LIFE CYCLE ASSESSMENT OF WOOD-BASED ETHANOL-DIESEL BLENDS (E-DIESEL)

EXECUTIVE SUMMARY

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ABSTRACT

Low ethanol-content diesel blends (E-diesel) have been studied in the present report. E-diesel can, in principle, provide an alternative energy source and, by displacing diesel (a fossil fuel), reduce its environmental burden. However, E-diesel production process itself consumes energy and has emissions to air.

To identify whether there are real savings in energy and emissions, a Life Cycle Assessment (LCA) has been carried out in order to thoroughly evaluate from cradle to grave all stages involved in E-diesel production and use, i.e. all by-products, transportation, raw materials production, disposal scenarios, etc. Two different E-diesel compositions (E-10 diesel and E-15 diesel) used in heavy duty diesel engines have been studied in the present report. Furthermore, the LCA covers two case studies: a bus fleet driven under urban traffic conditions and a truck fleet run mainly on highways.

Ethanol has been considered to be based on lignocellulosic material, more specifically on woodchips. E-diesel needs a fuel additive to enable a stable ethanol-diesel blend. The emulsifier used in this LCA is Akzo Nobel's Beraid® ED10.

Advantages and drawbacks of E-diesel implementation as fuel for captive fleets in Sweden have been identified in this report. On the one hand, negative aspects have been mainly referred to the issue that E-diesel is an experimental fuel yet. It is currently undergoing a very active demonstration stage towards governmental and engine manufactures acceptance, which is crucial to further steps aiming its commercialisation. On the other hand, there are many positive facts regarding the environmental performance of E-diesel. Impact on global warming diminish with about 10% in CO_2 emissions compared to ordinary diesel by replacing "fossil" CO_2 emissions with bioethanol's "green" CO_2. Air quality at the local level is either improved (20% and 10% decrease in particulate matter and SO_2 emissions) or remains stagnant (NO_x, CO and HC emissions, which may be reduced after fixing an optimised exhaust gases aftertreatment).

Results from this study present thus E-diesel as an attractive option due to its environmental behaviour and engine performance (it can be successfully implemented in unmodified diesel engines). Moreover, a future competitive market price makes this fuel a real and feasible alternative to traditional diesel.

1 INTRODUCTION

1.1 Aim

The main goal of this Life Cycle Assessment (LCA) is to evaluate low ethanol-content diesel blends (E-diesel) use as automotive fuel. Ethanol included in the study is produced from lignocellulosic raw materials, more specifically from woodchips. The LCA was carried out under a cradle-to-grave perspective. Therefore, all activities involved in the production of diesel, ethanol and additives, mixing of the different components and final use of the chosen fuel were taken into account.

Two case studies were applied to compare E-diesel vs. diesel under different traffic conditions: buses in a city and trucks on a highway. Results are compared in order to determine strengths and weaknesses of ethanol-diesel blends as a renewable biomass-based alternative to traditional transportation fuels. In order to achieve this, inventories of emissions will undergo an assessment and will be grouped as global or local environmental impacts for further interpretation of results.

1.2 Background

Over the past several decades, a growing vehicle fleet has spurred escalating fuel use, air pollutants in traffic fumes have sickened and killed people, while highways and urban development has devoured nature's lebensraum. Gases continuously coming out from exhaust pipes are considered to be a major role player in main target environmental problems such as global warming (due to uncontrolled emissions of greenhouse gases) and air pollution. The environmental burden of road transportation is very important and can be estimated as high as 5% of a country's GDP (see table 1) [Brown et al., 2001]. Therefore, it is not the fuel combustion alone, but its whole life cycle that has an impact upon nature and society and consequently has to be properly addressed.

