ENERGY CONSUMPTION AND ENVIRONMENTAL EFFECTS OF PASSENGER TRANSPORT MODES - A LIFE CYCLE STUDY ON PASSENGER TRANSPORT MODES

English Summary

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1 INTRODUCTION

Energy consumption and environmental effects of different passenger transport modes vary on the different stages of the fuel chain and during the production and maintenance of vehicles and infrastructure. Energy consumption and the environmental effects calculated per passenger mileage depend strongly on the vehicle occupancy. The properties of transport modes on urban areas and on the long distance transport have been evaluated in this study. The energy consumption and environmental effects calculated per passenger mileage have been assessed for passenger car, bus, tram, train, aeroplane and ferry. The emissions have been evaluated during the whole fuel chain. In this study only the airborne emissions have been taken into account. In the energy consumption calculations the energy content of vehicles and the infrastructure, the energy consumption during the fuel chain and during the end use have been taken into consideration.

2 ENERGY CONSUMPTION

2.1 Infrastructure

The energy consumption of the transport infrastructure consists of the energy consumption of the building and maintenance of the infrastructure and the manufacturing and the maintenance of the machinery used in the building process. In the road and waterway transport the great majority of the energy consumption is due to the maintenance operations. In the rail transport the share of the building of the rail network is relatively higher. In the air and waterway transport the share of the building and the maintenance of the infrastructure can't be defined at the same way. The most notable share of the air transport infrastructure are the airports and in the waterway transport the harbour operations. In the table 2.1 is shown the average energy content of the infrastructure and the energy consumption of the network maintenance allocated for the different passenger transport modes.

Table 2.1 The energy consumption of the transport infrastructure for different modes of transport.

transport mode	energy consumption calculated for transport performance and passenger mileage	
	[MJ/km]	[MJ/passengerkm]
car	0,6	0,286
bus	0,1	0,006
tram	5,5	0,138
metro	1,3	0,013
local train	15	0,152
express train	18	0,152
aeroplane	2 - 15	0,093
ferry	56	0,056

2.2 Energy content of the vehicles

The road transport vehicles correspond for the majority of the total energy content of the passenger transport vehicles. The energy content of the vehicles has been calculated by using the average energy consumption values for each main group of the raw material used in the manufacturing process. The energy content of the raw materials in an average passenger car is approximately 42 GJ and in an average bus approximately 517 GJ. The total energy content of the Finnish passenger car fleet is approximately 90 million GJ. The share of passenger cars is around 86 % of the total energy content, which is higher than their share of the passenger mileage. In the ferry transport the energy content is much higher than the share of the passenger mileage.

Table 2.2 The energy content if the vehicle fleet calculated per transport performance and passenger mileage.

transport mode	energy content calculated per transport performance and passenger mileage	
	[MJ/km]	[MJ/passengerkm]
car	0,21	0,154
bus	0,66	0,050
local train	2,37	0,026
express train	2,78	0,021
aeroplane (1	0,16	0,001
ferry (2	na	2,37

(1 domestic and international traffic of Finnish companies
(2 ferries in water transport, including departure or arrival in Finland
na not available

2.3 Production and the distribution of fuel

The majority of the passenger car traffic uses gasoline. The share of the diesel-powered cars is approximately 13 % of the total passenger car mileage. The most common gasoline types at the year 1993 were 95- and 98-octane unleaded gasoline, which corresponds approximately 85 % of the total gasoline amount. The bus traffic in Finland is diesel-powered.

In the long distance rail traffic one third of the passenger mileage comes from diesel-powered trains and two thirds from electrically driven trains. The fuel used in the diesel locomotives is standard diesel oil.

The most common fuel at the air transport is air petrol (kerosine). The energy consumption of the production and distribution of the air petrol is approximately the same as the diesel fuel.

The ferries at the domestic transport use mainly heavy fuel oil, bunker fuel, which corresponds for 60 % of the total energy consumption of the domestic waterway transport. Small vessels and the auxiliary machines of the big vessels use mainly marine diesel oil, which is light fuel oil.

In the figure 2.1 is shown the energy consumption during the refining, transportation and distribution of different types of fuels calculated for a produced energy unit (MJ per produced MJ of fuel).

