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How much transport can the climate stand?—Sweden on a sustainable path in 2050

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Abstract

In this paper an image of a sustainable transport system for Sweden in 2050 is outlined. The emissions per capita in this image may be generalized to a global population of 9 billions, and still be consistent with a stabilization of the carbon dioxide concentration at 450 ppm (parts per million). Swedish transport energy use per capita is 4.6 MWh in the image, compared to 12.5 MWh at present. The aim is, first, to widen the perspective of sustainable transport futures and, second, to provide a basis for present decisions in areas characterized by a high inertia, e.g. regarding infrastructure and the built-up environment. All transport generated by the lifestyles of Swedish residents are included. The reduction of energy use in the image is primarily achieved by an introduction of energy efficient vehicles and a conscious combination of IT-services and urban planning. The latter aims at increasing functional accessibility while reducing commuting. A prioritization of leisure travel to structurally-enforced travel gives the possibility to increase leisure travel per capita by one third. However, this is contingent on a 50% reduction of per capita car travel in cities. Given the set-up target, it may be concluded that the need for new arterial road capacity in cities often is negligible, even with a considerable population increase.

Keywords: Sustainable transport; Climate change; Backcasting; Carbon dioxide; Mobility management; Telecommuting

1. Introduction

Society is dependent on a well-functioning transport system. The transport system, however, causes a number of serious health and environmental problems and uses considerable quantities of finite resources, primarily fossil fuels. Transport was responsible for 19% of global emissions of greenhouse gases in 1971, a figure which in 1997 had risen to 23% (Price et al., 1998). It is the sector in which emissions are growing the fastest in both Sweden and the European Union (National Energy Administration, 2001; Eurostat, 2004). Between 1990 and 2001 emissions of carbon dioxide from transport increased by 24% in EU-25 (Eurostat, 2004).

With CO_2-emissions being a major obstacle to sustainable development, and the transport share of such emissions increasing, a crucial issue is to investigate what a future transport system with sustainable emissions of CO_2 could look like and how it could be realized. In this paper, we analyse a possible future transport system which is energy-efficient and consistent with a stabilization of the carbon dioxide concentration in the atmosphere at 450 ppm.

The approach used is backcasting. Höjer (2000) and Höjer and Mattsson (2000) identify four steps or tasks that constitute a backcasting study. The first step is the setting of one or a few long-term targets. In the second step, each target is evaluated against the current situation, prevailing trends and expected developments. The third step is the generation of images of the future that fulfil the target. The fourth and final step is to analyse the images of the future in terms of, e.g. feasibility and paths towards the images.

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It can be noted that a full backcasting study is only suitable when the targets do not seem to be reached by adjustments to a business-as-usual development. Moreover, the fourth step can be more or less emphasized (Robinson, 1990; Dreborg, 1996; Höjer & Mattsson, 2000). Sometimes it is seen as very important to actually point out a detailed path between the future images and the current situation. However, due to the inherent uncertainty of the future, the authors of this paper do not adhere to this view. A realistic policy must be sufficiently flexible or robust to cope with surprises. Nevertheless, the images of the future may provide recommendations on what policies to start with, in order to link the development towards the targets and avoid detrimental lock-in situations. The latter especially holds for structures with a high inertia, e.g. road- and rail infrastructure and the built-up environment. The most characteristic parts of backcasting are the setting of non-negotiable targets and the development of images of the future fulfilling those targets. A result of this combination can be that none of the images of the future are conceived as realistic. This in itself may be an important result of a backcasting study. A number of futures studies covering transport and its environmental impact have been published recently (e.g. Rienstra et al., 2000; Banister et al., 2000; Topp, 2002; Azar et al., 2003).

The aim of this paper is to provide a basis for a public discussion about sustainable transport and to give advice on present decisions regarding structures/systems with a high inertia, e.g. transport infrastructure and the built-up environment. Present decisions in these areas will greatly influence the preconditions to realize a sustainable transport system in 2050 and later on. In order to avoid "dead ends" regarding greenhouse gas emissions (and, for instance, land use and intrusion), it is therefore important to take a long-term perspective. Another aim is to clarify what types of choices society faces and the magnitude of changes that are required in order to move towards sustainable alternatives.

In this paper we use the case of Swedish transport. Sweden may be roughly representative of a Western European country today. According to Eurostat (2004), transport energy per capita in Sweden is 17% above the EU-15 average. The system delimitation used includes all transport generated by the citizens of Sweden. All journeys, domestic and international, made by Swedish residents are included in our analysis. In principle, the total freight transport generated by Swedes' consumption should be included. However, the statistics in this area are poor. Therefore the following approximations are used. All rail transport within Swedish borders is included. Transport by Swedish lorries both in Sweden and abroad are included, but not foreign lorries driving in Sweden. Imports, but not exports, made by sea and air are also included. In addition to the energy content of the fuels provided to the vehicles, the energy use for producing the vehicle fuels is also included in the analysis. Transport according to this delimitation is henceforth called Swedish transport.

2. What is sustainable transport?

In this paper a stabilization of the concentration of carbon dioxide in the atmosphere at 450 ppm (parts per million) is defined as sustainable. This target is roughly consistent with a target of 550 ppm (CO_2-equivalents) for all greenhouse gases, which has been adopted by the EU (IPCC, 2001b). IPCC has developed stabilization profiles for various concentrations. We have chosen the middle value of C-emissions, 5 Gt C/year by 2050 from the 450 ppm profile (IPCC, 2001a). This is equivalent to a 37% reduction of CO_2-emissions between 1990 and 2050, given that emissions from land-use changes are reduced to the same extent. However, since emissions from fossil fuels increased from 6.13 Gt C per year in 1990 to 6.61 Gt C per year in 2000 (Marland et al., 2003), the required reduction from 2000 until 2050 becomes 42%. Given a global population increase from 6 to 9 billion people, this is equivalent to a 61% decrease of per capita emissions.

For air transport not only emissions of CO_2 matters, emissions of NO_x and H_2O also contributes substantially to radiative forcing. The ratio of total air transport induced radiative forcing to that from CO_2 alone was 2.7 in 1992 (IPCC, 1999). The effects of the emissions of NO_x and H_2O are not explicitly included in our analysis. Their possible developments in the sustainable image are discussed in Section 7.

