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The economy of alternative fuels when including the cost of air pollution

Bengt Johansson[1]

Department of Environmental and Energy Systems Studies, Lund University, Gerdagatan 13, SE-223 62 Lund, Sweden

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Abstract

In this study, the costs involved in the use of petrol, diesel, natural gas, biogas, and methanol (produced from natural gas and biomass) in cars and heavy trucks are compared. The cost includes fuel cost, extra capital cost for vehicles using alternative fuels, and the environmental cost of VOC, NO_x, particulate and CO_2 emission based on actual 1996 and estimated 2015 emission factors. The costs have been calculated separately for rural, urban and city-centre traffic. A complete macroeconomic assessment of the effect of introducing alternative fuels is not, however, included in the study. The study shows that no alternative fuel can compete with petrol and diesel in rural traffic when the economic valuation of CO_2 emission is taken as current Swedish CO_2 taxes ($200/tonne C). In cities with a natural gas network, natural gas is the fuel with the lowest cost for both cars and heavy trucks, based on 1996 emission factors. Methanol from natural gas and biogas from waste products can also compete with diesel in urban traffic. With predicted improvements in technology and subsequent emission reductions, no alternative fuel can compete with petrol in any of the traffic situations studied by 2015, and only in city-centre traffic will alternative fuels be less costly than diesel in heavy vehicles. Of the biomass-based fuels studied, low-cost biogas from waste products is the most competitive one and is, already at current CO_2 taxes, the fuel with lowest cost for heavy trucks in urban traffic in areas where natural gas networks do not exist. To enable the more wide-spread use of biomass-based fuels, i.e. using feedstocks such as energy crops or logging residues that are available in larger amounts, the economic valuation of CO_2 emission has to be 2–2.5 times higher than current Swedish CO_2 tax level.

Keywords: Alternative fuels; Transportation; Environmental costs; Emissions

1. Introduction

Pollution from mobile sources, including different means of transport and machinery, has increased and today constitutes about 60% of the total nitrogen oxide (NO_x) emission, 35% of

[1] Tel.: 00 4646 222 9730; fax: 00 4646 222 8644; e-mail: Bengt.Johansson@miljo.lth.se

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the non-methane volatile organic compound emission (NMVOCs) and 17% of the carbon dioxide (CO_2) emission in European countries (EUROSTAT, 1995). These fractions are even higher (80%, 40% and 44% respectively) in Sweden (Statistics Sweden, 1997). Mobile sources are also significant producers of particulate matter (PM).

Alternative fuels have been proposed to help solve these problems. Alternative fuels are, however, more costly to produce than diesel and petrol and, in many cases, are not the most cost-efficient method of solving the problems. Energy efficiency improvements, improved exhaust treatment technology, and a reduction in the demand for transport are important alternatives to the introduction of alternative transportation fuels.

Appropriate emission reductions cannot be defined objectively based on scientific concepts such as critical loads, but must be established in their social context. One way of weighing environmental and social aspects in the evaluation of alternative fuels is to include the cost of environmental impact in the cost calculations. Although there are major difficulties in estimating these environmental costs correctly, such cost calculations may provide increased knowledge regarding the economic efficiency of using alternative fuels to reach environmental targets. Therefore, the aim of this study was to compare the costs associated with different fuels including not only direct costs (fuel, vehicles, etc.) but also the cost of environmental effects due to the exhaust gases from the vehicles.

2. Methodology and assumptions

In this study, the costs associated with the use of petrol, diesel, natural gas, biogas and methanol (produced from natural gas and biomass) in cars and heavy trucks are compared. Petrol is, however, only studied for passenger cars. The study is based on Swedish conditions. The cost calculations include fuel cost, extra capital cost for vehicles using alternative fuels, and environmental costs associated with the emission of CO_2, VOC, NO_x and particulate matter (PM).[2] Sulphur emission is not included in the analysis since the emission from Swedish road transport is very low and has been reduced by about 90% since 1985 as a result of the introduction of low-sulphur fuels (Swedish National Road Administration, 1996). Currently, about 80% of the petrol sold in Sweden has a sulphur content below 100 ppm and almost 90% of diesel fuel has a sulphur content lower than 0.1%. A recent analysis (Hansson, 1997) indicates that sulphur emission constitutes less than 0.5% of the total cost of air pollution arising from Swedish road transport.

Calculations have been carried out for both 1996 and 2015. The extra capital cost is calculated as the difference between the cost of the vehicle using alternative fuels and the vehicle cost of petrol-fuelled cars and diesel-fuelled trucks. Feedstock costs for biomass-based transportation fuels are based on production costs and not on market prices. This allows agricultural subsidies to be excluded from the cost calculations.

The studied CO_2 emissions are life-cycle emissions, whereas only end-use emissions of NO_x, VOC and PM are analysed. The reason for that is that the environmental impact of CO_2 emission is independent of the location of the emission whereas the impact of the other studied pollutants

[2] In this study PM includes all material that can be collected on a test filter at a temperature of $+52°C$.

is heavily dependent of the location of the emission. It is far outside the scope of this study to estimate current and future locations of up-stream emissions (from extraction, transportation and conversion of the fuels). It is clear that the emission of especially NO_x from the extraction, transportation and conversion of the fuels can be significant but there is a major potential to reduce these emissions in the future (Blinge et al., 1997, Johansson, 1995).

Environmental costs are calculated for three different geographical areas, rural, urban, and city centres. The geographic location is assumed only to affect the cost of damage caused by a certain emission, not the amount of emission itself. This simplification has been made as complete emission data for the different fuels in different traffic situations are not available.

All costs are in 1996 US$ (1 US$ were in 1996 equal to 6.7 SEK (Swedish crowns)). Investment costs have been annualised using a 6% discount rate. Annual driving distances are assumed to be 13,000 km for cars and 35,000 km for heavy trucks. The average lifetimes of cars and trucks are assumed to be 15 and 10 years, respectively.[3]

2.1. Fuel and vehicle costs

The cost of many alternative fuels is uncertain since the markets are small. The costs assumed in this study are given in Table 1. For petrol and diesel, costs were taken as the 1996 fuel prices, excluding taxes. For natural gas, two different values are given, one for areas where a gas network exists (existing infrastructure), and one for areas where there is no gas network (new infrastructure). In Sweden, there is a natural gas network only in the southern and western parts of the country. Long-term, large-scale production costs have been used for natural-gas-based methanol. This value corresponds relatively well with current market prices (Elam et al., 1994; Östman, 1996; Alternative Fuel Committee, 1996) and the same value has therefore been used for both 1996 and 2015. Both methanol and natural gas are commercially available although their use as transportation fuels is limited.

Two different cost estimates have been used for biogas: one based on the cost of biogas from waste products (sewage, municipal waste, etc.), and one based on the production cost of biogas from energy crops (lucerne). Both biogas production and distribution costs depend largely on local conditions, with especially large variations in feedstock costs. The cost estimates are based on the assumption of local consumption of the biogas. There is as yet no commercial plant for the production of biomass-based methanol and the cost estimates are therefore based on chemical process simulations.