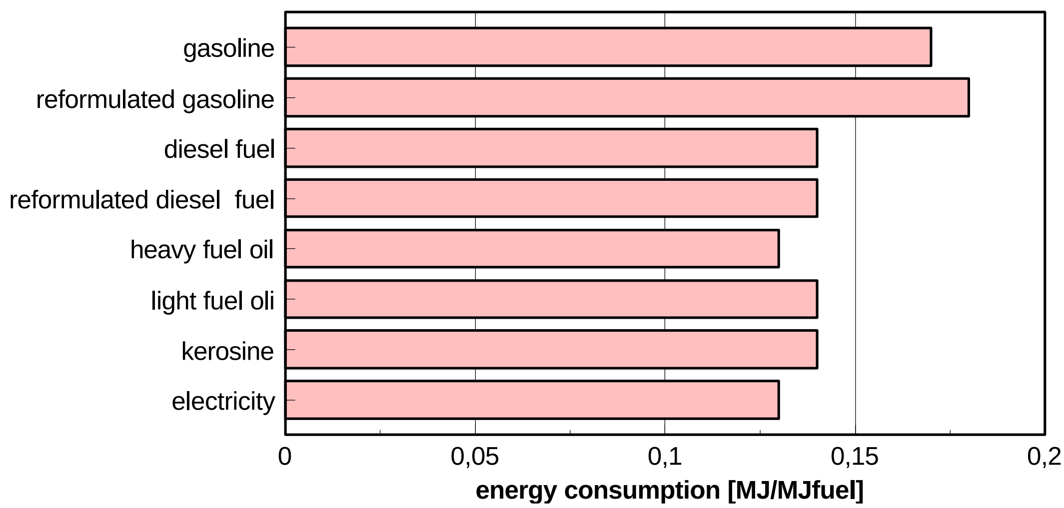

Figure 2.1 The energy consumption during the production and distribution of fuel calculated per one produced and distributed fuel unit [MJ/MJ$_{pa}$].

2.4 Transport process

The energy consumption depends on the properties of the vehicle, transport environment and the driving cycle. On the urban areas the energy consumption of the average gasoline-powered passenger car is 3,8 MJ/km and of a diesel-powered vehicle 3,4 MJ/km. On the long distance transport on the rural roads and highways the corresponding values are 2,3 MJ/km and 2,1 MJ/km.

The vehicle occupancy varies strongly during a day. The number of passengers is highest on long distance trips and free-time trips. On the short distance trips the average number of passengers in Finland is 1,6 persons/vehicle and on the long distance trips 2,0 persons/vehicle. By taking account the number of passengers per vehicle, the average energy efficiency of the present passenger vehicle fleet is 2,5 MJ/passengerkm at Finnish urban areas and 1,2 MJ/passengerkm at the highways. At the taxi the average occupancy is 0,7 passengers/vehicle, when the driver is not counted as a passenger. The mean energy consumption calculated per passenger mileage in taxi traffic is 4,7 MJ/passengerkm.

The average energy consumption of bus traffic is 13,8 MJ/passengerkm. Energy consumption depends on the vehicle fleet and the range of use. At the urban traffic the energy consumption varies between 10 and 20 MJ/km due to the traffic conditions and the size of the urban area. The occupancy level at the bus traffic has strong spatial and temporal variations. The average number of passengers calculated with the traffic mileage and the traffic performance is 12,5. In the urban traffic the average vehicle occupancy is 20 persons per vehicle. The energy efficiency calculated per passenger mileage is in urban areas 0,8 MJ/passengerkm and in the long distance traffic 0,9 MJ/passengerkm.

The energy consumption of the tram in Helsinki is approximately 16,9 MJ/km and in the metro 18,0 MJ/km. A modern light rail transit would demand approximately 11,2 MJ/km. The energy consumption of metro is relatively small, because the stop spacing is longer compared to the tram and light rail transit. At the urban transport the occupancy variations of rail transport are close to the occupancy variations of bus traffic. The energy efficiency calculated per passenger mileage is in the tram 0,42 MJ/passengerkm and in the metro 0,18 MJ/passengerkm.

In Finland the majority of passenger kilometers on the railways is originated from electrically driven trains. The energy consumption on rail transport depends on the rolling stock properties. The express trains are more heavily built but they stop less frequently than the local trains, for which the stop spacing is normally 2 - 5 km. The higher stop density includes more accelerations and braking than longer stop spacing. The energy efficiency for the local train 0,17 MJ/passengerkm and for different types of express trains 0,3 - 0,8 MJ/passengerkm.

In the air traffic the energy consumption for different plane types and on the trips of different length is approximately 2,8 - 3,3 MJ/passengerkm. The energy efficiency calculated per passenger mileage in water transport is not unambiguous, because the ferries also carry cargo, which allocates part of the energy consumption to the freight transport. In the ferry transport the energy consumption is approximately 2,7 MJ/passengerkm.

The energy efficiency for a motorcycle is approximately 1,9 MJ/passengerkm and for a moped 0,8 MJ/passengerkm. The energy consumption of walking and cycling is normally not assessed at the same way as in motor vehicle transport. In walking and cycling only renewable energy sources are consumed; the energy consumption has no significance in the total energy consumption of transportation. The energy consumption of walking is approximately 0,16 MJ/km and for cycling 0,06 MJ/km.

2.5 Total energy efficiency

In figure 2.2 is shown the total energy consumption calculated per passenger mileage for different transport modes. In figure 2.2 can be seen the shares of the different parts of the life cycle. The average vehicle occupancy levels have been utilized in the calculation. In the urban areas the most energy intensive transport modes are car and taxi. Least energy intensive modes are walking, cycling and rail and bus transport. The relative share of the infrastructure is biggest in rail transport, where the energy demand during the transportation process is very low. The energy content of vehicles varies between 1 and 8 %, the energy consumption of the fuel production and distribution between 7 and 12 %, and the energy demand of transportation process between 60 - 80 % of the total energy consumption for different transport modes. The energy content of vehicles calculated per passenger mileage is small, because the vehicles are utilized often 24 hours per day. In taxi the high energy consumption is due to the relatively small average number of passengers.

