVEL ([www.infovel.ch](http://www.infovel.ch))

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

The decisive cost factor are the batteries, all the other components can be produced at low costs in series. The costs for the batteries increase with an increasing specific energy and performance and are currently as follows:

Type	cost (€/kWh)	vehicle price (example)
Lead / Acid	130 – 165	(no serial production)
Nickel / Cadmium	275 – 385	15,000 € (Citroen Saxo electric, Peugeot 106 electric)
Sodium / Sulphur	275 – 500	(no serial production)
Lithium-ion	220	(no serial production)

For some new developments of batteries the costs cannot be estimated so far. For the existing battery technologies costs between 5,000 to 20,000 € per battery set are estimated to achieve an appropriate performance and range. This is an important cost factor, which makes a price increase against conventional drive technologies unavoidable.

#### **Ecology figure:**

During operation battery driven electric vehicles do not emit any CO<sub>2</sub>. The generation of CO<sub>2</sub> depends only on the preceding process chain which is necessary to charge the battery with energy.

#### **Efficiency figure:**

As the superior form of the electrical energy is used as introductory energy along the entire energy provision chain only comparably low efficiencies can be observed.

- Components of the power-train: up to 95 % efficiency
- Components of the charging technology: up to 70 % efficiency

The result is a total efficiency between 60 to 70 %.

### Quantitative assessment of the module for the present state

Output unit:	Passenger car [veh-km]
<b>Economy:</b>	
costs per output unit	0.40 €
<b>Ecology:</b>	
emission of CO <sub>2</sub> (kg) per output unit	0
emissions of other pollutants	0
<b>Efficiency:</b>	
GJ output energy per GJ input energy	60 to 70 %

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance	x				
Range	x				
Refuelling procedure	x				
<b>Other indicators</b>					
Readiness for market					x
Hazardousness				x	
Complexity of technique					x
Standardisation					x

<b>No.:</b>	<b>C4-R11</b>	<b>Road Traffic – Fuel Cell on Gaseous Hydrogen</b>
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Class	4	Input from:	C3T5, C3P1
Category	Road Traffic	Output to:	-

### General description of the process

The fuel cell technology intends to profit from the advantages of the electric drive (no emissions of pollutants, low noise emission) avoiding the constraints of the battery technology. The components of the drive (electric engine) are the same as for the battery powered electric vehicle and therefore do not represent any technical or economic problem. The storage of hydrogen and the transformation into electric energy are the difficulties that arise. As the storage of hydrogen in gaseous or liquid form represents two completely different situations for the application and the infrastructure the storage technology will be described in two separate modules (C4R11 - GH<sub>2</sub> and C4R12 - LH<sub>2</sub>).

The fuel cell makes it possible to obtain electricity directly via the transformation of hydrogen and oxygen into water. This method has the advantage that it does not generate in place any CO<sub>2</sub>, pollutants or noise. Furthermore this process can be operated with a very high efficiency when compared to the operation of the internal combustion engine.

Of all different types of fuel cells special attention is given to the application of the PEM-fuel cell in road traffic. The advantages of this type of fuel cell are as follows: it can be operated at ambient temperature, the power density is very high and the electrolyte doesn't consist of any critical toxic substances. Most developers consider the PEM to be most suitable fuel cell for vehicles, only some are focusing on alkaline fuel cells or solid oxide fuel cells (SOFCs). At the moment the disadvantages of all fuel cells are the high price, the lack of long term stability and the impossibility to make practical use of the theoretically very high efficiency.

For road vehicles the fuel cell technology is in the transition stage between research and test phase. There are already numerous passenger cars and buses under operation in various field tests.

The storage of hydrogen is the second big issue. The problems that have to be dealt with are the very low specific energy of gaseous hydrogen and the safety aspect (explosion hazard). The storage of gaseous hydrogen is done with pressurized hydrogen or with the help of the hybrid storage. For the pressures of 250 bar that were state of the art by now the specific energy of the hydrogen related to the volume is relatively low and therefore efforts are made to achieve pressures up to 700 bar for the storage using new materials.

The following table lists a comparison of the energy densities of hydrogen at different pressures:

Pressure	Specific energy [kwh/kg]	Specific energy [kwh/l]	Example: Contents of a 50 l tank [kwh]
250 bar = 20 MPa	33.3	0.49	25
350 bar = 35 Mpa	33.3	0.77	38
700 bar = 70 MPa	33.3	1.23	61
metal hydrid storage	0.2 – 0.4	1-1.5	50 - 75
Reference: Petrol (Super)	12	8.97	450

It becomes obvious that relatively high storage volumes are necessary for the gaseous storage of hydrogen. The pressurization of hydrogen is done in cylindrical storage basins of aluminium or steel, of late for very high pressures aluminium reinforced with carbon fibre is used. Different security systems prevent an explosion in case of fire. At the moment major emphasis is put on the research for the development of 700 bar storage basins. It is predicted that the technical problems will be solved and the 700-bar-storage will be the standard in the next two or three years.

As a further possibility to store hydrogen the metal hybrid storage is taken into consideration. In this case atomic hydrogen is stored this leading to an advantage with respect to safety engineering. The refuelling of the basin is accompanied by heat losses and on the other hand to release the hydrogen from the basin heat is needed. The specific energy that can be achieved is higher with respect to the volume and lower with respect to the weight in comparison with pressurized hydrogen.

#### **State of the art of fuel-cell passenger-cars and fuel-cell busses:**

At the present state there are numerous automakers involved in the development of fuel cell vehicles powered by  $\text{GH}_2$ . A full overview is available at [www.h2cars.de](http://www.h2cars.de) (in english language). The most promising developments are listed in the following table:

Automaker	Vehicle name	Vehicle type	Energy storage	Power	Range	Speed
DaimlerChrysler	Necar 4	pass. car.	2.5 kg, 35 MPa	75 kw	200 km	145 km/h
Toyota	FCHV5	pass. car.	35 l, 50 MPa	90 kw	500 km	
Ford	Think FC5	pass. car.	35 MPa	75 kw		
Honda	FCX V4	pass. car.	130 l, 35 MPa	60 kw	300 km	140 km/h
DaimlerChrysler	Sprinter	Light duty vehicle	35 MPa	55 kw	150 km	120 km/h
Toyota	Hino Bus	bus	25 MPa	180 kw	300 km	80 km/h
DaimlerChrysler	Citaro Bus	bus	35 MPa	250 kw	300 km	80 km/h

#### **Regional specifications in the EU**

Not relevant.

#### **Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

The entire sector of the fuel cell technology is still in a stage of development with a promising and high optimisation and expansion potential.

For an **intermediate scenario** there will take place various field test, for example the "CUTE"-Project which will demonstrate the operation of 30 fuel cell powered transit buses over a period of two years in inner city areas of ten European metropolitan areas (2002/2003). Furthermore the launch of the first prototype vehicles of fuel cell passenger cars is expected by 2004 (Honda FCX-V4, Toyota FCHV-4, DaimlerChrysler with NECAR). The mass production of 700-bar-storage is expected in the near future. For the **long-term scenario** it can be assumed that there will be big improvements with respects to efficiency and the performance of fuel cells as well as a major reduction both of the size and the costs of fuel cells.

#### **Internal and external resources**

DRI WEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

UNIVERSITY OF STUTTGART, INSTITUTE OF ROAD AND TRANSPORTATION STUDIES: Begleituntersuchung zum Pilotvorhaben Brennstoffzellenbus, unpublished report, (writer: Wacker, M.; Schubert, J.), 1999

FUEL CELL ALLIANCE OF DAIMLERCHRYSLER, FORD AND BALLARD ([www.ballard.com](http://www.ballard.com)) ([www.xcellsis.com](http://www.xcellsis.com))

CALIFORNIA FUEL CELL PARTNERSHIP ([www.fuelcellpartnership.org](http://www.fuelcellpartnership.org))

L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) ([hydrogen.org](http://hydrogen.org))

BRENNSTOFFZELLENAUTOS.COM ([www.brennstoffzellenautos.com](http://www.brennstoffzellenautos.com))

CLEAN URBAN TRANSPORT FOR EUROPE (CUTE) ([www.fuel-cell-bus-club.com](http://www.fuel-cell-bus-club.com))

## Description of the calculation to obtain the quantitative figures

### **Economy figure:**

According to calculations of the German VES (=Energy Strategy for the Economy on Transportation) the following price structures for the intermediate and long-term scenario can be expected:

Scenario	Cost of vehicle		Additional costs of fuel cell against conventional	Costs for operation [ct/km]		Additional costs fuel cell against conventional
	conventional	Fuel cell CGH <sub>2</sub>		Conventional	Fuel cell CGH <sub>2</sub>	
Intermediate (2005-2010)	≈ 18,000 €	≈ 23,000 €	≈ 25 %	≈ 20 ct	≈ 31 ct	≈ 55 %
Long-term (2010 – 2020)	≈ 18,800 €	≈ 21,000 €	≈ 10 %	≈ 20 ct	≈ 29 ct	≈ 45 %

These figures are confirmed by the data given in the Study of Arthur D. Little.

### **Ecology figure:**

The operation of a vehicle running on hydrogen is CO<sub>2</sub> free. That means that for the calculation of the CO<sub>2</sub>-emissions only the energy chain leading to the hydrogen used is of importance.

To calculate the energy demand of a vehicle the efficiency of the electric engine and of the fuel cell has to be taken into consideration. The fuelling of the different engines is also of importance.

### **Efficiency figure:**

It is important to consider the efficiency of the whole powertrain to assess the potentialities of fuel cell cars. The powertrain consists mainly of the electric engine and the fuel cell. Also losses at fuelling are to consider.

At the present state of knowledge following efficiency figures are taken into account:

- electric engine: 95 %

- PEM-fuel cell: today up to 50%, but there are big improvements presumed. In spite of the spark ignition engine with a theoretical efficiency figure of about 40%, the fuel cell has a theoretical efficiency figure of 100%. Because of heat losses - which can never be avoided – a practical max. efficiency figure of 80% ist likely.

- Fast fuelling of CH<sub>2</sub> : 88 - 95 % (greatest losses in case of compression up to a maximum of 700 bar)

The conclusion is that at best the efficiencies for the total energy conversion chain in the vehicle can amount to about 70 %. Therefore the efficiency of the spark ignition engine is remarkable exceeded.

The total amount of consumed energy has to be seen in comparison with the energy consumption of the conventional car, that means for the reference vehicle. The reference vehicle is set to a consumption of 3.6 l petrol or 3.3 l diesel/100 km (according 90g CO<sub>2</sub>/km), corresponding to an input energy of 115 MJ/100km (according about 40 MJ/100km mechanical energy).

This leads to an input energy amount of 57 MJ/100km.

<b>Quantitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)		
<b>Output unit:</b>	Passenger car [100 veh-km]	Bus [100 veh-km]
<b>Economy:</b>		
Costs per output unit	30 €	140 €
<b>Ecology:</b>		
Emission of CO <sub>2</sub> (g) per output unit	0	0
Emissions of other pollutants	4.3 kg H <sub>2</sub> O	23.9 kg H <sub>2</sub> O
<b>Efficiency:</b>		
GJ input energy	57 MJ	310 MJ
Efficiency factor	up to 70 %	up to 70 %

<b>Qualitative assessment of the module for the long term perspective</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption					x
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market		x			
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	<b>C4-R12</b>	<b>Road Traffic - Fuel Cell on Liquid Hydrogen</b>
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Class	4	Input from:	C3T5, C3P2
Category	Road Traffic	Output to:	-

**General description of the process**

For the description of the fuel cell technology see module C4R11. This module deals only with the liquid storage of hydrogen.