Country, region or city	**Year**	**Share of GDP (%)**	**Costs Included in the Study**						
			Accidents	**Smog**	**Climate**	**Noise**	**Roads**	**Land & Parking**	**Congestion**
United States	1989	5.50	x	x	x	x	x	x	
European Union	Early 1990s	4.63	x	x	x	x	x		x
United Kingdom	1993	4.68 – 5.79	x	x	x	x	x		x
Mexico City	1993	5.60	x	x				x	x
Santiago, Chile	1994	6.71	x	x		x	x	x	x

Table 1. Estimates of societal costs of road transport as share of GDP. [Brown et al., 2001]

Renewable fuels or so-called "biofuels" can, in principle, provide a renewable energy source and, by displacing fossil fuels, reduce greenhouse gas emissions to the atmosphere. However, biofuels production process itself consumes energy and emits polluting gases. To identify whether there are real savings in energy and emissions, thorough evaluation from cradle to grave must be carefully carried out, including all stages involved in the studied fuel production and use, i.e. all by products, transportation, raw materials production, disposal, etc. An optimal tool to carry out such a thorough study is LCA, a methodology explained in ISO 14040s international standards.

There is a varied palette of biofuels available today (e.g. biodiesel, reformulated gasoline, etc.). From all different options, E-diesel has been chosen to be the target of the present study. Low ethanol-content diesel blends (i.e. E-diesel) reduce the formation of some pollutants by adding oxygenates to the fuel matrix [Ahmed, 2001] [Spreen, 1999]. Two fuel configurations are the most popular nowadays: E-10 diesel (10% ethanol, 88% diesel and 2% fuel additive) and E-15 diesel (15% ethanol, 83% diesel and 2% fuel additive).

Renewable fuels have to be biomass-based, hence ethanol in E-diesel is produced from biological feedstocks. From the various available options, lignocellulosic raw materials were selected as aim of the study. More specifically, ethanol is produced from woodchips, i.e. a waste generated at sawmills. And this is precisely the most attractive advantage of the technology taken into account, it is very flexible regarding possible feedstocks and most of them are considered to be residues: corn stover or wheat straw (agricultural waste), garden waste, paper waste, etc.

E-diesel use has been limited to captive fleets[1] in the present LCA, as many experts agree upon [McCormick, Parish, 2001]. Two different types of heavy duty diesel vehicles were taken into account: buses (driven under urban traffic conditions) and trucks (run under highway traffic conditions).

E-diesel has been recognised to be an attractive option due to its environmental behaviour and engine performance (it can be used in unmodified diesel engines). Moreover, a competitive market price makes this fuel a real and feasible alternative to traditional diesel.

Nevertheless, E-diesel is still an experimental fuel, which has not reached its commercialisation stage yet. This situation is due to some drawbacks that have been identified as:

- E-diesel cannot be safely handled as conventional diesel, but as gasoline due its physical properties.
- Engine manufactures are already waiting for more operation performance data to award E-diesel with an OEM warranty acceptance.
- Environmental officers have not recognised E-diesel as fuel yet. [AFDC, 2002]

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[1] Captive fleets are those with their own centralised fuel distribution infrastructure.

2 RESULTS

2.1 Life Cycle Impact Assessment

The transportation sector generates a big proportion of the overall emissions released to air. Moreover road transport of people and goods contribute to a great extent of the overall transportation-related emissions. [EEA, 2002a] [EEA, 2002b]

%	TRUCKS		BUSES			
	Diesel vs. E-10		Diesel vs. E-10		Diesel vs. E-15	
CO_2	-8	-3	-14	-8	-19	-11
CO	-8	-3	-20	-17	-27	-23
NO_X	-2	< 1	-4	< 1	-5	< 1
SO_2	-12	4	-8	-3	-11	-6
HC	16	-5	---	-4	---	-6
Particles	-18	-1				

Vehicles	Life Cycle

Table 2. Comparison of decrease or increase emission rates for all fuels and vehicles included in this LCA.

Aggregated figures of selected emissions from all LCIs are summarised in table 2. Variations (%) observed between the results from diesel and E-diesel use are presented. These results were classified into different impact categories (see sections 8 and 11 in the main report), so that they could be grouped on a nominal basis into two main sets. Those two selected groups were emissions with an impact either at the global level (e.g. global warming) or at the local level (e.g. "London" and "Los Angeles" smog). Thus, figures in red (see table 2) represent the effect of substituting diesel by E-diesel at the local level, i.e. taking into account those emissions measured at vehicles' exhaust. Figures in blue stand for the same (see table 2), but taking into account the whole life cycle (i.e. global environmental impact) of the studied fuels.

If an emission was found to be related to two or more impact categories, it was then assigned to that category that was found most relevant to be grouped according to the aim and scope of the present LCA.