In the long distance car transport the energy consumption is approximately half of the energy consumption in the urban conditions. The most energy intensive long distance transport modes are ferry and aeroplane. In the air traffic almost 85 % of the total energy consumption is originated from the transport process itself. For the other transport modes the energy content of vehicles corresponds 2 - 10 % and the production and distribution of the fuel 10 - 12 % of the total energy consumption. The share of the infrastructure is relatively highest in the rail transport and lowest in the bus and air transport. The share of the infrastructure varies between 0,5 and 30 % of the total energy consumption. In the ferry transport the energy content of the vehicle is exceptionally high, because the ferry involves also other facilities, like accommodation and restaurant services, which need considerable amount of space. Because the distances are comparably short and the travelling speed low, the transport performance is relatively small and the energy efficiency calculated per passenger mileage is high.

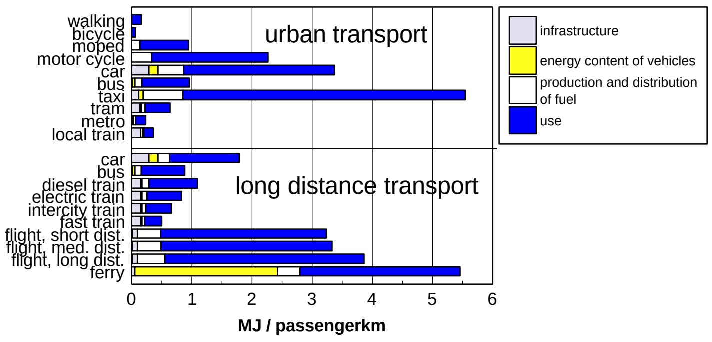

Figure 2.2 The energy consumption of infrastructure, the energy content of vehicles, the energy consumption during the production and distribution of fuel and the transportation process [MJ/passengerkm]. For walking and cycling the energy consumption of infrastructure and the energy content of the vehicle are not taken into account.

3 EMISSIONS TO AIR

3.1 Production and distribution of fuel

The amount of airborne emissions during the production and distribution of fuel depends on the energy consumption during the transportation process. The amount of emissions during the fuel chain has been calculated by using the emission factors assessed in the SIHTI Research Programme. The share of the production and distribution of fuel is approximately 10 - 15 % of total amount of emissions.

The difference in the amount of emissions during the production and distribution of diverse types of hydrocarbon fuels is relatively small. The heavy metal compounds are mainly emitted during the production process. The majority of the emissions with the exception of sulfurdioxide and hydrocarbon compounds originate from the end use of the fuel or the transportation process. In the electrically driven modes all the emissions originate from the production of the electricity. The carbon monoxide and particulate emissions of the electricity production are bigger than the emissions from the production and distribution of hydrocarbon fuels. Also the heavy metal emissions are bigger than in the production and distribution of gasoline, diesel fuel or fuel oil.

3.2 Transport process

The emissions during the transportation process for the passenger car and bus fleet have been calculated by using the emission factors defined in the LIISA-database, which is a Finnish database for the emissions of road vehicle emissions. The emissions of the diesel-powered rail transport have been calculated based on the specific emission factors defined for one consumed fuel unit. The emissions of the air traffic have been calculated with the factors defined in VTI, Sweden. The emissions of ferry transport have been evaluated based on the specific emission factors and the factors defined in VTI. The emission factors have been proportioned to passenger mileage by using the average occupancy level defined for each transport mode.

80 - 90 % of the airborne emissions originate from the transportation process. The emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) are almost totally due to the transportation process.

3.3 Total emissions

In the table 2.3 have been collected the emissions during the whole fuel chain without the heavy metal compound emissions. The figures for air traffic include also estimated indirect emissions due to the land transport services on air fields.

The hydrocarbons emissions (HC) of the car transport are considerably higher than for the other transport modes. The HC emissions of an electrically driven train are extremely low compared to a car, bus or diesel-powered train. In the long distance transport the difference between the HC emissions of these three transport modes is relatively small. In the long distance transport the HC emissions of aeroplane and car calculated per passenger mileage are higher than for the other modes. In figure 3.1 is shown the amount of HC emissions during the whole fuel chain.

Table 2.3 Emissions during the fuel production and distribution and the transport process for different transport modes [g/passengerkm].