The liquid storage offers by far the highest specific energy with respect to mass and volume and therefore it is particularly suited for the implementation in road vehicles. However the technological requirements are extreme as hydrogen liquefies only at extremely low temperatures. The liquefaction is a very energy-intensive process and the storage requires costly installations.

As basins for liquefied hydrogen highly isolated tanks can be used. Due to the fact that heat penetration cannot be avoided the hydrogen in the tank will vaporize to a certain extent and this will lead to an increase of the pressure in the tank. The gaseous hydrogen generated this way must be let off. The tanks for the storage of liquid hydrogen are costly and sophisticated constructions. Besides the fuelling unit has to be invested with complicated appliances in order to ensure a high isolation of the refuelling adapter. The refuelling takes <10 minutes.

The liquefaction of hydrogen requires a high input of both technology and energy. Hydrogen is available at first always as a gas and therefore liquefaction will always be an additional process. Nevertheless this sophisticated procedure is worthwhile as the energy content of volume related LH<sub>2</sub> is considerably higher even than that of gaseous pressurized hydrogen at 700 bar:

Fuel	Specific energy [kWh/kg]	Specific energy [kWh/l]	Example: Energy content of a 50 l tank [kwh]
LH <sub>2</sub>	33.3	2.36	118
GH <sub>2</sub> (700 bar = 70 MPa)	33.3	1.23	61
Reference : petrol (Super)	12	8.97	450

Liquid hydrogen represents a very attractive solution for road vehicles. The range of a fuel cell vehicle powered by LH<sub>2</sub> will be higher than that of a vehicle with GH<sub>2</sub> (even at a pressure of 700 bar). Ranges of 500 km or even more seem achievable. Or the other way round in case of a moderate range the size of the tanks can be kept comparably small.

However the usage of liquid hydrogen is connected to serious technical and economic difficulties. At present liquid hydrogen can be stored only for a few days in heat isolated tanks that are state of the art. Active thermal shields (for instance loss cooling via liquid nitrogen or air) can improve this to achieve storing periods up to two weeks. Further problems are generated by the fact that the volume of the tanks can be used only up to 80% as otherwise the pressure would rise too fast. Besides the technical execution of the tank is very sophisticated (double walled execution, external armatures, 70 to 100 layers in vacuum super-isolation).

**State of the art of fuel-cell passenger-cars and fuel-cell busses** (There are not as many vehicles powered by LH<sub>2</sub> as vehicles powered by GH<sub>2</sub>):

Automaker	Vehicle name	Vehicle type	Energy storage	Power	Range	Top Speed
Opel	HydroGen3	pass. car.	4.8 kg	75 kw	650 km	180 km/h
Renault	Laguna	pass. car.		30 kw	300 km	
MAN / Linde	SL 202	bus	600 l	140 kw	300 km	75 km/h

<b>Regional specifications in the EU</b>
Not relevant
<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
<p>The general feasibility of the usage of LH<sub>2</sub> storage systems has been proved. But the technical difficulties connected to the storage of liquid hydrogen are higher than those connected to the storage of gaseous hydrogen, therefore greater problems have to be solved before a large-scale use. Because of the higher complexity of the technology only a few car manufacturers focus on the development of fuel cell vehicles powered by LH<sub>2</sub>.</p> <p>At present there exist prototypes of vehicles from Opel (HydroGen3) and BMW (745h) or the MAN /Linde – bus that use LH<sub>2</sub>. The BMW 745h does not use a fuel cell but an internal combustion engine. Big improvements on all aspects of the LH<sub>2</sub>-technology can be expected leading especially to a price reduction. In a long-term focus the advantage of the high energy density of LH<sub>2</sub> could be a decisive factor.</p>
<b>Internal and external resources</b>
<p><u>Information from web pages:</u></p> <p>FRAUNHOFER INSTITUT SYSTEMTECHNIK UND INNOVATIONSFORSCHUNG, BRENNSTOFFZELLENSYMPOSIUM (<a href="http://www.brennstoffzellensymposium.de">www.brennstoffzellensymposium.de</a>)</p> <p>CALIFORNIA FUEL CELL PARTNERSHIP (<a href="http://www.fuelcellpartnership.org">www.fuelcellpartnership.org</a>)</p> <p>L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) (<a href="http://hydrogen.org">hydrogen.org</a>)</p> <p>FUEL CELL ALLIANCE OF DAIMLERCHRYSLER, FORD AND BALLARD (<a href="http://www.ballard.com">www.ballard.com</a>) (<a href="http://www.xcellsis.com">www.xcellsis.com</a>)</p>

<b>Description of the calculation to obtain the quantitative figures</b>						
<b><u>Economy figure:</u></b>						
According to calculations of the German VES (=Energy Strategy for the Economy of Transportation) the following price structures are to be expected for the intermediate respectively long-term scenario:						
Scenario	Vehicle costs		Additional fuel cell in contrast to conventional	Operational costs		Additional fuel cell in contrast to conventional
	Conventional	Fuel cell LH <sub>2</sub>		Conventional	Fuel cell LH <sub>2</sub>	
Intermediate (2005-2010)	≈ 18,000 €	≈ 23,000 €	≈ 25 %	≈ 20 ct	≈ 33 ct	≈ 65 %
Long-term (2010 – 2020)	≈ 18,800 €	≈ 21,000 €	≈ 10 %	≈ 20 ct	≈ 29 ct	≈ 45 %
<b><u>Ecology figure:</u></b>						
A fuel cell vehicle operates CO <sub>2</sub> free. That means that for the CO <sub>2</sub> -emissions only the energy chain leading to the hydrogen used is of importance.						
For the calculation of the energy demand one has to take into consideration the efficiency of: the electric engine, the fuel cell and of the refuelling process. In case of liquid storage the energy losses during idling have to be taken into consideration.						
<b><u>Efficiency figure:</u></b>						
It is important to consider the efficiency of the whole powertrain to assess the potentialities of fuel cell cars. The powertrain consists mainly of the electric engine and the fuel cell. Also losses at fueling are to consider (see also module “Road Traffic – Fuel Cell and gaseous hydrogen (GH <sub>2</sub> )”):						
At the present state of knowledge following efficiency figures are taken into account:						

- electric engine: 95 %

- PEM-fuel cell: today up to 50%, but there are big improvements presumed. In spite of the spark ignition engine with a theoretical efficiency figure of about 40%, the fuel cell has a theoretical efficiency figure of 100%. Because of heat losses - which can never be avoided – a practical max. efficiency figure about 80% is likely.

- Idling losses: 5 – 100 % (extreme case), during normal operating very low

The conclusion is that at best the efficiencies for the total energy conversion chain in the vehicle can amount to about 70 %. Therefore the efficiency of a LH<sub>2</sub>-car can be considered as comparable to the GH<sub>2</sub>-car, leading to a similar amount of input energy: 57 MJ/100km.

<b>Quantitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)	
<b>Output unit:</b>	Passenger car (100 veh-km)
<b>Economy:</b>	
Costs per output unit	29 - 33 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> (kg) per output unit	0
Emissions of other pollutants	4.3 kg H <sub>2</sub> O
<b>Efficiency:</b>	
GJ input energy	57 MJ
Efficiency factor	up to 70 %

<b>Qualitative assessment of the module for the long term perspective</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption					x
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range				x	
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market		x			
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	<b>C4-R13</b>	<b>Road Traffic – Fuel Cell on Methanol</b>
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Class	4	Input from:	C3T1
Category	Road Traffic	Output to:	-

### General description of the process

The enormous difficulties arising in connection with the handling of hydrogen lead to the idea to produce hydrogen onboard during the operation of the vehicle from an energy carrier that can be handled more easily.

Along with experiments with petrol and ethanol the most promising fuel is methanol (CH<sub>3</sub>OH). Methanol can be used in two different ways: one way is to obtain hydrogen from methanol and to use it for the operation of the fuel cell (Indirect methanol Fuel Cell, IMFC), the second possibility is to operate the fuel cell directly with methanol (Direct methanol Fuel Cell, DMFC).

Methanol is a very cost-efficient fuel when compared to hydrogen both with respect to handling and to the specific energy. The handling is a lot more easier as methanol is in liquid form at ambient temperature and therefore the safety problems are smaller.

Fuel	Specific energy [kwh/kg]	Specific energy [kwh/l]	Example: Energy content of a 50 l tank [kwh]
Methanol	5.6	4.42	221
LH <sub>2</sub>	33.3	2.36	118
GH <sub>2</sub> (700 bar = 70 Mpa)	33.3	1.23	61
Reference: Benzin (Super)	12	8.97	450

The most common and best developed fuel cell for the vehicle sector is the PEM-fuel cell. This fuel cell must operate on high-purity hydrogen that can be principally produced from carbonaceous energy carriers like natural gas, liquid gas, petrol or methanol. These are the reasons for which methanol is considered to be a promising fuel for the future.

To obtain hydrogen from methanol a reformer is used. There exist three different technologies leading to three different ways to obtain hydrogen. The most promising technology for the automobile sector is the steam reforming (CH<sub>3</sub>OH + O<sub>2</sub> → H<sub>2</sub> + CO<sub>2</sub>). Prototypes for this type of technology are state of the art.

As the reforming process is sophisticated bringing about energy losses, intense efforts are made to develop a possibility to achieve a direct conversion of the methanol in the fuel cell. In this case we talk about the Direct-methanol-Fuel-Cell (DMFC). The DMFC is very attractive for vehicles as it requires less space and is cheaper than a combination of fuel cell and reformer. Furthermore the deconvolution performance and the dynamics are higher. The development of the DMFC is based upon the development of the PEM fuel cell. The DMFC converts the methanol at the anode into protons and CO<sub>2</sub>. For this procedure even liquid methanol could be used and this way the process chain would be simplified considerably. However the DMFC is still in the stage of research. There still exist serious technological problems which need to be clarified before this procedure can be used on an industrial scale. Problems occur due to the fact that the fuel cell is polluted by methanol permeating the membrane leading to a loss in fuel and a decrease of the efficiency. At the anode the toxic substance CO is developed. This carbon monoxide attacks the catalysts.

The choice whether the reformer in combination with the PEM fuel cell or the DMFC will come into application in future will be taken by comparing the performances that can be achieved and the corresponding costs. The efficiency of a reformers lies between 60 to 80 % and that of a PEM fuel cell of over 50 % and in combination this would lead to a total efficiency of 30 to 40 %. This value has to be

overcome by the DMFC.

The handling and the storage of methanol are uncritical as it is in liquid form at ambient temperature and has a high specific energy. The boiling point of methanol lies at 64.7°C and this temperature is higher than the temperatures measured in extremely warm countries. For this reason the filling of the vehicles can be done in analogy to the filling with conventional fuels. Certain safety aspects have to be observed: It is very toxic to inhale or to swallow methanol. Furthermore chronic intoxications can be generated by a continuous contact with small quantities of methanol. In this respect methanol is not different from conventional fuel.

### Regional specifications in the EU

Not relevant

### Foreseeable intermediate (5-10 years) and long-term (25-30 years) development

#### **Intermediate scenario:**

First vehicle fit for operation powered by a methanol fuel cell in the test phase: DaimlerChrysler NE-CAR 5 und Jeep Commander 2, both are vehicles invested with a reformer, readiness to market in „a couple of years“

#### **Long-term scenario:**

Due to the serious intense research and due to the early stage of development of the DMFC it is to be expected that this type of fuel cell will represent a promising alternative.