The assumed extra investment costs for vehicles using alternative fuels are given in Table 2. They are based on estimates from a major Swedish research programme studying the potential for introducing alcohol and biogas into the Swedish transportation sector (for a summary of the results of this programme, see Månsson (1998). Large-scale production of vehicles has been assumed. Until vehicles running on alternative fuels have gained the advantages of mass production, the difference in cost between these vehicles and those using petrol and diesel will be greater.

[3] The combination of driving distances and economic lifetimes used is in accordance with Swedish vehicle utilisation patterns, see e.g Möller (1989) and Henriksson (1994).

Table 1
The cost of various transportation fuels excluding taxes (all costs include distribution costs)

	1996 US$/MWh	2010 US$/MWh
Petrol [a]	36	36
Diesel [a]	33	33
Natural gas (existing infrastructure) [b]	33	33
Natural gas (new infrastructure) [b]	43	43
Methanol from natural gas [b]	52	52
Biogas from waste [c]	51	51
Biogas from lucerne [d]	96	90
Methanol from cellulosic biomass [e]	82	75

[a] 1996 average prices according to NUTEK (1997), used for both 1996 and 2015.
[b] Based on data from the Alternative Fuel Committee (1996).
[c] The production cost is estimated to be 150 SEK/MWh and the cost of upgrading, compression and filling to be 190 SEK/MWh. KFB (1996) estimates that biogas from sewage and municipal solid waste could be produced at a cost of 100–150 SEK/MWh, from waste water at a cost of 150–250 SEK/MWh, and from landfills at a cost of 100–250 SEK/MWh. The cost of producing costs biogas from manure is significantly higher (400–500 SEK/MWh). The Alternative Fuel Committee, 1996 estimated that the cost of upgrading, compression and filling would be 120–260 SEK/MWh.
[d] Cost of biogas production from lucerne taken from Johansson (1996a). For the cost of compression, etc., see note c.
[e] Based on Johansson (1996a). The difference between 1996 and 2015 is a result of reduced feedstock costs resulting from advances in plant breeding and new cultivation practices.

Table 2
Extra investment costs for vehicles using alternative fuels compared to investment costs for vehicles running on conventional fuels (petrol in cars and diesel in trucks) [values are based on Olsson, 1996; Johansson, 1996a; Månsson, 1998] [a]

	Cars, extra cost compared with petrol US$/vehicle	Heavy trucks, extra cost compared with diesel US$/vehicle
Diesel	1500	–
Natural gas and biogas	2000	11 200
Methanol	600	2200

[a] Estimating future vehicle costs is a difficult task. Some international studies have suggested that the extra investment cost for natural gas cars would be around 30–50% of the values given in Table 2 (Stephenson, 1991; OECD, 1993; Singh and Mintz, 1997). The extra vehicle investment cost for a methanol-fuelled car might, according to some studies, be as low as $100–200/vehicle (OECD, 1993; Singh and Mintz, 1997). Other international reports, such as that by Ingersoll (1996), however, support the estimates given.

2.2. Energy use and vehicle emissions

Both methane and alcohols are excellent Otto-engine fuels and it is assumed that they can be used with 15% lower specific energy use than petrol in cars (Johansson, 1996a). The same efficiency advantage is assumed for diesel-fuelled vehicles compared to petrol vehicles. Methanol is assumed to give the same specific energy use as diesel in heavy vehicles, whereas natural gas and biogas are assumed to give 15% higher specific energy use due to the assumed use of Otto engines instead of diesel engines (Johansson, 1996a). The specific energy use of cars is assumed to be 35% lower and the specific energy use of heavy vehicles 10% lower in 2015 than in 1996. These esti-

Table 3
Assumed specific energy use and emissions in vehicles for 1996 and 2015

	Cars				Heavy trucks			
	Energy kWh/km	VOC g/km	NO_x g/km	PM mg/km	Energy kWh/km	VOC g/km	NO_x g/km	PM mg/km
1996								
Petrol	0.73	0.89	0.26	13	–	–	–	–
Diesel	0.63	0.13	0.63	56	3.5	0.37	11.5	300
Natural gas/biogas	0.63	0.05	0.14	7	4.1	2.3	4.5	10
Methanol	0.63	0.82	0.07	0	3.5	0.04	6	10
2015								
Petrol	0.54	0.08	0.04	1.2	–	–	–	–
Diesel	0.47	0.02	0.04	16	3.2	0.15	4.1	100
Natural gas/biogas	0.47	0.01	0.02	1	3.8	0.8	0.8	5
Methanol	0.47	0.03	0.01	0	3.2	0.02	1	5

mated improvements are based on a study of Michaelis and Davidsson (1996). Assumed specific energy use for the vehicles are given in Table 3.

Specific emissions of VOC, NO_x and PM for 1996 and 2015, are based on values from Egebäck et al. (1997) and are also given in Table 3. 1996 estimates are based on measured emission levels, while for 2015, the estimates are based on levels which are assumed to be technically feasible by 2010 for the various transportation fuels. The values have been corrected for cold-starts, climate, driving cycle and deterioration of emission-reduction systems.

The life-cycle CO_2 emissions used in this study are presented in Table 4.

2.3. Environmental costs

The estimates of environmental costs due to the emission of VOC, NO_x and particulate are based on Johansson (1997), Table 5. His values are based on the same sources that were used

Table 4
CO_2 emissions for the studied fuels based on emission values from Blinge et al. (1997)

	Pre-combustion [a] emission, g/kWh	End-use emission, g/kWh	Total emission, g/kWh
Petrol	19	266	285
Diesel	13	261	274
Natural gas	6	201	207
Methanol from natural gas	69	256	325
Biogas from waste	3	0	3
Biogas from lucerne	68	0	68
Methanol from biomass	30	0	30

[a] Emission from fuel extraction, transportation and conversion.

Table 5
Cost of the environmental impact of VOC, NO_x and particulate emissions in Sweden based on Johansson (1997)

	Cost of environmental damage	Health effects [a]		
	US$/kg	Rural US$/kg	Urban US$/kg	City centre US$/kg
VOC, petrol and diesel	2.5	0	7.3	36.6
VOC, other fuels [b]	1.3	0	3.7	18.4
NO_x	6.0	0	7.3	36.6
Particulates	0	26.9	135	1256

[a] The values are estimates for Gothenburg, a city in Sweden with approximately 460,000 inhabitants. The cost per unit emission of local health effects in a smaller town, such as Falun (35,000 inhabitants) might be only one-fourth of that in Gothenburg (SIKA, 1996).