2.1.1 Global impact

Global warming is the overwhelmingly major impact at the global level and carbon dioxide is the main greenhouse gas emitted by the transportation sector. In 2000, 92% of the CO_2 emitted by transport media in Europe was due to road vehicles, i.e. 25% of the overall CO_2 emissions were due to road transportation. [EEA, 2002a]

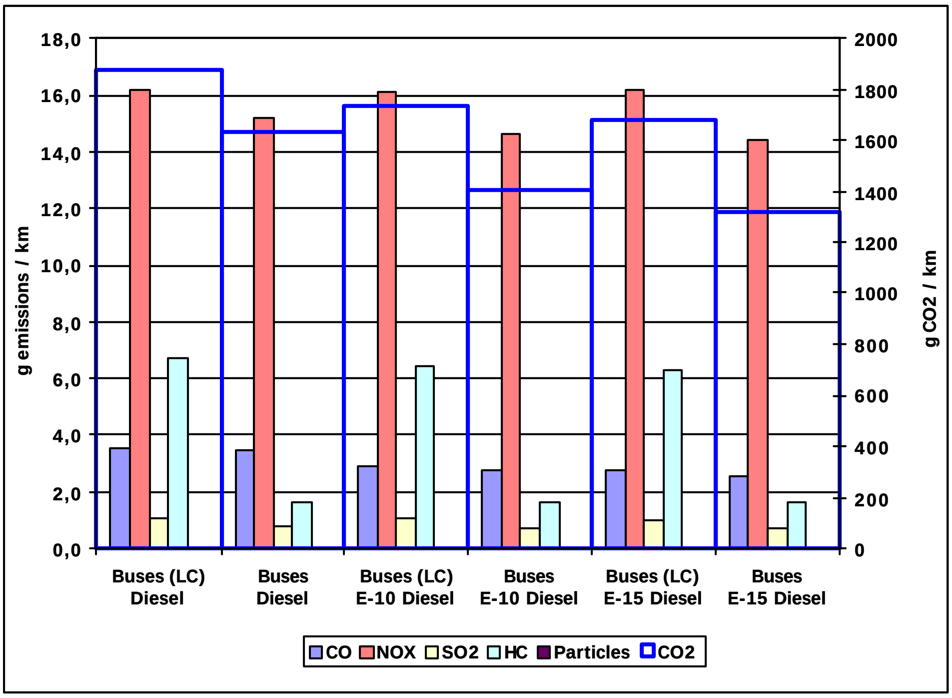

Figure 1. Overall emissions for buses under urban traffic conditions: whole life cycle (LC) and locally produced emissions.

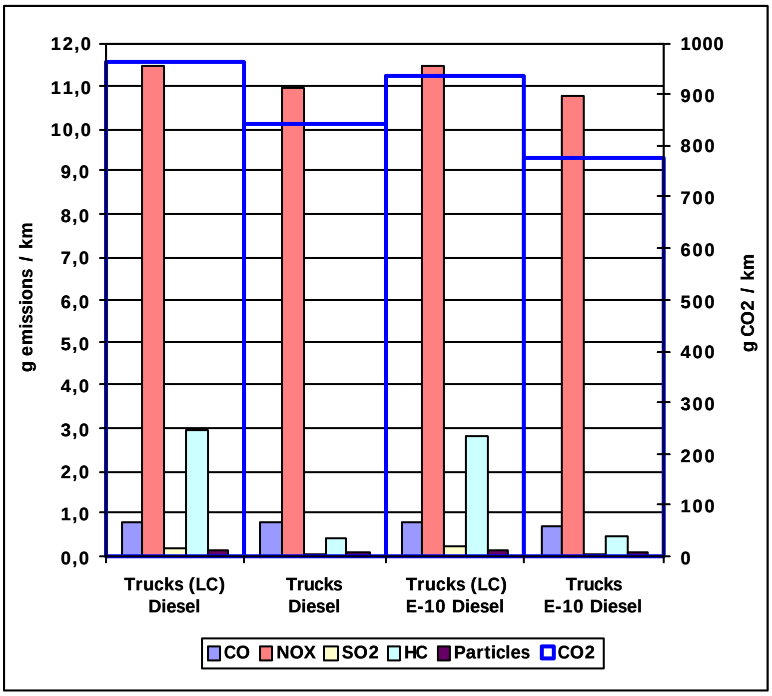

Figure 2. Overall emissions for trucks under highway traffic conditions: whole life cycle (LC) and locally produced emissions.