### Internal and external resources

FORSCHUNGSZENTRUM JÜLICH (ED.): Verfahrenskonzepte für den Betrieb eines Direkt-Methanol-Brennstoffzellensystems Forschungszentrum Jülich 1998, (writer: Menzer, R.; Höhle, B.; Schmidt, V.M.), 1998

FRAUNHOFER-INSTITUT FÜR SOLARE ENERGIESYSTEME (ISE) ([www.fraunhofer.de](http://www.fraunhofer.de))

HYCAR ([www.hycar.de](http://www.hycar.de))

METHANOL INSTITUTE ([www.Methanol.org](http://www.Methanol.org))

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

Not to be estimated yet, still in the stage of research. But the fuel cell on methanol has to be able to compete with the other types of fuel cells.

#### **Ecology figure:**

The usage of methanol as a fuel in a fuel cell generates the emission of CO<sub>2</sub>. This means that the CO<sub>2</sub>-emission depends on the method used for the production of the fuel. The number in the fact sheet based on the competitiveness of the fuel cell on methanol with fuel cell on hydrogen.

If methanol is reformed to get H<sub>2</sub> CO and traces of NO<sub>x</sub> can be generated. As the CO will damage the fuel cell it have to be oxidised to CO<sub>2</sub>. But still a vehicle with a methanol reformer is a nearly zero emission vehicle.

#### **Efficiency figure:**

Not to be estimated yet, still in the stage of research.

<b>Quantitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)	
<b>Output unit:</b>	Passenger car (100 veh-km)
<b>Economy:</b>	
Costs (€) per output unit	unknown
<b>Ecology:</b>	
Emission of CO <sub>2</sub> (kg) per output unit	5.7 kg CO <sub>2</sub>
Emissions of other pollutants	Traces of NO <sub>x</sub>
<b>Efficiency:</b>	
GJ input energy	80 MJ [≈ 5,33l Methanol ]
Efficiency factor	up to 50%

<b>Qualitative assessment of the module for the long term perspective</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>			x		
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market		x			
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	C4-R14	<b>Road Traffic – Fuel Cell on Petrol</b>
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Class	4	Input from:	C3T6, C3P3
Category	Road Traffic	Output to:	-

<b>General description of the process</b>
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One of the biggest obstacles in introduction fuel cell cars is the undeveloped hydrogen supply infrastructure. In order to enable a market introduction of fuel cell cars and to give the consumer experience in handling these types of vehicles, petrol based fuel cell cars are a possible alternative.

This vehicles run with conventional petrol which is converted into hydrogen with the help of a reformer. The fuel cell works with this produced hydrogen and operates an electric motor.

This method has nearly no positive impact on emissions compared with the conventional combustion engine. The amount of emitted CO<sub>2</sub> is almost the same. The only advantage is that the fuel cell has a higher efficiency factor compared with a conventional piston engine.

A further disadvantage is the growing complexity of the fuel cell power unit. A larger stack is necessary, which leads to a heavier fuel cell unit.

Recently three vehicles have been presented which work with fuel cell, petrol and reformer: The Chevrolet S10 FC from General Motors, the Toyota FCHV-5 and the DaimlerChrysler JEEP Commander.

<b>Regional specifications in the EU</b>
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Not relevant.

<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
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The petrol based fuel cell is only a strategy for an intermediate scenario. Longterm aim for 2020 and later is to build a supply net for hydrogen. Then fuel cells without reformer can substitute the petrol based fuel cells.

<b>Internal and external resources</b>
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DRIWEFA AND ARTHUR D. LITTLE: Future Powertrain Technologies, Lexington; Cambridge, 2001

Information from web pages:

AUTOMOTIVE INTELLIGENCE ([www.autointell.de](http://www.autointell.de))

NEW LOOK ELECTRONIC PUBLISHING GMBH, Auto-News ([www.auto-news.de](http://www.auto-news.de))

U.S. DEPARTMENT OF ENERGY; U.S. ENVIRONMENTAL PROTECTION AGENCY, Fueleconomy ([www.fueleconomy.gov](http://www.fueleconomy.gov))

GENERAL MOTORS ([www.gm.com](http://www.gm.com))

HYCAR ([www.hycar.de](http://www.hycar.de))

L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) ([hydrogen.org](http://hydrogen.org)) ([www.hydrogen.org](http://www.hydrogen.org))

UTE LANGHAKI INFORMATIONSTECHNOLOGIE ([www.kfz-elektronik.de](http://www.kfz-elektronik.de))

TOYOTA ([www.toyota.com](http://www.toyota.com))

ZTEK CORPORATION ([www.ztekc corp.com](http://www.ztekc corp.com))

<b>Description of the calculation to obtain the quantitative figures</b>
<p><b><u>Economy figure:</u></b> As the existing fuel supply net can be used, the fuel costs stay moderate.</p> <p><b><u>Ecology figure:</u></b> The reforming process emits CO<sub>2</sub>.</p> <p><b><u>Efficiency figure:</u></b> The aim of General Motors and Opel is a efficiency factor of nearly 40% for a fuel cell stack with reformer system</p>

<b>Quantitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)	
<b>Output unit:</b>	Passenger car
<b>Economy:</b>	
Costs (€) per output unit	n/a
<b>Ecology:</b>	
Emission of CO <sub>2</sub> (g/km)	135
Emissions of other pollutants (g/km)	n/a
<b>Efficiency:</b>	
GJ input energy	n/a
Efficiency factor	up to 40%

<b>Qualitative assessment of the module for the long term perspective</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>		x			
Emissions of other pollutants		x			
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market		x			
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	C4-T1	<b>Railway - Conventional Piston Engine</b>
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Class	4	Input from:	C3T5, C3P3
Category	Railway	Output to:	-

**General description of the process**

The range of application of modern internal combustion piston engines running on diesel is universal. They are used in the whole range from high speed long distance to regional transportation both in passenger and freight transportation. Another field of application for diesel engines is shunting.

The basic principle of the functionality of the engines is the same as that of diesel engines used in the road traffic sector with accordingly higher performances. Diesel engines are very effective in rail transport due to loading and acceleration behaviour. Besides diesel engines have high total lives of up to 80,000 hours of operation, low maintenance rates and an efficiency of 30 to 45 %. Diesel engines can be used as primary drive (diesel hydraulic) or as driving component (diesel electric) for power generation. The fuel consumption can be assumed for 200 g/kWh for all types of engines. The range of the performance is listed below (examples from Germany):

- For motor rail coaches there exist engines with 275 to 550 kW when the engine is below the platform and with 390 to 630 kW when the engine is installed otherwise.
- For motor rail coaches and high-speed trains there exist engines with 785 to 2,000 kW.
- Locomotives for long-distance travel require engines with 1,000 to 4,000 kW.
- Shunter locomotives require a power between 630 kW to 1,000 kW. These shunter locomotives can also be used for the regional part-load traffic.
- ICE-TD output 4\*560 kW = 2,240 kW, Maximum speed 200 km/h. This way the train has an operational period of approximately 5 hours at full load and can be used in long-distance travel.
- For heavy haul locomotives there exist engines with 5,600 kW.

The fuelling of the diesel motor rail coaches and locomotives is done at special filling stations that have to be invested with a special collector against leakage.

Modern diesel motor rail coaches comply with the exhaust emission standard EURO 2. Engines for motor rail trains and high-speed trains comply with the exhaust emission standard ERRI (European Rail Services). Emission limit values for diesel engines in rail vehicles:

Effective from	Motor capacity	NO <sub>x</sub> [g/kWh]	HC [g/kWh]	CO [g/kWh]	Particles [g/kWh]	Guideline by
2003	> 560 kW > 1000 l/min	9.5	0.8	3	0.25	UIC 624 (ERRI)
2005		7.4	0.8	2	0.28	EPA
2008	> 560 kW	6	0.5	2	0.15	UIC 624 (ERRI)

Translated from ([www.zeppelin.de/D/powersystem/02eisenbahn/pdf/emission.pdf](http://www.zeppelin.de/D/powersystem/02eisenbahn/pdf/emission.pdf))

**Regional specifications in the EU**

Diesel engines are used all over Europe with different shares of the rail transportation. Cross border long distances are exceptions.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

No general technical changes planned for diesel engines for the next 10 to 20 years, adaptations to the development of diesel engines for lorries, related to regulations of the exhaust emissions.

### Internal and external resources

Deutsche Bahn AG: DB Arguments, Mobility to come

FEDERAL OFFICE FOR THE PROTECTION OF THE ENVIRONMENT, 1999: Handbook for Emissions Factors, (data bank on CD-ROM, version 1.2) - Infrac AG, Bern, 1999

#### Information from web pages:

DEUTSCHE BAHN AG ([www.bahn.de](http://www.bahn.de))

CUMMINS INC. ([www.cummins.com](http://www.cummins.com))

DEUTZ AG ([www.deutz.de](http://www.deutz.de))

MAN AG ([www.man.de](http://www.man.de))

MTU FRIEDRICHSHAFEN GMBH ([www.mtu-friedrichshafen.com](http://www.mtu-friedrichshafen.com))

S.E.M.T. PIELSTICK ([www.pielstick.com](http://www.pielstick.com))

SVEN WITZEL, Lokführer online ([www.switzel.de/220/](http://www.switzel.de/220/))

FEDERAL ENVIRONMENTAL AGENCY, Germany

([www.umweltbundesamt.de/uba-info-daten/daten/kohlendioxidemissionen.htm](http://www.umweltbundesamt.de/uba-info-daten/daten/kohlendioxidemissionen.htm))

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

Fuel costs:  $\approx$  0,30 Cent per litre

Performance ICE-TD: 2240 kW

Fuel Consumption 300 l / 100 veh.-km

#### **Ecology figure:**

Consumption of the diesel engines: approximately 246 kg/100 veh.-km.

Emissions [kg/kg diesel]:

CO <sub>2</sub>	3.17
NO <sub>x</sub>	0.0095
CO	0.003
HC	0.0008

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	100 veh-km (Passenger train)
<b>Economy:</b>	
Costs per output unit	approx. 90 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	approx. 780
Emissions of other pollutants [kg]	NO <sub>x</sub> : approx. 2.3 CO: approx. 0.7 HC: approx. 0.2
<b>Efficiency:</b>	
Energy demand [MJ]	10,537
Efficiency factor	30 to 45 %

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants	x				
Emissions of noise		x			
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market					x
Hazardousness			x		
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	C4-T2	<b>Railway – Biodiesel Piston Engine</b>
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Class	4	Input from:	C3T3
Category	Railway	Output to:	-

<b>General description of the process</b>	
<p>Internal combustion piston engines operating on biodiesel have to comply with the same requirements as a conventional diesel engine. By using biodiesel of the standard E DIN 51606 the exhaust of soot, carbon monoxide and hydrocarbons is reduced and there is no emission of sulfur and carbon dioxide but a higher emission of NO<sub>x</sub>. If biodiesel is used in combination with an oxidation catalyst the emissions reduce even more. As the exhaust emissions of the biodiesel do not contain any sulfur, the exhaust cleaning device will have a lasting and appropriate function. In rail traffic there exists the possibility to operate on pure biodiesel or on a blend of biodiesel and conventional diesel. Attention must be paid to the fact that the fuel filter has to be changed after several fill-ups with biodiesel if the engine had been running for a longer time on conventional diesel. Due to the fact that biodiesel acts like a solvent the residues from conventional diesel could lead to the clogging of the fuel filters. In some cases the usage of biodiesel could lead to an increased fuel consumption or to a reduced output of the diesel engine. If biodiesel is used the oil should be changed twice as often as is necessary if conventional diesel is used. Using some additives the Cold Filter Plugging Point (CFPP) is –20°C.</p> <p>Apart from an around 10 % higher fuel demand all relevant boundary conditions like performance are comparable to those of the conventional diesel.</p> <p>The fuelling of diesel motor rail coaches, trains and locomotives can be done at the same filling stations as for conventional diesel. Because biodiesel is easily bio-degradable, it cannot pollute the ground water.</p> <p>Today there exist only single regional applications of biodiesel in the railway transportation sector. There are no plans of the usage of biodiesel for the long distance transportation.</p>	

<b>Regional specifications in the EU</b>	
<p>The CFPP (=cold filter plugging point) of biodiesel is –20° C. This means that there can occur problems in the very northern regions of Europe.</p>	
<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>	
<p>No technical changes planned for diesel engines for the next 10 to 20 years.</p>	

### Internal and external resources

DEUTSCHE BAHN AG: DB Arguments, Mobility to come

OEHLMÜHLE LEER CONNEMANN GMBH & CO: Start with biodiesel into a flourishing future

#### Information from web pages:

DEUTSCHE BAHN AG ([www.bahn.de](http://www.bahn.de))

[www.biodiesel.de](http://www.biodiesel.de) (July 2002)

CUMMINS INC. ([www.cummins.com](http://www.cummins.com))

DEUTZ AG ([www.deutz.de](http://www.deutz.de))

MAN AG ([www.man.de](http://www.man.de))

MTU FRIEDRICHSHAFEN GMBH ([www.mtu-friedrichshafen.com](http://www.mtu-friedrichshafen.com))

S.E.M.T. PIELSTICK ([www.pielstick.com](http://www.pielstick.com))

[www.switzel.de/220/](http://www.switzel.de/220/) (July 2002)

### Description of the calculation to obtain the quantitative figures

#### Economy figure:

Biodiesel is more expensive than conventional diesel (about 0.35 € per litre).