Assumptions regarding the potential supply of renewable energy are important when fossil CO_2 is to be reduced. Our assumptions regarding this issue are based on a couple of energy scenarios (Grübler et al., 1995; Lenssen and Flavin, 1996; Johansson et al., 1993; Ishitani and Johansson, 1996; Azar et al., 2003). The highest estimate of renewable energy supply in any of these studies is 72 PWh (Ishitani and Johansson, 1996) and this figure is also close to that made by Azar et al. (2003). In 2000 the global fossil energy supply amounted to 92 PWh (IEA, 2003). Reducing carbon dioxide emissions by 42% then requires that fossil energy use is reduced to 53 PWh, given that the present relative mix of oil, gas and coal remains the same. Adding a renewable potential of 72 PWh gives a total primary energy supply of 125 PWh. If development is successful, capture and sequestration of CO_2 might substitute for some of the renewable potential during a transitional phase. Nuclear energy is not assumed to play a significant role in the global energy system.

Today, industrialized countries use considerably more energy per capita than developing countries. With a fairness principle included in the sustainable development concept, a more even energy use might be called for. Although there will always be differences in energy use among different countries, in this paper we explore a case where energy use per capita in Sweden is equal to the global average. We assume that the global population will be 9 billion in 2050 and that Sweden's population will be 10.6 million. Given a global energy supply of 125 PWh in 2050, this means an average global (and thus Swedish) energy use of 13.9 MWh per capita.

How much of this energy could then be attributed to Swedish transport? In 2001, transport energy accounted for 26% of the final energy use in Sweden and 31% in EU-25 (Eurostat, 2004). To include energy for fuel production, these figures should be increased by 5–10% (see Table 3). In this paper we settle for a future share similar to the present, that is one-third of the total energy use. There are arguments in favour of both a higher and a lower share, but neither group of arguments is conclusive. On the one hand it is often argued that marginal costs for energy reductions are higher for transport than for other sectors, i.e. industry and buildings (IPCC, 2001b). However, marginal reduction costs depend on the actual level of energy use. This means that given that (final) marginal costs should be the same in all sectors, each sector's share of energy use will depend on the total level of energy use in society. For instance, in buildings it may be comparatively easy to achieve moderate reductions in energy use. However, since the turnover of housing stock, at least in developed countries, is very slow, it may be quite difficult to achieve more substantial reductions, e.g. more than 50% per unit housing. In the transport sector, on the contrary, the typical life-length of vehicles is only 15–20 years and there is a potential to reduce energy use for new vehicles by up to 75% by 2050.

We then conclude that 4.6 MWh per capita may be used for transport in the sustainable image of the future. This is a reduction of more than 60% compared to the year 2000.

Table 1
Potential to reduce energy use per passenger-km. Occupancy and speed are supposed to be unaltered, except for air travel (see text in Section 3)

	kWh/passenger-km, 2000	Potential change by 2050 (%)	kWh/passenger-km, 2050
Car, combustion mode, 1,2 pass/car (<100 km)	0.75	−75	0.20
Car, electric mode (<100 km)			0.10
Small electric city vehicle			0.07
Car, combustion mode, 2 pass/car (>100 km)	0.32	−65	0.12
Bus (<100 km)	0.22	−60	0.09
Bus (>100 km)	0.13	−40	0.07
Ferry (20 knots)	0.60	−30	0.42
High speed ferry (40 knots)	1.80	−30	1.30
Rail (<100 km)	0.16	−50	0.08
Rail, 200 km/h (>100 km)	0.11	−50	0.05
Air	0.57	−44	0.32

Sources: See text in Section 3.

Table 2
Potential to reduce energy use per tonne-km. Load factor and speed are supposed to be constant. For light lorries there is no statistical data on goods carried, but total energy use and emissions of carbon dioxide are known

	kWh/tonne-km, 2000	Potential change by 2050 (%)	kWh/tonne-km, 2050
Lorry (<100 km)	0.70	−40	0.42
Lorry (>100 km)	0.25	−30	0.17
Light lorry (<3.5 tonnes)	—	−45	—
Rail	0.05	−30	0.03
Ferry (20 knots)	0.20	−30	0.14
Cargo ship	0.05	−30	0.04
Air	3.00	−44	1.68

Sources: See text in Section 3.

3. Is technology enough?

In this section the potential for improving the energy efficiency of vehicles is analysed. The results are shown in Tables 1 and 2. The three modes, car, air and lorry, together account for about 85% of Swedish transport energy use (Steen et al., 1997). When making comparisons we refer to energy (or fuel) intensity, by which we mean energy use per passenger-km or tonne-km. All figures refer to fleet averages unless otherwise stated.

The car is the most energy intensive mode for short distance travel (<100 km). There is, however, a considerable potential to reduce fuel consumption by lowering empty weight, improving aerodynamic properties and not least by improving drivetrain efficiency. IPCC (1996) has estimated the potential to reduce fuel intensity by 2025 to between 35% and 80%. According to Åhman (2001), a highly efficient drivetrain consisting of a fuel-cell hybrid using hydrogen or a diesel hybrid using methanol in combination with reduced vehicle road load might yield a reduction of fuel intensity by 60% compared to a state-of-the-art gasoline car. We conclude that it is possible to reduce fuel consumption by 65% in highway driving and by 75% in city driving. However, for short trips (less than about 40 km) hybrid electric cars may rely solely on electricity charged to the batteries from the grid. In such cases they may achieve about the same efficiency as a pure battery electric vehicle, yielding a further 50% reduction of energy intensity (Åhman, 2001). For a small pure electric vehicle with two seats the energy intensity may be 65% lower than for the future hybrid vehicle in combustion mode.

In the FESG (ICAO Forecasting and Economic Support Group) 2050 scenarios, a 23–33% reduction of fuel intensity for the average of production aircraft in 2050 compared to the year 1997 is assumed (IPCC, 1999). The lower figure corresponds to a scenario with design for aggressive NO_x reduction. An estimate made by Green suggests that a 30–35% reduction of fuel intensity between 2001 and 2050 is possible for production aircraft (Green, 2002). In the ESCAPE-project the potential reduction of fuel intensity for two types of aircraft was estimated to be 37–45% (Peeters Advies, 2000). The lower figure relates to a 1000 km flight made by a 150-seat aircraft, while the higher potential relates to a 7000 km flight made by a 400-seat aircraft. Baseline is defined by a Boeing 737-400 and a Boeing 747-400. We conclude from this that a 40% reduction of fuel intensity per available seat kilometre is possible by the year 2050. If we also take into account a projected increase in occupancy from 70% to 74% (Airbus, 2002) we get a 44% decrease of fuel intensity per revenue passenger kilometre.