	CO	HC	NO_x	SO_x	part.	CO_2	N_2O
urban areas							
road transport							
car (**	8,339	1,098	0,799	0,091	0,077	194	0,0497
bus	0,333	0,199	1,170	0,031	0,059	67	0,0262
rail transport							
tram	0,010	0,019	0,029	0,028	0,027	9,2	0,0011
metro	0,004	0,008	0,012	0,012	0,011	3,9	0,0005
local train	0,003	0,006	0,008	0,008	0,008	2,7	0,0003
long distance transport							
road transport							
car (**	2,659	0,308	1,034	0,066	0,079	119	0,0391
bus	0,360	0,245	1,460	0,029	0,163	62	0,0301
rail transport							
diesel train	0,195	0,179	0,953	0,103	0,023	67,5	0,0003 *
electric train	0,014	0,026	0,040	0,038	0,037	12,5	0,0015
Intercity train	0,011	0,019	0,030	0,028	0,027	9,3	0,0011
fast speed train	0,007	0,013	0,020	0,019	0,018	6,1	0,0007
air transport							
short distance (200 km)	0,574	0,234	0,741	0,204	0,007 *	217	0,0012 *
medium distance (300 km)	0,605	0,309	1,055	0,210	0,008 *	230	0,0012 *
long distance (> 500 km)	0,717	0,429	1,799	0,245	0,009 *	268	0,0014 *
ferry transport	0,344	0,218	4,536	1,610	0,137	220	0,0011 *

* includes only the emissions during the production and distribution of the fuel
(** passenger car fleet at year 1994

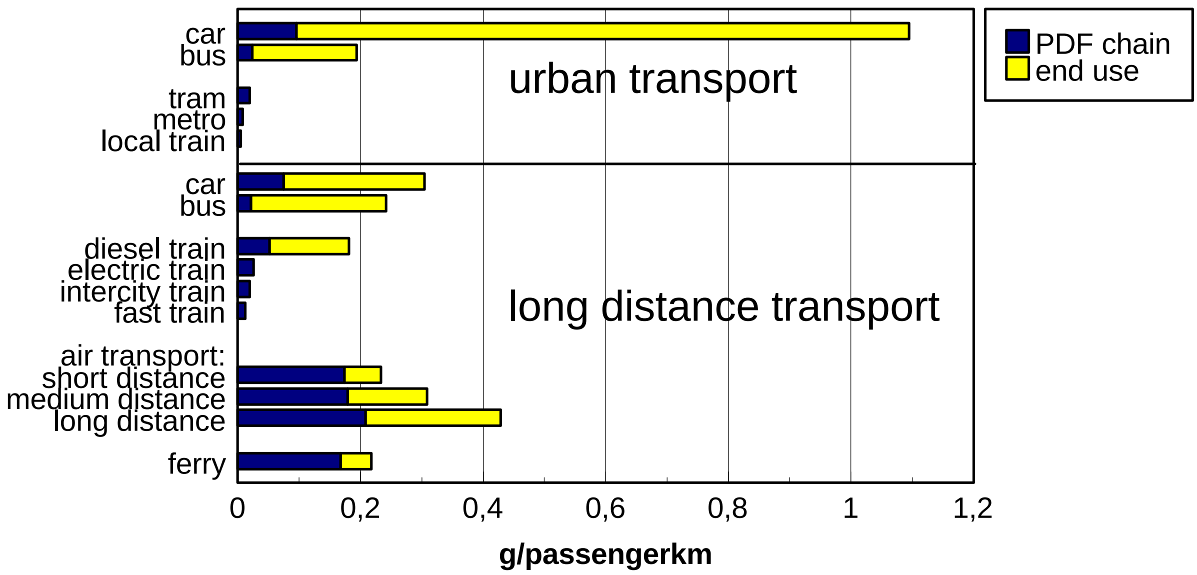

Figure 3.1 HC emissions during the production and distribution of the fuel (PDF) and the transport process.

The majority of the NO_x emissions originate from the transportation process. In figure 3.2 is shown the distribution of NO_x emissions between the production and distribution phase and the transport process. In the diesel-powered transport (bus , diesel train and ferry) the NO_x emissions are notably bigger than in the electrically driven or gasoline-powered modes. The particulate and NO_x emissions of electrically driven trains are very small. The emissions of nitrous oxide (N_2O) are biggest in car and bus transport. The amount of N_2O emissions during the transportation process in air transport has been estimated to be relatively high.