Better results regarding CO_2 emissions were observed in buses (average 10% reduction) than in trucks (neutral). This is mainly attributable to the fact that releases from buses were calculated to include only "fossil" CO_2. Tailpipe exhaust gases measurements in trucks include "green" CO_2, which has been neglected in buses. This is a valid approach regarding global impacts, since it takes into account the existing closed carbon cycle when biomass-based fuels are used.

2.1.2 Local impact

Carbon monoxide emissions by road transportation represented 55% of the overall European CO emissions in 2000 [EEA, 2002b]. CO emissions are major contributors to photochemical smog. Hence they are considered to have an impact on the local level. Results vary considerably from one author to another [Hansen et al., 2001b] [Spreen, 1999] [Wang et al., 1999] [WVU, 1999]. Therefore it is quite hard to state any definitive conclusion on CO emissions. However, even if the improvement in the environment cannot be exactly evaluated, it can be affirmed that E-diesel yields no major changes in air quality when introduced as a diesel substitute.

The main effect of both NO_x and HC was assumed to be their contribution to photo-oxidant formation ("Los Angeles" smog). Average contribution to European emission rates in year 2000 were 45% for NO_x and 30% for HC [EEA, 2002b]. Therefore they have an impact on the local environment and human health. One the one hand, very slight decreases in NO_x emissions show that no major changes are experienced at the exhaust pipe. On the other hand, E-diesel combustion does not increase HC releases.

It is very important not to forget that no after-treatment was installed at any measurement test. Therefore, it is assumed that proper fixing of catalysts and fuel injection optimisation will decrease these emission rates.

In cold and wet weather conditions, SO_2 emissions play a major role regarding "London" smog formation. This phenomenon is a big concern regarding human health issues. In both cases emissions are reduced at the local level. In the trucks case it was due to the diesel quality (ultra low sulphur diesel), whereas in the buses the reduction was mainly due to the reduction of diesel content in the fuel matrix.

27% of the overall particulate matter emissions in Europe were generated by road vehicles [EEA, 2002b]. Particles are strongly linked to human-health issues and thus to impacts on the local environment. It is mostly agreed among all authors that reduction of particulate emissions is the strongest asset of E-diesel as an alternative fuel. [Ahmed, 2001] [Hansen et al., 2001b] [Hansen et al., 2002] [Löfvenberg, 2002] [Spreen, 1999] [Wang et al., 1999] [WVU, 1999]

2.1.3 Ethanol production

Ethanol production contributes significantly both to local and global environmental impact of E-diesel. Carbon dioxide emissions attributable to ethanol range from 3.5% to 6% of overall releases to air (depending on its concentration in the fuel matrix). If they are compared with diesel production (11-12%), ethanol environmental impact regarding global warming is two, three times smaller, which is a rather big contribution.

Local impacts due to ethanol production are NO_x, CO and particulate matter emissions. NO_x release to air because of ethanol is somewhat bigger than half of what is emitted while refining diesel. Contributions to both CO and particles are bigger than those due to diesel production. Carbon monoxide emissions are almost twice as big as those at the refinery. Ethanol contribution to overall particles release to air is 12% versus 7.5% coming out from diesel.

All emissions are mainly allocated to heat generation (particles, NO_x and CO_2) and wood production (particles, NO_x, CO and CO_2). Heat comes from the surrounding factories at Domsjö industrial estate, whereas wood production operations include usage of machinery and transportation.

2.1.4 Beraid® ED10 production

Beraid® ED10 contributes only to local impacts attributable to E-diesel use. Particles released to air due to the production of Beraid® ED10 are important (about half of those generated at a diesel refinery).

On the other hand, 11.2% and 4.5% of SO_2 emissions are respectively allocated to Beraid® ED10 in low sulphur content and high sulphur content E-diesel blends. The contribution of this fuel additive is bigger as sulphur content grows, because the lower the sulphur content is, the more demanding that the diesel refining process becomes. Therefore at high sulphur contents in diesel, most of emissions are due to fuel combustion in vehicles, whereas at low sulphur concentrations releases are originated at E-diesel production (mainly due to fuel additive and diesel production).