The potential to reduce the fuel intensity of lorries is lower than for passenger cars. The diesel engine is already quite efficient, and cargo comprises a large share of gross vehicle weight. Moreover, ever stricter limits for emissions of NO_x and particulate matter is in conflict with improved fuel efficiency (Duleep, 1997). Despite this there is some potential for reduced fuel intensity, e.g. by improved aerodynamic properties, lower curb weight, hybridization of distribution vehicles and possibly by introducing fuel cells. IPCC (1996) has estimated the potential to reduce fuel intensity by 2025 to between 20% and 60%. IPCC (2001) refers to Interlaboratory Working Group (1997) which estimates the sum total of all improvements to yield a 37.5% reduction of fuel intensity. Taking into consideration the conflict mentioned above between high fuel efficiency and emissions of NO_x and particulate matter (which has become even more relevant in recent years), we conclude that a 30% reduction of fuel intensity is within reach by 2050 for long-distance lorries and 40% for distribution lorries. The potential for improving light lorries (defined as having a maximum cargo capacity of less than 3.5 tonnes) is estimated to be slightly higher than for heavy distribution vehicles, since the group light lorries contains both petrol and diesel vehicles. We thus estimate that a 45% reduction of fuel intensity is within reach by 2050.

The energy use of sea, bus and rail transport together stands for less than 15% of the total transport energy use. The potential efficiency improvement for these modes, are taken from Steen et al. (1997).

Energy intensities for the base year are from Steen et al. (1997). Fuel intensity of Swedish cars dropped by about 5% between 1995 and 2000. However, a reduced occupancy counteracts this effect. Regarding buses and lorries reductions of fuel intensity have been insignificant during the last decade. Assumptions regarding energy intensities for all modes are shown in Tables 1 and 2.

3.1. *Summing up the technology potential*

The potential for improving the energy efficiency of vehicles is substantial. By 2050 it seems to be technically possible to reduce the fuel intensity for passenger transport modes by between 30% and 75% (see Table 1). The higher potential refers to short distance car travel. For freight transport the potential is lower, but still between 30% and 45% (see Table 2).

3.2. *Fuel production*

The energy used to produce the final fuel is called primary energy. Crude oil is a comparatively refined product already when it is pumped out of the earth and switching to fuels based on renewable energy generally implies decreased energy efficiency from primary energy to fuel in tank. The efficiencies on which the calculations are based are shown in Table 3. Bunker oil and aviation fuel are assumed to have the same efficiency as diesel. For electricity only distribution losses are included. It is uncertain what the choice of fuel will be in a future based on renewable energy. Options are, for instance, liquid biofuels and hydrogen. We have made calculations based on hydrogen and renewable electricity. We have assumed that half of the hydrogen is produced

Table 3
Efficiency from primary energy to "fuel in tank"

Fuel	Efficiency
Year 2000 and 2050	
Petrol	0.91
Diesel	0.94
Bunker oil	0.94
Aviation fuel (kerosene)	0.94
Electricity	0.95
Year 2050	
Hydrogen (350 bar) from biomass	0.59
Hydrogen (350 bar) from solar, wind or hydropower	0.74
Electricity from solar, wind or hydropower	0.95

Sources: Uppenberg et al. (2001) and Åhman (2001).

from biomass and half from electricity generated by solar, wind or hydropower.

3.3. Combining technical potential and transport volume forecasts

The question is then, would it be sufficient to reach the target level, if this technological potential was realized and a substantial amount of renewable energy was used? We have based our Reference scenario on the forecasts of the Swedish Institute for Transport and Communications Analysis (2002). This forecast only covers the period up to 2020 and does not include international air transport. For air transport we have assumed a 5% growth rate between 2000 and 2020. We have then assumed a halved growth rate between 2020 and 2050 compared to the period 2000 to 2020 for all transport modes. The transport volumes according to our Reference scenario are shown in Tables 4 and 5, in Section 5. When those volumes are combined with the estimates of technological potential as shown in Tables 1 and 2, we get the energy use for our Reference scenario. The results are shown in Fig. 1. It can be seen that, although energy use per passenger-km and tonne-km is approximately halved, total energy requirement is about the same as in 2000, and consequently far from the sustainable level set up in Section 2. The reason is that transport volumes are forecasted to double during this period. However, a combination of much improved technology and transport volumes similar to the ones in 2000, would nearly reach the target level, as illustrated by the third column in Fig. 1.

Table 4
Annual passenger transport (passenger-km/capita)

	2000	Reference 2050	Sustainable 2050
Short-distance travel (< 100 km)			
Car, combustion mode	7600	9600	2300
Car, electric mode	—	—	700
Small city vehicle	—	—	700
Bus	700	700	1100
Rail	600	600	1100
Bicycle	200	300	900
Walk	300	300	800
Long-distance travel (> 100 km)			
Car, combustion mode	3200	6700	1400
Bus	400	200	700
Rail	500	700	1800
Ferry (20 knots)	50	300	100
High-speed ferry (40 knots)	20	100	40
Air	2900	13800	3000
Total, passenger transport	16500	33300	16900

Sources: Travel in 2000 refers to average for the 3 years 1999, 2000 and 2001 which are from the Swedish National Transport Survey (authors' own run). Reference 2050 is a business as usual case based on a forecast until 2020 made by the Swedish Institute for Transport and Communications Analysis (2002). Air transport is assumed to increase by 5% between 2000 and 2020. Between 2020 and 2050 a halved growth rate is assumed for all modes. Sustainable 2050 is the image of the future presented in Section 5.

Table 5
Annual freight transport (tonne-km/capita)

	2000	Reference 2050	Sustainable 2050
Lorry (< 100 km)	700	1500	700
Lorry (> 100 km)	3400	5500	2300
Rail	2300	3400	2600
Ferry	500	800	300
Cargo ship	12300	14800	8200
Air	40	180	30
Total freight transport	19300	26200	14200

Sources: Freight transport in 2000 are from Swedish Institute for Transport and Communications Analysis (2001, 2003) and authors' own calculations based on Steen et al. (1997). Reference 2050 is a business as usual case based on a forecast until 2020 made by the Swedish Institute for Transport and Communications Analysis (2002). Air transport is assumed to increase by 5% between 2000 and 2020. Between 2020 and 2050 a halved growth rate is assumed for all modes. Sustainable 2050 is the image of the future presented in Section 5.