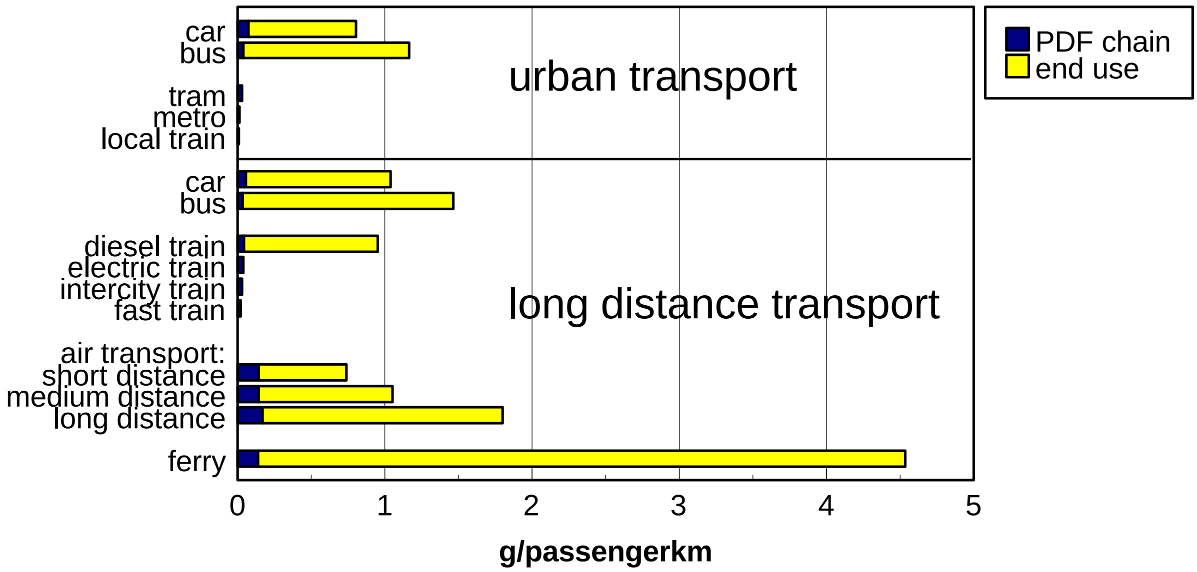

Figure 3.2 NO_x emissions during the production and distribution of the fuel (PDF) and the transport process.

The majority of the SO_x emissions caused by transportation originates from the production and distribution of the fuel. In the urban areas the SO_x emissions of a car are bigger than for the other modes. In the long distance transport the ferry, aeroplane and diesel-powered train cause more emissions than other modes, when emissions are calculated per passenger mileage. SO_x emissions of electrically driven train are approximately the same as of a bus. In urban areas the most significant particulate emissions calculated per passenger mileage are caused by car and in the long distance transport by bus and aeroplane.

The emissions of CO_2 are directly related to the energy consumption and efficiency of energy production. The share of the production and distribution of fuel corresponds for 10 % of the total CO_2 emissions. In the urban transport the CO_2 emissions of a car are higher than for other modes, when the emissions are calculated with average occupancy levels. In the long distance transport the aeroplane and ferry cause more CO_2 emissions than the other modes. The CO_2 emissions calculated per passenger mileage are for a car double as high as for a bus. In the electrically driven trains the emissions are substantially smaller than in the combustion engine driven transport. In figure 3.3 is shown the dependence between CO_2 emissions and occupancy level.

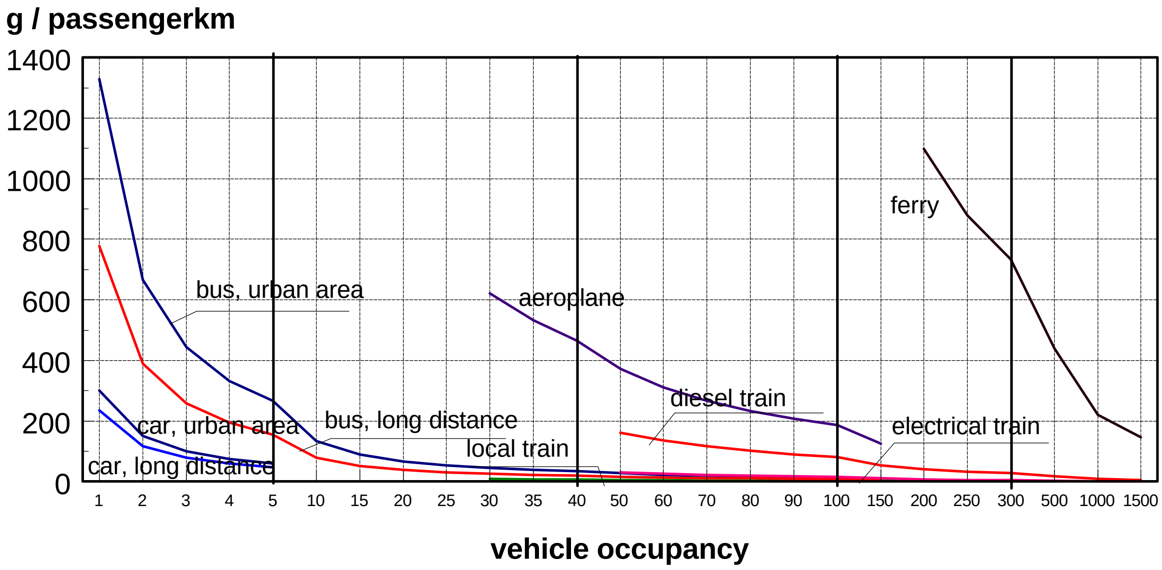

Figure 3.3 The relationship between CO_2 emissions and occupancy level for some passenger transport modes.

4 ENVIRONMENTAL IMPACTS

The airborne emissions due to the transportation sector cause diverse types of environmental impacts, which can be classified as impacts to individuals and neighbourhood, local impacts, regional impacts, and global impacts. Impacts to individuals and neighbourhood are direct health effects, changes in the environment and material effects. Local impacts are effects on the local environment of the emission source. Typical local impacts are health effects caused by increased air pollutant concentrations due to the cumulative emissions. Regional impacts allocate to a level of a country or continent. In the development of global impacts the long-term accumulation of emissions is usually an important factor.