#### Ecology figure:

Biodiesel features considerable advantages with respect to hydrocarbons, carbon monoxide and particles when compared to conventional diesel. The table below indicates different values of biodiesel compared with conventional diesel (direct injection):

Pollutants	
CO	-10%
HC	-10%
NO <sub>x</sub>	+12%

An increased fuel demand of about 10 % must be taken into account. The release of CO<sub>2</sub> of biodiesel accounts for about 25 % of the diesel values.

The biodiesel molecule contains approx. 11% oxygen. The oxygen improves the combustion process and the quantity of soot generated by this process is reduced.

The cetane number of biodiesel (58) is higher than the cetane number of mineral diesel (49-53). The high cetane number leads to a reduction of the ignition delay meaning that the pressure in the cylinder is lower. This way the wear of the engine is reduced ensuring a greater smoothness in running.

Biodiesel does not contain benzene or other aromatic compounds.

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	Passenger train (100 veh.-km)
<b>Economy:</b>	
Costs per output unit	approx. 1.08 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	215
Emissions of other pollutants [kg]	NO <sub>x</sub> : approx. 2.6 CO: approx. 0.6 HC: approx. 0.2
<b>Efficiency:</b>	
Efficiency factor	30 to 45 %

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants	x				
Emissions of noise		x			
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market			x		
Hazardousness				x	
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	C4-T3	<b>Railway – Methane Gas Piston Engine</b>
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Class	4	Input from:	C3T4, C3P2
Category	Railway	Output to:	-

**General description of the process**

Natural gas can be used as an alternative fuel in rail vehicles. The advantages of natural gas as a fuel are the extremely clean burning process and the low content of carbon and this way the exhaust emissions lie considerably below those of the diesel engine. Another advantage is the low noise level. The main disadvantage is the very low specific energy related to the volume (see table below).

Fuel	Specific energy [kWh/kg]	Specific energy [kWh/l]
Methane (200 bar)	13.8	2.2
Reference: Diesel	12.0	9.8

In Germany first tests with the natural gas drive have been made in rail traffic. The first locomotive used in the tests was a re-equipped shunter locomotive of the product line BR 760 of the DB AG (=German Rail Company). The locomotive is invested with an 8-cylinder engine of Caterpillar (G 3508 TA-54) build in upright. The engine has a piston capacity of 34.5 litres and an output of 472 kW (fairly the same output like the diesel engine). The drive functions on a diesel hydraulic basis. The natural gas needed is transported in a LNG (=liquid natural gas) tank at a temperature of -138° Celsius and a pressure of 5 bar. The advantage of the LNG tank is that it is designated to economize space within the vehicle and at the same time to improve the range of the vehicle in comparison with the conventional storage technologies of natural gas. The range of the locomotive operating on natural gas lies between 250 to 300 km.

The implementation of motor coach rails in regional traffic requires an engine power of 472 kW and the usage of a LNG tank. The gas tanks could be placed on top of the locomotive comparable to the gas tanks on buses. Another alternative would be to use the natural gas locomotive in regional part-load traffic.

The special features of these gas engines invested with a controlled three-way catalytic converter are the extremely low emissions of gaseous pollutants like NOX or HC lying clearly below the limiting values of the exhaust emission standard Euro 3. Another advantage of the natural gas engines is the burning free of residues so that the emission of particles lie also below the limiting values of the Euro 3 standard. The small rest of emissions occurring results from the lubrication oil consumption in the engine. The maximum performance of a re-equipped natural gas engine currently amounts to 170 kW/231 PS with the highest torque at 860 Nm.

The energetic consumption of a gas engine is approximately 35 % higher than the one of the diesel engine. This increase is the result of a reduction of the compression from 17.5:1 to 11:1 and of the heat losses through the throttle valve.

The use of natural gas is not practical for long distance transportation. Natural gas has a low energy density related to the volume, therefore the range is too little.

<b>Regional specifications in the EU</b>
Not relevant.
<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
The tests in Germany will run until 2003. The result of the tests will show whether new developments will be initiated.
<b>Internal and external resources</b>
<p>Information from web pages:</p> <p>DEUTSCHE BAHN AG (<a href="http://www.db-ftz.de">www.db-ftz.de</a>)</p> <p>DEUTSCHE BAHN AG (<a href="http://www.erdgaslok.de">www.erdgaslok.de</a>)</p> <p>ZEPPELIN GMBH (<a href="http://www.zepelin.de/D/powersystem/02eisenbahn.html">www.zepelin.de/D/powersystem/02eisenbahn.html</a>)</p> <p>RUHRGAS AG (<a href="http://www.erdgasinfo.de">www.erdgasinfo.de</a>)</p>

<b>Description of the calculation to obtain the quantitative figures</b>
<p><b><u>Economy figure:</u></b> No data available.</p> <p><b><u>Ecology figure:</u></b> The locomotives powered by natural gas develop considerably less noise than comparable diesel powered locomotives. If the engine flap is open the noise level lies only at 50 % of the noise level of diesel powered locomotives. The reduction of the emissions of NO<sub>x</sub>, CO and HC lies between 50 to 80 %. The release of CO<sub>2</sub> of natural gas is about 25 % less than the diesel values. Locomotives powered by natural gas do not emit soot.</p> <p><b><u>Efficiency figure:</u></b> No data available.</p>

Quantitative assessment of the module for the present state	
<b>Output unit:</b>	
<b>Economy:</b>	
Costs (€) per output unit	n/a
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	approx. 585
Emissions of other pollutants [kg]	NO <sub>x</sub> : approx. 1.2 – 1.8 CO: approx. 0.4 - 0.6 HC: approx. 0.1 - 0.2
<b>Efficiency:</b>	
Input energy	n/a

Qualitative assessment of the module for the present state					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>			x		
Emissions of other pollutants				x	
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure				x	
<b>Other indicators</b>					
Readiness for market			x		
Hazardousness			x		
Complexity of technique				x	
Standardisation				x	

<b>No.:</b>	C4-T4	<b>Railway – Gas Turbine</b>
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Class	4	Input from:	Module : C3T5, C3P1, C3P2, C3P3
Category	Railway	Output to:	-

**General description of the process**

In gas turbines the energy conversion is done continuously. A compressor heats the air intake and compresses it to 5 bar. A part of this air pre-heated in the heat exchanger is burned in the gas turbine combustor together with the fuel to be cooled down to approximately 1,300°C with the rest of the air at the exit of the turbine. The remaining temperature gradient will be reduced at the connected turbine. The adjustment to the different load demand is done via the regulation of the temperature of the working gases as well as by moving the guiding blades of the compressor and the turbines. The high working temperatures lead to high demands with respect to the components used. Gas turbines achieve efficiencies between 33 to 42 %.

Gas turbines can power locomotives, motor rail coaches and motor-coach trains. The advantage of the gas turbines is given by the fact that they are smaller and lighter than common diesel engines with three to four times the power of the diesel engines. The major disadvantage is that the fuel consumption is approximately double the consumption of a conventional diesel engine, which leads to a considerably reduced range. Another disadvantage is the high noise level. Fuels that can be used are: natural gas, diesel, kerosene and jet fuel.

Other negative aspects accompanying the above mentioned disadvantages are the reduced suitability for low performance ranges, the poor response characteristic in comparison with the piston engine, the costs of 15 to 25 €/kW. The lifespan lies only between 2,000 to 4,000 hours of operating.

Principally gas turbines are suitable for the re-equipment for the operation on hydrogen. The operation with a mixed gas is effected without any problems today as one can rely on experiences on the addition of up to 80 % of H<sub>2</sub>. The usage of pure hydrogen however generates considerably problems. Due to higher combustion temperatures as in case of the operation on natural gas the operation on pure hydrogen will lead to increased emissions of NO<sub>x</sub> that can be reduced via water injection but cannot be brought under the required limiting values.

In the USA there is one application of the gas turbine for long distance transportation on the market. Bombardier Transportation has developed a so called jet train with a maximum speed of 240 km/h, designed for the North-American market. This Bombardier JetTrain is powered by a gas turbine derived from a Pratt & Whitney PW 150, which replaces the traditional diesel engine found in most current rail equipment, but which is also fuelled with diesel. The acceleration is twice compared to an diesel engine whereas the emissions and the release of CO<sub>2</sub> are considerably lower.

However, there do not exist any usages of gas turbines for railways in Europe today.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

The use of gas turbines for railways is not expected to come on the market in the future in Europe.

<b>Internal and external resources</b>
BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000
<u>Information from web pages:</u>
DR. IHLI INGENIEURPLAN GMBH (www.gasturbine.de)
MTU FRIEDRICHSHAFEN GMBH (www.mtu-friedrichshafen.com)
SULZER LTD. (www.sulzer.com)
VERICOR POWER SYSTEMS (www.vericor.com)
BOMBARDIER TRANSPORTATION (www.transportation.bombardier.com)

<b>Description of the calculation to obtain the quantitative figures</b>
<b><u>Ecology figure:</u></b>
Greenhouse gases: -30 % (Bombardier JetTrain)
No further data available.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption	x				
Release CO <sub>2</sub>	dependent on fuel				
Emissions of other pollutants					x
Emissions of noise	x				
<b>Vehicle aspects</b>					
Performance				x	
Range		x			
Refuelling procedure	dependent on fuel				
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness	dependent on fuel				
Complexity of technique		x			
Standardisation	x				

<b>No.:</b>	C4-T5	<b>Railway – Fuel Cell on Hydrogen</b>
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Class	4	Input from:	C3T4, C3T5, C3P1, C3P2
Category	Railway	Output to:	C4T7

<b>General description of the process</b>	
<p>Principally hydrogen could be a potential energy carrier in rail vehicles. Detailed specifications of fuel cells in general can be seen at the road transportation descriptions. However there do not exist any concrete and plausible technical solutions so far. For rail traffic the coupling of a fuel cell with an electric engine is considered to be an alternative for an advantageous drive system. Such a solution would follow the extensive experience about electric traction already available. The hydrogen used in this case will be transported in corresponding tanks in form of liquid hydrogen. This solution could offer a sensible alternative to diesel traction for long-distance not electrified routes. Locomotives powered by hydrogen could even be an alternative for short-distance travel.</p> <p>In the USA there are actuation concepts developed based upon the PAFC fuel cell (= phosphor-acid fuel cell) as here the demand for electrification is low. The first fuel-cell powered locomotive operated in a mine in the USA.</p> <p>The performance spectre of the PEM-fuel-cell (proton-exchange-membrane) lies between 1 kW to 1MW whereas the performance of the MCFC-fuel cell (molten carbonate fuel cell) amounts to 300 kW to 10MW.</p>	

<b>Regional specifications in the EU</b>	
Not relevant.	
<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>	
There are no foreseeable developments for an application for railway traffic in the near or remote future.	
<b>Internal and external resources</b>	
<p><u>Information from web pages:</u></p> <p>L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) (<a href="http://www.hydrogen.org">www.hydrogen.org</a>)</p> <p>MTU FRIEDRICHSHAFEN GMBH (<a href="http://www.mtu-friedrichshafen.com">www.mtu-friedrichshafen.com</a>)</p> <p>VIEREGG-RÖSSLER GMBH (<a href="http://www.vr-transport.de">www.vr-transport.de</a>)</p>	

**Description of the calculation to obtain the quantitative figures**

No data available.