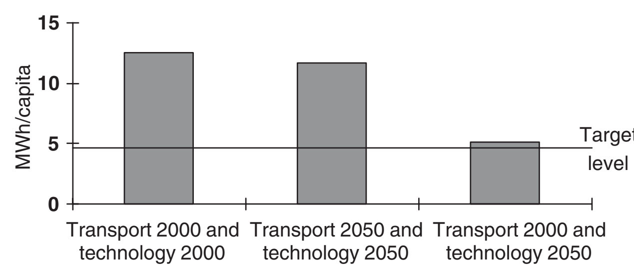

Fig. 1. Energy use in the transport sector. The left-hand column indicates present-day (2000) energy use for Swedish transport. The middle column builds on a Reference case for 2050. The right-hand column indicates a case with the transport volume of 2000 in combination with hypothetical realization of the technology potential in Tables 1 and 2. The figure also shows the assumed target level for sustainable energy use in the transport sector, 4.6 MWh/capita. All data are per capita.

4. The rise and fall of transport growth

The analysis above indicates that it will not be possible to reach a sustainable transport system (as defined in this paper) if current transport trends prevail, not even with substantial increases in energy efficiency. Somehow the trend of ever-increasing transport volumes must be curbed.

How could this be accomplished while maintaining or increasing welfare? In Steen et al. (1997) it was suggested that travel could be divided into *desired* travel and *structurally enforced* travel (see also Berg, 1996). Desired travel is such that is done to reach an attractive destination. Structurally enforced travel, on the other hand, is travel that, given present structures in society, is necessary in order to realize certain vital functions; earning a salary, getting everyday commodities, etc. The structures of society, e.g. location of home and jobs and organization of work, are hard to change in the short term. This implies that a sudden external event, like drastically higher oil prices, in the short term mainly will lead to a decrease of desired travel. In the long term the spatial and organizational structures in society can be changed, opening up the possibility to reduce structurally enforced travel instead of desired travel. The opportunities that can unfold might be easier to imagine by using the concepts of *geographical* and *functional accessibility*, where the former is access to, e.g. a market or service through physical mobility and the latter is a wider concept including any kind of access, e.g. via information technology.

We divide transport into three categories: short-distance passenger transport, long-distance passenger transport and freight transport. In terms of present energy use short-distance travel is dominating with about 45% of the sector's energy use. The other two use about one quarter each.

4.1. Short-distance travel

Short-distance travel (<100 km one way) in Sweden is dominated by car driving with a share of 75% of the transport volume and more than 95% of energy use (see Tables 1 and 4). Two-thirds of those trips are structurally enforced travel, mainly in terms of commuting. Short-distance travel only increased slightly between 1995 and 2000 (Swedish National Travel Survey, authors' own run).

Today's Western society is highly mobile, and there are strong actors interested in a further increase of mobility. The spatial enlargement of labour regions is currently a popular theme for planning. However, this in many ways positive development has a rarely mentioned drawback; it can lead to a dramatic increase in energy use for transport, even when the commuting mode is rail. In daily policy making, all rail transport is perceived as "environmental transport", but larger transport volumes require more energy, whatever the mode is. Increased rail transport can only reduce energy use if it substitutes for more energy-intensive modes, or is coupled with a reduction in travel distances.

A sample calculation may be illustrative. Currently an enlargement of the Stockholm region is facilitated by heavy investments in transport infrastructure. The building of a ring with high-standard rail around the Lake Mälaren is an important part of this. It will soon be possible to travel from cities some 100 km (e.g. Eskilstuna) from Stockholm city in 45–50 min by rail, thus within reasonable commuting distance. But how sustainable is such commuting?

The specific energy use for various transport modes varies considerably (see Table 1). For passenger rail transport it is about 0.11 kWh/pkm. This means that a 100 km trip by rail uses some 11 kWh. A car commuter could travel about 15 km, approximately the average commuting distance in Greater Stockholm, with the same energy use. The average commuter in Stockholm uses less energy since the car share is only about 50%. The average commuter from Eskilstuna would in practice use much more energy, both because of many trips being by car and because often a car is used to get from home to the railway station. Fig. 2 gives examples of energy use for various kinds of commutes.

Evidently, these comparisons can be debated, but the major point is that it is very difficult to reduce energy use for transport at the same time as regions grow, even if the travel growth consists of rail travel. Moreover, the potential for technical reductions of energy use is greater for cars than for other modes (see Table 1). Therefore, the difference between modes becomes less important, and this makes distance relatively more important. This is illustrated in Fig. 3, where the same trip relations as in Fig. 2 are used, but now including the technical improvements discussed in Section 3, and a shorter average commute in accordance with Section 5.

If there is little hope of a spontaneous saturation of transport demand, transport could perhaps be reduced if more attractive alternatives arose. In the past, accessibility has been associated with physical mobility and the ease of reaching various activities or services (see e.g. Jones, 1987; Berge et al., 1992). However, as pointed out in Gudmundsson and Höjer (1996), such a definition

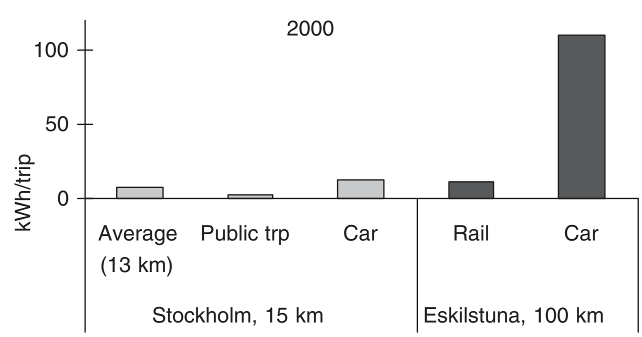

Fig. 2. Energy use in 2000 for commuting to Stockholm within Greater Stockholm, and from a city located 100 km from Stockholm. "Average" is calculated as the current mix of transport modes and with the average commute distance, 13 km, of 2000. *Sources*: Table 1 in this paper and Office of Regional Planning and Urban Transportation (2004).

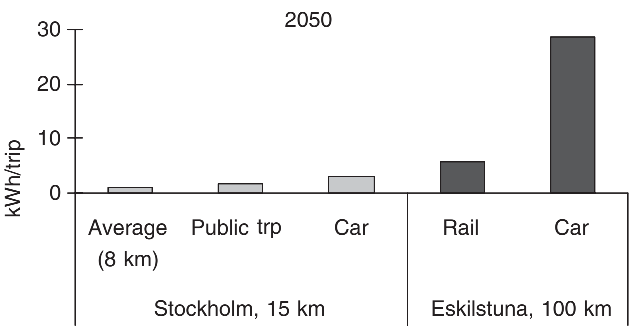

Fig. 3. Energy use in 2050 for commuting to Stockholm within Greater Stockholm, and from a city located 100 km from Stockholm. Average is calculated with the mix of modes and average distance, 8 km, that is used in the image of the future in this paper. Note different scale compared to the previous figure. *Sources*: Table 1 in this paper.

neglects non-physical ways of attaining access to services, e.g. through the use of information and communication technology. This is one example of the opportunities for change that are opened up by differentiating between geographical and functional accessibility.

