Working Paper

Carbon Emissions in the Passenger Transport Sector Technology and Alternative Fuels

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Foreword

In 1987 global carbon dioxide emissions associated with energy use were about 5.7 Gt carbon. The transport sector accounts currently for some 1.2 Gt carbon emissions annually, or for slightly less than 25 percent of global energy-related carbon dioxide emissions. Perhaps more important than the absolute magnitude of the emissions is the voracious growth of the transportation demand in both developed and developing countries even during the periods of rising energy prices. Consequently, carbon dioxide emissions derived from the transportation sector are the fastest growing component of all anthropogenic greenhouse gases.

In this report, Andreas Schäfer analyzes technological options for reducing carbon dioxide emissions for passenger transport. His analysis covers the major modes including aircraft, automobiles and railways and it also covers the energy supply chains that deliver transportation fuels. Thus, the mitigation and efficiency improvement potentials are assessed by the examination of whole energy and emission chains from raw material extraction through end-use. The major options considered in the paper for mitigation of carbon dioxide emissions associated with passenger transport include both the efficiency improvements of the vehicles and the whole energy and transport system and the use of alternative fuels with lower specific carbon content and/or lower carbon emissions.

Moreover, some aspects of consumer's behavior are also considered such as load factors and occupancy of vehicles. The analysis identifies a large carbon emissions reduction potential in passenger transport by both technological measures and changes in consumer's behavior. In general, alternative fuels such as alcohols have on balance a limited if any real advantage over gasoline and diesel vehicles, while the electric propulsion is identified to have the largest reduction potential irrespective of whether electricity is generated by a "conventional" power plant mix or by alternative energy sources without any carbon emissions. In some cases that also leads to an interesting result that for short-range trips highly efficient individual transport modes such as the well-designed electric cars might have the best performance even when compared to public transport systems with respect to both carbon emissions and energy use.

This paper represents the first in a series of studies that will analyze the technical, economic and environmental performance of technologies as well as the data pertinent to innovation, commercialization and diffusion characteristics and prospects of future technologies in conjunction with the data base designed to enter, update and retrieve information on carbon dioxide reduction and removal technologies. The objective of this and subsequent publications and the data collected in the data base is to facilitate the assessment of carbon dioxide reduction strategies by combining many individual technologies together, i.e., to analyze measures throughout the energy chain from primary energy extraction to measures to improve energy end-use efficiencies.

Contents

Abbreviations

CC	Combined Cycle Plant (natural gas fired)
CNG	Compressed Natural Gas
EI	Energy Intensity
EV	Electric Vehicle
GE	Gasoline Equivalent
GHE	Greenhouse Effect
h	Reaction Enthalpy
l	Liter
LHV	Lower Heating Value
LF	Load Factor
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
NER	Net Energy Consumption Ratio
pass-km	passenger kilometer
seat-km	seat kilometer

Chemical Compounds

CH_4	Methane
CH_3OH	Methanol
C_2H_5OH	Ethanol
CO	Carbon Monoxide
H2	Hydrogen
HC	Unburnt Hydrocarbons

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1. Introduction

Almost 20 years after the first oil crisis the discussion on alternative fuels in passenger transport is experiencing a renaissance, this time because of environmental concerns, rather than worries about supply: the transport sector represents the fastest growing source of emissions.

The world passenger car fleet (currently about 500 million) more than doubled since 1972. Kilometers driven were approximately constant per car, but progress in fuel economy could not stop emissions due to the rapid growth in vehicles.

Technological measures against environmental degradation were introduced during the 1970s in the Japanese and US transportation market: three-way catalysts in passenger cars reduce the release of nitrogen oxides (NO_X), unburnt hydrocarbons (HC) and carbon monoxide (CO) up to 90% under certain conditions. A time constant of 20 years for complete diffusion in the US market (Nakicenovic, 1987) can serve as a basis for forecasting their diffusion and amount of emission reduction in other regions such as Europe .

Because of the dramatic vehicle fleet growth, traffic related greenhouse gas emissions are expected to increase substantially during the next decades. Between 1972 and 1988 global passenger car released carbon emissions increased from about 360 megatons to about 450 megatons per year. A still more dramatic development is characterized by road delivery vehicles: while the current number of trucks is about one-fourth of passenger vehicles[1], data show that their carbon emissions converge against the values derived from passenger cars. Carbon dioxide releases, contributing slightly more than 50% to the greenhouse effect (GHE), can be reduced technologically by more efficient engines or by a shift towards low carbon and no-carbon fuels. A variety of alternative fuels exist. This paper assesses their degree of environmental benignity, considering the whole emission chain - from raw material extraction to end use conversion. It covers the three main modes of passenger transport, i.e. motor vehicles, railway systems and aircraft.

Obviously there is much potential for efficiency improvements of technologies based on conventional fuels, e.g. the gasoline powered car. This, however, is no reason for not examining other transportation fuels: other transportation fuels examined here generally have a still larger potential for engine efficiency improvements compared to gasoline.

2. Considered Fuels and Technologies

Table 1 summarizes the considered fuels for the three transport modes, passenger cars, railways and aircraft. Fuel data are given in Appendix 1 of this report.

Worldwide, gasoline and diesel fuels power most cars. Ethanol has become the most used transportation fuel in Brazil, while CNG is in limited use in Italy, Canada and New Zealand. Methanol and LH2 have been tested successfully in vehicle fleets in several countries, e.g. in West Germany. In most applications gaseous fuels are compressed for on-board storage. This strategy requires considerably more space than conventional fuels. However, low load factors and a trend towards still lower values in OECD countries may make this less of a problem than in the past.

On a global scale electric (primarily intercity trains) and diesel railways predominate. Hard coal was still being used for railway transportation in some developing countries such as China until recently. The introduction of high speed trains began in Japan in 1969, in France during the 80's and Germany followed in 1991. This trend towards more service oriented end use technologies will probably continue with magnetic levitation trains (MAGLEV), which are currently under test.

The range of possible alternative fuels is much tighter for aircraft than for road transport. Weight and cargo space are the two decisive economical parameters for air transportation. Aircraft fuels should have a high mass specific energy density in order to meet the first criterium and a high volume specific energy density to meet the latter. Basically LNG and H2 (the latter has an extremely high energy density per unit mass) are the only interesting candidates for alternative fuels for air transport. Jet A is today's

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[1] A considerable share of road good vehicles consist of light trucks, being used for passenger transport as well (or exclusively). Consequently the distinction between passenger and freight transport can't be met clearly.

	examined Technology	
	conventional	innovative
Passenger Car	Gasoline, Diesel	Alternative Fuels: Methanol, Ethanol, CNG, LH2
Railways	Steam Locomotives Electric Intercity Trains Diesel Locomotives	High Speed Trains MAGLEV
Aircraft	Jet A (M<1)	M<1: Efficiency Improvements (Jet A) Alternative Fuels: LNG, LH2 M>1: Jet A, LH2

Table 1 Considered Fuels and Technologies for each Transport Mode

principal fuel used for aviation. In 1956 the first (partially) hydrogen powered aircraft, a modified B-57 made a 17 min flight. In 1988 and 1989 a Soviet Tu-155 passenger aircraft flew with one of the three engines running on LH2 and another on CH4. The German section of Airbus Industry together with Tupolev are currently modifying a conventional passenger aircraft for LH2 application; hydrogen will be delivered from Canada where abundant hydroelectric power permits cost efficient electrolysis of water.

3. The Supply Sector

The supply sector extends from raw material extraction through vehicle refueling. Data of raw material extraction, however, vary considerably from case to case (on-shore, off-shore). Consequently I consider the energy and carbon chain from fuel production on. Efficiency data of chain calculation is summarized in Appendix 2 of this report.

3-1 Fuel Production

In the following efficiencies for fuel production will be given. I distinguish between petroleum based and directly used fuels (natural gas, hard coal) on one hand and synthetically produced fuels on the other hand. The latter are produced by relatively extensive and energy intensive technologies.

3-1.1 Petroleum based and directly used Fuels

Gasoline, Diesel, Jet A

Gasoline, diesel and Jet A are products of crude oil refinery. Production efficiency of petroleum based fuels range from 88% (Heitland *et al.*, 1990; value corresponds to both gasoline and diesel) to 92, 94 and 97% (Fabri *et al.*, 1990; the former two values are related to gasoline with different octane ratings and the latter to diesel). I assume an average value of 90% for both gasoline and diesel. Jet A is assumed to have the same conversion efficiency. The production process is assumed to be powered exclusively with crude oil.

Natural Gas, Hard Coal

While hard coal is assumed to be used directly, natural gas is desulphurized before pipeline shipment (pipeline quality). The energy input for desulphurization was neglected.

3-1.2 Synthetic Fuels

3-1.2.1 Synthetic Fuels derived from Natural Gas

The industrial production of the synthetic fuels considered here is based on natural gas. Normally the following two-step process is taken:

(i) **endothermic** production of a synthesis gas (mixture of CO and H2). In the reformer natural gas is catalytically cracked according to

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \Delta h_{273K,\,0.1MPa} = +\,206.28 \text{ kJ/mol}$$

(ii) **exothermic** synthesis of the new fuel based on the stoichiometry required.

Hydrogen Production from Natural Gas

After having produced the synthesis gas, additional hydrogen can be formed by the exothermic shift reaction of CO to CO_2

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta h_{273K} = -\,41.16 \text{ kJ/mol}$$

Consequently the endothermic net equation is

$$CH_4 + H_2O \rightarrow 4H_2 + CO_2 \qquad \Delta h_{273K,\,0.1MPa} = +\,165.12 \text{ kJ/mol}$$

Technically there are two possible ways to follow, depending on the method of heat transfer to the reformer: (i) external heating with heat provided by the feedstock or high temperature heat by e.g. nuclear reactors (tubular reformers) and (ii) autothermal reforming, i.e. partial combustion of hydrogen feedstock with oxygen within the reformer (secondary reformer). The second strategy is more energy intensive and more complex due to the use of oxygen. Its application is focussed on methanol production, where H2-CO mixtures are desired for methanol synthesis. The former path is used for hydrogen production.

Taking into account the energy flows of natural gas, electricity and hydrogen, the thermal efficiency of hydrogen production from natural gas is about 70% (LURGI, 1991). However, by-products are not considered[2].

Figure 1 shows the carbon emissions during catalytic steam reforming of methane (values are related to the plant described in footnote 2): each MJ energy input "produces" 15.4 gram of carbon if electricity input is neglected (only about 0.6% of methane energy input). Following the steam reformed methane path, the only carbon emissions appear during hydrogen production. This offers the opportunity of concentrated carbon collection as suggested by Marchetti (1989) for natural gas cracking with nuclear heat and subsequent carbon injection in gas fields or on-shore oil fields for tertiary oil recovery.

Methanol

As mentioned above, the autothermal reactor is used for synthesis gas production. The stoichiometry necessary for methanol synthesis (higher carbon monoxide concentrations) can be achieved by additional reforming of natural gas with carbon dioxide according to $CH_4 + CO_2 \rightarrow 2H_2 + 2CO$.

The subsequent steps consist of

(exothermic) synthesis of methanol in a multistage cycle with periodical separation of formed methanol. The reactions are

$$CO + 2H_2 \rightarrow CH_3OH \qquad \Delta h_{300K} = -90.77 \text{ kJ/mol}$$

$$CO_2 + 3H_2 \rightarrow CH_3OH \qquad \Delta h_{300K} = -49.16 \text{ kJ/mol}$$

Separation of pure methanol from water and other impurities by distillation.