**Qualitative assessment of the module for the present state**

	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	C4-T6	<b>Railway – Electric Propulsion by Battery</b>
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Class	4	Input from:	-
Category	Railway	Output to:	-

**General description of the process**

An electric actuation via electric engine powered by batteries does not generate any emissions during operation and this fact makes it environmentally-friendly. Besides the electric actuation is a low noise actuation. In rail traffic electric locomotives powered by batteries, the so-called accumulator locomotives are rather the exception. Due to the low capacity of the batteries the range of these vehicles is reduced. Other disadvantages of batteries are the long charging time, the reduction of performance due to idling and cold weather.

As such accumulator locomotives do not operate continuously the breaks can be used for the charging of the batteries. A replacement of the empty batteries by charged batteries is possible only under certain conditions. Some of these accumulator locomotives operate only on battery electricity, others are powered via current collectors or conductor rails and usually the batteries can be recharged during operation. For this reason accumulator locomotives are used as working locomotives for the removal of defective motor coaches, to move working devices within the area of defective or non-existent conductor lines and for shunting.

The characteristics of the lead batteries used are:

Specific capacity:	30 to maximum 50 Wh/kg
Specific performance:	150 to 400 W/kg
Life span:	3 to 5 years
Number of charging cycles:	500 to 1,000

The costs for lead batteries are relatively low lying between 100 to 150 €/kWh in comparison to the costs for nickel/cadmium batteries of 225 to 300 €/kW. This means that the number of batteries needed influences the decision for a certain type of battery. The higher the number of batteries needed the more sensible it would be to use lead batteries.

If the accumulator locomotive is powered by two electric engines of 2\*154 kW with a starting tractive power of 135 kN and a maximum speed of 40 km/h the locomotive could reach a battery performance of 640V respectively 360Ah. The period of operation would be 45 minutes. This shows that battery powered locomotives will remain the exception when it comes to vehicle traffic on a regular basis.

The low capacity of batteries in combination with the long charging periods makes batteries unsuitable for rail traffic, especially for long distance transportation.

**Regional specifications in the EU**

The implementation of the accumulator locomotives in the colder regions of the EU in the North would be a problem because of the particular characteristics of a battery.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

The use of electric propulsion by battery for railways is not expected to come on the market in the future in Europe.

<b>Internal and external resources</b>
BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000
KIEPE ELEKTRIK GMBH (www.kiepe-elektrik.com/sonderfahrzeuge/muenchen)

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	kWh
<b>Economy:</b>	
Costs (€) per output unit	Lead battery: 100 to 150 Nickel/cadmium: 225 to 300
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	n/a
Emissions of other pollutants	n/a
<b>Efficiency:</b>	
Input energy	n/a

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance	x				
Range	x				
Refuelling procedure	x				
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness				x	
Complexity of technique					x
Standardisation					x

<b>No.:</b>	C4-T7	<b>Railway – Fuel Cell on Methanol</b>
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Class	4	Input from:	C3T1, C4T5
Category	Railway	Output to:	-

**General description of the process**

Liquid methanol as carrier for hydrogen could only be used for railway transportation provided that the existing infrastructure has been slightly adapted. A direct reforming to hydrogen and the following supply of a fuel cell or the conversion of the chemical energy of the methanol into electrical energy in a direct-methanol-fuel-cell (DMFC) at present under development would be possible. If the infrastructure does not suffer any modifications the efficiency would decrease as the reforming of hydrogen requires by 20 to 25 % of the specific energy of the methanol.

Its low ozone producing potential in comparison with diesel and its rather simple production from synthesis gas gives the advantages of methanol as fuel. The disadvantages of methanol are mainly the high toxicity and the low specific energy of about 50 % in comparison to diesel (see table below). The building up of a new infrastructure is not considered to be sensible at present.

Fuel	Specific energy [kWh/kg]	Specific energy [kWh/l]
Methanol	5.6	4.42
LH <sub>2</sub>	33.3	2.36
GH <sub>2</sub> (700 bar)	33.3	1.23
Reference: Diesel	12.0	9.80

Depending on the further development e.g. concerning handling, efficiency, capacity performance and costs it must be decided if the PEM-fuel cell with reformer or the direct-methanol-fuel-cell (DMFC) will be applied.

Fuelling with methanol can be done in analogy to the conventional filling up with diesel fuel, whereas the high toxicity of methanol must be attended and adequate precautions must be made.

However, there do not exist any usages of fuel cell with methanol for railways in Europe today.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

There is no indication of the use of methanol-based fuel cell for railway transportation in the near or remote future.

**Internal and external resources**

BEWAG Innovationspark Brennstoffzelle ([www.innovation-brennstoffzelle.de](http://www.innovation-brennstoffzelle.de))

BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000

**Description of the calculation to obtain the quantitative figures**

No data available.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>			x		
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique		x			
Standardisation		x			

<b>No.:</b>	<b>C4-S1</b>	<b>Shipping - Conventional Piston Engine</b>
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Class	4	Input from:	C3T5, C3P3
Category	Shipping	Output to:	-

**General description of the process**

Inland navigation and costing require engines with a high performance and broad application spectre. Furthermore vessel engines must have a very high reliability. There exist engines with several different types of construction. The main features are as follows:

- Diesel engines with water or air cooling
- 2-stroke and 4-stroke diesel engines in row design with 4 to 6 cylinders
- 48°V-design or 90°-design with 8, 9, 10, 12 and 16 cylinders
- Aspirating engine design with exhaust gas turbocharger and charge cooling most often invested with boost control (waste-gate procedure)

Fuel injection is done under normal or high pressure. The engines have a high specific output, a low noise level, a soft and smooth run, a reduced fuel consumption in the entire load sector and long life in connection with a reduced demand for maintenance.

Principally all conventional vessel engines can operate on diesel oil or heavy fuel. The heavy fuel must be brought to a temperature of 125 degrees Celsius before combustion. Only after this heating procedure it can be injected into the combustion engine. Heavy oil is formed of the residues of the refinery process of crude oil to petrol, diesel and other light heat oils. 80 % of the vessels worldwide operate on heavy oil. The ISO 8217 standard refers to the fact that the vessel fuels must consist of mixtures of hydrocarbons resulting from the oil refinery process. According to this standard fuels should not contain any other additives or chemical residues. For this reason the vessel engine manufacturer recommend a quick test of the quality of the bunker oil in order to avoid engine damage.

Diesel vessel engines can be classified into the operational categories light, medium and heavy operation whereas the diesel engines could be 2-stroke engines running at slow speed with 400 rotations per minute. This type of engine has a very favourable efficiency and can combust residues with an extremely high viscosity. A disadvantage are the rather high NO<sub>x</sub> emissions, a high weight and the fact that it requires a lot of space. The 4-stroke engines running at medium speed with 400 to 1200 rotations per minute are also combusting residue oils and have a high thermal efficiency. They require less space, but a gearbox must be installed between the engine and the propeller.

Fast running engines with more than 1,200 rotations per minute have small weights and require only little space. They are used mainly on ferries and passenger vessels. This type of engine has a reduced efficiency in comparison with the 2-stroke or 4-stroke engine and requires bunker oils of higher quality (more expensive). The efficiency of vessel diesel engines lies between 20 to 40 %.

The inland vessel types can be classified as follows:

	Carrying capacity [t]	Motor capacity [kW]
Motor tanker	400-3,200	184-1471
Motor freight vessel	220-3,000	74-2,206
Pushing motor barge	1,240-5,000	368-4,418
Passenger vessel	-	184-1,471

The fuelling of the inland waterway vessels can be done in harbours or docked to special fuel vessels which can refuel the vessels at full speed. Refuelling of coast motor vessels is done in harbours. A fuel

vessel can carry between 5,000 to 10,000 l of diesel, whereas the price for the fuel amounts to approximately 0.30 €/l. Fuel for navigation is tax exempted. Germany had 184 fuelling stations for vessels and fuel vessels in the year 2000.

The life time of a ship amounts to several decades. Therefore it is obvious that the implementation of new technologies takes a long time. To speed up this transition period, also further developments in the existing fleet are necessary.

### **Regional specifications in the EU**

Norway and Sweden operate with a graduated system of harbour and area taxes aimed to reduce the emissions of NO<sub>x</sub> and SO<sub>2</sub> in sea transport. Ships with low emissions are granted a harbour discount.

### **Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

No technical changes planned for diesel vessel engines for the next 10 to 20 years.

### **Internal and external resources**

UNIVERSITÄT BREMEN, Koordinationstelle (Ed.): Das sozial- und umweltfreundliche Schiff – eine Innovations- und Beratungsaufgabe (S.U.S), (writer: Ulrich, P.), 2000

BERATERGRUPPE FÜR VERKEHR UND UMWELT GMBH (BVU); INSTITUT FÜR WIRTSCHAFTSFORSCHUNG (IFO); PLANCO; ITP: Traffic forecast 2015, by order of the Federal Ministry for Traffic, Construction and Housing, München; Freiburg; Essen, 2001

GAUSS: Umweltverträgliche Entsorgungskonzepte für die Seeschifffahrt, 1997

FEDERAL ASSOCIATION OF THE GERMAN INLAND WATERWAYS; ASSOCIATION FOR EUROPEAN INLAND WATERWAY TRAFFIC AND WATERWAYS: Inland waterway traffic in figures 1994

KOEHLER, H. W.: Worldwide NO<sub>x</sub> Emissions From Merchant Shipping, 24th Annual Marine Propulsion Conference 2002, The Motor Ship, 10-11 April 2002, Copenhagen, 2002

CENTRAL COMMISSION FOR NAVIGATION ON THE RHINE: Rheinschiffsuntersuchungsordnung (Rhein-SchuUO), 1995, edition 2000, Strasbourg 2000

#### Information from web pages:

WWW VITRUAL LIBRARY, Admiralty and Maritime Law Group ([www.admiraltylawguide.com](http://www.admiraltylawguide.com))

BUNDESVERBAND DER DEUTSCHEN BINNENSCHIFFFAHRT (BDB), Germany ([www.binnenschiff.de](http://www.binnenschiff.de))

BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE (BSH), Germany (<http://www.bsh.de/Schiffahrtssdienste/Seeschiffsbestand.htm>)

DEUTZ AG ([www.deutz.de](http://www.deutz.de))

CENTRAL COMMISSION FOR NAVIGATION ON THE RHINE ([www.ccr-zkr.org](http://www.ccr-zkr.org))

INTERNATIONAL MARITIME ORGANIZATION (IMO) ([www.imo.org](http://www.imo.org))