When differentiating between these two types of accessibility, and combining this with a generation of telecommunicators (i.e. people with high skill in using IT for communicating over a distance—telecommunicating; Höjer, 2002a), old ideas regarding network organizations (see e.g. Bieber et al., 1994; Ingelstam, 1995; Berg, 1996; Castells, 1996) get a new actuality. Suddenly it may not be so difficult to imagine having some people as daily, physical workmates at a physical working place near home; whereas colleagues, people you do work with, can have their working places virtually anywhere. This change in the work activity from having been space dependent to now being virtual opens up new opportunities for the location of homes and workplaces. It makes it possible for people with space-independent jobs to work close to home and has the same effect on their spouses. If one person in a household can work anywhere, then they can live near the place of the other person's work. Moreover, it becomes possible to change jobs without changing workplace and to change workplace without changing jobs (see also Höjer, 2002a).

This also has implications on the choice of transport mode. A much higher degree of shorter trips reduces the need for immediate access to a car. At the same time alternative modes, such as bicycling and walking, and maybe new transport concepts get a better chance to compete with the car.

4.2. Long-distance travel

Global air travel has increased more than 5% annually in the 1990s, reaching a total of 3300 billion passenger-kilometres in 2000 (Airbus, 2002; IATA, 2003). Air travel by Swedes amounted to about 2900 km per capita in 2000 (Swedish National Travel Survey, authors' own run), a distance which corresponds to *one* annual return trip Stockholm–London. This is still about five times more than the global average. About one-third of Swedish air travel is for business purposes and two-thirds are for leisure purposes (Swedish National Travel Survey, authors' own run). In 2000, air travel contributed to about 15% of the energy use and one-third of greenhouse gas emissions from Swedish transport.

There are several factors fuelling air transport growth. Air travel is highly correlated to economic growth although increasing even faster. Aircraft has become successively more economic, one part of this being a considerable improvement in fuel efficiency. Deregulation of air travel markets and the emergence of low-cost carriers have pressed down ticket prices and boosted demand. Last-minute booking on the Internet makes it possible to buy very cheap tickets and foster habits of frequent air travel for those less well off today, e.g. students. The globalization of businesses and private relations increases the demand for air travel. However, there are also impeders to air travel growth. Air travel is rather sensitive to the oil price which has been high at some periods. Terrorism is another impeder. After September 11, 2001 there was a significant drop in air travel.

High-speed trains might substitute for some air travel, although this potential might be exaggerated. Most air travel is at long distances; for instance, only one-sixth of air travel by Swedes is domestic. Fast trains and convenient sleepers could probably also substitute for some air travel to the less remote destinations in continental Europe, giving a total replacement potential of maybe 15%. Videoconferences might have an impact of the same magnitude, and this solution might entail economic gains even if emission reductions are not considered. It is here again important to focus on the *functional accessibility* and not to take a demand for mobility for granted (to look beyond a demand which might be manifested at present). This may be even more so when the telecommunicators are to choose between a time-consuming air transport and a virtual face-to-face contact.

4.3. Freight transport

Freight transport by lorry and air is increasing fast. Between 1991 and 2001 total freight transport in EU-15 increased by 30%, while road freight increased by 38% (European Commission, 2003). Drivers behind this growth are improved infrastructure and vehicle technology which lower transport costs. It is also encouraged by lowered or abolished trade barriers. Free trade agreements like EU and NAFTA are aimed at increasing trade and consequently also increase transport volumes. The enlargement of EU to 25 countries will add considerably to transport volumes in Europe. The widespread use of IT has made it easy to find and order products from far away. Although IT until now most probably has enhanced freight transport growth, it also entails some seeds for reducing transport intensity. By using IT, it may be possible for trans-national companies centrally to develop products and co-ordinate production processes worldwide, while physical production may be decentralized and comparatively transport efficient (Banister et al., 2000). IT is a necessary condition for such a "glo-cal" production paradigm but it is not sufficient. More even income levels and/or considerably higher transport costs must also materialize.

The freight transport growth is mainly attributable to increased transport distances. In many industrialized countries transport volumes carried have decreased slightly in recent years. Although increased transport distances have by far outweighed this decrease, it could be seen as a first small step towards a dematerialization.

5. An image of sustainable Swedish transport in 2050

In this section, we develop an image of a sustainable transport system in Sweden in 2050, based on previous sections. A lead principle when developing the image has been to reduce as much as possible the structurally enforced travel (and freight), and thus allowing for maintained or increased desired travel. The technology potential estimated in Section 3 has been used in the image. About half of transport fuels are derived from renewable primary energy.

The energy use for transport depends on specific energy use and transport volumes. In Fig. 4 these dimensions are illustrated for three cases; 2000, Reference 2050 and Sustainable 2050. The shape of the "skyscrapers" in the figure shows both travel volumes and energy use. Thicker parts of the skyscrapers indicate a higher energy intensity, while the height of the skyscrapers shows travel volume per capita. Thus, energy use is proportional to the area of the boxes. The figure shows that total travel per capita in Sustainable 2050 is about the same as in 2000, but a lot less than in Reference 2050. The main differences between the two 2050-cases are that