The production of methanol from natural gas has a conversion efficiency of 68% (H.Heitland *et al.*, 1990; Fabri et *al.*, 1990). Figure 2 shows the amount of carbon emissions during this step. Again it is assumed that electricity input is negligible compared to the energy input of natural gas. As for steam reforming of natural gas, the energy input of 1MJ corresponds to 15.4 g carbon. Methanol, however, consists of carbon too - 0.68 MJ energy output (corresponding to 1 MJ of energy input) correspond to 11.9

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[2] Data from manufacturer LURGI describes a steam reforming plant with 1000 Nm^3 hydrogen output at a pressure of 25 bar. The input consists of 450 Nm^3 natural gas, 25 kWh electricity, 2 tons feed water and 1 m^3 cooling water. In addition to hydrogen, saturated steam at a pressure of 40 bar and process condensate are produced. Note that these data refer to an average steam reforming plant. Practically flue gases of other hydrocarbon processes are used as additional feedstock resulting in different H2 production efficiencies.

g carbon. Consequently each MJ of methane input releases 3.5 g of carbon during methanol processing. As in steam reforming of natural gas, this amount of carbon could be used as a raw material or stored under the earth.

3-1.2.2 Renewable Fuels

Ethanol

Large-scale production of ethanol from biomass is only feasible in appropriated regions providing sufficient crop land. Only Brazil has allocated such resources, establishing the world's major alternative fuel program during the 70's. In most other world regions, this strategy can only be of local importance. Sugarcane is the most attractive feedstock for ethanol production because: (i) sugarcane provides one of the highest ethanol yield per unit area and year of all biomass feedstocks (about 3500 l/ha/yr; World Bank, 1980) and (ii) it offers the possibility of self-fueling production using the by-product bagasse as energy source. Basically the production process can be divided into

(i) juice extraction (milling, screening of sugar cane)
(ii) exothermic fermentation of glucose primarily forming ethanol, water and carbon
(iii) ethanol distillation

Production efficiency of autothermal ethanol production from sugarcane is about 32.5% (A.Kristoferson and V.Bokalders, 1986). Taking into account the energy stored in the by-products (surplus bagasse and stillage), the production efficiency of ethanol, i.e. the output-input-ratio of energy flows would obviously increase. However, the use of stillage is constrained (World Bank, 1980; Smil, 1983) and the surplus of bagasse (or a major part of it) may be used for stillage removal. One indication of the productiveness of biofuels is net energy consumption ratio (NER) which is 0.12 for Brazil[3]. This means that the equivalent of 12% of produced ethanol is used for growing and harvesting the feedstock crops and for alcohol production if the energy stored in by-products are considered. Taking this value into account for the calculation of ethanol production, efficiency decreases to 31.4%[4]. However, raw material extraction was not considered for other fuels as well. Consequently I assume that commercial energy input is equal to by-product energy, i.e. NER = 0.

Carbon emissions during ethanol production can be taken from Figure 3. One MJ energy input results in 8.4-10.6 g carbon emissions, of which 2.9 g are released during

[3] defined as $NER = (CE-BE)/LHV$, being CE the total commercial energy input for growing and harvesting the crops as well as for alcohol production, BE the by-product energy and LHV the lower heating value of ethanol. If $NER > 1$, the energy balance is negative. Obviously values are desired to be as small as possible. The value of 0.12 for Brazil is based on the use of stillage as fertilizer.

[4] The ratio 31.4/32.5 = 97% signifies, that additional losses for the whole ethanol production chain are 3%. This value is roughly comparable to raw material extraction losses of fossil fuels.

fermentation and 5.5-7.7 g during burning of bagasse for steam generation. Ethanol contains 6.3 g carbon per MJ energy input. Ranges in carbon emissions stem from varying indications about heating values of bagasse (5.44 MJ/kg[5] - 7.62 MJ/kg[6]). Bagasse itself is assumed to be 50% moist and dry bagasse to have a carbon content of 45%.

Hydrogen

Electrolysis of Water with Renewable Energy Input

Data given by Wendt (1986) indicates that efficiency of hydrogen production via electrolysis is 75%. This value accounts for losses and energy input to all auxiliary systems such as pumps. Electricity supply for electrolysis is considered to stem from hydropower with a production efficiency of 92%.

Electricity

Hard coal and natural gas were considered as fossil primary energy carriers for electricity production. The power plant efficiency burning coal was assumed to be 33%. Due to the high carbon emission factor of hard-coal and the relatively low conversion efficiency of coal power plants, electricity from a coal fired power plant represents the most carbon intensive case. In the present work it was assumed that natural gas was used in a combined cycle (CC) plant having an efficiency of 50%. This path represents the most efficient and least carbon intensive strategy for fossil fuel use. The 1988 US fuel mix (57.5% coal, 5.5% oil, 9.4% gas, 19.4% nuclear and 8.2% hydroelectric power) was considered resulting in an average power plant efficiency of 33%.

3-2 Fuel Transmission and Distribution

Liquid Fuels

First order efficiencies of transport are related to the heating value of the transported fuel. The basic quantity represents the energy input E_{in} for fuel transportation which is approximately constant per unit volume for different fuels. With a given efficiency for gasoline transmission and distribution, $\eta = \Delta H/(\Delta H + E_{in})$, the energy input can easily be calculated by $E_{in} = (1/\eta - 1)\Delta H$. The efficiency for gasoline transmission and distribution is 97% (Fabri *et al.*, 1990; H.Heitland *et al.*, 1990). Consequently, the transmission efficiency for diesel fuel is 97%, for methanol 94% and for ethanol 95%.

Gaseous Fuels

Sperling and DeLucchi (1989) calculate an efficiency of natural gas pipeline transport of 97%, where natural gas is used as the energy source for compressor operation. Hydrogen, having only about one-third of the volume-specific heating value of natural

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[5] cited by Smil (1983)

[6] indicated in Braunstein *et al.* (1981)

gas would normally require a three-fold shipment velocity (roughly three-fold compressor power) in order to produce the same energy flow for the same pipeline diameter. Optimized pipeline shipment costs are dependent on the pipeline diameter, resulting in 1.4m for natural gas and 2m for hydrogen (Carpetis, 1986). Consequently, the efficiency for hydrogen shipments is roughly the same as for natural gas. While liquid fuels were assumed to be transported by trucks or by product pipelines with electricity input, gaseous fuels are in our case exclusively shipped in pipelines. The energy requirement for compression stations is taken from the gas to be transported.

Solid Fuels

This chapter is related to hard coal transport by railways. The calculation of energy use and carbon emissions was based on transportation efficiencies of 94% for a locomotive of the mid 19th century (1855) and 98% for the mid 20th century. The efficiencies are derived from following assumptions:

(i) an average distance of 500 km for coal transport, i.e. coal mine to railway station
(ii) each transport is carried out with the same locomotive which is used for passenger transport
(iii) wagons for coal transport are characterized by the payload ratio "mass of cargo per total mass (.i.e. mass of cargo plus mass of wagon (empty))" being 67% for STEAM 1855 and 70% for STEAM 1955 (based on data from Technical Museum Vienna), respectively.

Electricity

A wide range of electricity transmission efficiency exists for various countries. While Japan has a rather efficient net (6.0% losses), India suffers extremely high transmission losses (21.5%) - according to statistics. In this study I selected transmission losses of 8% which correspond to countries like USA and France (Nishimura, 1991).

3-3 Compression, Liquefaction of Gaseous Fuels

While the compression of natural gas and the liquefaction of hydrogen are carried out with electricity, liquefaction of natural gas is powered by the fuel itself. Efficiencies are given in Table 2. The efficiency of natural gas compression is related to a storage pressure of 207 bar.

	Efficiency	Source
Compression, CH4	0.96	Sperling and DeLucchi, 1989
Liquefaction, CH4	0.83	Sperling and DeLucchi, 1989
Liquefaction, H2	0.77	Carpetis, 1986

Table 2 Efficiencies of Fuel Compression and Liquefaction

4. End-Use Sector

4-1 Technologies

The end-use sector was divided into three categories of transport means, i.e. passenger cars, railways and airplanes. Combustion in passenger car engines, aero engines and fossil power plant was assumed to be complete. This contradicts reality. On average the combustion of a gasoline powered car is about 97% efficient. Aero engines release about 6% of the fuel carbon as CO and HC while taxing, but a negligible amount while airborne. Taxing corresponds to a small share of the whole flight phase for long-range aircraft which are the objective in this context. Consequently, if not studying carbon containing trace gases, this approximation is sufficiently exact. In the following the transport means will be briefly described.

4-1.1 Passenger Cars

The potential for efficiency improvement of gasoline powered cars is considerably high. The reduction of vehicle mass and aerodynamic drag, more efficient engines and transmissions as well as recovery of braking energy can decrease average fuel consumption to the range of 3 liters of gasoline per 100 km. In the following calculations I assumed a typical gasoline powered car with a fuel consumption of 10 liters per 100 km. Fuel consumption of alternative fuels is related to special dedicated engines. These technologies are assumed to be on the same technological level as today's average gasoline engine. Each vehicle with a combustion engine is supposed to have 4 seats. Subsequently only cargo space becomes smaller when gaseous fuels (at normal conditions) such as CNG, LH2 are used. This is a valid consideration, because load factors in OECD countries are about 40%.

Gasoline — The gasoline car was assumed to have a fuel consumption of 10 liters of gasoline per 100 km. This value corresponds to the basis to which fuel consumption of other technologies and fuels are related.

Diesel — Higher efficiencies of self ignition diesel engines compared to the spark ignition gasoline car result in lower fuel consumption, here supposed to be 7.8 liter of gasoline equivalent (lGE).

Ethanol — Alcohols offer considerable advantages compared to gasoline powered engines, such as significantly higher compression ratios, higher heat of vaporization and leaner air-fuel mixtures. Data from Volkswagen Brazil shows, that the first generation of ethanol dedicated engines have a 12% lower fuel consumption compared to its modified gasoline predecessor (Geller, 1985). However, ethanol powered cars are still based on gasoline engines resulting in too low efficiencies. In the present study I assume a fuel consumption of 8 lGE per 100 vehicle kilometers.

Methanol A methanol powered engine is still more efficient than the ethanol engine. This is because of a still higher evaporation heat permitting engine weight reduction. An extensive literature review indicates a 20 to 30% lower fuel consumption than a gasoline powered car (TUV Rheinland, 1984; Gray and Alson, 1989, Heitland et al., 1990). I calculated that a first generation methanol powered car would consume 7.5 lGE per 100 kilometers.

CNG All of today's natural gas vehicles are powered by gasoline engines. Practically no data of energy consumption of natural gas dedicated combustion engines for passenger transport exists. Due to the extremely high octane rating of methane, such a vehicle is assumed to have the same energy consumption as the ethanol engine, i.e. 8.0 lGE per 100 km.

Hydrogen Engine efficiencies of hydrogen powered cars differ widely (DeLucchi, 1989). However, all examined vehicles had significant higher efficiencies than comparable gasoline engines. Essentially efficiencies are between 20 and 50% higher, in one case even 63% but with 23% less power output. I assume a performance increase of 20% resulting in an energy consumption of 8 lGE per 100 km.

Electric Car Several car designs for electrically powered vehicles exist. The conventional solution is the simple replacement of the combustion engine by the electric device. Obviously this solution results in the often discussed key-problem of too short range. Significantly better results can be achieved by adapting the vehicle design to the battery, i.e. the design of an extremely light weight vehicle. Several commercial cars exist, with electricity consumption of less than half a liter of gasoline equivalent per 100 km (Fester, 1990). Two seat "Impact" prototype by General Motors delivers similar results, achieving a range of almost 200 km, a maximum speed of 160 km/h and an energy consumption of 0.54 lGE (Amann, 1991). Moreover four seat electric cars with an energy consumption of about 1.5 lGE per 100 km (like the BMW E1) try to penetrate in the transportation market. In the present study I selected a two seat electric car consuming 0.5 lGE per 100 km which obviously corresponds to a four seat electric car consuming 1 lGE per 100 km on a seat-km unit. The efficiency of the battery and the battery charger was assumed to be 75% and 95%.

4-1.2 Railways

Traction efficiencies of different locomotives are related to the same service, i.e. all locomotives are assumed to draw modern second class passenger wagons with about the same number of seats.