[b] Johansson (1997) gives the cost of environmental damage for a specific amount of VOC from biogas/natural gas and alcohol as an interval from 0 to the same level as for petrol and diesel (VOC emissions from different fuels consist of different compounds which are not equally harmful). In this study, a kg of VOC from gas and methanol is valued to 50% of a kg of VOC from petrol and diesel. This choice does not affect the ranking of the studied fuels.

when defining recommended values for calculating social costs for infrastructure investments in Sweden. The costs are divided into the cost of damage to the environment, mainly as the result of eutrophication, acidification and high ozone concentrations, and health damage. The cost of environmental damage is derived from existing taxation levels on large-scale power plants in Sweden and is assumed to be independent of whether the emission source is situated in rural or urban areas. This assumption seems to be reasonable as acidification, eutrophication and high ozone concentrations are regional problems and their detrimental effects appear, to a large extent, at significant distances from the emission location. For example, only one-third of the Swedish nitrogen emission is deposited in the country (Statistics Sweden, 1996).

The cost of health damage was based on estimates of the value of reducing population doses. This value was obtained from surveys in which people were asked about their willingness to pay for dose reductions.[4] The value of reducing population doses was then transformed into a value of reducing vehicle emissions, utilising different dispersion models, wind, climate and population data. The value of reducing the emissions was then used as the cost of the emission.

Existing estimates of the environmental costs of CO_2 emissions vary significantly and are very uncertain. For example, Nordhaus (1993) estimated the CO_2 emission cost to be US$10/tonne C, whereas Azar and Sterner (1996) estimated the cost to be US$250–590/tonne C. The higher value of Azar and Sterner is almost completely due to the choice of discount rate and the weight assigned to the costs in the developing world so that they reflect real welfare losses. For comparison, Swedish CO_2 taxes are approximately US$200/tonne C (0.36 SEK kg/CO_2) (NUTEK, 1997). In this study, current Swedish CO_2 taxes are used as base-case estimates of the cost of CO_2 emissions but the effects of other estimates are also analysed.

Johansson (1997) compared his calculated costs of local and regional environmental impact with the results of several recent international studies (Maddisson et al., 1996; Bell, 1994; Bleijenberg et al., 1994; Mayeres et al., 1996) and concluded that both lower and higher values have

[4] The economic valuation of the inhalated dose underlying the cost estimates in Table 5 is 4 SEK/mg NO_x, 4 SEK/mg VOC and 40 SEK/mg of particulate matter (Johansson-Stenman and Sterner, 1998).

been found compared with those used in Sweden. The magnitude seems to be about the same in the different studies.[5]

3. Results

The total cost (including environmental cost) for the alternatives studied can be found in Table 6.

All the alternative fuels are associated with higher costs that petrol and diesel in rural areas. With 1996 technology and an economic valuation of CO_2 emission equivalent to current Swedish CO_2 taxation, natural gas can, however, compete with petrol and diesel in cars and heavy trucks in cities where there is an existing natural gas network, see Figs 1 and 2. In cities, methanol from natural gas and biogas from waste are also associated with lower costs than diesel in heavy trucks (Fig. 1) and they are the preferred fuels in cities where there is no natural gas network. In cities the cost of local and regional environmental effects dominates the cost (Fig. 4). In city centres, all the alternative fuels can compete with petrol and diesel, due to the high environmental costs of

Table 6
The cost of using different transportation fuels including costs resulting from CO_2, NO_x, VOC and particulate emission

	1996			2015		
"Current CO_2" US$200/tonne C	Rural $/10 km	Urban $/10 km	City centre $/10 km	Rural $/10 km	Urban $/10 km	City centre $/10 km
Cars						
Petrol	0.42	0.51	0.92	0.28	0.29	0.33
Diesel	0.47	0.59	1.11	0.35	0.37	0.47
Natural gas (existing infra)	0.45	0.47	0.55	0.37	0.37	0.38
Natural gas (new infra)	0.51	0.53	0.62	0.41	0.42	0.43
MeOH (nat. gas)	0.50	0.54	0.68	0.38	0.38	0.39
Biogas (waste)	0.49	0.51	0.59	0.40	0.40	0.41
Biogas (lucerne)	0.79	0.81	0.90	0.60	0.60	0.61
MeOH (biomass)	0.59	0.62	0.77	0.41	0.41	0.42
Heavy trucks						
Diesel	2.4	3.6	8.7	1.8	2.2	4.0
Natural gas (existing infra)	2.5	3.0	4.7	2.2	2.3	2.6
Natural gas (new infra)	3.0	3.4	5.1	2.6	2.7	3.0
MeOH (nat. gas)	2.9	3.3	5.2	2.4	2.5	2.7
Biogas (waste)	2.8	3.2	5.0	2.4	2.5	2.9
Biogas (lucerne)	4.8	5.2	6.9	4.0	4.1	4.5
MeOH (biomass)	3.4	3.8	5.6	2.6	2.7	3.0

[5] For example, Bell (1994) analysed the environmental values used by 37 government, utility, and research agencies in the USA, and found estimates for VOC varying between 0.34 and 21.2 US$/kg, with an average of 6.0 US$/kg, and estimates of NO_x varying between 0.04 and 40 USD/kg with an average of 8.0 US$/kg.

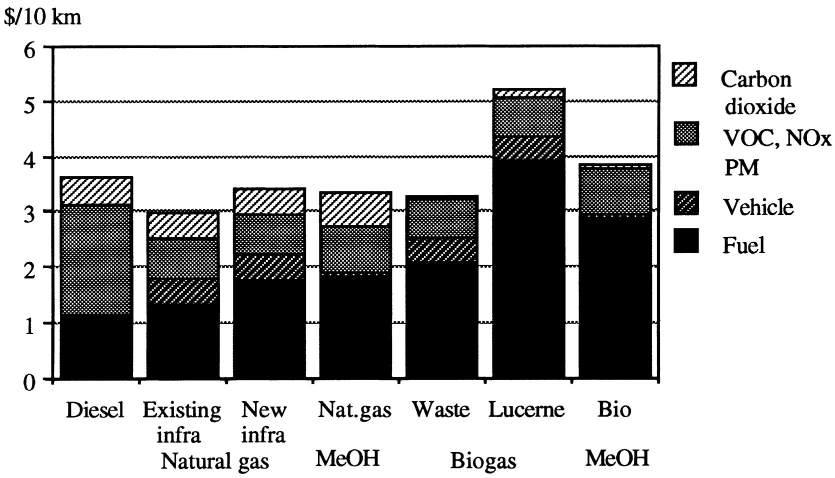

Fig. 1. Cost associated with using heavy trucks in cities under 1996 conditions and at the current CO_2 taxation level.