The evaluation of the combined effects of different pollutants is difficult, because the effects, allocation and exposure time can be very different for different types of pollutants and transport modes. The quality and severeness of the environmental impacts depend on the emission quantity, frequency and duration, atmospheric dispersion of pollutants and the extension of the area of influence. Several kinds of classification methods have been developed as instruments to assess the combined effects of the different pollutants. In this study the applied classification methods are toxicity, acidification potential, environmental load and global warming potential of the emissions.

The toxicity of the emissions has been assessed with a German estimate of the toxicity of different pollutants compared to carbon monoxide (CO equivalent). In addition the toxicity of emissions has been evaluated with a Dutch HCA-value (human-toxicological classification value for air), which describes the relative health effects of the airborne emissions. In figure 4.1 has been shown the relative toxicity and in figure 4.2 the relative HCA-value for different transport modes. The classification values have been calculated with average vehicle occupancy levels.

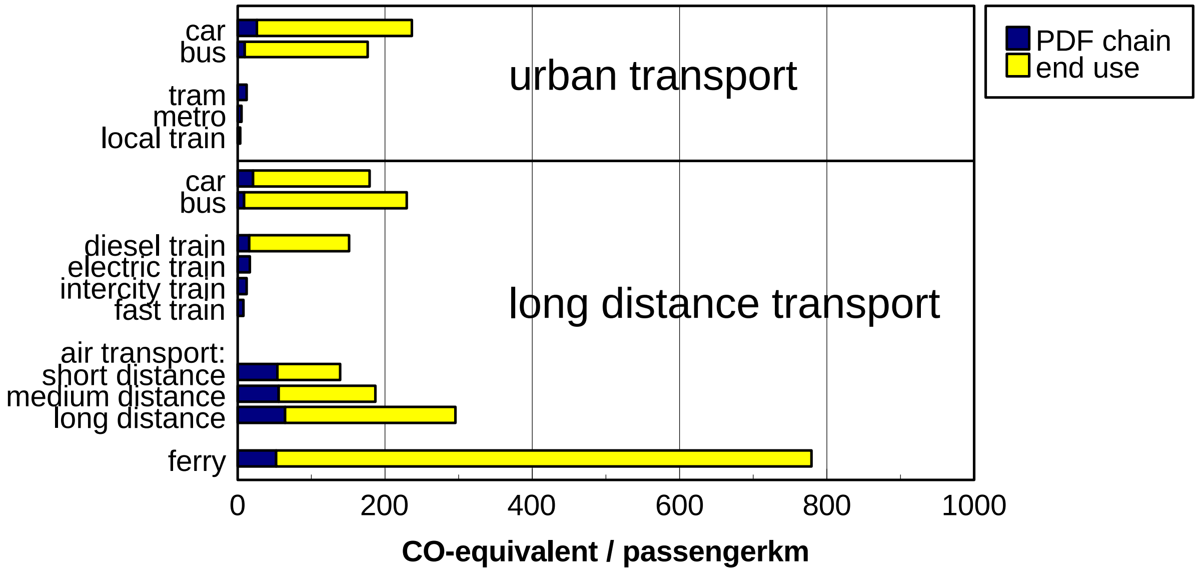

Figure 4.1 The relative toxicity of the emissions of different transport modes (CO equivalent).

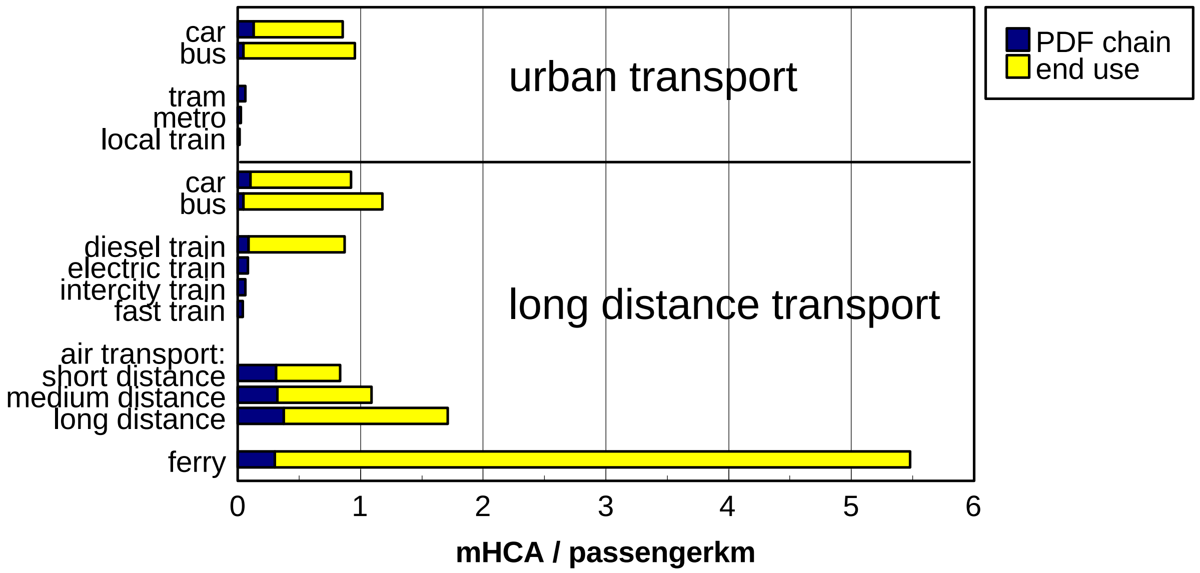

Figure 4.2 The relative HCA value (Human-toxicological classification value for airborne emissions) of different transport modes.