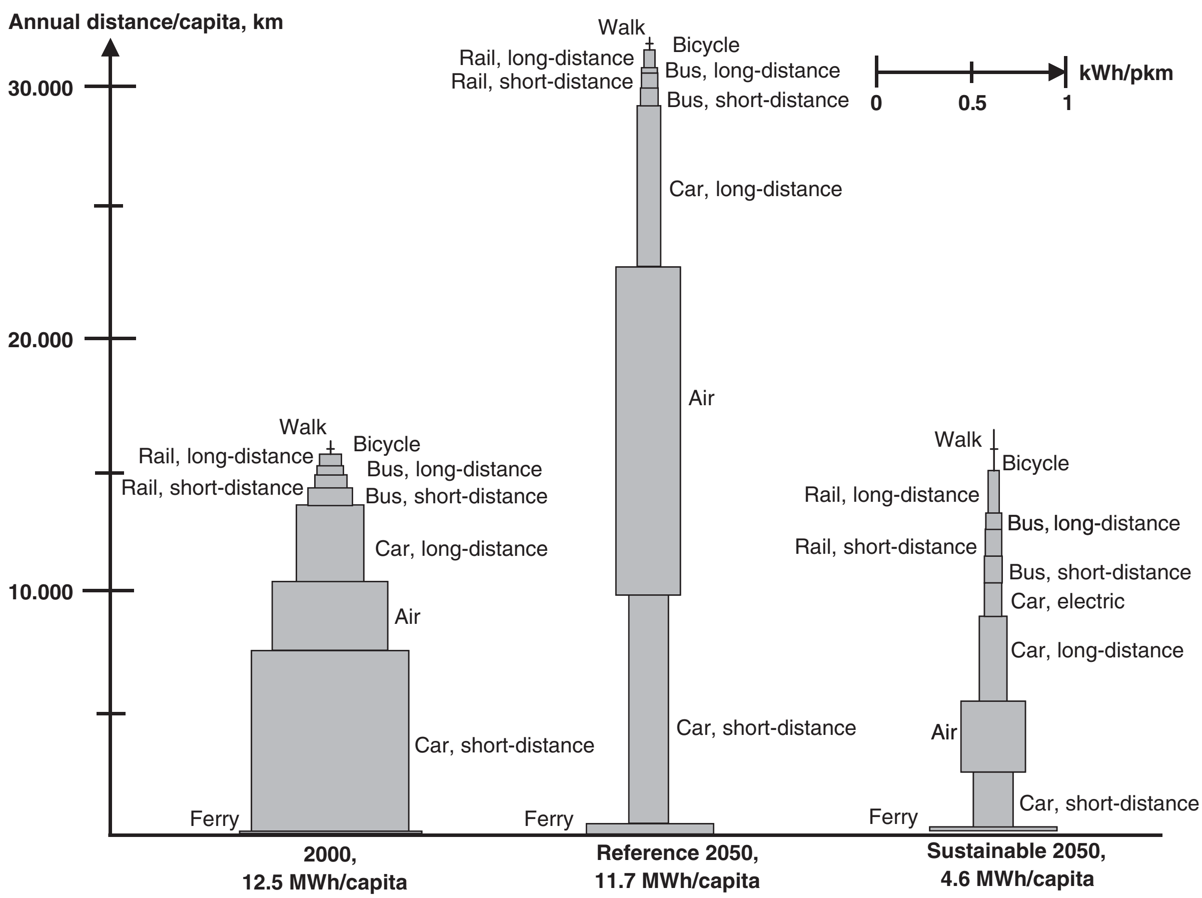

Fig. 4. Average annual per capita travel in the three cases 2000, Reference 2050 and Sustainable 2050. The width of the modes' boxes indicates the respective energy intensity. The height indicates the travel length. Thus, the areas of the boxes represent the energy used for each mode.

"Air" and "Short-distance car" are much lower in the Sustainable image. The generally slimmer skyscrapers in Reference 2050 and Sustainable 2050 are a consequence of improved energy efficiency between 2000 and 2050.

5.1. Short-distance travel—cutting distance and switching mode

In the image, much structurally enforced travel has been made obsolete by a change in today's working patterns, resulting in a structure where many people work in network organizations. Prerequisites for this have been changes in infrastructure and location of functions.

The image builds on a society where daily life is in a way much the same as today's life in Western cities, but with one major difference—the distance to work has decreased considerably. This has been possible through a combination of technological development, learning and change of habits. The most important of these three changes may be the rise of a generation of "telecommunicators" (see above). The high number of people with space-independent jobs has altered the character of cities and landscapes. In general people tend to take just as many trips as before, but now at shorter distances. Mixing of housing and workplaces has increased. This is an effect both of the networkers' willingness to work near home, and of all the service jobs related to the new offices that this way are created in areas previously completely dominated by housing.

A new form of network society at several levels has been built, and it is characterized by its many nodes. In cities, former stations for rail commuting systems have become nodes in not only the public transport system, but also in network enterprises, which consist of workers located in various other nodes and connected with high-capacity communication technology. The nodes also work as local centres of various importance. The change towards networking has created a market for local centres and thus for a more vivid local environment. Altogether commuting distances per capita are reduced by 30%, which is consistent with Höjer (2002b). The reduction in volumes is mainly reached by shorter commutes. Except for leading to a reduction in energy use, just by travelling less, a structure of this kind would also allow for a higher share of non-motorized travel.

Home-delivery of everyday commodities and a better local service make it possible for many people in cities to do without a car of their own. Instead alternatives, such as, increased car rental or various forms of collective ownership of cars in car pools, have become common. This enables the use of different kinds of vehicles for different purposes, which reduces energy use. With a decreased car ownership, other modes are used for many shorter trips, leaving car transport to situations when the car has its greatest advantages, such as when travelling with luggage or in a small group. Thus, this would reduce energy use even further. Altogether the car use per capita for short-distance trips in the image is 50% of today's car use, whereas trips by other modes have increased by a factor 1.5–4.

5.2. Long-distance travel—curbing air travel growth

In the sustainable image for the year 2050, total air travel per capita is about the same as in 2000. Business travel has been reduced by one-third, while leisure travel has increased by 20%. Although this is a significant increase, it corresponds to only 4 years of air travel growth in the 1990s. For travel within Sweden and to continental Europe, fast trains and comfortable sleepers have taken considerable market shares. A concerted EU action for a truly integrated rail system in Europe has been a prerequisite for this development. The combination of trains and rental cars (or pool cars), easily accessed by smart cards, is popular. Regarding business travel, people are accustomed to virtual meetings. Teleconferences are used extensively for meetings where people have already met face-to-face. Companies′ growing awareness of potential cost savings has also contributed to this development. In all, business travel per capita has been reduced by 25% despite an increase in international contacts.

Leisure travel by air, on the other hand, has increased slightly in line with the prioritizing of desired travel. The average duration of long-distance trips has increased and so has total time spent at leisure destinations. Local and regional holiday destinations have gained in popularity. These are often reached by train or car. Although the car is the most energy- and space-intensive mode for short distance (urban) travel, it is at the same time significantly *less* energy-intensive than air for long distance travel (especially in the Image 2050). One of the major niches where the car is superior to other modes is for leisure purposes when occupancy is high and a lot of luggage is needed, e.g. when a family travels to a summerhouse.