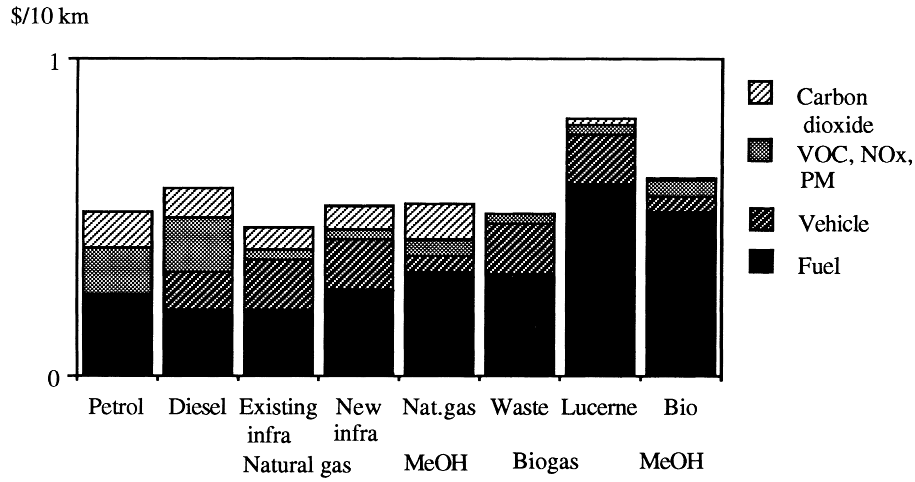

Fig. 2. Cost associated with using cars in cities under 1996 conditions and at the current CO_2 taxation level.

the latter (Fig. 3 and Table 6). Methanol from biomass cannot, however, compete with natural gas, fossil-based methanol or biogas from waste at the current CO_2 tax level.

With the assumed reduction of specific emissions the importance of local and regional environmental impact on cost will decrease (Fig. 4). Therefore, the use of alternative fuels in rural traffic will result in significantly higher costs than petrol and diesel for both cars and heavy trucks in 2015 (Table 6). The use of natural gas (existing infrastructure) and methanol from natural gas will result in about the same costs as when using diesel in urban traffic in 2015 (Fig. 5) and significantly lower costs in city centres (Fig. 6). In 2015 none of the alternative fuels will have nearly as low costs as petrol in any of the traffic situations studied at the current CO_2 taxation level (Table 6).

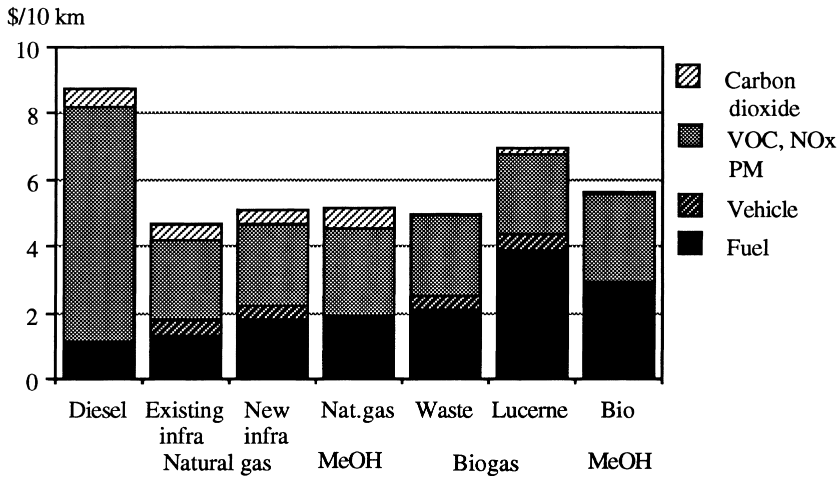

Fig. 3. Cost associated with using heavy trucks in city centres under 1996 conditions and at the current CO_2 taxation level.

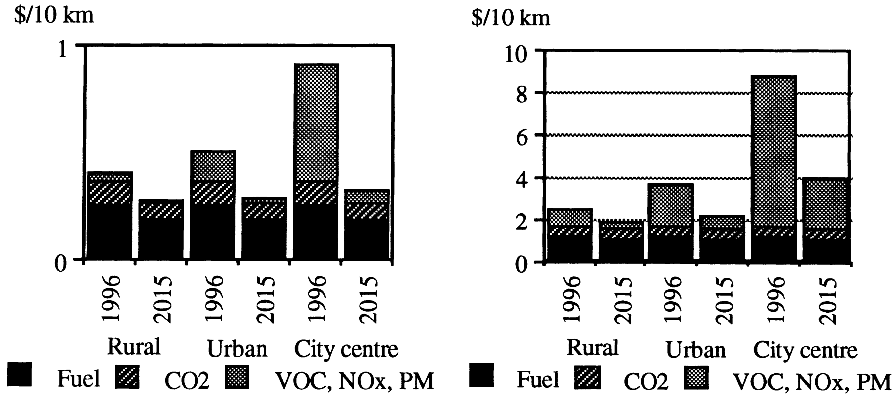

Fig. 4. Cost associated with petrol-fuelled cars (left) and diesel-fuelled trucks (right) divided into the cost of fuel, CO_2 emission and regional and local environmental impact.

To make biomass-based methanol competitive with fossil-fuel-based fuels, the economic valuation of CO_2 emissions, in 2015, must in general be 2–2.5 times higher than the current taxation level. For heavy vehicles in city centres an economic valuation of CO_2 emissions 1.5 higher than the current level might be sufficient, if natural gas is not available. Biogas from waste can compete at somewhat lower level of CO_2 valuation than methanol from biomass.

3.1. Uncertainty and sensitivity analysis

The cost of biomass-based transportation fuels is very uncertain as a result of both untested fuel production technologies and uncertainties in feedstock cost. Biomass production costs from commercial cultivation are heavily dependent on productivity and are still quite uncertain. Fur-

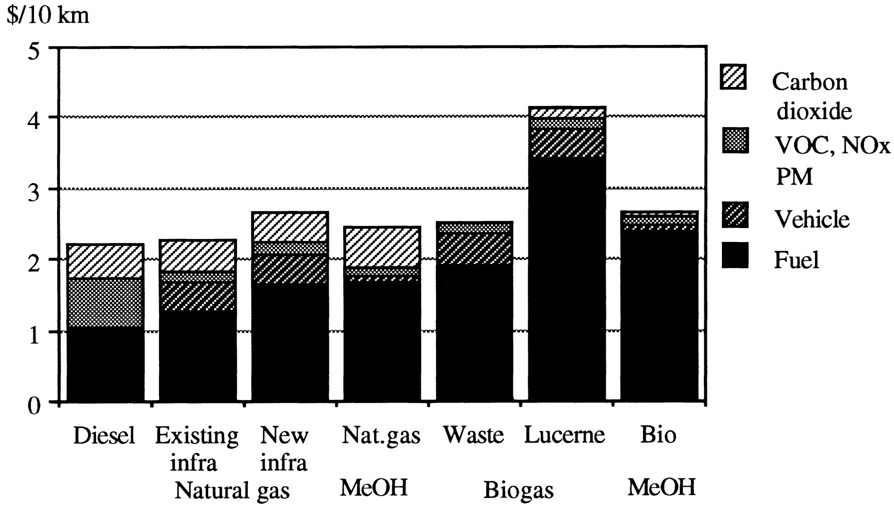

Fig. 5. Cost associated with the use of heavy trucks in cities under assumed conditions for 2015 and the current CO_2 tax level.