MAN B&W DIESEL GROUP ([www.manbw.de](http://www.manbw.de))

MTU FRIEDRICHSHAFEN GMBH ([www.mtu-friedrichshafen.com](http://www.mtu-friedrichshafen.com))

ROLLS-ROYCE DEUTSCHLAND LTD. & CO KG ([www.rolls-royce.de](http://www.rolls-royce.de))

SCANIA ([www.scania.se](http://www.scania.se))

SCHIFFSSERVICE BERLIN ([www.schiffsservice.de](http://www.schiffsservice.de))

VOLKSWAGEN MARINE ([www.volkswagen-marine.com](http://www.volkswagen-marine.com))

VOLVO GROUP ([www.volvopenta.com](http://www.volvopenta.com))

## Description of the calculation to obtain the quantitative figures

### **Economy figure:**

Fuel consumption: 270 l/100 veh.-km up to 1,700 l/100 veh.-km

Fuel price: 0.30 €/l

### **Ecology figure:**

Emissions [kg/kg diesel]:

CO <sub>2</sub>	3.20
NO <sub>x</sub>	0.072
CO	0.0085
HC	0.0026

Since 2002 the Rhine navigation has new exhaust fumes limits for new installed engines of inland navigation vessels. (n= number of revolutions) [Zentralkommission für die Rheinschifffahrt: Rheinschiffsuntersuchungsordnung (RheinSchuUO), 1995, edition 2000]:

Motor rating [kW]	CO [g/kWh]	HC [g/kWh]	NO <sub>x</sub> [g/kWh]	Particles [g/kWh]
37 up to 75	6.5	1.3	9.2	0.85
Over 75 up to 130	5.0	1.3	9.2	0.70
Over 130	5.0	1.3	n≥2800/min = 9.2 500≤n≤2800/min = 45	0.54

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	100 veh.-km (Ship)
<b>Economy:</b>	
Costs per output unit	81 - 510 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	approx. 4,460
Emissions of other pollutants [kg]	NO <sub>x</sub> : approx. 100.0 CO: approx. 12.0 HC: approx. 3.6
<b>Efficiency:</b>	
Input energy	2,640 – 16,588 kWh
Efficiency factor	20 to 40 %

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants	x				
Emissions of noise		x			
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market					x
Hazardousness			x		
Complexity of technique					x
Standardization				x	

<b>No.:</b>	C4-S2	<b>Shipping - Biodiesel Piston Engine</b>
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Class	4		C3T3
Category	Shipping	Output to:	-

**General description of the process**

In general it is possible to operate ships with biodiesel. Piston combustion engines running on bio-diesel nowadays have to fulfil the same requirements as the conventional vessel diesel engines. The combustion of bio-diesel according to the standard E DIN 51606 produces less soot, CO and hydrocarbons and is free of carbon dioxide and sulphur. These emissions can be reduced even more if bio-diesel is used in combination with an oxidation catalyst. The fact that bio-diesel does not contain any sulphur ensures the optimal and durable functioning of this exhaust cleaning device.

Inland waterway shipping can use both pure bio-diesel and a blend of conventional diesel and bio-diesel. Attention must be paid to the fact that the fuel filter has to be changed after several fill-ups with bio-diesel if the engine had been running for a longer time on conventional diesel. Due to the fact that bio-diesel acts like a solvent the residues from conventional diesel could lead to the clogging of the fuel filters. In some cases the usage of bio-diesel could lead to an increased fuel consumption or to a reduced output of the diesel engine of the vessel. If bio-diesel is used the oil should be changed twice as often as is necessary if conventional diesel is used. Using some additives the Cold Filter Plugging Point (CFPP) is  $-20^{\circ}\text{C}$ .

Engines running on bio-diesel can drive inland waterway vessels or can function as additional components on vessels. A test engine running on bio-diesel with a power of 770 kW can drive a motor freight ship, a light pushing motor barge or a passenger ship. The engine operates on a conventional injection pump but is invested with special washers at the cylinders. This re-equipment has no financial significance. The consumption of the bio-diesel engine is about 10 % higher compared with conventional diesel.

Another possibility would be using a mixture of conventional and bio-diesel as fuel. Scientists at the University of Oldenburg found out that even the addition of small quantities of bio-diesel could lead to a considerable increase of the bacterial count if this mixture is stored at  $25^{\circ}\text{C}$ . So the long-term storage of this type of fuel could be problematic as the micro-organisms will degrade it and will corrode the tanks. In the end the fuel will lose its utility value due to the impurities in it. The usage of this fuel mixture would be especially problematic in inland waterway shipping as these ships often carry with them high quantities of fuel.

Like conventional diesel, the fuelling of the inland waterway vessels is done in harbour or by special fuel vessels that can fill up the ships while on speed. Biodiesel getting into the water causes much less damage than conventional diesel does.

**Regional specifications in the EU**

The CFPP (=cold filter plugging point) of biodiesel is  $-20^{\circ}\text{C}$ . This means that there can occur problems in the very northern regions of Europe.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

No technical changes planned for diesel vessel engines for the next 10 to 20 years.

**Internal and external resources**

OEHLMÜHLE LEER CONNEMANN GMBH & CO: Starten Sie mit Biodiesel in eine blühende Zukunft

Information from web pages:

BUNDESVERBAND DER DEUTSCHEN BINNENSCHIFFFAHRT (BDB), Germany ([www.binnenschiff.de](http://www.binnenschiff.de))

OELMÜHLE LEER CONNEMANN GMBH & CO ([www.biodiesel.de](http://www.biodiesel.de))

MAN AG ([www.man.de](http://www.man.de))

MAN B&W DIESEL GROUP ([www.manbw.de](http://www.manbw.de))

MAN NUTZFAHRZEUGE AG ([www.mn.man.de](http://www.mn.man.de))

MTU FRIEDRICHSHAFEN GMBH ([www.mtu-friedrichshafen.com](http://www.mtu-friedrichshafen.com))

SCHIFFSSERVICE BERLIN ([www.schiffsservice.de](http://www.schiffsservice.de))

UNIVERSITÄT OLDENBURG, PRESSE UND INFORMATION  
([www.uni-oldenburg.de/presse/uni-info/ui-9604/wifo.htm](http://www.uni-oldenburg.de/presse/uni-info/ui-9604/wifo.htm))

VOLKSWAGEN MARINE ([www.volkswagen-marine.com](http://www.volkswagen-marine.com))

**Description of the calculation to obtain the quantitative figures**

**Economy figure:**

Fuel consumption: 300 l/100 veh.-km up to 1,900 l/100 veh.-km

Fuel price: 0.35 €/l

**Ecology figure:**

Biodiesel features considerable advantages with respect to hydrocarbons, carbon monoxide and particles when compared to conventional diesel.

Emission of pollutants by biodiesel compared to conventional diesel:

Pollutants	Direct injection	Chamber engines
CO	-10%	-12%
HC	-10%	-35%
NO <sub>x</sub>	+12%	+8%

The release of CO<sub>2</sub> of biodiesel accounts for about 25 % of the values of diesel engines.

An increased fuel demand of about 10 % must be taken into account.

Whereas in case of mineral diesel the share of sulphur has to be reduced by way of an energy-intense process leading also to an increase of the release of CO<sub>2</sub> and to a loss of the oiliness of the fuel bio-diesel can be considered as sulphur-free (max. concentration of sulphur: 0,001%) and despite of this fact it has excellent lubricating properties and this way the wear of the engine is reduced. The fact that bio-diesel is actually sulphur-free allows for an optimum and trouble-free usage of an oxidation catalyst.

The cetane number of bio-diesel (58) is higher than the cetane number of mineral diesel (49-53). The high cetane number leads to a reduction of the ignition delay meaning that the pressure in the cylinder is lower. This way the wear of the engine is reduced ensuring a greater smoothness in running.

Bio-diesel does not contain benzene or other aromatic compounds.

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	100 veh km (Ship with chamber engine)
<b>Economy:</b>	
Costs per output unit	approx. 105 - 665 €
<b>Ecology:</b>	
Emission of CO <sub>2</sub> per output unit [kg]	approx. 1,230
Emissions of other pollutants [kg]	NO <sub>x</sub> approx. 108.0 CO approx. 10.6 HC approx. 2.3
<b>Efficiency:</b>	
Input energy	2,810 – 17,808 kWh
Efficiency factor	20 to 40 %

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>	x				
Emissions of other pollutants	x				
Emissions of noise		x			
<b>Vehicle aspects</b>					
Performance					x
Range					x
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market		x			
Hazardousness				x	
Complexity of technique			x		
Standardization			x		

<b>No.:</b>	C4-S3	<b>Shipping - Methane Gas Piston Engine</b>
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Class	4	Input from:	C3T4, C3T5, C3P1, C3P3
Category	Shipping	Output to:	-

**General description of the process**

Natural gas can be an alternative energy for ships. The advantages of natural gas as a fuel in comparison to diesel are the very clean combustion and the low carbon content leading to an obvious reduction of the emission of pollutants. Besides the combustion is very smooth as a result of the fact that the engines operate on an externally supplied ignition. The typical composition of natural gas is: 90 % methane and 10 % ethane. The main disadvantage is the low energy content with regard to the volume:

Fuel	Specific energy [kWh/kg]	Specific energy [kWh/l]
Methane (200 bar)	13.8	2.2
Reference: Diesel	12	9.8

Another alternative that can be used as a drive in vessels is the diesel-gas-engine. This engine can operate both on diesel and on natural gas. The change from liquid to the gaseous fuel is possible without an engine stop. The fuel is directed over a gas injection device to the engine. In this kind of engines extremely meagre mixtures can be ignited safely as required to comply with the NO<sub>x</sub> limiting values without catalyst exhaust treatment. These gas engines are particularly suitable for the simultaneous production of electrical and thermal energy. Due to the very small heat losses occurring (usage of the heat of the exhaust gas, cooling water, lubrication oil and charge air) a total efficiency of almost 90 % can be achieved. The output of the diesel-gas engine amounts to 2,400 kW in combination with a fuel consumption of 200g/kWh. The fuel consumption of a gas engine is approximately 35 % higher than the one of the diesel engine. This increase is the result of a reduction of the compression from 17.5:1 to 11:1 and of the heat losses through the throttle valve. The efficiency amounts to 41 %. The emissions of gaseous pollutants like NO<sub>x</sub> or HC are lying clearly below the limiting values of the Euro 3 standard for lorries.

The development of a new gas engine was aimed towards the usage of as many components of the diesel engine as possible to keep costs at a low level. By adding a throttle valve and a gas mixer as well as an ignition device the engine was adjusted to the principle of the Otto engine.

The natural gas needed is stored on board the ship under high pressure (200 bar) in gas cylinders. With the help of the gas pressure regulator the natural gas expands to the ambient pressure and is directed to the gas mixer. The formation of the mixture is done outside the burner in a gas mixer. During this procedure the natural gas will be mixed with fresh air in a kind of Venturi–nozzle at the tightest position in the negative pressure sector.

All components of a natural gas engine have to fulfil the highest standards with respect to impermeability and firmness.

**Regional specifications in the EU**

The diesel-gas engine could be used especially in countries with great deposits of natural gas.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

There are no foreseeable developments for an application for inland navigation in the near or remote future.