5.3. Freight transport—switching mode and curbing volume growth

Freight transport per capita in the sustainable image is 27% lower than it was in 2000. This is in stark contrast to the considerable growth rate at the turn of the century. One reason for the reduced freight transport in the image of the future is shorter transport distances. This applies especially to flows of products with a low cost/weight ratio, such as, basic food, fuels, and building materials. The trade with this kind of goods makes a relatively small contribution to the economy, but stands for a large share of freight transport volumes. Products with a high cost/weight ratio, like electronic equipment, vehicles, etc., are still now in 2050 to a large extent traded in global markets and so are products like coffee, wine and bananas. However, a significant increase of ‘‘glocal production’’ has been achieved since the turn of the century. Glocal production means that while company management and product development may be centralized, physical production may be decentralized and situated close to consumer markets. Since transport costs have increased considerably, much of the ‘‘cross-freight transport’’, so common in the early 2000s, has disappeared. Another effect is a significant change in modal split. Long-distance lorry transport has been reduced by one-third, while rail transport has increased slightly compared to the year 2000. An overall dematerialization of society (e.g., through lighter and more durable products) has also contributed to the reduction in freight transport.

The system of distributing everyday commodities has largely changed its character. Many of these commodities are ordered via computer networks, and small efficient hybrid lorries deliver to the home. Bread, fresh fruit, and other perishables can be ordered in this way, but they can also be bought in local shops and markets at the nodes.

5.4. *The image in figures*

Structurally enforced per capita travel has been reduced by one-third and freight transport by 27%. This has given room for a 30% increase of desired travel (see Fig. 5). Long-distance train travel has increased by 250%. Long-distance car travel has increased slightly and still stands for a large share in this travel segment. Total air travel is about the same as in 2000. In Tables 4 and 5, in Section 3, transport volumes per capita according to mode are shown for Sweden 2000, a Reference scenario for 2050, and for the Sustainable image 2050.

6. A policy for sustainable transport

The future is uncertain and will bring surprises in our way. This fact necessitates a planning strategy that is *adaptive* (Dreborg, 2004). Creating detailed plans for getting from the present to an image of the future is not very meaningful. At the same time, signs of a changing climate are already possible to discern. In combination with the high inertia both in the Earth’s climate system and in the socio-technical systems of society, this makes firm action urgent. When outlining a policy for the present, it is important to bear in mind the long-term sustainability targets. Present decisions regarding the structure of urban areas and transport infrastructure will much affect the preconditions for sustainability 50 years or more from now. The high inertia in buildings and infrastructure makes it of vital importance to avoid ‘‘dead ends’’, e.g. urban structures like Los Angeles. While building new road infrastructure may often provide a negative lock-in with regard to sustainable development, investing in rail infrastructure may provide a positive lock-in (commitment) in that it can attract dense housing around its stations. What thus should be in focus is to find *robust* and/or *flexible* policy packages. It is also necessary to combine several policy measures into packages in order to achieve changes of the magnitude illustrated by the image of the future, in an efficient and acceptable way (Banister et al., 2000).

What more is required from policy measures/packages that should be implemented early? Packages that trigger positive spirals should be given high priority. Public transport is a case in point here. If public transport gets more passengers, it is possible to increase frequency of departures, which in turn may attract new passengers and so on. Measures, which imply synergies with areas outside the environmental domain, may be comparatively easy to introduce at an early stage. Examples are home delivery of food, and telecommuting, which saves time for households. Another is increased cycling and decreased car travel yielding better public health. Regarding fuels it is still

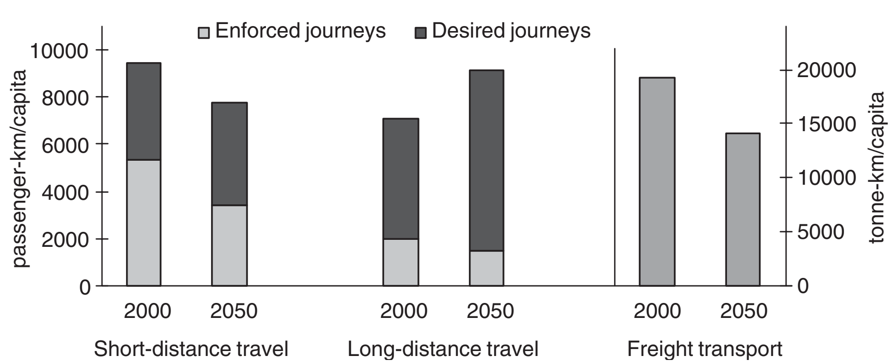

Fig. 5. Volumes of desired travel, enforced travel and freight transport in the Sustainable image of 2050 and in 2000.

unclear what constitutes the best alternative for the future. Therefore the emphasis should be on research and demonstration programmes rather than an immediate large-scale fuel switch. Such a policy might be complemented by demand-orientated policies directed towards alternatives that avoid the risk of leading to premature lock-in situations. One such alternative is comparatively cheap flexible fuel vehicles, for instance such that may be filled with any mix of petrol and ethanol. A demand pull policy for such vehicles may consist of concerted actions among fleet owners and households for buying a large amount of vehicles at a reasonable price. Another example is to exempt such vehicles from charges. The former policy has already been used in Sweden, while the latter is being considered for the Stockholm congestion charge trial starting in 2005.

In this paper we distinguish between four types of measures. These are:

(1a) Measures to stimulate new environmentally benign alternatives for accessibility/transport.

(1b) Measures which improve existing environmentally benign alternatives.

(2) Measures which limit more harmful transport modes.

(3) Measures which reduce specific emissions and energy use for the respective transport modes.

We have concluded that technology, that is measures of type 3, are not enough to reach the targets. In addition transport growth has to be curbed and modal shifts accomplished. To realize this, it is necessary both to improve more environmentally benign ways of getting functional accessibility and to limit more harmful transport modes. It is not sufficient only to improve the more environmentally benign modes of transport/accessibility, e.g. only improving public transport does not reduce car traffic much. Consequently, realistic policy packages should include both measures of type 1 and measures of type 2.

Regarding structurally enforced travel (work, service, shopping) the temporal implementation of measures might be as follows. First, one has to provide satisfactory alternatives for functional accessibility. It may be more or less novel solutions, such as, telecommuting, carpooling or small and clean urban vehicles, as well as improvement of cycling and public transport. The second step is to get people's attention to these alternatives and demonstrate them. This step is important but not in itself sufficient. A third step is necessary and it consists of measures which limit the use of more harmful modes of transport, e.g. by economic incentives.