Steam 1855: "1B n2-Schnellzuglokomotive" of the "Preußischen Staatsbahn" of 1855. On a flat ground this locomotive could pull wagons with a weight of 172 tons at a velocity of 83 km/h (Maedel, 1965). Assuming an average mass of 45 tons for a modern passenger wagon this train could pull 3.8 modern wagons with 76 seats each. I suppose that 3 wagons are for passenger transport. An overall efficiency from energy input through wheel-rail interaction of 3% is assumed resulting in an energy intensity of 1.54 MJ/seat-km. Obviously inclined tracks reduce the number of wagons that can be drawn. Consequently this case corresponds to the best performance.

Steam 1955: The extremely advanced "1C2h2t-Baureihe 66, DB" of 1955 could draw 10 modern passenger wagons (76 seats each) at 85 km/h. One wagon is supposed to be for freight transport. The efficiency, here defined as the ratio of cylinder power and the energy flow from coal, was 11.2 % (Giesl-Gieslingen, 1986). Taking into account gear transmission losses as well as losses at wheel-rail track, I assume an 8% efficiency from energy through wheel-rail interaction resulting in an energy intensity of 0.61 MJ/seat-km.

Diesel A diesel powered locomotive has a traction efficiency of about 29%. Assuming a train with 10 passenger wagons (76 seats each), of which one wagon does not account for passenger transport, the energy intensity for a 1500 kW diesel locomotive is 0.33 MJ/seat-km in the end use. This value is based on a locomotive efficiency of 29%.

Int.city The "Baureihe 103" (BR 103) from German intercity traffic, operational since 1971 was selected as electric intercity train. This train pulls 10 wagons (first and second class) with 612 seats. The energy intensity results in 0.11 MJ/seat-km from substation[7] (Jänsch, 1990).

ICE The Intercity Express (ICE), Germany's high speed train, pulls between 10 and 14 passenger wagons at a cruise speed between 250 and 300 km/h. An ICE drawing 12 wagons (corresponding to 645 seats) has an energy consumption of 0.21 MJ/seat-km from substation (Jänsch, 1990).

MAGLEV Data of the magnetic levitation train differ considerably from source to source. The maglev producers Thyssen/Henschel indicate even lower values for energy consumption than for the ICE (supposing the same velocity and seat capacity), but other studies conclude that maglev energy consumption will be significantly higher (Steierwald *et al.*, 1990). This is because of higher cruise speed and higher acceleration potential. A study of Thyssen/Henschel for two tracks in West Germany lead to and energy consumption of about 0.35 MJ per seat-km for a maglev with 328 seats (Konsortium Anschubgruppe Transrapid, 1989). I calculate with an energy consumption given between two values, i.e. a lower value corresponding to ICE per unit seat-km (0.21 MJ/seat-km) and a higher value equal to 0.3 MJ/seat-km for a maglev with 656 seats, (i.e. a German Transrapid with 8 sections) in maglev operating regime from substation.

[7] Energy consumption of electric railway normally is calculated from substation, being the interface of electricity transmission from the power plant (with a voltage of e.g. 110 kV) and the electric railway grid (e.g. 15 kV).

4-1.3 Aircraft

4-1.3.1 Wide Body Aircraft

The dependence of aircraft fuel consumption on various parameters can be seen easily if considering the basic equation:

$$\frac{Fuel\ Burned}{Seat*km} = \frac{SFC*W}{Seat*V*L/D}$$

being SFC the average specific fuel consumption of engines (kg fuel per hour per kg thrust), W the average flight gross weight (kg), V the average flight velocity (km/hr) and L/D the average flight lift-to-drag ratio. Fuel burned per seat-km can be reduced by reducing SFC and weight or increasing velocity (theoretically, because SFC would increase as well) or L/D. SFC has been improved significantly by increasing engine by-pass ratio. However, higher by-pass ratios increase both, weight and drag. Weight has been reduced with time by using advanced materials. L/D has not improved in a regular fashion with time due to the requirement to provide more internal space for passenger comfort (wider seats, wider and more aisles, and more storage for carry on luggage). Wing span being a major factor in L/D is limited because it increases wing weight

	SUBSONIC (M=0.85)				SUPERSONIC (M=2.7)	
	B 747-400	JET A	LNG	LH2	JET A	LH2
EI (MJ/seat-km)	0.879	0.762	0.724	0.637	2.550	3.520
No. Seats	400				234	
Range (km)	10200				7780	

Table 3 Energy intensity (end use), seat capacity and range of several aircraft. B747-400 is operational since 1989. The other air carriers are projected for the 1990s.

(BOEING, 1991). This means, that progress in fuel economy is limited (trade-off between weight and engine performance as well as weight and aerodynamics) and from a certain point only alternative fuels have the potential for a further significant decrease in energy intensity.

Projections for future aircraft performance based on conventional (Jet A) and alternative (liquified natural gas and liquid hydrogen) fuels were carried out by Lockheed Aircraft Company during the 1970s. As described by Brewer (1981), data correspond to advanced 1990s aircraft with "supercritical airfoils, active controls, composite structure, advanced engine technology, and automatic flight management systems". Table 3 summarizes the energy intensities for passenger transport. In addition the performance of BOEING 747-400 operational since 1989 is indicated (Steiner, 1989).

4-1.3.2 Short Range Aircraft

Commuter aircraft have not been involved in the discussion on alternative fuels up to now. For the present analysis I selected a Dornier 228 with two turboprop engines and 19 passenger seats. Energy intensity depends on range and additional cargo, two sensitive parameters for small aircraft. Data from aircraft manufacturer Dornier indicate, that energy intensity ranges from 1.78 MJ/seat-km for a range of 400 nm (741 km) to 2.12 MJ/seat-km for a range of 100 nm (158 km). Higher ranges with fewer passenger seats generally result in higher energy consumption per seat-km. For the present work I selected an average energy intensity of 1.9 MJ/seat-km.

4-2 Load Factors

Aircraft load factors vary from 0.68 for scheduled flights to 0.9 for chartered flights, resulting in an average load factor of 0.7 (IATA, 1989). Commuter flights were assumed to have occupied 75% of all seats, because typical break even points in direct operating

Transport Mean	*Load Factor*
Aircraft, long range	0.70
Aircraft, commuter	0.75
Passenger Cars	0.40
EV, two seats	0.55
Railway (Int.City, Steam)	0.35
Railway (High Speed)	0.35 - 0.60

Table 4 Transport means and corresponding load factors

costs are load factors between 60 and 70%. Different data sources indicate that automobiles in OECD countries typically carry about 1.6 passengers, resulting in a load factor of 40 % for a 4-seat passenger car. Electric vehicles with two seats were supposed to carry 1.1 passengers in average. Data on German intercity traffic indicate a current load factor of 0.35 (Jänsch, 1990). Due to uncertainty for high speed mass transport (ICE, MAGLEV) occupation, the same value was taken as the lower limit. The upper boundary is an average value given by MAGLEV manufacturer Thyssen/Henschel for a German track Hamburg-Hannover and Essen-Bonn (Konsortium Anschubgruppe Transrapid, 1989). Table 4 summarizes the indicated load factors.

5. Results

5-1 Passenger Cars

The average gasoline car requires about 1MJ/seat-km of which almost 15% is used for gasoline refinery and transmission, as shown in Figure 4. Diesel and CNG powered vehicles require about 20% less energy over the whole chain. All alternative fuels considered in this study are more efficient at the point of end use conversion[8]. However, these efficiency gains are at least offset by the considerable amount of energy required for synthetic fuel production: a methanol car requires 25% less energy per unit service, but the about three-fold higher energy input for methanol production (compared to gasoline) offsets the efficiency gain at end use. At this point we see, that the performance of end use technologies is of primary interest: if the methanol car had the same fuel consumption as the gasoline powered car (i.e. 10 liters of gasoline equivalent per 100 km), the primary energy intensity would be about 36% higher compared to a gasoline car. Liquid hydrogen production from natural gas is still more energy intensive than methanol production due to H2 liquefaction (electricity is derived from 1988 US fuel mix). This suggests - under an energy perspective - the direct use of natural gas. Otherwise vehicle efficiencies of H2-powered cars have to be considerably higher compared to natural gas vehicles in order to make steam reformed hydrogen competitive on an energetic point of view (about 3.7 liter of gasoline equivalent per 100 km). A less energy intensive strategy represents H2 production via electrolysis of water and subsequent H2 liquefaction with electricity from hydropower. Lowest energy intensities can be achieved with well designed electric cars, requiring almost half of the energy per seat-km compared to a gasoline vehicle. Because of the average power plant efficiency of 33% for both, the US fuel mix (57.5% coal, 5.5% oil, 9.4% gas, 19.4% nuclear and 8.2% hydroelectric power) and a coal power plant, energy intensity is in both cases the same. If electricity is produced from natural gas in a combined cycle power plant primary energy intensity achieves a minimum below 0.4 MJ/seat-km.

Before starting an engine, quite some carbon emissions have already been released: carbon emissions of the supply sector typically are almost 15% of total carbon emissions for gasoline, diesel and natural gas (see Figure 5). The gasoline powered car releases almost 20 g per seat-km. Vehicles powered by methanol and diesel release about 20% less carbon. The direct use of natural gas has a reduction potential of 30% compared to the gasoline vehicle. However, CH4 leakages and losses during vehicle refueling have to be taken into account[9].

The selected hydrogen vehicle powered by steam reformed natural gas as described in section 3-1.2.1 causes about 40% more carbon emissions as an average gasoline powered

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[8] according to the data given in Chapter 4.

[9] Calculating with a half life of 11 years for the reaction of atmospheric methane to carbon dioxide the break-even point in carbon emissions related to the gasoline vehicle results in a leakage rate of 5.4% for methane for a greenhouse potential per unit mass of 21 related to carbon dioxide and 2.0% for a potential of 58, respectively. Both values are related to a time scale of 20 years.

car. Note that a considerable share of the carbon emissions is because of H2 liquefaction with electricity derived from the 1988 US fuel mix. However, the steam reforming process offers the possibility of concentrated carbon removal as already mentioned. Generally synthetic fuels emit considerably more carbon during the fuel production process. Especially ethanol production is extremely carbon intensive due to the use of bagasse as the fuel.

Dedicated electric vehicles provide astonishing good results. Even in the worst case of coal fired electricity generation carbon emissions are less than for CNG vehicles. In addition EVs have the advantage of concentrated carbon removal. Obviously there are no carbon emissions associated with non-fossil H2 production. This is also true for sugar cane derived ethanol, if no fossil energy is used for fuel production, harvesting, transportation, etc.

5-2 Railways

Considerable progress has been made over the last hundred years in energy efficiency as demonstrated in Figure 6. Energy intensity of intercity trains, ICE and MAGLEV are the same for electricity from coal power plant and fuel mix. This because the efficiency of an average coal based power plant was selected to be 33%, equal to the mean value of US power plant efficiency related to fuel mix.

Progress in energy efficiency of steam locomotive technology resulted in significantly reduced carbon emissions per seat-km as demonstrated in Figure 7. Faster modern electric railways are not necessarily cleaner compared to advanced steam locomotives: high speed trains like the German ICE or magnetic levitation trains (MAGLEV) can produce more carbon per seat-km if supplied with electricity from coal power plants. This case corresponds to the upper boundary of carbon emissions. The lower boundary for electric trains are zero carbon emissions, being realized by carbon removal at electricity generation facilities or by the use of renewable or non fossil energy. The lower boundary for carbon emissions when electricity is derived from fossil fuels is given by combustion of natural gas in combined cycle power plants, where in all cases carbon emissions are lower compared to the 1955 steam locomotive. In addition carbon emissions related to the 1988 US fuel mix are indicated. Note that countries such as Switzerland and France where most electricity is produced by nuclear power and hydropower practically run carbon free electric railways.

5-3 Aircraft

Although natural gas and hydrogen exhibit lower energy intensities at the end use, the primary energy input can increase due to more energy intensive fuel supply (Figure 8). This is primarily true for steam reformed natural gas, when H2 liquefaction is carrried out with electricity derived from the fuel mix considered here. Comparing the renewable LH2 path with the conventional Jet A path, we recognize that the hydrogen aircraft is almost as efficient as to compensate for the higher energy input for fuel production and the energy input for H2 liquefaction. All fuels examined indicate that a three-fold increment in cruise speed results in about a four-fold increase in energy intensity.