All emissions are mostly generated at the production of B and C (Beraid® ED10 components found in bigger proportion). Product B contributes specially to global warming (CO_2). Its contribution is also very important regarding CO, NO_x and SO_2. On the other hand, product C has a major role in HC emissions. Particles are mainly due to product B and A.

2.2 Fuel performance of E-diesel

Many studies have proved that engines and their parts are not affected by the use of E-diesel. Engine oil does not show any changes after being analysed. Furthermore, no modifications had to be introduced neither in diesel engines run on E-diesel, nor in their maintenance. Moreover, drivers have not reported any need for changing their driving behaviour. [CTA, 2000] [Hansen et al., 2001b] [Löfvenberg, 2002]

The two most referenced long-term durability tests on heavy duty diesel vehicles driven on-road are:

- Archer Daniel's Midland (ADM) Trucking demonstration program. This project was initiated in November 1998 and consisted of six trucks: four running on E-diesel and two as reference vehicles operated on diesel. The program completed more than 400,000 km and succeeded in demonstrating good operational characteristics, excellent cold temperature performance, proper fuel economy and oil filters presented no problems. [Ahmed, 2001]
- Chicago Transit Authority (CTA) "Oxygenated Diesel Project". Thirty CTA buses were involved in this multi-stakeholder project during 1999 and 2000. It was demonstrated the ease of transition from diesel to E-diesel. During this project, some challenging problems arose regarding water contamination at E-diesel storage and how to tackle them. Results from emissions and driveability of buses driven on E-diesel were in line with those from ADM's project. [CTA, 2000]

Many interesting projects have been recently run, like the one the trucks case study is based on (see section 6.6.3 in the main report). There are several interesting projects like the initiative of Waste Management Inc.[2] to demonstrate E-diesel feasibility for off-road waste handling equipment. They have been running Brooklyn's waste transfer station with satisfactory results. Other successful project has been the one run on John Deere 9400 and Caterpillar Challenger 95E tractors driven on E-diesel to check the applicability of this renewable fuel to off-road farming activities. No abnormal operation (based on oil analyses) was observed after 700 hours accumulated during two Spring and one Autumn seasons in each type of tractor.

2.3 Economical feasibility of E-diesel

Economical feasibility is usually addressed as the Achilles' heel of alternative fuels. Higher production costs and lower energy contents (i.e. higher final prices) make them uncompetitive against traditional fuels. Therefore, a study based on data for Swedish diesel production was carried out to assess the market competitiveness of E-diesel.

In order to compare E-diesel with diesel, the two typical ethanol-diesel blends (E-10 diesel and E-15 diesel) were used. Moreover, three different scenarios ("low price", "high price" and "future") for lignocellulose-based ethanol production were also included and compared to diesel price (see figure 3 and figure 4):

- State-of-the-art technology ranging from low and high estimated production costs based on the dilute acid hydrolysis process. Figures are based on studies carried out in the U.S. applying the current price of Swedish lignocellulosic feedstock. Thus, ethanol's final price ranges from 3 SEK/l to 4 SEK/l (i.e. 0.33 EUR/l to 0.44 EUR/l)[3] [BAFF, 2003] [Graff, 2000]. Based on these prices, both "low price" and "high price" scenarios were designed (see figure 3 and figure 4).
- Long-term future[4] process optimisation yielding lower production costs, which could reach a bottom line of 1.08 SEK/l (i.e. 0.12 EUR/l) [BAFF, 2003] [Graff, 2000]. Based on this price, a "future" expected scenario was created (see figure 3 and figure 4).

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[2] Waste Management Inc. is the largest solid waste management companies in the USA.
[3] Conversion factor: 1 SEK = 0.109 EUR. [Oanda Corp., 2003]
[4] Ethanol production costs by year 2030 (maintaining nowadays raw material price).