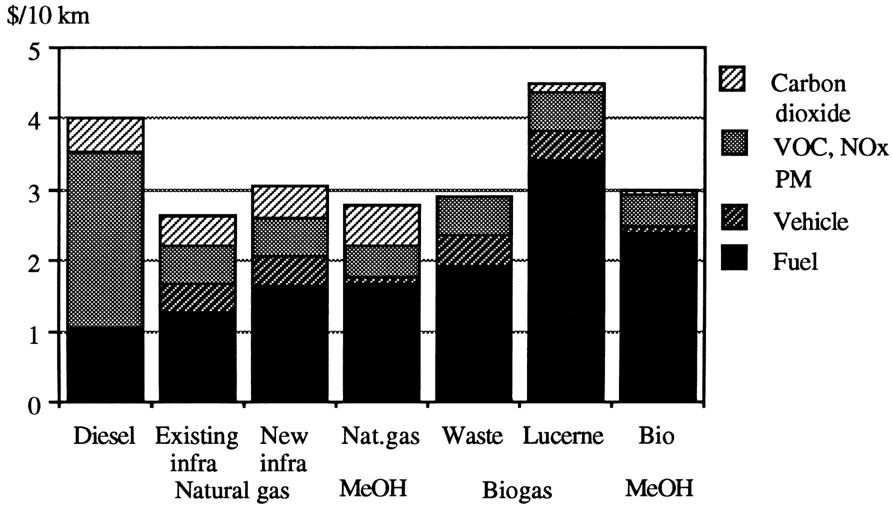

Fig. 6. Cost associated with the use of heavy trucks in city centres under assumed conditions for 2015 and the current CO_2 tax level.

thermore, Börjesson (1998a,b) has shown that there are considerable environmental benefits from growing perennial crops instead of annual crops. The economic value of purification of municipal waste water and sludge, and the reduction in soil erosion and nutrient leaching achieved in some areas when growing perennial crops (e.g. Salix) can be significant. It has been estimated that Salix equivalent to about 10 TWh/yr could be produced in Sweden at a cost of less than US$4/MWh, if the environmental benefits were valued monetarily. This can be compared with the direct production cost of about US$16/MWh (Börjesson, 1998b). About 80 TWh/yr could be produced at a cost of less than US$12/MWh. Biomass costs of US$4/MWh and US$12/MWh would result in methanol costs of approximately US$53/MWh and US$66/MWh, respectively, or 70–90% of the costs given in Table 1. Furthermore, several studies (e.g. NUTEK, 1996; Johansson, 1996a) indicate that the utilisation of forest logging residues can, if well managed, be combined with high environmental demands. In areas with high nitrogen deposition, a positive effect of the extraction of logging residues in combination with wood ash recirculation could be the removal of surplus nitrogen from forests. The value of such removal has been estimated to be about as high as the production cost of logging residues (100 SEK/MWh) (Burström and Johansson, 1995). If poorly managed, the utilisation of logging residues might, however, cause negative environmental impact.

Technology for the production of methanol from biomass exists only on a pilot scale and production costs are therefore uncertain. For example, Johansson (1996a) gives an interval for the cost of methanol production ranging from US$60/MWh to US$90/MWh. The production cost for biogas also varies considerably due to local conditions The estimates used for biogas produced from waste are based on sewage and municipal and industrial waste. The potential for producing biogas from these in sources in Sweden has been estimated to be about 4 TWh/yr or approximately 5% of Sweden's petrol and diesel consumption (Brolin et al., 1995; NUTEK, 1997). Biogas is preferably used in local systems and the feasibility of biogas must therefore be evaluated for each project.

The cost of driving passenger cars and heavy trucks in the year 2015 as a function of methanol cost is shown in Fig. 7. At current CO_2 taxation level MeOH from biomass would be competitive with fossil fuels in cars at a fuel cost of about US$50/MWh and in heavy vehicles at a cost at about US$60/MWh. A combination of low-cost feedstock, and the successful development of efficient and low-cost methanol production plants might be sufficient to make biomass-based methanol competitive with fossil fuels in urban traffic, even at the current CO_2 taxation level and fossil fuel prices.

Future fossil fuel prices are uncertain. For example, IEA (1995) has defined scenarios where fossil fuel prices remain stable up to 2010 as well as scenarios where prices increase by approxi-

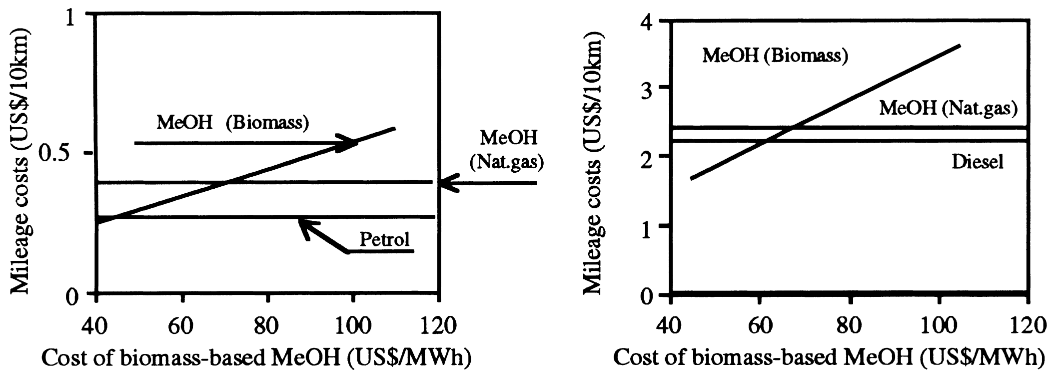

Fig. 7. The cost of using methanol-fuelled vehicles in urban traffic in 2015 (cars on the left, heavy- trucks on the right) at the current CO_2 taxation level, as a function of varying methanol cost. The cost of using petrol, diesel and methanol from natural gas are given for comparison.

Table 7
The cost of using the fossil fuel with the lowest driving cost and biomass-based methanol at current fossil fuel prices and with an assumed increase in fossil fuel cost of 3% per annum from 1996 to 2015 (current CO_2 taxes are included in all values)

	2015 Current fossil fuel prices			2015 Increase in fuel prices [a]		
	Cost of using lowest cost fossil fuel US$/10 km	Lowest cost fossil fuel	Cost ofusing MeOH (biomass) US$/10 km	Cost of using lowest cost fossil fuel US$/10 km	Lowest cost fossil fuel	Cost ofusing MeOH (biomass) US$/10 km
Cars						
Rural	0.28	Petrol	0.41	0.37	Petrol	0.41
Urban	0.29	Petrol	0.41	0.38	Petrol	0.41
City centre	0.33	Petrol	0.42	0.42	Petrol	0.42
Heavy trucks						
Rural	1.8	Diesel	2.6	2.2	Diesel	2.6
Urban	2.2	Diesel	2.7	2.6	Diesel	2.7
City centre	2.6/2.8	Gas/MeOH	3.0	3.0/3.3	Gas/MeOH	3.0

[a] The price increase corresponds to an increase in petrol, diesel, natural gas and fossil methanol costs of US$15/MWh, US$13/MWh, US$10/MWh and US$15/MWh, respectively.

mately 4% p.a. These prices would be affected by the policy adopted for energy efficiency improvements and the introduction of renewable energy sources.