A shift towards fuels other than Jet A can reduce carbon emissions substantially as demonstrated in Figure 9. However, as we noticed for the passenger car sector, hydrogen production from hydrocarbons, i.e. natural gas normally does not represent a cleaner solution if carbon emissions are not removed: also in the aircraft sector the direct use of natural gas is superior to LH2 production from natural gas. Reduced flight time by increasing cruise speed results in a considerable increase of carbon emissions.

There is a trade-off in the contribution of aircraft to the GHE if selecting alternative fuels such as H2: while as carbon emissions over the whole renewable hydrogen path are zero, H2 powered aircraft contributes to the GHE via cirrus clouds being produced in the upper troposphere by water vapor emissions. Scientists fear an increase in cirrus clouds by a few percent might enhance the GHE comparable to a doubling of CO_2 (U.Schumann, P.Wendling, 1990). Figure 10 demonstrates the drastic increase of water vapor emissions for supersonic aircraft in general and for hydrogen powered supersonic aircraft in particular.

5-4 Comparison of all Transport Modes

Figure 11 indicates the primary energy intensity of various transport modes. As mentioned already, transport systems powered by alternative fuels generally require less energy at end use but considerable more energy for fuel production. Consequently alternative synfuels can only offer an interesting alternative if end use efficiency is substantially higher. The most energy intensive transport means (supersonic aircraft powered by natural gas derived hydrogen) requires an about 20 fold primary energy input per seat-km compared to the least energy intensive transport means considered here (conventional intercity train powered by electricity from a combined cycle plant burning natural gas).

Comparing carbon releases per unit seat-km of aircraft, passenger cars and railways, we find that carbon emissions of modern long-range aircraft are roughly comparable to those of passenger cars and coal-based high-speed trains[10] as indicated in Figure 12. However, comparisons should be made on the same range. Consequently turboprop commuter aircraft have to be considered as a competitor to ground traffic, releasing more than twice as much carbon as an average passenger car does. The lowest carbon emissions are produced by intercity trains and dedicated electric vehicles. The latter, however, are still limited to ranges below 200 km. The shift to higher cruise speeds generally implies a trade-off with regard to carbon emissions because of higher energy requirements. This can be seen in the comparison of supersonic aircraft with subsonic

[10] Note that carbon emissions of ground vehicles and aircraft are not easily comparable with respect to total GHE, due to their much longer residence time in higher altitudes. Moreover other aircraft emissions such as NO_X (which is a major source for ozone depletion as well) and water vapor are of major concern related to the GHE.

airplanes or high speed trains with intercity trains.

Comparing different transport means, it should be noted that the performance of all passenger cars is related to an average gasoline powered car consuming 10 liters per 100 km. A range of considerably higher efficient (commercially available) cars with a fuel consumption of about the half of the selected gasoline exists (Bleviss, 1988), resulting in comparable carbon emissions of coal based electric vehicles and intercity trains. Obviously no carbon at all is released by transport modes based on renewable produced or non-fossil fuels, e.g. electricity from hydro power or nuclear power, renewable hydrogen, ethanol from sugarcane, etc.

The reduction potential of carbon emissions through change in consumer's behavior as reflected in load factors is indicated in Figure 13 (white section of the stack bars, i.e. the difference of carbon emissions per pass-km and carbon emissions per seat-km). In ground traffic systems, carbon reductions of more than half could be achieved under a consumer's perspective. For example, commuter aircraft, releasing about twice the amount of carbon per unit seat-km compared to the average gasoline engine, emit a comparable amount of carbon per unit pass-km. The crucial influence of the load factor on carbon emissions per pass-km can also be seen for electric high-speed transport systems: a change in load factor from 0.35 to 0.6 results in an about 40% decrease of carbon emissions per unit pass-km.

6. Conclusions

Transport related carbon emissions can be reduced technologically by efficiency improvements and the use of low carbon fuels and/or zero-carbon fuels. While efficiency improvements can be implemented without any lead time, a shift towards alternative, cleaner fuels requires both time and large capital investments (large-scale fuel production, modification and exchange of infrastructure, etc.). This is primarily true for hydrogen because of additional problems related to H2 storage and cost efficient production, etc. Under this perspective a shift towards renewable produced fuels might be rather an evolutionary process than an immediate exchange of technologies. This evolution will occur in stages and the transition to a hydrogen dominated transport system might rely on other alternative fuels discussed in this study. On the other hand there is a huge potential for the reduction of carbon emissions by consumer's behavior alone. Other parameters exist which could influence a carbon reduction strategy[11].

Efficiency improvements over the whole fuel chain are an important measure for the reduction of carbon emissions. High end-use efficiency is of major interest because fuel (and carbon) savings are cumulative: requiring less final energy per unit service means requiring less energy input for fuel production and transportation. Consequently carbon

[11] economic requirements (energy security, costs), availability of resources, geographical requirements (spatial structure and demand)

emissions are reduced along the entire emission chain. This is of particular importance for alternative fuels where high efficient end use technologies can offset energy intensive synfuel production such as for a methanol powered car where the fuel is produced from natural gas.

Considering the passenger car sector it remains questionable whether synthetic fuels derived from other fossil fuels such as natural gas could be superior to more efficient gasoline technology. This can be seen clearly in Figure 14 which depicts energy and carbon intensities of transport systems. Straight lines through the zero-point represent a constant ratio of carbon emissions per energy input, i.e. the carbon emission factor. These lines are given for the highest emission factor (hard coal) and the lowest fossil emission factor (natural gas). All fuels based on the same feedstock are positioned on the same straight line. The about 20% lower carbon emissions of a first-generation methanol car (compared to the average gasoline vehicle) can be achieved with average diesel technology as well. Moreover the use of diesel fuel is about 20% less energy intensive. A 50% reduction in fuel consumption of a gasoline powered car is indicated (dashed arrow) putting the now twice efficient gasoline car into the range of a coal based electric vehicle (efficiency improvements correspond to a movement towards the zero-point along a straight line through the zero-point). This demonstrates the potential role of efficiency improvements in both energy intensity and carbon emissions. However, the criteria for the selection of alternative fuels are manyfold. Methanol is environmentally cleaner on the whole emission scale (if the controversial formaldehyde emissions are not being considered) and the use of additional devices (three-way catalysts, filters) can offset methanol's advantage of reduced overall emissions only by suffering efficiency losses and consequently additional carbon releases.

An interesting solution under a carbon perspective provides carbon collection at the fuel production facility. However this strategy requires a higher energy input (about 50% for aircraft and 70% for passenger cars if electricity for H2 liquefaction is derived from 1988 US fuel mix). If carbon is not collected during synfuel production, the direct use of natural gas is superior from both an energetic point of view and a carbon perspective[12].

Hydrogen produced by renewable/non-fossil energy, is the only zero carbon fuel which meets the potential of large scale application (road vehicles, trains, aircraft). In addition to H2 there are renewable biomass derived fuels, but these are only of regional importance. The most prominent candidate is ethanol produced from sugarcane. As we have seen, the energy input generally is still considerably high due to low conversion efficiencies. High conversion efficiencies are of particular importance for biomass fuels, due to both competition between fuel and food production and problems related to by-product disposal such as stillage from ethanol distillation. Next to vehicles operating on renewable derived fuels dedicated electric vehicles - still limited by range (up to 200 km)

[12] a leakage rate of 5.4% for a carbon dioxide related greenhouse potential of 21 per unit mass and 2.0% for greenhouse potential of 58 represent the break-even point with carbon emissions released from the examined gasoline car. These values are related to a time scale of 20 years after emissions.

- represent the least carbon intensive transport system per unit pass-km. Due to both high efficiency and fuel flexibility they have the potential of a long-term solution.

As we have seen in this study, total carbon emissions (which include also emissions from fuel refining and transmission) of a gasoline powered car are about 15% higher than direct vehicle emissions. Consequently the 1988 amount of carbon emissions derived from passenger cars (about 450 megatons) really account for 520 megatons. Putting this into perspective of alternative fuels, a world passenger car fleet consisting of diesel and methanol vehicles would release 420 megatons, of CNG vehicles 340 megatons and of well designed electric vehicles 280 megatons for coal based electricity and 110 megatons for natural gas based electricity produced in combined cycle power plants. A world fleet consisting of EVs powered with electricity of 1988 US fuel mix would cause 190 megatons of carbon emissions.

Generally ground mass transport systems are less energy intensive and consequently release less carbon per unit seat-km than individual transport means. Even in the worst case, if electricity were derived from a coal power plant, the carbon emissions of high speed transport systems would be comparable to those of an average gasoline car. However, if load factors of electric railways are still lower than 35%, e.g. branch lines, highly efficient individual transport means might be less carbon intensive. Thus mass transport systems only can mitigate carbon emissions in high density, high load factor corridors.

A shift towards more service oriented public mass transport systems does not necessarily lower carbon emissions: higher velocities require higher energy input and consequently result in higher carbon emissions if based on the same fuel. This trend was demonstrated for high speed ground transportation (ICE, MAGLEV) and for supersonic aircraft as well. Carbon emissions of the former can be reduced by changing the fuel mix to less carbon intensive fuels. Reducing carbon emissions within the aircraft sector by a shift from petroleum based Jet A towards hydrogen might be offset by with water vapor emissions affecting the earth's radiation balance as well.

We have seen the huge potential of carbon emission reduction by consumer's behavior alone: the typical passenger car emits 20 g of carbon per seat-km, but 50 g of carbon per pass-km. Shifts towards higher load factors primarily in ground traffic transport is a considerable means for mitigation of the greenhouse effect.

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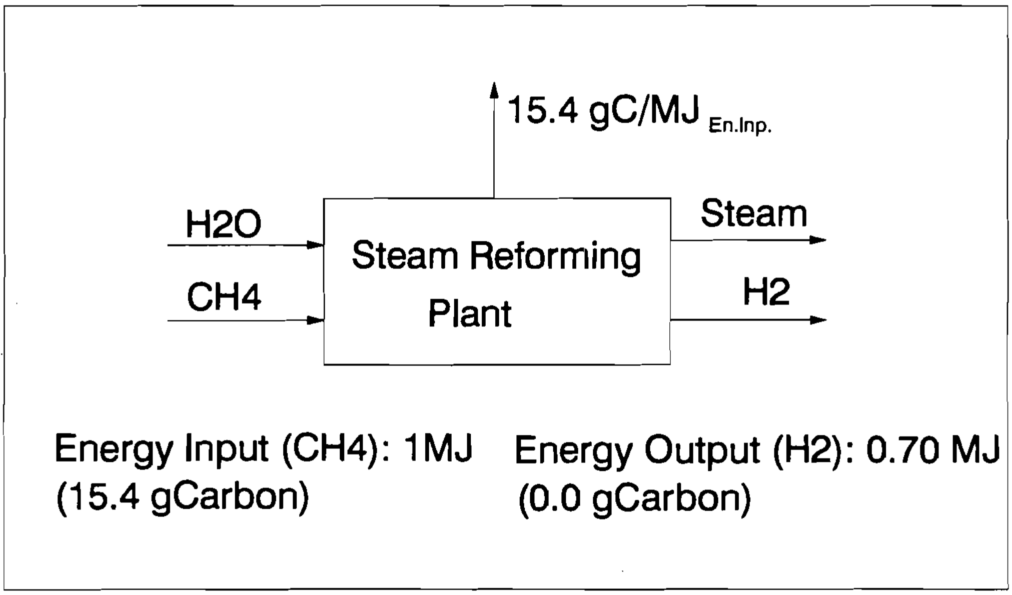

Figure 1 Carbon emissions during autothermal steam reforming of methane: 1 MJ energy input releases 15.4 g carbon. Carbon emissions related to the electricity input into the steam reforming was neglected due to the small fraction of electric energy related to natural gas (about 0.6%). Source: LURGI, 1991