In the urban transport the toxicity effects of the car and bus traffic are greater than the effects of the electrically driven modes. The emissions of the electricity production concentrates often outside the urban areas, and thus the population exposed to the emissions is smaller than on the urban environment. In the long distance transport the emissions of ferry and air traffic have the highest toxicity value. The high toxicity of the emissions of a bus in the long distance transport is caused by the high NO_x and particulate matter emission levels.

The second toxicity measure HCA emphasizes the significance of the NO_x and SO_x emissions. The particulate emissions have no importance, and the HC and CO emissions have only small weight in calculating the HCA value. In the urban areas the HCA value of bus and car transport is clearly higher than the value of electrically driven rail transport modes. The HCA value of a bus is slightly higher than the value of a car. In the long distance transport the HCA value of ferry transport is substantially higher than the values of other modes.

The acidification potential is often measured as an acidification equivalent, which describes the molar acidification potential of emissions. In assessing the acidification potential only the NO_x and SO_x emissions are taken into account. The acidification potential of the emissions during the whole fuel chain is shown in figure 4.3. The values have been calculated for average occupancy levels.

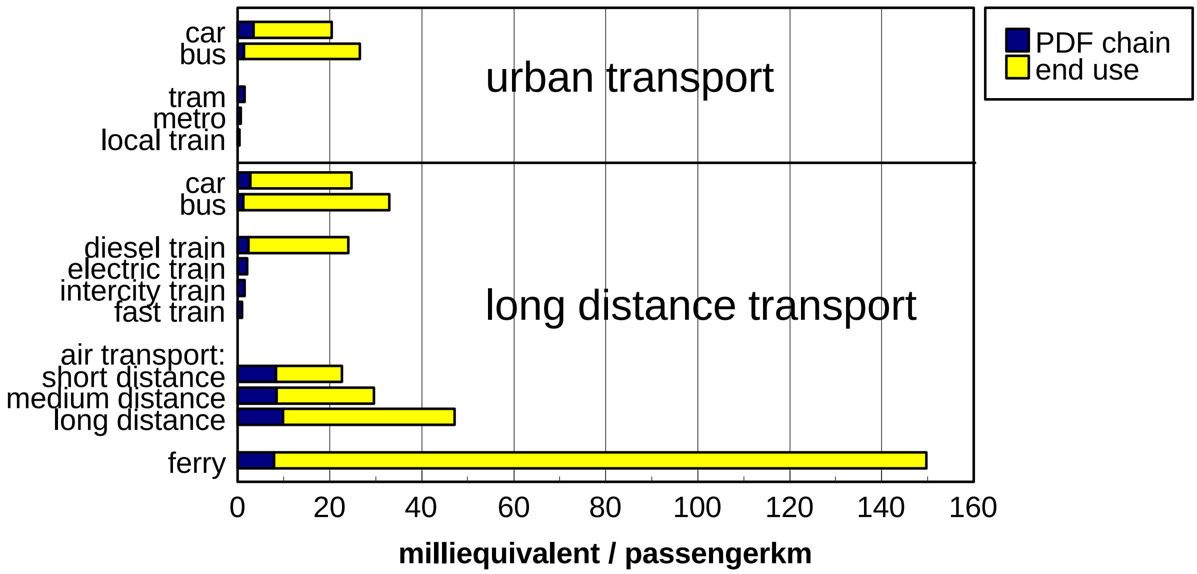

Figure 4.3 The relative acidification potential of the emissions of the different transport modes.

In the urban transport bus has the highest acidification potential and in the long distance transport ferry, aeroplane and bus. The acidification effects of electrically driven modes are very small compared to internal combustion engine driven transport modes.

The global warming potential (GWP) of the emissions is often evaluated with CO_2 equivalent unit, which describes the climate change effects of a pollutant in relation to the effect of CO_2. The relative importance of CFC compounds and nitrous oxide (N_2O) is highest. CO_2 emissions correspond for approximately half of the climate change impacts of the greenhouse gases.

The global warming potential of the fuel chain emissions for different transport modes is shown in figure 4.4. The results have been calculated by using the average vehicle occupancies. In the urban transport the GWP of car is notably higher than the GWP of the other modes. In the long distance transport greenhouse gas emissions of the ferry, aeroplane and car transport are most significant. The N_2O emissions of the aeroplane, ferry and diesel-powered train are not taken into account in defining the GWP of the transport modes.