The effect of a 3% p.a. increase in fossil fuel prices from 1996 to 2015 is indicated in Table 7. Such an increase significantly reduces the cost difference between biomass-based methanol and fossil fuels and would make it competitive to fossil fuels in city centres at current CO_2 valuation.

Average emissions of petrol-fuelled passenger cars in real traffic might exceed the emissions measured in emission tests by several times (see e.g. Calvert et al., 1993; Knapp, 1994; Sjödin and Lenner, 1995; Ross and Wenzel, 1997). Although the emission factors used in this study are corrected for cold starts, climate, driving cycle and deterioration of emission-reduction systems, the emission estimates must still be considered uncertain.

The cost of using different fuels in cars as a function of assumed deviation of real traffic emissions from the emission levels used in this study is shown for urban traffic, Fig. 8. It shows that the cost advantage of petrol in relation to alternative fuel, would be much less if real emissions should prove to be significantly higher than the values used in this study.

The economic valuation of health and environmental effects might change in the future. With better knowledge of the impact of different pollutants, the economic valuation of the emissions may change. Furthermore, with growing incomes the willingness to pay for avoiding negative environmental impact may increase, which would affect the feasibility of the different transportation fuel alternatives, see Table 8. Therefore no ranking of the fuels can be final, but will change as environmental damage is revalued in the future.

As gas-fuelled vehicles are associated with significant extra vehicle costs they are relatively sensitive to estimates of driving distance. Compared with the results above, gas-fuelled transport will be more competitive in vehicles with greater yearly driving distances. The estimates for heavy vehicles are for trucks. Buses often have longer driving distances and would therefore be able to

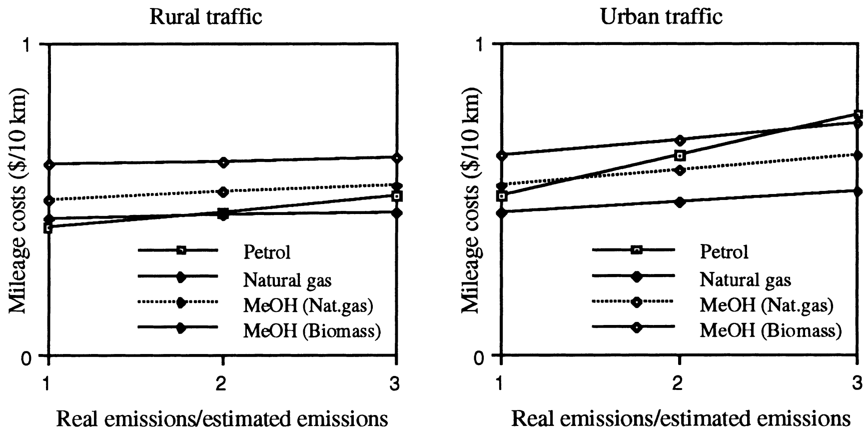

Fig. 8. Cost of using petrol, natural gas, methanol from natural gas and methanol from biomass in rural and urban traffic in 1996 as a function of the ratio between real NO_x and VOC emission levels and estimated emission levels (Table 3).

Table 8
Cost difference between biomass-based methanol and petrol in cars and diesel in heavy trucks by 2015, with different economic valuation of local and regional environmental impact[a]

	Current CO_2 taxes			Double current CO_2 taxes		
	Base case US$/10 km	Costs for VOC, NO_x and PM +35%[b] US$/10 km	Costs for VOC, NO_x and PM +120%[b] US$/10 km	Base case US$/10 km	Costs for VOC, NO_x and PM +35%[b] US$/10 km	Costs for VOC, NO_x and PM +120%[b] US$/10 km
Cars						
Rural	0.13	0.12	0.12	0.05	0.05	0.04
Urban	0.12	0.12	0.11	0.05	0.04	0.04
City centre	0.09	0.07	0.04	0	−0.2	−0.06
Heavy trucks						
Rural	0.79	0.72	0.53	0.37	0.30	0.11
Urban	0.45	0.25	−0.22	0.03	−0.17	−0.64
City centre	−1.02	−1.73	−3.45	−1.43	−2.14	−3.86

[a] Cost calculations were made assuming current Swedish CO_2 tax and double current CO_2 taxes. A minus sign indicates that the biomass-based methanol is associated with lower costs than petrol and diesel.

[b] An increase in the economic valuation by 35% between 1996 and 2015 can be the result of an economic growth of 1.5% and an income elasticity for environmental commodities of 1, and the increase by 120% is equivalent to an economic growth of 2.0% and an elasticity of 2.

bear higher extra investment costs than trucks. In other respects, the results presented here for heavy trucks could be representative for buses as the environmental effects of the fuels are similar in all types of heavy vehicles (Egebäck et al., 1997). The cost of using natural-gas-fuelled vehicles is heavily dependent on the vehicle cost. For example, with more optimistic assumptions of extra vehicle investment costs ($600/vehicle compared with a petrol-fuelled car, see Table 2) the use of natural gas vehicles would involve lower costs than the use of petrol-fuelled vehicles in all the traffic situations studied (provided that there is an existing natural gas network). The vehicle cost for alcohol-fuelled vehicles is of less importance, and more optimistic assumptions regarding the cost development of these vehicles would only have a minor impact on the total cost.

There is leakage of methane from biogas and natural gas systems which contributes to the greenhouse effect. Ecotraffic (1992) has estimated the leakage from a biogas system to be 3%. Blinge et al. (1997) used the same figure for the current situation but estimate that the leakage may be reduced by more than 90% in the future. The net effect of methane emission from biogas production from sewage etc. depends on the alternative methods used to treat the waste. In some applications, the feedstock would anyway have been anaerobically decomposed, and the utilisation of the feedstock for biogas results in a net reduction of methane emission.

The leakage of natural gas from newer systems can be less than 1% (Ecotraffic, 1992). In older systems the leakage might be significantly higher, with an average for Europe of 2–3%. A 1% leakage would increase the greenhouse effect from using natural gas by approximately 7%, calculated in a 100-year perspective. The ranking of the fuels in this study would not change if the leakage of methane were included in the calculations.

4. Discussion

Certain conclusions can be drawn from the results presented above. Regional and local environmental impact can motivate the use of alternative fuels instead of petrol and diesel in certain traffic situations, even if the cost of CO_2 emission is not regarded. Then it is the fossil-based alternatives (natural gas or fossil-based methanol) that are competitive. At current CO_2 tax level biogas from waste is competitive where no natural gas is available. To enable a greater use of biomass-based fuels, the economic valuation of CO_2 emission would have to be 2–2.5 times higher than current CO_2 taxes.