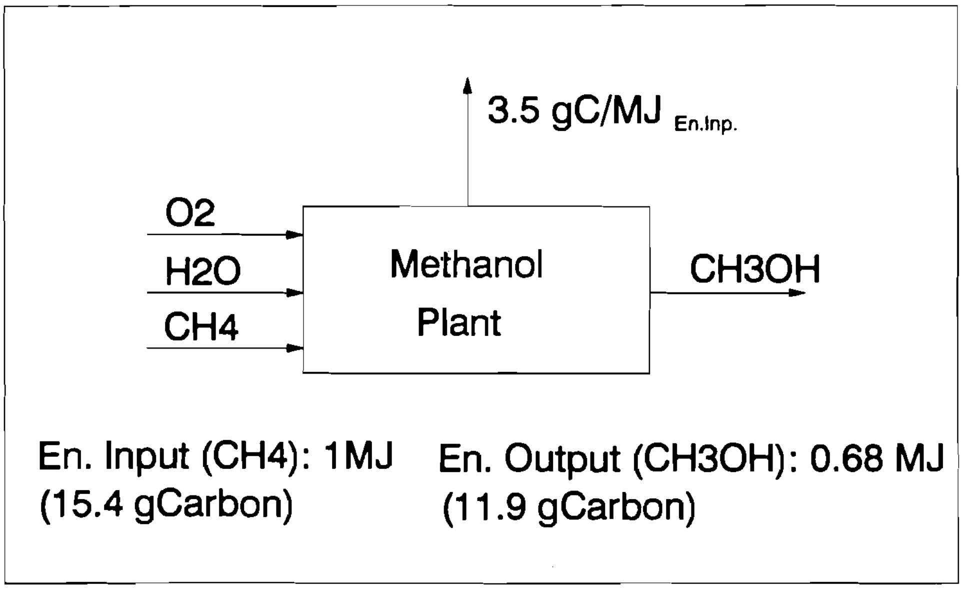

Figure 2 Carbon emissions during methanol production based on methane feedstock: 1 MJ energy input releases 3.5 g carbon. Again carbon emissions related to electricity input were neglected. Source: Heitland *et al.*, 1990, Fabri *et al.*, 1990

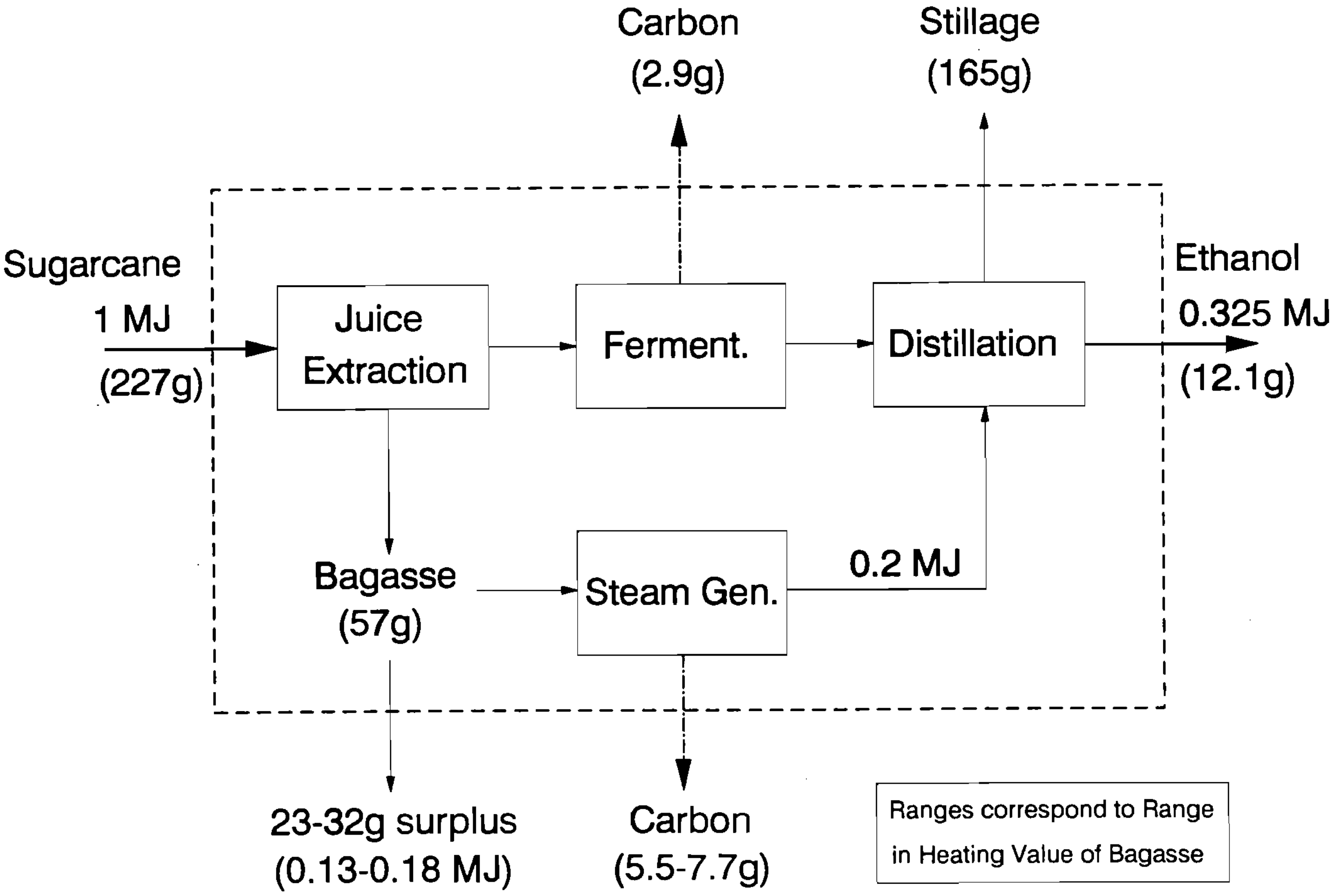

Figure 3 Carbon emissions during ethanol production: 1 MJ energy input results in 8.4-10.6 g carbon emissions, of which 2.9 g are released during fermentation and 5.5-7.7 g because of burning bagasse for steam generation. Ethanol contains 6.3 g carbon per MJ energy input. Ranges in carbon emissions stem from varying indications about heating values of bagasse (5.44 MJ/kg - 7.62 MJ/kg). Bagasse itself is supposed to be 50% moist and dry bagasse to have a carbon content of 45%. Source: World Bank (1980), Kristoferson and Bokalders (1986), Smil (1983), Braunstein *et al.* (1981).

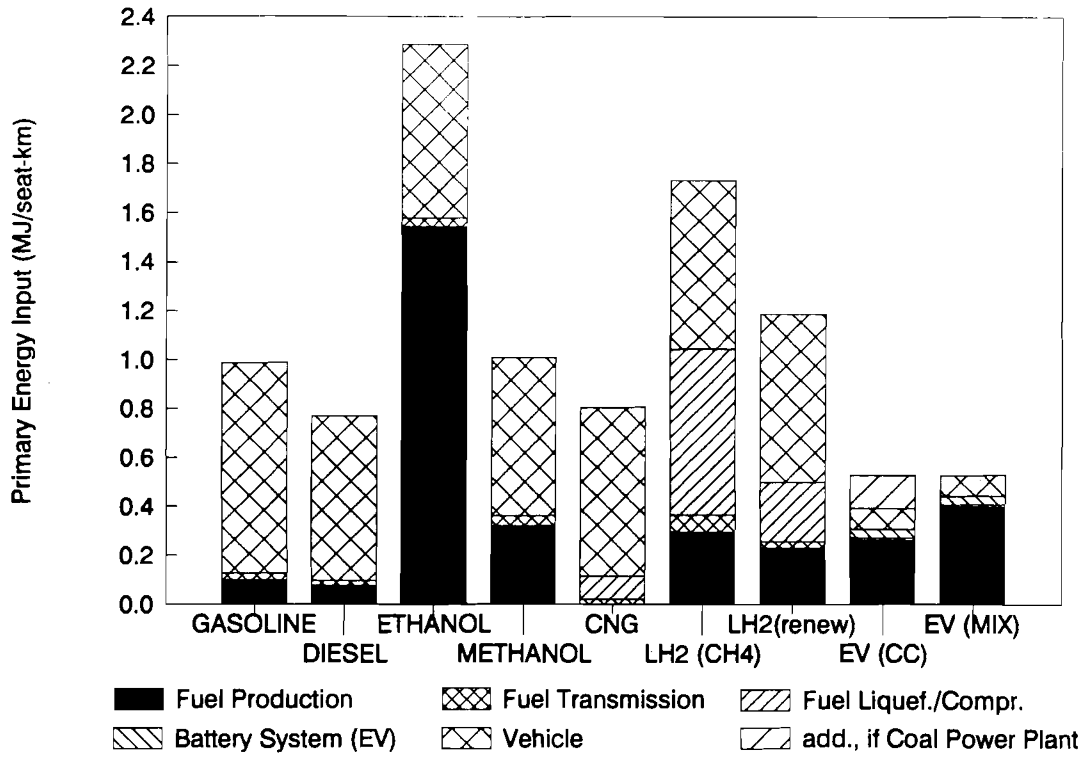

Figure 4 Primary energy intensity of passenger cars; "MIX" corresponds to electricity derived from the 1988 US fuel mix and "CC" to electricity derived from a combined cycle power plant burning natural gas. Compared to the gasoline car, all considered alternative fuels are less energy intensive within the end use sector, i.e. final to useful energy conversion. However, the energy requirement for fuel production is considerably higher. Well designed EVs require the least energy input per unit seat-km.

Chain description:
Gasoline, Diesel: fuel refining - fuel transmission with trucks - end use by gasoline/diesel vehicle; **Ethanol:** autothermal fuel production from sugarcane - fuel transmission with ethanol powered trucks - end use by ethanol vehicle; **Methanol:** fuel production from natural gas - fuel transmission with methanol powered trucks - end use by methanol vehicle; **CNG:** fuel transmission by pipeline with compressor stations powered by natural gas - compression powered by 1988 US fuel mix - end use by CNG vehicle; **LH2 (CH4):** hydrogen production from natural gas - fuel transmission by pipeline with compressor stations powered by electricity from 1988 US fuel mix - H2 liquefaction with electricity derived from 1988 US fuel mix - end use by CNG vehicle; **LH2 (renew):** hydrogen production by electrolysis of water with electricity derived from hydropower - H2 transmission by pipeline with compressor stations powered by electricity from hydropower - H2 liquefaction with electricity derived from hydropower - end use by H2 vehicle; **EV:** electricity production in a combined cycle power plant burning natural gas (CC), in a coal power plant (given increment) or by 1988 US fuel mix (MIX) - electricity transmission - battery system - end use by EV.