<b>Internal and external resources</b>
BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000
<u>Information from web pages:</u>
ARAL (www.aral.de)
BUNDESVERBAND DER DEUTSCHEN BINNENSCHIFFFAHRT (BDB), Germany (www.binnenschiff.de)
MAN AG (www.man.de)
MAN B&W DIESEL GROUP (www.manbw.de)
MAN NUTZFAHRZEUGE AG (www.mn.man.de/index/1/fr/aa/aa24.rtf)

<b>Quantitative assessment of the module for the present state</b>	
<b>Output unit:</b>	
<b>Ecology:</b>	
Emission of CO <sub>2</sub> (kg) per output unit	n/a
Emissions of other pollutants	n/a
<b>Efficiency:</b>	
Output energy per input energy	n/a
Efficiency factor	38%

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>			x		
Emissions of other pollutants				x	
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure				x	
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique				x	
Standardization			x		

<b>No.:</b>	C4-S4	<b>Shipping - Hydrogen Piston Engine</b>
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Class	4	Input from:	C3T5, C3P1, C3P2
Category	Shipping	Output to:	-

<b>General description of the process</b>
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The use of hydrogen as a fuel for shipping is in general possible. But there are only few single projects implemented in this field. One is the use of hydrogen for fisher boats in Iceland.

Hydrogen is one of the most promising energy carriers for the future. The usage of hydrogen as fuel for piston engines combines a high efficiency with low emissions. As actuation for ships, a direct injecting hydrogen diesel engine with high power density and low emissions could be used. When using hydrogen instead of diesel respectively heavy oil for fuel in big-size diesel engines the characteristic features of hydrogen have to be taken into consideration by implementation of an adjusted combustion concept.

Hydrogen differs from conventional hydrocarbons in its extremely wide limits of inflammability lying between 4 to 75 volume % hydrogen in air. The burning speed of hydrogen can be increased up to several hundred meters per second under favourable conditions. These characteristics can be used to burn very meagre mixtures with very low emissions of nitrogen oxides and despite of this to maintain a high efficiency. However these characteristics could also lead to very hard burning processes for instance if a smooth running deflagration turn over into a detonation. The strong pressure amplitudes occurring generate a considerable mechanical stress of the combustion area and of the moved parts. In order to achieve an efficient and reliable combustion procedure the basic knowledge about the influence of temperature, pressure, turbulences, gas composition and stream ratio is of major importance. In a ship combustion engine with direct injecting hydrogen the compression relations can increase up to 25. The maximum final compression pressure lies at approx.150 bar. The pressure during combustion can amount up to 200 bar.

<b>Regional specifications in the EU</b>
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Not relevant.

<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
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There are no foreseeable developments for an application for inland navigation in the near or remote future.

<b>Internal and external resources</b>
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Information from web pages:

TECHNISCHE UNIVERSITÄT MÜNCHEN, LEHRSTUHL FÜR THERMODYNAMIK ([http://www.thermo-a.mw.tu-muenchen.de/Lehrstuhl/Forschung/dorer\\_precht.html](http://www.thermo-a.mw.tu-muenchen.de/Lehrstuhl/Forschung/dorer_precht.html))

<b>Description of the calculation to obtain the quantitative figures</b>
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No data available.

<b>Qualitative assessment of the module for the present state</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption			x		
Release CO <sub>2</sub>					x
Emissions of other pollutants				x	
Emissions of noise			x		
<b>Vehicle aspects</b>					
Performance				x	
Range				x	
Refuelling procedure		x			
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique		x			
Standardization		x			

<b>No.:</b>	C4-S5	<b>Shipping - Gas Turbine</b>
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Class	4	Input from:	C3T5, C3P1, C3P2, C3P3
Category	Shipping	Output to:	-

**General description of the process**

The energy conversion in gas turbines is done continuously. In a compressor the aspired air will be brought to an operational pressure of approximately 5 bar. A part of this air pre-heated in the heat exchanger is burned in the gas turbine combustor together with the fuel to be cooled down to approximately 1,300°C with the rest of the air at the exit of the turbine. The remaining temperature gradient will be degraded at the connected working turbine. The adjustment to the different load demands is done via the temperature regulation of the working gases as well as via the moving of the guide blades on the compressor and on the turbine. The high operational temperature makes high demands on the components used. The efficiency achieved by gas turbines can lie between 30 to 45 %. The shaft output of realised gas turbines covers a range between 3,431 and 42,700 kW.

Gas turbines are especially attractive for yachts, high-speed ferries, freighters operating on liquid natural gas (=LNG) hovercraft (speeds up to 50 knots) and patrol boats as they are smaller and lighter than conventional diesel engines with three to four times the power of such a diesel engine but the fuel consumption is approximately the double of the one of the diesel engine and the noise level is high. Natural gas, diesel, kerosene or jet fuel can function as fuel. Gas turbines can also be used as on board support components for on-board power generation on vessels. The weight of the gas turbines in the performance class of 3,430 to 7,409 kW lies between 602 kg to 1,400 kg and the fuel consumption in this performance class comes to 930 kg/h gas and for oil of 1,000 kg/h. Gas turbines can be used independently or in combination with a diesel engine or a fuel cell (proton exchange membrane PME or solid oxide fuel cell SOFC) with an efficiency between 55 to 72 %, the electric output lying between 1 to 600 MW. Principally gas turbines can also be used for the adaptation to hydrogen operation. The operation on a mixture of gases functions without any problems today as admixtures of H<sub>2</sub> up to 80 % have been tested already. However the usage of pure hydrogen is more problematic. Due to higher burning temperatures as in case of the operation on natural gas the operation on pure H<sub>2</sub> generates higher emissions of NO<sub>x</sub> which can be reduced by water injection but cannot be brought below the limiting values required.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

There are no foreseeable developments for an application for inland navigation in the near or remote future.

**Internal and external resources**

BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000

Information from web pages:

L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) (hydrogen.org)

MTU FRIEDRICHSHAFEN GMBH (www.mtu-friedrichshafen.com)

NAVAL TECHNOLOGY, The Website for Defense Industries (www.naval-technology.com)

SULZER LTD. (www.sulzer.com)

VERICOR POWER SYSTEMS (www.vericor.com)

**Description of the calculation to obtain the quantitative figures**

No data available.

**Qualitative assessment of the module for the present state**

	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption	x				
Release CO <sub>2</sub>	dependent on fuel				
Emissions of other pollutants					x
Emissions of noise	x				
<b>Vehicle aspects</b>					
Performance				x	
Range		x			
Refuelling procedure	dependent on fuel				
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness	dependent on fuel				
Complexity of technique		x			
Standardization	x				

<b>No.:</b>	C4-S6	<b>Shipping - Fuel Cell on Hydrogen</b>
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Class	4	Input from:	C3T4, C3T5, C3P1, C3P2, C3P3
Category	Shipping	Output to:	-

<b>General description of the process</b>	
<p>Basically it is possible to use a fuel cell as a drive of ships. The fuel cell makes it possible to obtain electricity directly via the transformation of hydrogen and oxygen into water. This method has the advantage that it does not generate in place any CO<sub>2</sub>, pollutants or noise. Furthermore this process can be operated with a very high efficiency when compared to the operation of the internal combustion engine.</p> <p>Of all different types of fuel cells special attention is given to the application of the PEM-fuel cell. The advantages of this type of fuel cell are as follows: it can be operated at ambient temperature, the power density is very high and the electrolyte does not consist of any critical toxic substances. Most developers consider the PEM to be most suitable fuel cell mobile applications, nevertheless some are focusing on alkaline fuel cells or solid oxide fuel cells (SOFC). At the moment the disadvantages of all fuel cells are the high price, the lack of long term stability and the impossibility to make practical use of the theoretically very high efficiency.</p> <p>Today there exist only some first approaches for the development of fuel cells for navigation. These approaches refer only to small ships like yachts and motor boats. There are no developments of ships for the transportation sector.</p>	

<b>Regional specifications in the EU</b>	
Not relevant.	
<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>	
<p>4-stroke medium speed diesel engines often function as auxiliary engines to produce onboard electricity. There exist estimates that this kind of engine could be powered by a fuel cell in the near future.</p> <p>There do not exist any approaches for long distance navigation operated by fuel cells until now.</p>	
<b>Internal and external resources</b>	
<p><u>Information from web pages:</u></p> <p>REBEZELL GMBH (<a href="http://www.fuel-web.de">www.fuel-web.de</a>)</p> <p>L-B-SYSTEMTECHNIK, the Hydrogen and Fuel Cell Information System (HyWeb) (<a href="http://hydrogen.org">hydrogen.org</a>)</p> <p>SIEMENS MARINE SOLUTIONS (<a href="http://www.marine-solutions.de">www.marine-solutions.de</a>)</p> <p>MTU FRIEDRICHSHAFEN GMBH (<a href="http://www.mtu-friedrichshafen.com">www.mtu-friedrichshafen.com</a>)</p> <p>SULZER LTD. (<a href="http://www.sulzer.com">www.sulzer.com</a>)</p> <p>SIEMENS (<a href="http://www.w4.siemens.de">www.w4.siemens.de</a>)</p>	

**Description of the calculation to obtain the quantitative figures**

No data available.

**Qualitative assessment of the module (Perspective estimation of possible effects)**

	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>					x
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure			x		
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique		x			
Standardization		x			

<b>No.:</b>	C4-S7	<b>Shipping - Fuel Cell on Methanol</b>
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Class	4	Input from:	C3T1
Category	Shipping	Output to:	-

**General description of the process**

Methanol is another alternative for the operation of a fuel cell. As the reforming process is sophisticated bringing about energy losses, intense efforts are made to develop a possibility to achieve a direct conversion of the methanol in the fuel cell. This is called Direct-Methanol-Fuel-Cell (DMFC). A big advantage of the DMFC is that it requires less space and is cheaper than a combination of a fuel cell and reformer. Furthermore the deconvolution of the performance and the dynamics are higher. The development of the DMFC is based upon the development of the PEM fuel cell. The DMFC converts the methanol at the anode into protons and CO<sub>2</sub>. For this procedure even liquid methanol could be used and this way the process chain would be simplified considerably. However the DMFC is still in the stage of research. There still exist serious technological problems which need to be clarified before this procedure can be used on an industrial scale. Problems occur due to the fact that the fuel cell is polluted by methanol permeating the membrane leading to a loss in fuel and a decrease of the efficiency.

The table below indicates the weight and volume related specific energies of methanol and for comparison of LH<sub>2</sub>, GH<sub>2</sub> and diesel.

Fuel	Specific energy related to weight [kWh/kg]	Specific energy related to volume[kWh/l]
Methanol	5.6	4.42
LH <sub>2</sub>	33.3	2.36
GH <sub>2</sub> (700 bar)	33.3	1.23
Reference: diesel	12.0	9.80

Fuelling with methanol can be done in analogy to the conventional filling up with diesel fuel, whereas the high toxicity of methanol must be attended and adequate precautions must be made.

As described in C4S6 there are only few approaches for the development of fuel cells for the navigation sector.

**Regional specifications in the EU**

Not relevant.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Not relevant.

**Internal and external resources**

BRAESS H.-H.; SEIFFERT, U.: Handbuch Kraftfahrzeugtechnik, 1. Ed., Vieweg Publishing House, Braunschweig, 2000

METHANOL INSTITUTE ([www.methanol.org](http://www.methanol.org))

<b>Description of the calculation to obtain the quantitative figures</b>
No data available.

<b>Qualitative assessment of the module (Perspective estimation of possible effects)</b>					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
Direct energy consumption				x	
Release CO <sub>2</sub>			x		
Emissions of other pollutants					x
Emissions of noise					x
<b>Vehicle aspects</b>					
Performance			x		
Range			x		
Refuelling procedure					x
<b>Other indicators</b>					
Readiness for market	x				
Hazardousness			x		
Complexity of technique		x			
Standardization		x			

<b>No.:</b>	C4-A1	<b>Kerosene Airplane</b>
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class	4	input from:	C3P2
category	Air traffic	output to:	

**General description of the process**

Currently kerosene is practically the only fuel used in air travel. There are serious environmental impacts caused by combustion. Especially the greenhouse gas carbon dioxide (CO<sub>2</sub>) is emitted to a large amount. Further pollutions occur through the emittance of nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), hydrocarbons (HC), sulphur dioxide (SO<sub>2</sub>) and soot.