We have in the image of the future prioritized desired travel which may increase by 30%. This increase in desired travel must, however, not be materialized mostly as air travel as is the present trend. Alternatives like train, bus, car and videoconference facilities are to a great extent already available, so limiting measures on air travel might be applied right away and then successively tightened. A greenhouse gas tax on air fuel is needed and could be implemented at the EU-level if no global agreement is reached. Such a tax should not only embrace the emissions of CO_2, but also the emissions of H_2O and NO_x, which when emitted at high altitudes also have a great impact on global warming (IPCC, 1999). Landing fees correlated to greenhouse gas emissions may be used until international agreements are realized.

Since transport is interrelated with all sectors of society, it is important that all policies in society work in the same direction. Examples of policy areas important for transport are agriculture, public procurement and taxes.

In Åkerman et al. (2000) initial policy packages were outlined for four transport segments; daily travel and freight transport in cities, daily travel and freight transport in rural areas, long-distance travel and long-distance freight. The policy packages should be regarded as illustrations to what is needed in order to achieve changes of the magnitude shown by the image of the future. The packages are mostly qualitatively formulated. For the timeframe considered, almost 50 years, it is impossible to quantify more precisely the required economic incentives. Required levels depend on e.g. changes in people's values, new scientific knowledge and technological development. A *flexible* policy in which measures are successively adjusted is needed.

7. Discussion

The image of a future transport system in Sweden presented in this paper is *one* illustration of what a sustainable transport system could look like. It does *not* constitute a forecast of a probable future. Instead, it pinpoints the tension between the non-negotiability of the targets and the power of current dominating developments and indicates what magnitude of change is necessary to reach sustainability targets. Mitigating climate change is the focus of the study, but the image may be relevant even for other issues, for instance oil supply. According to some sources, the price of oil may become persistently high within 10 or 20 years, and the oil-producing countries may be more and more concentrated to a limited area (Campbell and Laherre, 1998; Cleveland and Kaufmann, 2003).

A development towards a sustainable transport system requires significant changes to the organization of daily activities and daily travel. Such changes do not necessarily have to stem from changes in preferences. Instead, they may, at least to a great extent, be a consequence of new opportunities and conditions. New opportunities to get access, e.g. via IT, in combination with altered conditions, e.g. improved scientific evidence on the effects of climate change, may also increase the acceptance for necessary complementary measures limiting energy use, e.g. increased fuel prices and congestion charging. Furthermore, although many trends certainly point in the wrong direction, there are some seeds for countertrends; less status connected to cars among young people, habits of communicating by IT are spreading fast, a growing dissatisfaction with present hectic and consumption-focused lifestyles, etc.

The effect of increased use of IT is a case in point regarding the importance of including a wider context. It may well be that IT, in a business-as-usual development, is generating more travel by increasing the ability of people to get in contact and stay in contact with people at a distance. At the same time, however, IT might constitute a vital part of integrated policy packages aimed at limiting travel volumes. IT has an important role to play since it may lower the threshold for commuters to reduce car travel, e.g. by working at telecentres or at home for some part of the week. The travel generating potential of IT, e.g. contributing to urban sprawl, could be counteracted by conscious urban planning and economic incentives. Images of the future may provide such comprehensive solutions, of which one aim is to increase the willingness to tread a sustainable path.

The reduced fuel intensity and the limited transport volume in the sustainable image require more than marginal changes of present trends. What would the energy use and emissions be with smaller changes? For this alternative calculation we have made the following changes compared to the sustainable image. Fuel intensity of cars is "only" reduced by 50% (compared to 65–75%). Car travel, air travel and freight transport growth is only slowed down to half the growth rate assumed in the Reference scenario. In such a scenario, which still would constitute a break of present trends, the energy use in 2050 would be approximately 150% above the target level.

Today short-distance, mostly daily, travel accounts for about 45% of energy use and carbon dioxide emissions from Swedish transport. However, in the sustainable image 2050, this share has shrunk to 20%, while at the same time, long-distance travel has increased from about 30% to slightly more than 40%. There are several reasons behind this. The technical potential for more efficient vehicles is better for short-distance travel, e.g. urban car driving, than for long-distance travel and freight transport. The potential for modal shift and limiting transport distance by means of urban planning and the use of IT is also better.

In the image, the Swedish transport energy use per capita is the same as the global average. This means that the travel and freight volumes of the sustainable image could roughly be seen as the global average, although different technology levels and different contexts would certainly shape local transport systems in different ways. In 1990 global passenger transport amounted to approximately 4200 km per capita and annum, while in the sustainable image for 2050, passenger transport amounts to 17 000 km per capita and annum. Thus, taking a global view, a fourfold increase in travel per capita may be consistent with a strong climate policy, but only if non-marginal changes similar to the ones in the sustainable image are realized.

The emissions of NO_x and H_2O caused by air transport are not explicitly included in the analysis. The target for CO_2-emissions imply a 61% reduction of global per capita emissions. In the sustainable image aircraft emissions per capita are only reduced by 42%. However, since the radiative forcing caused by NO_x, and in particular H_2O, depends on altitude of emissions, it might be possible to achieve a 60% reduction of radiative forcing by lowering flight altitudes (Åkerman, 2005).

The sustainable transport image for 2050 presented in this paper implies a 42% reduction of greenhouse gas emissions and is consistent with a stabilization of the carbon dioxide concentration at 450 ppm. However, such stabilization is contingent on a further 50% reduction between 2050 and 2100 and even more thereafter. It will be difficult to increase substantially the use of biomass above the 50 PWh assumed for 2050. Main options seem to be an increasing use of solar or wind energy or carbon capture and sequestration, although costs and environmental consequences of such strategies are today unclear.

8. Conclusions

It does not seem possible to reach the target level for sustainable greenhouse gas emissions set up in this paper, only by relying on technology. Improved technology in conjunction with renewable fuels is important, but transport volume growth also has to be curbed.

However, if much of present demand for structurally enforced travel (commuting, service- and shopping travel) and freight transport is substituted for by e.g. IT and multinuclear urban planning, it might be possible to increase leisure travel by 30% and still remain within the target level. Swedish total travel per capita is then about the same as in 2000, but functional accessibility is significantly higher. This shows, on the one hand, that a sustainable transport system need not entail decreased accessibility. On the other hand, for such a development to come true, substantial changes regarding both spatial and institutional structures are necessary. It is important that society be structured so that people are not forced to be highly mobile in order to uphold a sufficient accessibility.

In the sustainable image total car travel is reduced by 32% (more in cities and less in the countryside). This has a strong implication on the need for new road infrastructure. Even in a city like Stockholm, with a projected population increase of 600 000 people (33%) by 2050, there would be little if any new road capacity needed in the arterial network.

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