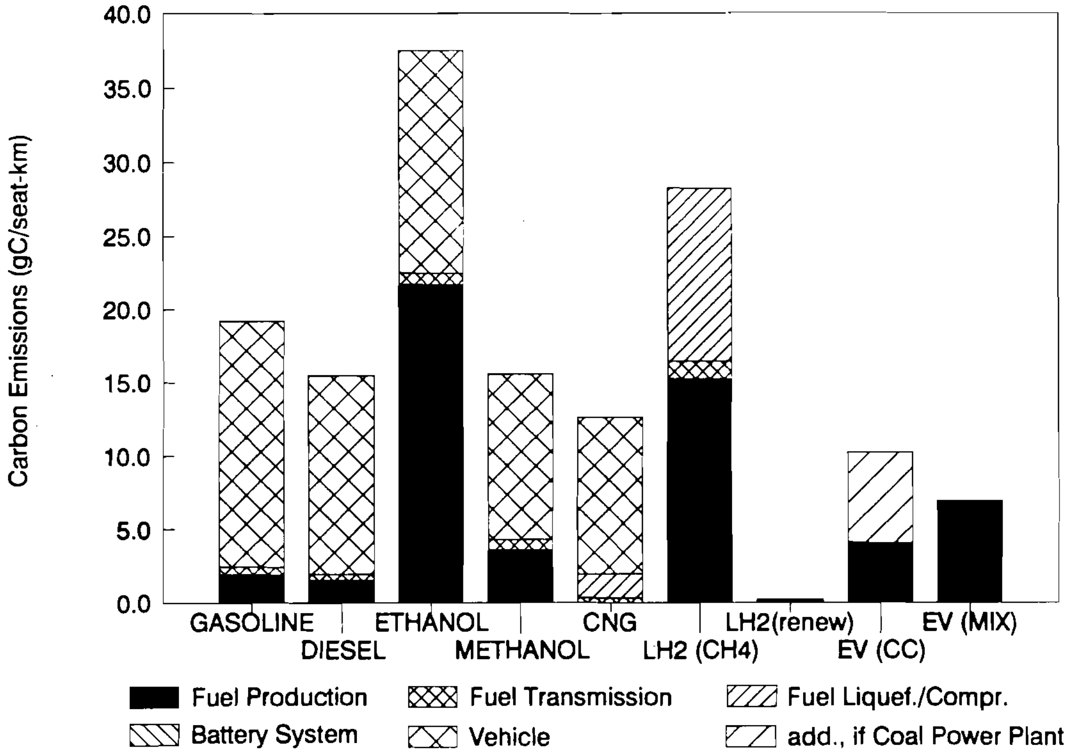

Figure 5 Carbon intensity of passenger cars. All alternative fuels considered here release less carbon than a gasoline powered car. For a car running on ethanol (from sugarcane) or on hydrogen from electrolysis of water with renewable energy input, carbon emissions are zero over the whole carbon cycle. Well designed EVs emit about half of carbon emissions of an average powered gasoline car even if electricity is produced by coal power plants.

Chain description:
Gasoline, Diesel: fuel refining - fuel transmission with trucks - end use by gasoline/diesel vehicle; **Ethanol:** autothermal fuel production from sugarcane - fuel transmission with ethanol powered trucks - end use by ethanol vehicle; **Methanol:** fuel production from natural gas - fuel transmission with methanol powered trucks - end use by methanol vehicle; **CNG:** fuel transmission by pipeline with compressor stations powered by natural gas - compression powered by 1988 US fuel mix - end use by CNG vehicle; **LH2 (CH4):** hydrogen production from natural gas - fuel transmission by pipeline with compressor stations powered by electricity from 1988 US fuel mix - H2 liquefaction with electricity derived from 1988 US fuel mix - end use by CNG vehicle; **LH2 (renew):** hydrogen production by electrolysis of water with electricity derived from hydropower - H2 transmission by pipeline with compressor stations powered by electricity from hydropower - H2 liquefaction with electricity derived from hydropower - end use by H2 vehicle; **EV:** electricity production in a combined cycle power plant burning natural gas (CC), in a coal power plant (given increment) or by 1988 US fuel mix (MIX) - electricity transmission - battery system - end use by EV.

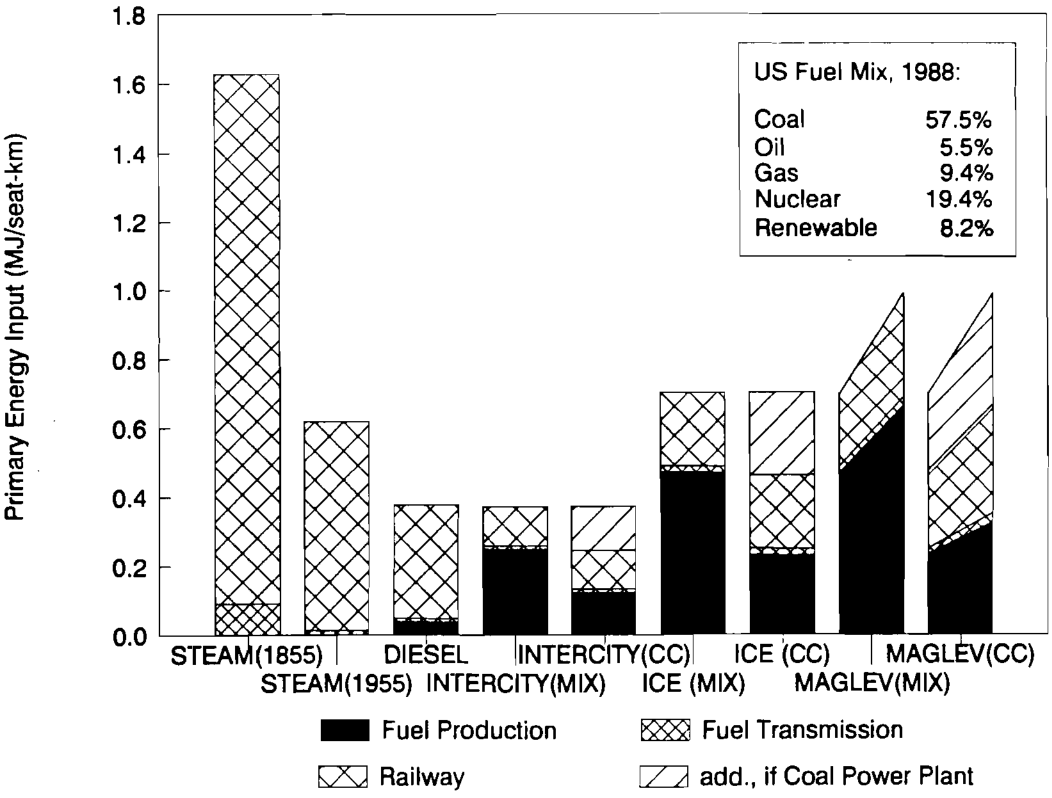

Figure 6 Primary energy intensity of railways. More service oriented technologies require a higher amount of energy input (Intercity-ICE-MAGLEV).

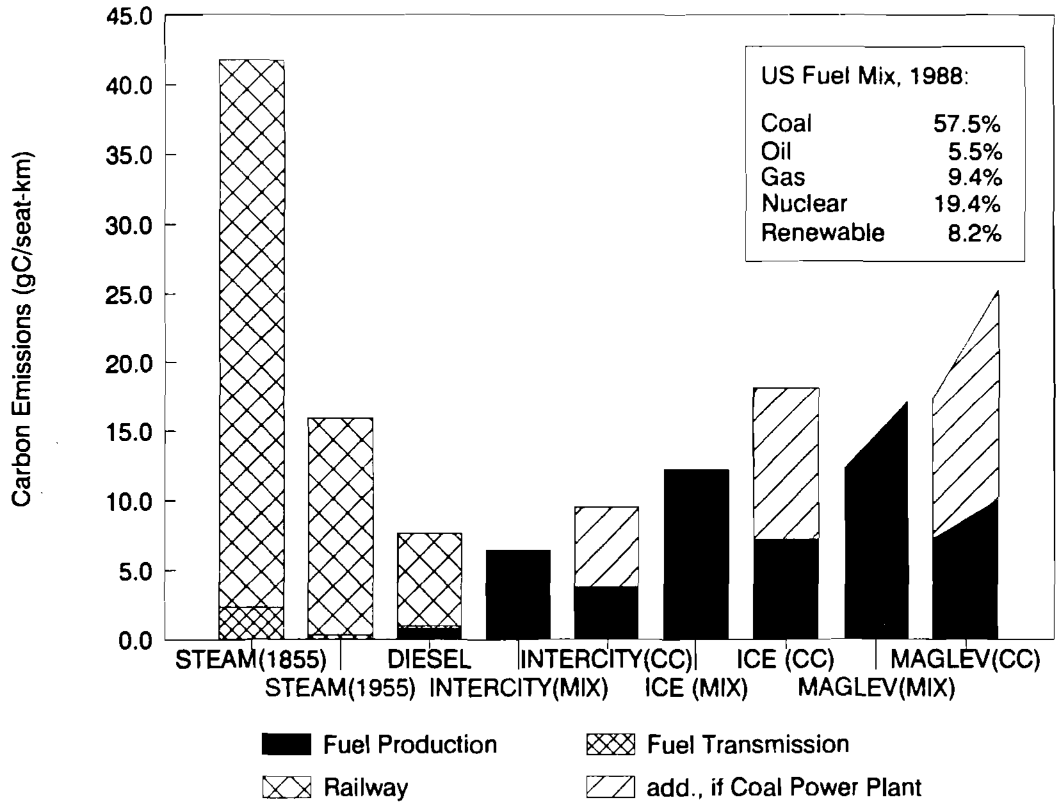

Figure 7 Carbon intensity of railways. Higher orientation on service (higher speed, more comfort) results in higher carbon emissions as it can be seen for Intercity - ICE - MAGLEV. The striped rectangle indicates additional carbon emissions if electricity were exclusively taken from coal power plants. In this case high-speed rail transport emits more carbon than an advanced steam locomotive from 1955.

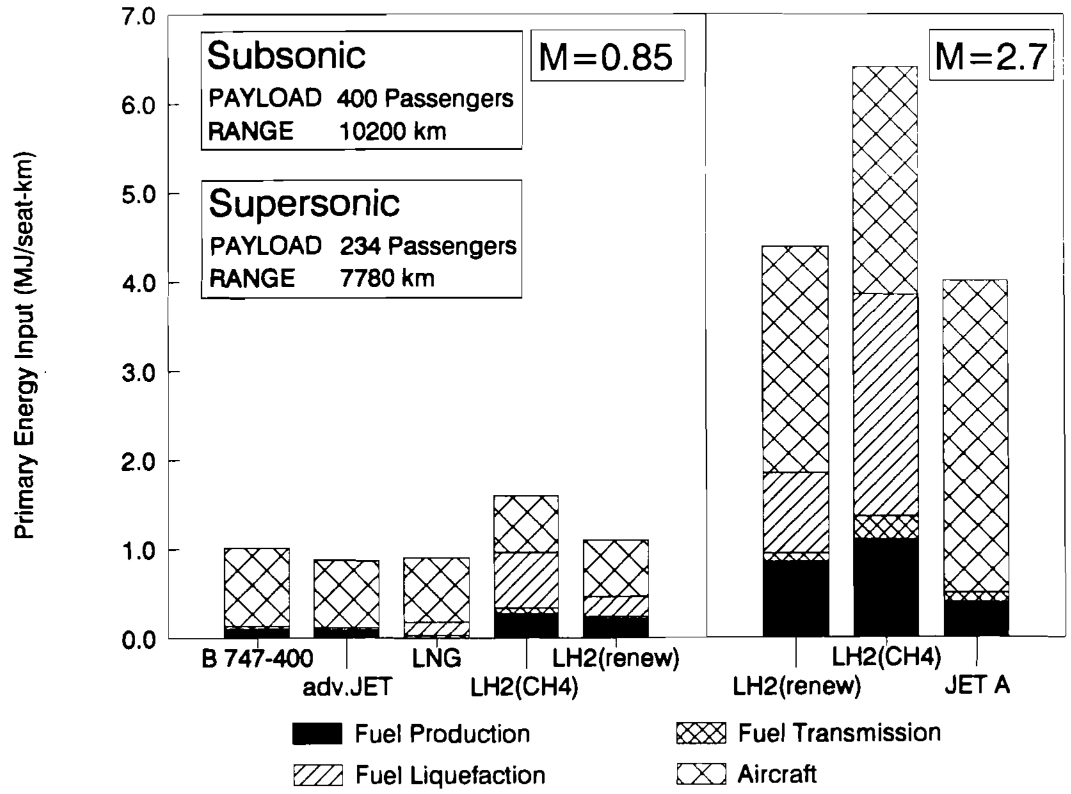

Figure 8 Primary energy intensity of aircraft. As we have seen for passenger cars, alternative fuels require a considerable energy input. Removal of carbon emissions after steam reforming of natural gas has its price: the whole primary energy input is about two-fold compared to the BOEING 747-400. Note the dramatic increase in energy intensity for supersonic aircraft.