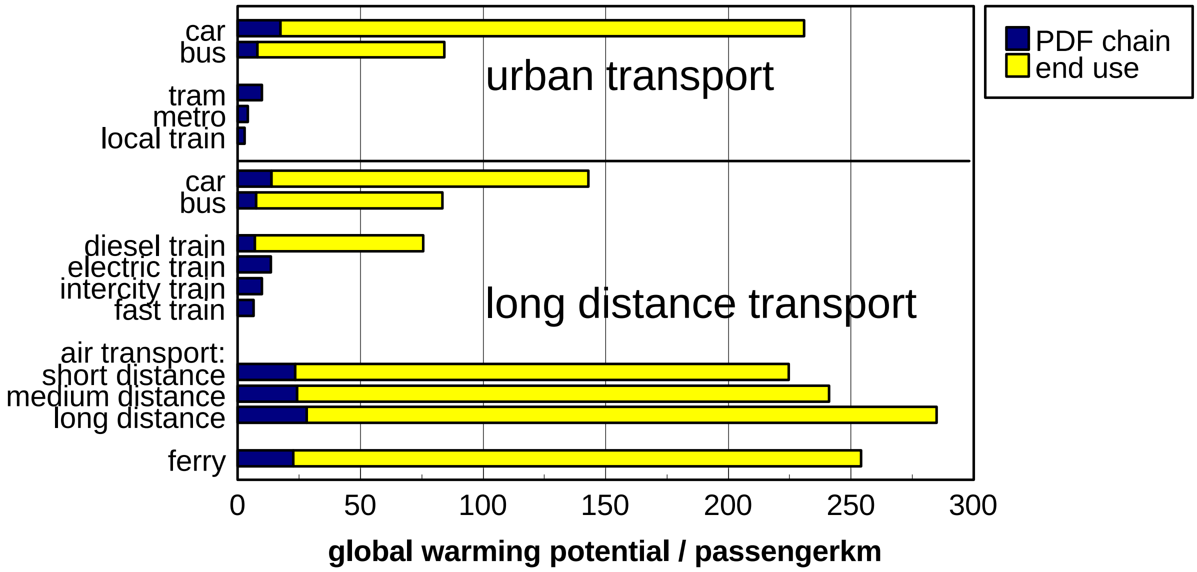

Figure 4.4 The relative effect of the different transport modes on the climate change.

5 CONCLUSIONS

The comparability of the transport modes by the means of the service level has to be taken into consideration, when comparing the energy consumption and the environmental effects of different transport modes. Different modes can't always substitute each other, often only a few modes are available. The demand, costs and level of service are factors that influence on the transport supply. The level of service and also the applicability of transport modes varies strongly in the different demand situations.

A well-designed transportation system consists of different transport modes that complement each other. The modal split depends on the local conditions. More efficient utilization of the present transportation system is the most productive way to reduce the energy consumption and the environmental effects of transportation. Especially in the bus traffic the vehicle occupancy level is often very low. Increasing the occupancy level in the public transportation requires displacements from the other modes with, for example, increasing the level of service in the public transportation. In order to reduce the total energy consumption of the transportation system, only the displacements from the energy intensive transport modes are rational. On the other hand, especially in the urban areas, the new public transport passengers have probably earlier been walking or cycling, or travelled as passengers in a car - so they represent groups that wouldn't anyway increase the total energy consumption of the transportation system. In an ideal public transportation system the size of the vehicle can be adapted to the number of passengers.

The study of the environmental classification methods shows that the transport mode producing the most emissions is not always the mode causing most severe environmental impacts. According to the classification methods, the toxicity of car and bus transport is almost equal. In the long distance transport ferry, aeroplane and bus transport have the highest toxicity values. When the toxicity of the emissions is evaluated, one has to take into account, that the emissions allocate into different kinds of areas where their environmental effects are different. The applied classification method doesn't take into account the differences in the allocation of the emissions. The pollutants of the ferry and air transport are emitted on the areas, where there is usually a relatively small population exposed to them. The toxicity of the emissions of the ferry and aeroplane has accordingly less importance than the toxicity of the emissions from urban transport modes.

The acidification effects of the long distance transport are higher than in the urban transport. The emissions of ferry, aeroplane and bus have the biggest acidification effect. The global warming potential is biggest for the most energy intensive transport modes. When comparing the different modes, the differences in the pollution areas have to be paid attention to. For example, the NO_x emissions originating from the air transport drift more easily to the upper levels of stratosphere than the emissions originating from land transport modes.

6 PUBLICATIONS WITHIN THIS PROJECT

MOBILE 209T-1 — Report 1. 1994. Hanna Kalenoja. Tampere University of Technology, Transportation Engineering. 27 p. (In Finnish)

MOBILE 209T-2 — Midibuses in public transport. Hanna Kalenoja. 1994. Tampere University of Technology, Transportation Engineering. 67 + 2 p. (In Finnish)

MOBILE 209T-3 — Annual Report 1994. Hanna Kalenoja. 1995. Energy consumption and environmental effects of passenger transport modes - a life cycle study on passenger transport - modes. Tampere University of Technology, Transportation Engineering. 111 + 2 p. (In Finnish)

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Abstract:
In this study the energy consumption and environmental effects of different passenger transport modes are estimated. Energy consumption and environmental effects are evaluated during the production and distribution of fuel and during the end use of vehicle. In addition, the energy content of vehicles and the energy use of transportation infrastructure for each mode of transport is assessed. Energy consumption and environmental effects calculated per passenger mileage depend strongly on vehicle occupancy.

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