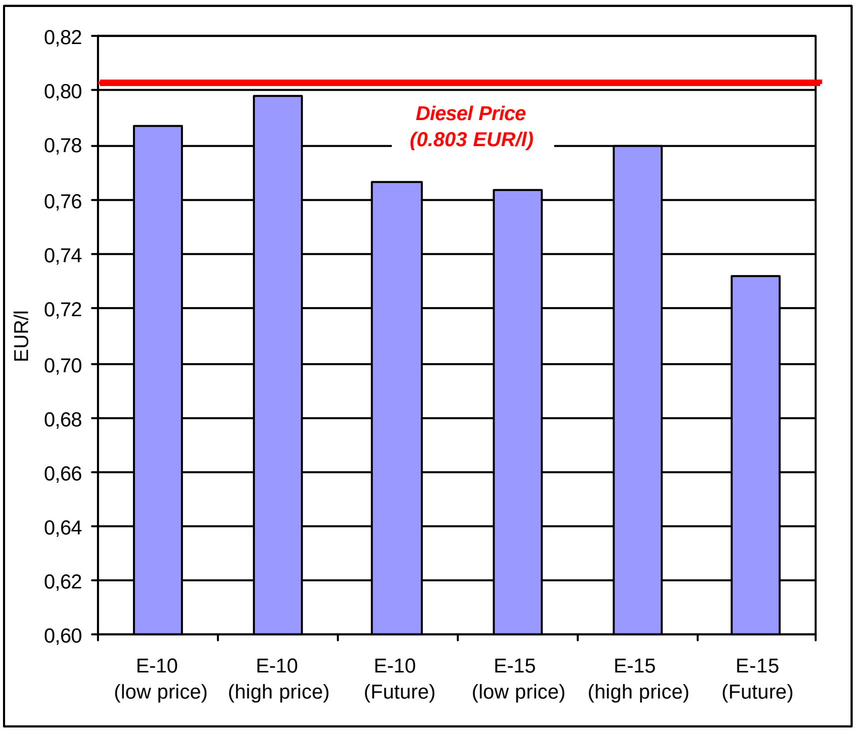

Figure 3. Price comparison of different E-diesel compositions and Swedish diesel.

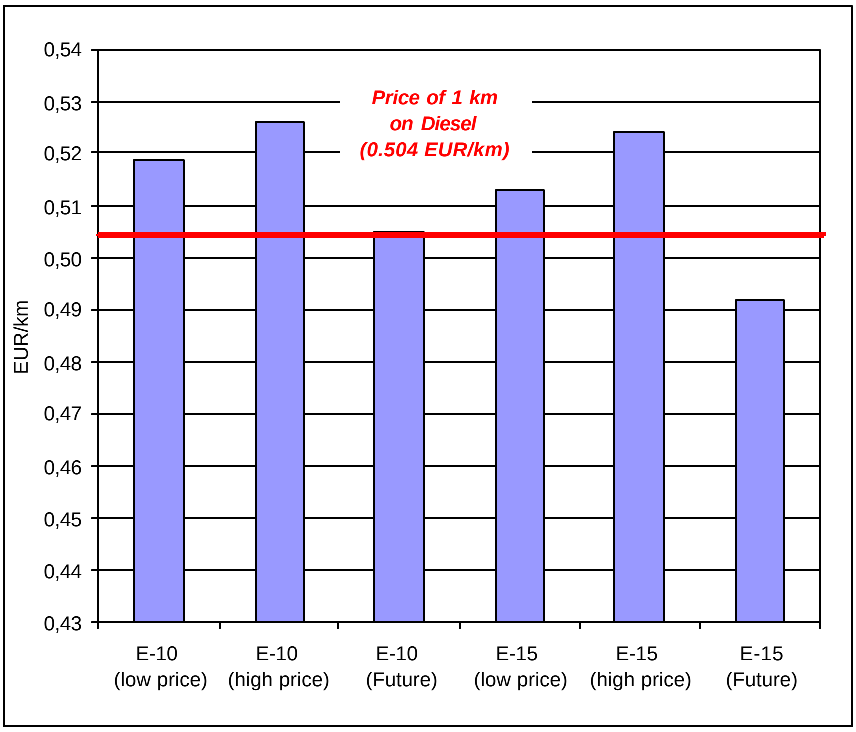

Figure 4. Price comparison of 1 km driven on different E-diesel compositions and Swedish diesel.