Chain description:
B 747-400, adv. Jet, Jet A: fuel refining - fuel transmission with trucks - end use by Jet A aircraft, **LNG:** fuel transmission by pipeline with compressor stations powered by natural gas - liquefaction powered by natural gas - end use by LNG aircraft; **LH2 (CH4):** hydrogen production from natural gas - fuel transmission by pipeline with compressor stations powered by electricity from 1988 US fuel mix - H2 liquefaction with electricity derived from 1988 US fuel mix - end use by H2 aircraft; **LH2 (renew):** hydrogen production by electrolysis of water with electricity derived from hydropower - H2 transmission by pipeline with compressor stations powered by electricity from hydropower - H2 liquefaction with electricity derived from hydropower - end use by H2 aircraft.

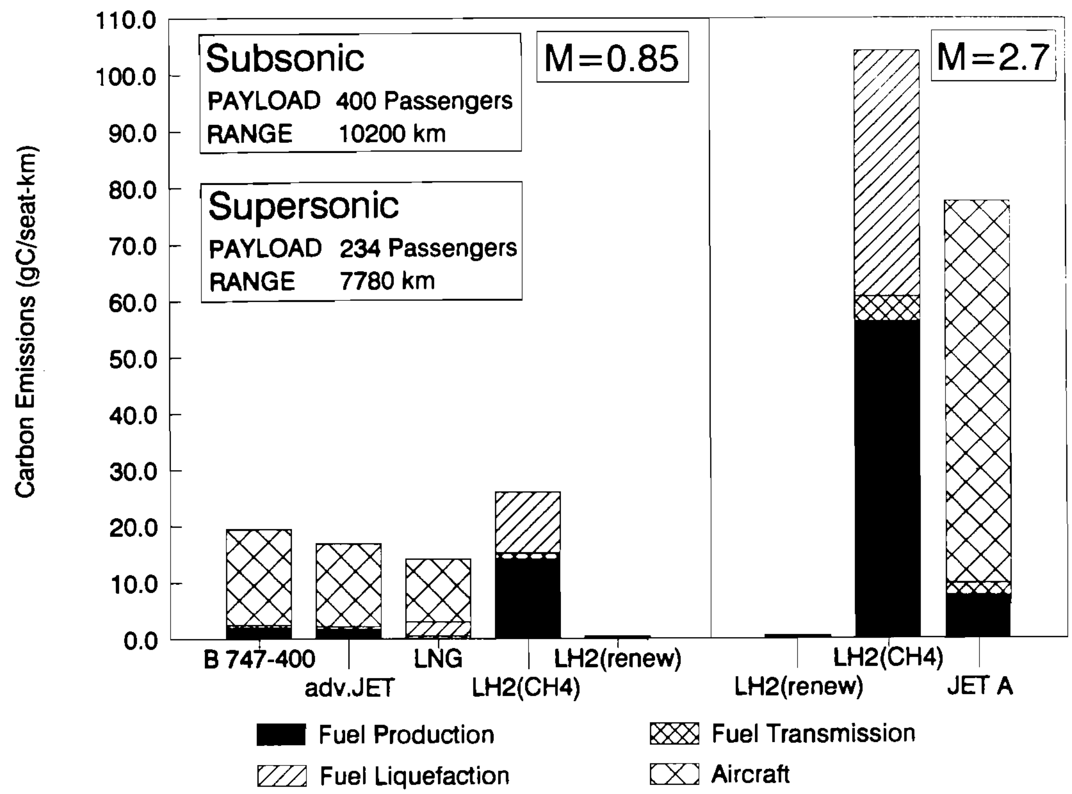

Figure 9 Carbon intensity of aircraft. All alternative fuels considered here have a potential for carbon emission reduction. If carbon emissions from steam reforming of natural gas were removed, overall carbon emissions would be approximately zero. Supersonic flight releases a considerably higher amount of carbon because of the higher energy input required.

Chain description:
B 747-400, adv. Jet, Jet A: fuel refining - fuel transmission with trucks - end use by Jet A aircraft, **LNG:** fuel transmission by pipeline with compressor stations powered by natural gas - liquefaction powered by natural gas - end use by LNG aircraft; **LH2 (CH4):** hydrogen production from natural gas - fuel transmission by pipeline with compressor stations powered by electricity from 1988 US fuel mix - H2 liquefaction with electricity derived from 1988 US fuel mix - end use by H2 aircraft; **LH2 (renew):** hydrogen production by electrolysis of water with electricity derived from hydropower - H2 transmission by pipeline with compressor stations powered by electricity from hydropower - H2 liquefaction with electricity derived from hydropower - end use by H2 aircraft.

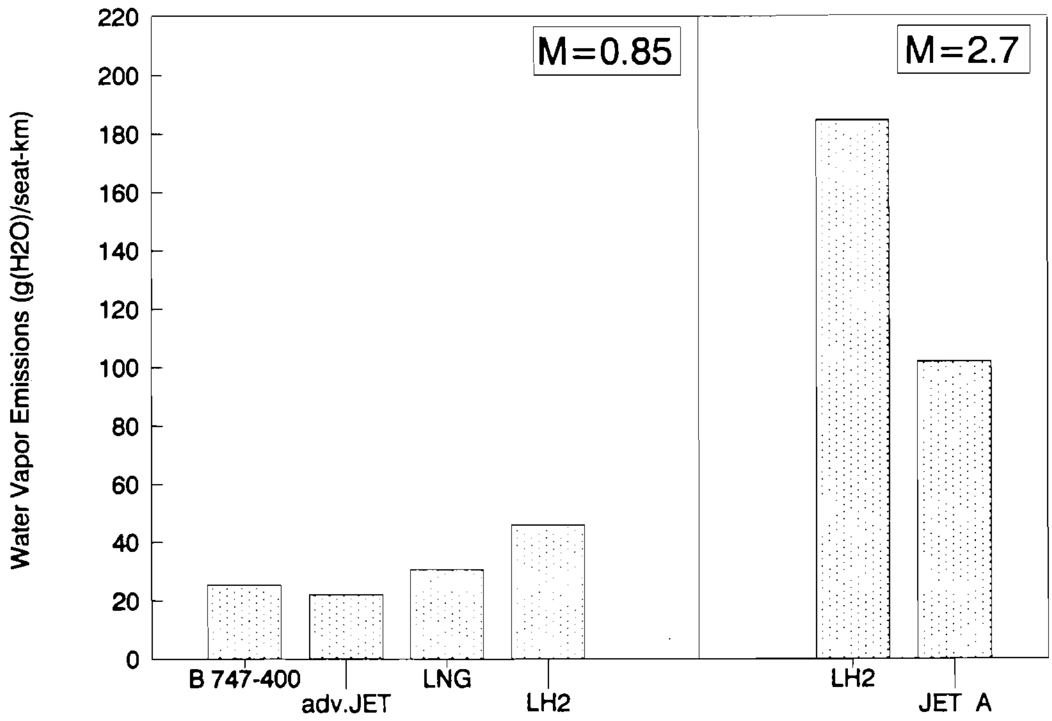

Figure 10 Water vapor emissions of aircraft. Reducing aircraft derived carbon emissions as a mitigation measure for global warming might be of limited value: water vapor emissions, responsible for the forming of high altitude cirrus clouds, contribute to the GHE as well. Water vapor emissions of a H2-powered aircraft are about two-fold compared to petroleum fuel based airplanes.

The combustion of 1kg Jet A fuel in air forms 1.24 kg water vapor. Combustion of hydrogen with the same energy equivalent results in the about 2.5 fold value (3.1 kg) (Schumann, 1990). If these values are related to 1 MJ energy output, 28.97 (33.2) gram water vapor are formed related to Jet A and 72.4 (75.0) to hydrogen (in brackets: theoretical value; higher because of complete combustion in oxygen). The theoretical value for natural gas delivers 46.3 gram water vapor per MJ ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$). Assuming that the ratio of theoretical value divided by real value is between this of Jet A and hydrogen, I supposed natural gas to release 42.5 gram water vapor if burnt in air.

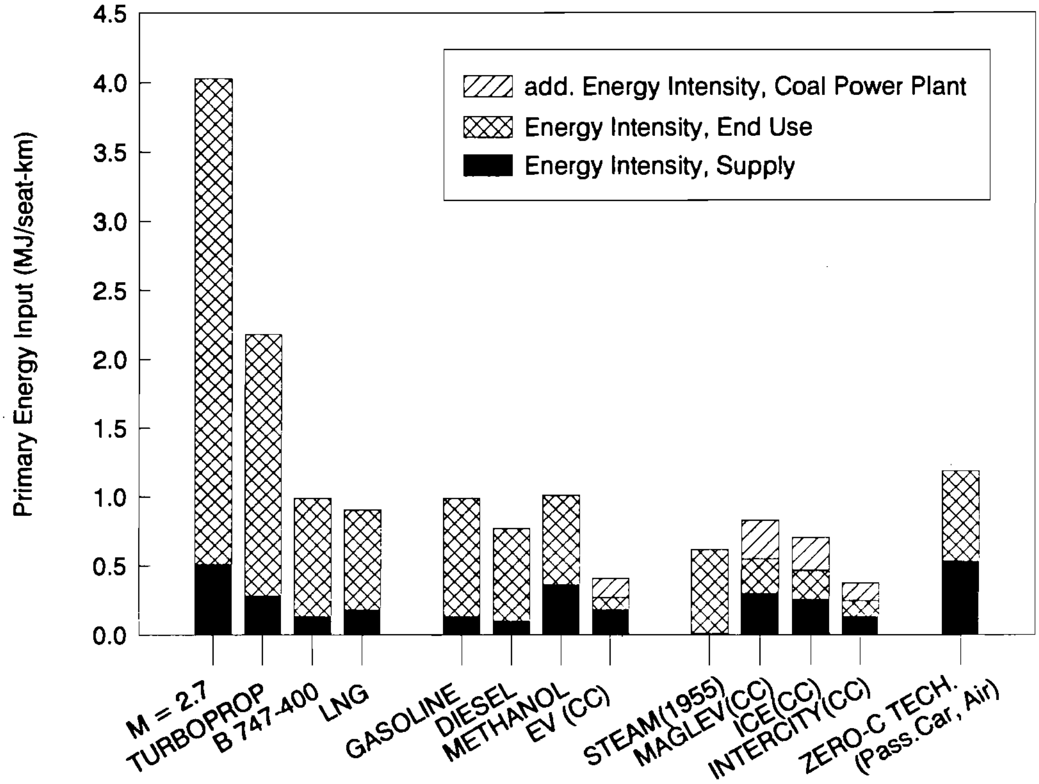

Figure 11 Primary energy intensity of transport modes. Supersonic aircraft with cruise speeds of M=2.7 require an almost 17 fold primary energy input per unit seat-km compared to the least energy intensive transport mean, i.e. the conventional intercity train. Zero carbon technologies here include an H2-powered passenger car and a H2 wide body aircraft requiring almost the same primary energy input per seat-km.