Such biomass-based fuels must based on low-cost cellulosic biomass such as Salix or logging residues to compete with fossil fuels. The only motivation for producing biogas from lucerne or energy grass is that there are other reasons for growing such crops than the energy aspect, for example a willingness to pay for preserving an open landscape. Annual crops such as wheat or rape seed are too costly to grow and are not suitable as feedstocks for transportation fuel production (Johansson, 1996a). Large agricultural subsidies would be necessary to enable the cultivation of such annual crops for energy purposes.

Increases in world market fossil fuel prices would have a similar effect on the competitiveness of the biomass-based fuels as would increased economic valuation of CO_2 emission. Global increases in the economic valuation of CO_2 emission through taxes or other measures would reduce the probability of increasing world market fuel prices. The risk of climate change seems to be a more acute reason for reducing fossil fuel use than the risk of fossil fuel depletion. Therefore, it seems unprobable that increased world market prices due to reduced availability of fossil energy sources would cause price increases large enough for a major transition to renewable energy sources quickly enough to reduce greenhouse gas emissions at an appropriate rate.

The economic valuation of CO_2 emissions used in this paper is based on Swedish CO_2 taxes. These taxes are high compared with those proposed internationally, for example in the European Union. A proposed energy/carbon tax that would reach US$10/barrel of oil by the year 2000 corresponds roughly to only about 50% of the Swedish CO_2 tax (van Well, 1995). The cost of using biomass-based transportation fuels to achieve CO_2 reduction is high compared with other alternatives. DeCicco and Ross (1993) and Sachs et al. (1992) showed that energy use for vehicles could be reduced by 40% through a variety of technological options at a marginal cost, less than US$400/tonne C (the average cost of the energy efficiency improvement was significantly lower). Macro-economic analyses indicate that a CO_2 tax of US$400/tonne C would be sufficient to reduce CO_2 emissions by 50% in the USA (IPCC Working Group III, 1996).

Using biomass instead of fossil fuels for heat and electricity production have lower CO_2 reduction costs than when biomass is used instead of fossil transportation fuels (Gustavsson et al., 1995). In combination with energy efficiency improvements and other fossil-free electricity generation, Swedish biomass might, however, also suffice for transportation fuels and only in such scenarios could CO_2 emissions be reduced by more than 50% (Johansson, 1996b). Thus, biomass-based transportation fuels might have a role to play in the energy system, but only if the aim is very large CO_2 emissions reductions.

The economic valuation of regional and local environmental impact is important in making alternative fuels viable. Future valuations of local and environmental impact are difficult to assess as the knowledge of the damage due to different pollutants will increase. Furthermore, the economic valuation of environmental impact may increase with time. Such an increase in environmental concern will improve the competitiveness of low-polluting transportation fuels. The continuing reductions in emission factors for diesel and petrol will, however, reduce the absolute advantage of using alternative fuels. The cost efficiency of improving vehicles for conventional fuels instead of using alternative fuels has, however, not been studied since cost data for such improvements have not been available.

Emissions in real traffic situations differ significantly from emissions measured in different vehicle tests, and the estimates of real traffic emissions are still uncertain. Major deviations from the emission levels used in this study might change the conclusions regarding which fuel would be the best choice in different traffic situations. Improvements of these estimates would significantly strengthen the results from a study such as this. As new control technologies reduce the general emission levels of VOC, NO_x and particulates in the future, the environmental concern associated with the fuel choice would turn from these pollutants towards the emission of CO_2, which can, be estimated more easily directly from the fuel consumption.

The concept of economic valuation of environmental impact has been criticised from many aspects; criticism that is broadly discussed by Stirling (1997). His conclusion is, however, that environmental valuation and other quantitative techniques are useful as "tools" rather than "fixes". In this study it was not assumed that the values used were exact or final values of the environmental impact. Instead a "what if- approach" was taken where the results illustrate how alternative fuels could compete under certain environmental valuations based on official estimates or other criteria.

The study included only vehicles with internal combustion engines. There is however on-going development of alternatives such as electric, hybrid and fuel-cell vehicles (see e.g. National Research Council, 1997). Cost data for these vehicles are still too uncertain to be included in a study such as this.

The cost of local and regional environmental impact has been calculated for Sweden, where air pollution is low relative to other countries (Nilsson and Johansson, 1995). In other geographical areas, the valuation of the emission may differ from that in Sweden and thus the competitiveness of the different fuels may be somewhat different from that in Sweden. The methodology used here might, however, be suitable for studying the usefulness of different fuels in different countries.

5. Conclusions

This study has shown that alternative fuels can be competitive with petrol and diesel in urban traffic, if the environmental impact of emission is valued monetarily. In cities with a natural gas network, natural gas has a lower total cost than diesel in heavy vehicles, both with current emission factors and estimated emission factors for 2015. In cars, natural gas has a lower cost than petrol in cities with current emission factors, but with estimated technological improvements and subsequent emission reduction no alternative can compete with petrol in any of the traffic situations studied.

Of the biomass-based fuels studied low-cost biogas from waste products is the most competitive and can, already at current CO_2 taxes, be the best choice for urban traffic in areas where there is no natural gas network. To enable the more widespread use of biomass-based fuels, i.e. using feedstocks such as energy crops or logging residues that are available in larger amounts, the economic valuation of CO_2 emission has to be 2–2.5 times higher than current Swedish CO_2 taxes ($200/tonne C).

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References

Alternative Fuel Committee, 1996. Alternative fuels for a better climate, environment and improved public health. Swedish Government Official Reports 1996:184, Fritzes, Stockholm.

Azar, C., Sterner, T., 1996. Discounting and distributional considerations in the context of global warming. Ecological Economics 19, 169.

Bell, K., 1994. Valuing emissions from Hermiston Generation Project. Convergence Research, Seattle.

Bleijenberg, A.N., van den Berg, W.J., de Wit, G., 1994. Maatschappelijke Kosten van het Verkeer: Literatuuroverzicht. Centrom voor Energiebesparing en Schone Technoogie, Delft.

Blinge, M., Arnäs, P-O., Bäckström, S., Furnander, Å., Hovelius, K., 1997. Livscykelanalys (LCA) av drivmedel. The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Börjesson, P., 1998a. Environmental effects of energy crop cultivation: identification and quantification. Biomass and Bioenergy (forthcoming).

Börjesson, P., 1998b. Environmental effects of energy crop cultivation: economic valuation. Biomass and Bioenergy (forthcoming).

Brolin, L., Hagelberg, M., Norström, A., 1995. Biogas som drivmedel för fordon. The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Burström, F., Johansson, J., 1995. Skogsbränsle minskar kvävebelastningen – Beräkningar av kväveflöden (Forest Fuel Reduces the Nitrogen Load – Calculations of Nitrogen Flows). Vattenfall, S-162 87 Vällingby.

Calvert, J.G., Heywood, J.B., Sawyer, R.F., Seinfeld, J.H., 1993. Achieving acceptable air quality: Some reflections on controlling vehicle emissions. Science 261, 37–45.