Diesel price (0.803 EUR/l) was obtained as an average for the Swedish market including production costs, excise duty tax and the value-added tax (see figure 5). [EEA, 2002c]

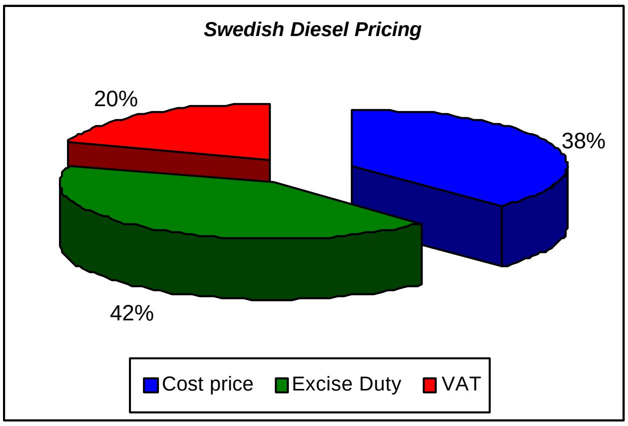

Figure 5. Swedish diesel price divided in cost price and taxes. [EEA, 2002c]

Many researchers have suggested that, if lignocellulosic ethanol production technologies are improved significantly in the future, ethanol could displace a large portion of traditional transportation fuels from the market [Wang, 1999]. Better environmental performance together with a better price will make ethanol-diesel blends a very attractive option compared to diesel fuel.

2.4 Future challenges for E-diesel

E-diesel has to face many technical barriers before its successful marketing (see section 5.2). Most problems are linked to safety issues. Its low flashpoint and tank vapour flammability hinders its handling as conventional diesel. As a matter of fact it has to be handled as gasoline. Therefore modifications have to be introduced in storage tanks an fuel handling equipment. Other physical properties like ethanol solubility in the fuel matrix, water tolerance and efficacy of fuel additives as emulsifiers must be properly studied and minimum requirements for these and safety-related issues must be established. [AFDC, 2002] [McCormick, Parish, 2001]

This is most important for the fuel in order to obtain the recognition from environmental governmental bodies. This official approval will trigger the acceptance of E-diesel by engine manufactures, so that OEM warranties will be issued for low ethanol-content diesel blends. To achieve this recognition by major vehicle and parts manufactures, more data on engine long-term durability are needed (ethanol is chemically very different from diesel and will differently interact with elastomers and metal surfaces). [AFDC, 2002] [McCormick, Parish, 2001]

Water contamination is a big issue as well, specially regarding fuel storage, since water will split the blend. If aqueous concentration grows too high, the fuel stratifies into various layers with varying percentages of fuel and water. Therefore, systems for detection of water leakages in fuel vessels need to be designed and further implemented. [CTA, 2000]

All issues come to limit somewhat the potential market available for E-diesel. It has been thoroughly discussed about hinders towards its broad commercialisation. Thus, many experts agree that it may be constrained into a narrower market, which includes captive, centrally refuelled fleets. Nevertheless this is still a very attractive market in terms of fuel consumption and willingness to shifting towards alternative environmental friendlier fuels like E-diesel [McCormick, Parish, 2001]

3 SUGGESTIONS

Cleaner fuels can reduce local air pollution, whereas optimised and environmentally friendlier production processes can tackle global environmental issues. According to this LCA results, some recommendations for future studies can be given:

- There is a need for more fuel tests, specially those including ULSD diesel, which will become the future standard for diesel both in Europe and North America.
- More results on efficiency and performance of additives together with ULSD diesel would be very useful as well.
- Better and more reliable data on emissions under real traffic conditions and results for full-scale production of ethanol are needed for a more accurate design of scenarios.
- Emissions from forestry industry must be checked. They contribute to a major extent to the environmental burden attributable to ethanol production. It is believed that they are somewhat imprecise due to their age. More recent data would probably yield better results.
- Further research is needed to evaluate the real potential of the captive fleet market in a proper way.
- Chances and barriers for E-diesel commercialisation towards private drivers should be investigated in detail to set where the real potentials for this market are.
- Accurate measurements of particulate matter emissions (PM_{10} and $PM_{2.5}$) should be performed to fully validate final results.

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