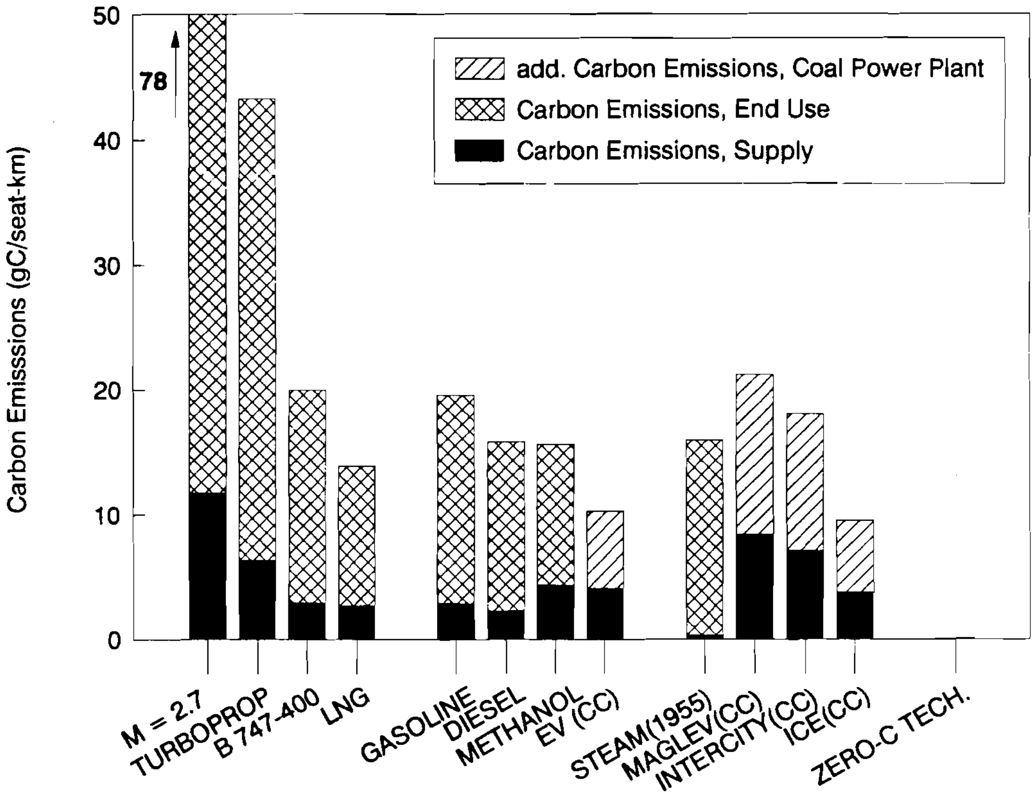

Figure 12 Carbon intensity of transport modes. The average gasoline powered car (10 l of gasoline per 100 km) releases about 20 gram of carbon per unit seat-km, roughly the same as a BOEING 747-400 and high speed railway systems running on electricity from a coal power plant. Carbon emissions of short range (turboprop) and supersonic aircraft are significantly higher.

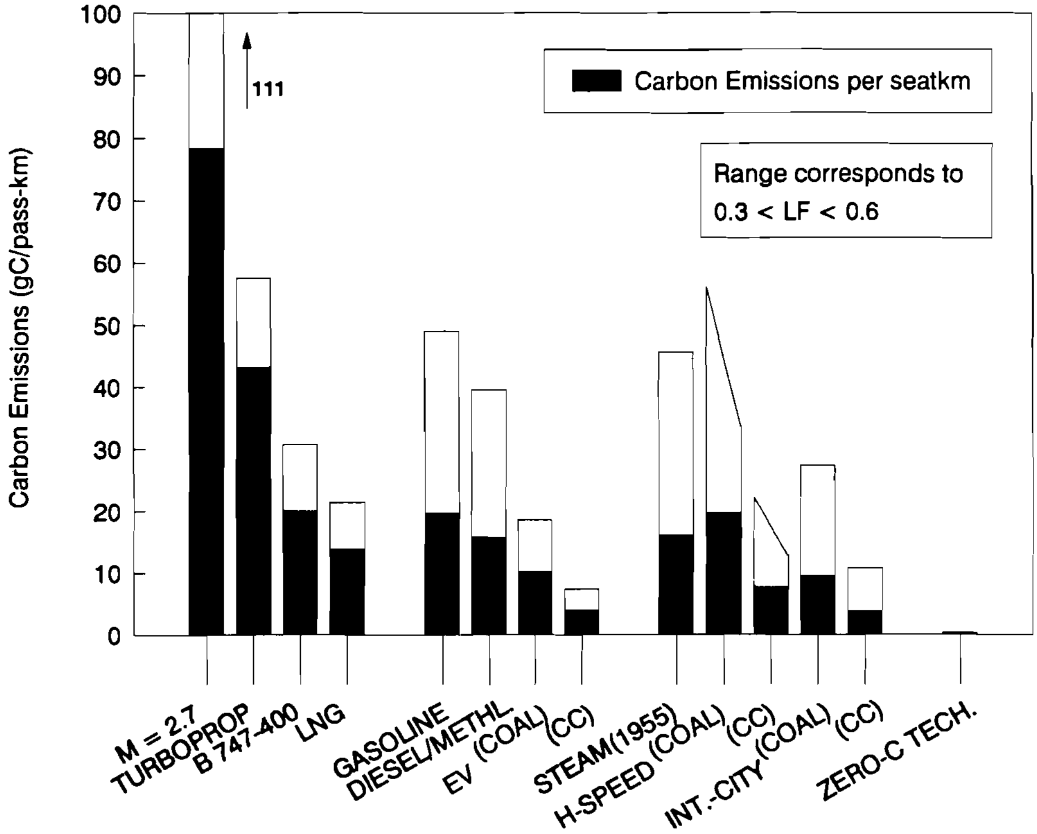

Figure 13 Carbon intensity of transport modes per seat-km and pass-km. The white share of the stack bars indicate consumer's potential for carbon reduction by increasing LF. Minimum carbon emissions per unit seat-km are achieved, when LF = 1, i.e. carbon emissions per pass-km = carbon emissions per seat-km. Due to the higher LF of two-seat EVs (at least 1/2) lowest carbon emissions are released per unit pass-km.

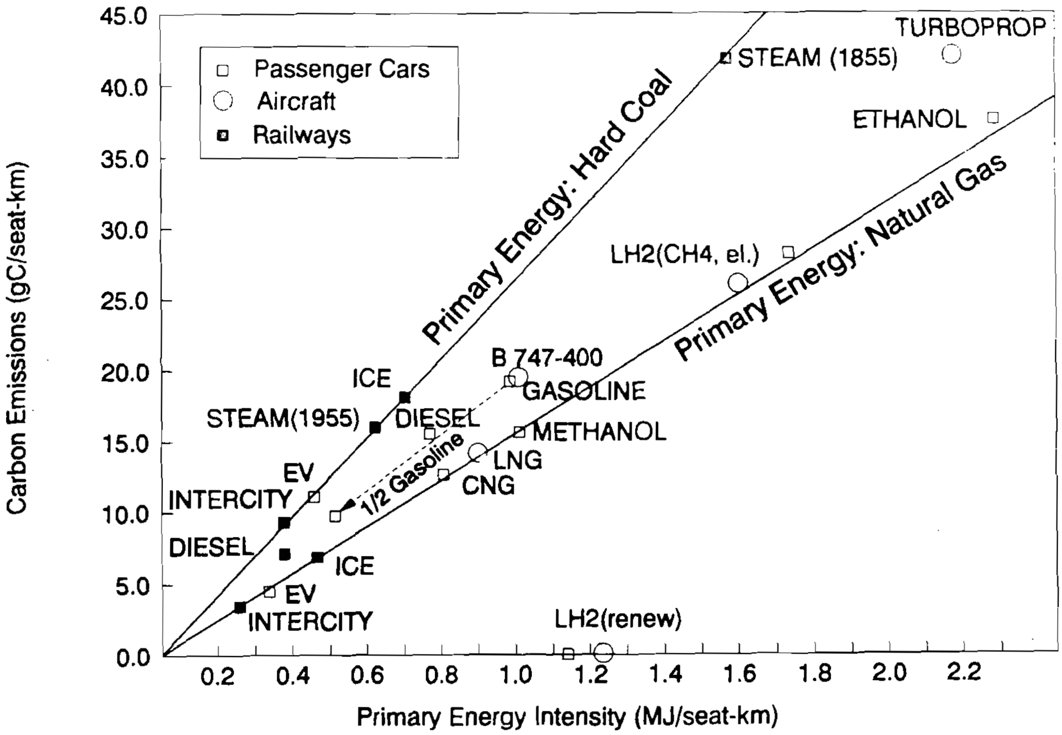

Figure 14 Energy and carbon intensity of transport systems. Straight lines through the zero-point represent a constant ratio of carbon emissions per energy input, i.e. the carbon emission factor. These lines are given for the highest emission factor (hard coal) and the lowest fossil emission factor (natural gas). All fuels based on the same feedstock are positioned on the same straight line. Pure efficiency improvements correspond to a movement towards the zero-point along a straight line through the zero-point. As an example the efficiency improvement by the double value is indicated (dashed arrow) for a gasoline car.

APPENDIX 1

	Hard-Coal	*Gasoline*	*Jet A*	*Diesel*	*Ethanol*	*Methanol*	*Nat.Gas*	*Hydrogen*
LHV (MJ/kg)	25.5	44.8	42.8	43.0	26.8	21.5	48.6[(1)]	120.0[(1)]
Dens.(kg/l) [(2)]	1.35	0.726	.811	0.840	0.790	0.790	$0.652\ 10^{-3}$	$0.838\ 10^{-4}$
C-EF (kg/GJ) [(3)]	25.69	19.42	19.31	20.13	21.32	17.44	15.43	0.0
H/C Ratio	0.05	2.25	1.3	1.75	3	4	4	infinite

Table App. 1 Physical Properties of the considered Fuels; LHV - Lower Heating Value, Dens. - Density, C-EF - C-Emission Factor; Carbon Emission Factor of 1988 US-Fuel Mix: 17.43 gC/MJ; Source: IEA 1991, Ullmann's Encyclopedia of Industrial Chemistry 1989,

(1) LHV(MJ/l) for LNG(T=112K) = 20.9 and for LH2(T=20K) = 8.5 (Peschka, 1984)

(2) at p = 1 atm and T = 293.15 K

(3) related to energy input

APPENDIX 2

Efficiencies	*Gasoline*	*Diesel*	*Methanol*	*Ethanol (Scane)*	*CNG*	*LH2 (CH4)*	*LH2 (renew)*	*EV (CC)*	*EV (Coal)*
Vehicle (lGE/100km)	10	7.8	7.5	8.0	8.0	8.0	8.0	0.5	0.5
Compression, Liquefaction	/	/	/	/	0.96	0.77	0.77	/	/
*Battery * Battery Charger*	/	/	/	/	/	/	/	0.75*0.95	0.75*0.95
Fuel Transmission	0.97	0.97	0.94	0.95	0.97	0.97	0.97	0.92	0.92
Electricity Production	/	/	/	/	0.33[1]	0.33[1]	0.92	0.50	0.33
Fuel Production	0.90	0.90	0.68	0.325	1.0	0.70	0.75	/	/
Raw Material Extraction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table App.2-1 Efficiency data of passenger cars, [1] electricity used for compression of natural gas and liquefaction of natural gas derived hydrogen; the efficiency of electricity transmission was selected to be 0.92 in all cases

Efficiencies	*Steam 1855*	*Steam 1955*	*Diesel*	*Int.City (Coal)*	*Int.City (CC)*	*ICE (Coal)*	*ICE (CC)*	*MAGLEV (Coal)*	*MAGLEV (CC)*
End Use (MJ/seat-km) [1]	1.54	0.61	0.33	0.11	0.11	0.21	0.21	0.21-0.30	0.21-0.30
Fuel Transmission	0.94	0.98	0.97	0.92	0.92	0.92	0.92	0.92	0.92
Electricity Production	/	/	/	0.33	0.50	0.33	0.50	0.33	0.50
Fuel Production	/	/	0.90	/	/	/	/	/	/
Raw Material Extraction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table App.2-2 Efficiency data of railways; [1] for electric railway from substation; the efficiency of electricity transmission was selected to be 0.92 in all cases

Efficiencies	*B 747-400*	*adv. Jet*	*LNG*	*LH2 (CH4)*	*LH2 (renew)*	*LH2 (renew)*	*LH2 (CH4)*	*Jet A*
Mach Number, Cruise	0.85	0.85	0.85	0.85	0.85	2.7	2.7	2.7
Aircraft (MJ/seat-km)	0.879	0.762	0.724	0.637	0.637	2.550	2.550	3.520
Fuel Liquefaction	/	/	0.83	0.77	0.77	0.77	0.77	/
Fuel Transmission	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Electricity Production	/	/	/	0.33	0.92	0.92	0.33	/
Fuel Production	0.90	0.90	1.0	0.70	0.75	0.75	0.70	0.90
Raw Material Extraction	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table App.2-3 Efficiency data of aircraft; the efficiency of electricity transmission was selected to be 0.92 in all cases