**Regional specifications in the EU**

Kerosene is used and stored at all airports throughout the EU.

**Foreseeable intermediate (5-10 years) and long-term (25-30 years) development**

Several technical improvements are planned. There is an emphasis on the development of engines with low nitrogen oxide (NO<sub>x</sub>) emissions. Currently there are engines with combustion technologies called “Dual annular Combustor” on the market. For instance, future technologies are the “Lean Premixing Prevaporising (LPP)” and the “Rich Burn Quick Quench (RBQQ)”. Moreover there are experiments with modifications of the aircraft body such as “raked wingtips” for reduction of wingtip vortices and laminations derived from fishsurfaces for drag reduction. Parts of these technologies proved their functionality in the experimentation phase, so an implementation in the future appears to be realistic (e.g. “winglets” in already in use with the newest Boeing 737 generation).

**Internal and external resources**

CARLSSON, F.; HAMMAR, H.: Incentive-based regulation of CO<sub>2</sub> emissions from international aviation, *Journal of Air Transport Management*, 365-372, 2002

DÖPELHEUER, A.: Aircraft emission parameter modelling, *Air & Space Europe Vol.2 No.3*, 34-37, 2000

HEINEN, F.: Maßnahmen zur Reduzierung der Schadstoffemissionen des Flugverkehrs, *Internationales Verkehrswesen* 11/2002

KLUG, H.G.; FAASS, R.: Cryoplane: Hydrogen fuelled aircraft – status and challenges, *Air & Space Europe vol.3 No.3/4*, 252-254, 2001

MARQUART, S.; SAUSEN, R.; PONATER, M.; GREWE, V.: Estimate of the climate impact of cryoplanes, *Aerospace Science and Technology vol.5*, 73-84, 2001

POHL, H.W.; MALYCHEV, V.V.: Hydrogen in future civil aviation, *International Journal of Hydrogen Energy Vol. 22, No. 10/11*, 1061-1069, 1997

SCHUMANN, U.: Influence of propulsion efficiency on contrail formation, *Aerospace Science and Technology vol. 4*, pp.391-401, 9/2000

INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO) (<http://www.icao.int>)

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) (<http://www.grida.no/climate/ipcc/aviation/>)

### Description of the calculation to obtain the quantitative figures

#### **Economy figure:**

Currently the kerosene price in Germany varies between 0,2 and 0,25 € / liter. The kerosene consumption per 100 passenger-km is about 5 l. (Average fuel consumption value for aircraft fleet derived from various sources e.g. Lufthansa)

#### **Ecology figure:**

Source: Döpelheuer, A.: Aircraft emission parameter modelling (Air & Space Europe Vol.2 No.3, pp.34-37, 2000)

#### **Efficiency figure:**

Currently, the propulsion efficiency for turbojet engines is around 0.39 whereas the propulsion efficiency for turbofan engines, that provide a greater air mass flow through the engine, is around 0.76. The overall efficiencies are 0.20 and 0.30 for the turbojet and turbofan engines respectively. The overall efficiency may reach 0.5 for new engines to be built by 2010 through improved air by-pass and compression rates and overall combustion technologies.

### Description of the finding of some qualitative evaluations

#### **Ecology:**

The assessment for the direct energy consumption can be seen as good because there will be improved technology in the future. Nevertheless the release of CO<sub>2</sub> will stay high due to the hydrocarbonbased fuel. The same counts for the emission of other pollutants. As there have been great improvements for noise reduction in the past, it is questionable if this can be continued further that way in the future.

#### **Vehicle aspects:**

Performance and range have improved from aircraft generation to generation and are at a high standard already today. There will be further improvements in the future.

#### **Other indicators:**

As the current aircraft technology is kerosene based with several decades of experience all the other indicators can be seen as very good.

Quantitative assessment of the module for the present state	
<b>Output unit:</b>	vehicle-km
<b>Economy:</b>	
costs (ct)	1 – 1,25 (per passenger-km)
<b>Ecology:</b>	
emission of CO <sub>2</sub> (g)	23,085
emission of H <sub>2</sub> O (g)	9,784
emission of NO <sub>x</sub> (g)	115
emission of CO (g)	39
emission of HC (g)	9.7
emission of SO <sub>2</sub> (g)	4.4
emission of CH <sub>4</sub> (g)	0.5
<b>Efficiency:</b>	
Input energy (MJ)	311.6
GJ output energy per GJ input energy	(overall efficiency turbofan ratio) 0,3

Qualitative assessment of the module for the present state					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
direct energy consumption			x		
release CO <sub>2</sub>		x			
emissions of other pollutants		x			
emissions of noise				x	
<b>Vehicle aspects</b>					
performance				x	
range					x
refuelling procedure					x
<b>Other indicators</b>					
readiness for market					x
hazardousness					x
complexity of technique					x
standardisation					x

<b>No.:</b>	C4-A2	<b>Hydrogen Airplane</b>	
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class	4	input from:	C3T6, C3P3
category	Air traffic	output to:	-

<b>General description of the process</b>
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Hydrogen can be used in combustion engines and turbines. In air travel, it has many advantages over kerosene jet fuel. Produced on the basis of renewable energy sources, hydrogen completely avoids direct emissions of the most important greenhouse gas carbon dioxide (CO<sub>2</sub>). Moreover carbon monoxide (CO), hydrocarbons (HC), sulfur oxides (SO<sub>x</sub>) and particles are avoided as well. Besides the primary combustion product water, a very small amount of nitrogen oxides (NO<sub>x</sub>) is emitted caused by the presence of nitrogen in the air.

Compared to the combustion of kerosene, the water emission is 2.6 times greater for hydrogen. The resulting water vapour provides a greenhouse effect, but depending on the flight altitude. Below 10 km it is in contrast to CO<sub>2</sub> negligible, above 10 km it continually grows and dominates beyond 12 km. Nevertheless the residence time for water vapour (0.5-1 year) is by far shorter than for CO<sub>2</sub> (more than 100 years).

As hydrogen is an extremely clean fuel, the life of the jet turbines will be increased by 25 %, and the need for maintenance and repairs will be reduced respectively [Brewer 1991]. Its high calorific value reduces fuel weight by a factor of 2.8, which enables to use smaller engines with less noise.

Compared with kerosene liquid hydrogen (LH<sub>2</sub>) has a lower density and therefore requires larger fuel tanks. The large volume (4 times more than for an equivalent mass of kerosene) will necessitate fundamental changes to the configuration of the aircraft. Apart from that it must be cooled down to the liquid state (-253°C) for reasons of volume and weight of tanks. These as well as the pipes and valves have to have a very good insulation.

Originally DASA Airbus planned to develop and fabricate a prototype demonstrator of a regional jet aircraft of the type DO 328 which should be operated with liquid hydrogen having a range of 1100 km. This project was stopped in the meantime. Current studies consider only the possibility of replacing the kerosene operated auxiliary power unit with a fuel cell.

<b>Regional specifications in the EU</b>
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Liquid hydrogen could generally be stored everywhere. The number of european airports that would have to be equipped with an LH<sub>2</sub> Infrastructure ranges at least in the amount of 70.

<b>Foreseeable intermediate (5-10 years) and long-term (25-30 years) development</b>
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According to DASA/Airbus it is necessary to start the development of cryoplanes within the next 5 to 10 years to reach a significant share of the airplane market until the middle of the century because of an average lifecycle of planes of about 20 years.

Airbus believes that the first markets for the hydrogen airplanes will be Scandinavia and the west coast of the USA. Here the general conditions for the hydrogen technology are best for both the industrial development and the government aid.

Generally can be said, that the technology is not competitive with respect to the current boundary conditions, especially the low kerosene price in comparion to the expected hydrogen price.

### Internal and external resources

- BIRKENSTOCK, W.: Hydrogen aircraft fuel research plans, Flug Revue 9, 1998
- BREWER, G.D.: Hydrogen aircraft technology, CRC Press 1991
- CARLSSON, F.; HAMMAR, H.: Incentive-based regulation of CO<sub>2</sub> emissions from international aviation, Journal of Air Transport Management, 365-372, 2002
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- ILLGMANN, G.: Gewinner und Verlierer einer CO<sub>2</sub>-Steuer im Güter- und Personenverkehr
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- POHL, H.W.; MALYCHEV, V.V.: Hydrogen in future civil aviation, International Journal of Hydrogen Energy Vol. 22, No. 10/11, 1061-1069, 1997

### Description of the calculation to obtain the quantitative figures

#### **Ecology figure:**

The operation of an airplane with hydrogen powered engines is CO<sub>2</sub> free. Therefore only the calculation of the CO<sub>2</sub>-emissions of the energy chain leading to the produced hydrogen is important.

Burning in comparison (10km flight altitude):

1 kg kerosine = 3,16 kg CO<sub>2</sub> (1,24 kg water, CO, Soot, NO<sub>x</sub>, SO<sub>2</sub>, UHC)

1 kg hydrogen = 0,0 kg CO<sub>2</sub> (9,63 kg water, NO<sub>x</sub>)

But contrails in general will contribute to the anthropogenic greenhouse effect. Generally, the amounts for all emissions vary vastly for different flight altitudes (e.g. the amount of water for the hydrogen aircraft is 70 times greater for 12km flight altitude than for 9km flight altitude)

#### **Efficiency figure:**

The propulsion efficiency for turbojet engines is around 0.39 whereas the propulsion efficiency for turbofan engines is around 0.76. The overall efficiencies are 0.20 and 0.30 for the turbojet and turbofan engines respectively.

### Description of the finding of some qualitative evaluations

**Ecology:**

Based on the knowledge of the experts the figure for direct energy consumption and release of CO<sub>2</sub> can be seen as very good because the efficiency rate for LH<sub>2</sub> is higher than for kerosene and it doesn't generate any CO<sub>2</sub> at all. As there will be little but not negligible emissions of NO<sub>x</sub> the overall view for the other pollutants is good. Due to the higher efficiency rate of LH<sub>2</sub> in combination with less weight, the engines can be smaller and therefore less noise generating.

**Vehicle aspects:**

For performance, range and refuelling procedure to the state of the art there's no real assessment possible as there has not been any experience yet.

**Other indicators:**

The readiness for market is currently bad as there are no airplane prototypes constructed yet. Therefore no standardisation is foreseeable. Complexity of technique is higher than for kerosene as the hydrogen has to be cooled down and requires a good isolation and has to be under a certain pressure.

<b>Quantitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)	
<b>Output unit:</b>	vehicle-km
<b>Economy:</b>	
costs (ct) per output unit	n/a
<b>Ecology:</b>	
emission of CO <sub>2</sub> (g) per output unit	0
emissions of other pollutants: NO <sub>x</sub> (g)	7.0
H <sub>2</sub> O (g)	23,152
<b>Efficiency:</b>	
Input energy (MJ)	311.6
GJ output energy per GJ input energy	(overall efficiency figure) 0,3

<b>Qualitative assessment of the module for the long term perspective</b> (no reasonable data for present state available)					
	very bad	bad	medium	good	very good
<b>Ecology</b>					
direct energy consumption					x
release CO <sub>2</sub>					x
emissions of other pollutants				x	
emissions of noise				x	
<b>Vehicle aspects</b>					
performance					
range					x
refuelling procedure					
<b>Other indicators</b>					
readiness for market			x		
hazardousness				x	
complexity of technique			x		
standardisation			x		