DeCicco, J., Ross, M., 1993. An Updated Assessment of the Near-Term Potential for Improving Automotive Fuel Economy. American Council for an Energy-Efficieny Economy, Washington.

Ecotraffic., 1992. The Life of Fuels. Motor Fuels from Source to End Use. Gamla Brogatan 29, 111 20 Stockholm.

Egebäck, K-E., Ahlvik, P., Westerholm, R., 1997. Emissionsfaktorer för fordon drivna med fossila respektive alternativa bränslen. The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Elam, N., Ekström, C., Östman, A. and Rensefelt, E., 1994. Metanol och etanol ur träråvara (Methanol and ethanol from Lignocellulosic Swedish Wood Fuels). Vattenfall Utveckling, SE-162 87 Vällingby.

EUROSTAT, 1995. Europe's Environment: Statistical Compendium for the Dobris Assessement. L-2920 Luxembourg.

Gustavsson, L., Börjesson, P., Johansson, B., Svenningsson, P., 1995. Reducing CO_2 emissions by substituting biomass for fossil fuels. Energy – the International Journal 20, 1097–1113.

Hansson, L 1997. The Internalization of External Effects in Swedish Transport Policy – A Comaprison Between Road and Rail Traffic. International Institute for Industrial Environmental Economics, Lund.

Henriksson, P., 1994. Årliga körsträckor skattade ur bilprovningens databas. Swedish Road and Transport Research Institute, S-581 01 Linköping.

IEA (International Energy Agency), 1995. World Energy Outlook. OECD, Paris.

Ingersoll, J.G., 1996. Natural Gas Vehicles. Fairmont Press, Lilburn.

IPCC Working Group III 1996. Climate Change 1995. Economic and Social Dimension of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate. Cambridge University Press, Cambridge.

Johansson-Stenman, O., Sterner, T., 1998. What is the scope for environmental road pricing? In: Button, K.J., Verhoef, E. (Eds.), Road Pricing, Traffic Congestion and the Environment: Issues of Efficiency and Social Feasibility. Edward Elgar, Aldershot.

Johansson, B., 1995. Strategies for reducing emissions of air pollutants from the Swedish transportation sector. Transportation Research A 29A, 371–385.

Johansson, B., 1996. Transportation fuels from Swedish biomass – environmental and cost aspects. Transportation Research D 1, 47–62.

Johansson, B., 1996. Will Swedish biomass be sufficient for future transportation-fuel demands?. Energy – the International Journal 21, 1059–1069.

Johansson, O., 1997. Kan minskade hälso- och naturskadekostnader motivera en satsning på biodrivmedel? The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Knapp, K.T., 1994. On-road vehicle emissions: US Studies. The Science of the Total Environment 146/147, 209–215.

Maddisson, D., Pearce, D., Johansson, O., Calthorp, E., Litman, T., Verhoef, E., 1996. The True Cost of Road Transport, Blueprint 5. CSERGE, Earthscan, London.

Månsson, T., 1998. Clean vehicles with bio-fuel. State-of-the art report. Swedish Transport and Communications Research Board, Box 5706, SE-114 87 Stockholm.

Mayeres, I., Ochelen, S. and Proost, S., 1996. The marginal external costs of urban transport. Public Economics Research Paper Nr 51. CES, Department of Economics, Katholike Univeristeit, Leuven.

Michaelis, L., Davidsson, O., 1996. GHG mitigation in the transport sector. Energy Policy 24, 969–984.

Möller, S., 1989. Beräkning av samband mellan fordonsålder och trafikarbete för några olika fordonstyper. Swedish Road and Traffic Research Institute, S-581 01 Linköping.

National Research Council, 1997. Review of the research program of the Partnership for a New Generation of Vehicles, Third report. National Academy Press, Washington.

Nilsson, L.J. and Johansson, T.B., 1995. Environmental challenges to the energy industries. In Expanding Environmental Perspectives. Lesson of the Past, Prospects for the Future, eds L.J. Lundgren, L.J. Nilsson and P. Schlyter, Lund University Press, Lund.

Nordhaus, W., 1993. Rolling the DICE: An optimal transition path for controlling greenhouse gases. Resource and Energy Economics 15, 27–50.

NUTEK (Swedish National Board for Industrial and Technical Development), 1996. Effekter av ökad biobränsleanvändning. En sammanställning av kunskapsläget. NUTEK Förlag, SE-117 86 Stockholm.

NUTEK, 1997. Energy in Sweden. Facts and Figures 1997. S-117 86 Stockholm.

OECD 1993. Choosing an Alternative Transportation Fuel. Air Pollution and Greenhouse Gas Impacts. OECD, Paris.

Olsson, L-O., 1996. Fordonskostnadens påverkan vid användande av biodrivmedel. The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Östman, A., 1996. Produktionskostnader för etanol, metanol och biogas. The Swedish Transport and Communications Research Board, Box 5706, 114 87 Stockholm.

Ross, M., Wenzel, T., 1997. Real-world emissions from conventional passenger cars. In: DeCicco, J., DeLucchi, M. (Eds.), Transportation, Energy and Environment: How Far Can Technology Take Us? American Council for an Energy-Efficient Economy, Washington.

Sachs, H.M., DeCicco, J., Ledbetter, M., och Mengelberg, U., 1992. Heavy Truck Fuel Economy: A Review of Technologies and the Potenital for Improvement. American Council for an Energy-Efficieny Economy, Washington.

SIKA (Swedish Institute for Transportation and Communications Analysis), 1996. Översyn av samhällsekonomiska kalkylvärden för den nationella trafikplaneringen 1994–1998. SAMPLAN Nr: 1995:14. P.O. Box 17213, S-104 62 Stockholm.

Singh, M.K., Mintz, M., 1997. Alternative fuels and vehicles: transition issues and costs, in DeCicco, J., DeLucchi, M. (Eds.), Transportation, Energy and Environment: How Far Can Technology Take Us?. American Council for an Energy-Efficient Economy, Washington.

Sjödin, Å., Lenner, M., 1995. On-road measurements of single vehicle pollutant emissions, speed and acceleration for large fleets of vehicles in different traffic environments. The Science of the Total Environment 169, 157–165.

Statistics Sweden, 1996. The Natural Environment in Figures, 5th ed. SE - 104 51 Stockholm.

Statistics Sweden, 1997. Emissions to air in Sweden – sulphur dioxide, carbon dioxide, methane, nitrous oxide and carbon monoxide in 1996. SE - 104 51 Stockholm.

Stephenson, J., 1991. Learning from Experiences with Compressed Natural Gas as a Vehicle Fuel. CADDET, Sittard.

Stirling, A., 1997. Limits to the value of external costs. Energy Policy 25, 517–540.

Swedish National Road Administration, 1996. Environmental Report, SE-781 87, Borlänge.

van Well, L., 1995. Environmental Governance and the European Community: The Case of Climate Change. The Swedish Institute of International Affairs, Box 1253, S-111 82 Stockholm.