



**KTH Architecture and
the Built Environment**

Transport systems meeting climate targets

– A backcasting approach including international aviation

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DOCTORAL THESIS

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Preface

In 1994 I picked up the phone to call Tomas B Johansson, who I knew was an experienced person in energy systems analysis. I was looking for a job and was interested in energy issues, in particular wind energy. The call was answered by a colleague of Tomas, Lars Nilsson, who told me that Peter Steen was setting up a research group in Stockholm focusing on sustainable transport. So, I called Peter and became part of *fms* (originally *Forskningsgruppen för miljöstrategiska studier*), which at that time was situated in the Old Town of Stockholm. Right from the start I came to like the familiar and creative atmosphere at *fms*.

From then Peter became a very important person for me, both professionally and as a friend. He, together with Karl Henrik Dreborg, introduced me to futures studies and especially backcasting. For a couple of months he was my first supervisor, until he unexpectedly died in May 2000. He is greatly missed.

I acquired a new supervisor at Stockholm University, Carl Folke, but unfortunately my focus on thesis writing varied a lot during the following years. My main interest was to explore the research field of sustainable energy and transport systems, and to disseminate policy relevant results to a wider public. These projects were not always compatible with thesis writing. These years were also somewhat turbulent for *fms*. In 2003 *fms* was split into two parts one at the Swedish Defence Research Agency and one at KTH. I belonged to the former part. In 2005 Greger Henriksson and I, after some struggle, managed to join the bigger part of *fms* at KTH.

Finally in 2009, I decided that all things must come to an end, so I shifted from Stockholm University and become a PhD student at KTH. At KTH I have had three excellent supervisors, Mattias Höjer, Göran Finnveden and Lars-Göran Mattsson, and consequently the final stretch of thesis writing went comparatively smoothly.

Stockholm, DKV 30, January 2011

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Abstract

Future transport systems consistent with long-term climate targets are examined in this thesis, using a systems perspective covering the entire transport system. Aviation is given particular attention, as expansion of this mode is difficult to reconcile with climate targets. The aim is to provide scientific decision support for current transport policy-making, especially regarding structures with high inertia, e.g. urban structure, roads, railways, fuel production systems and vehicle fleets. An additional aim is to widen the perception of possible transport futures consistent with meeting climate targets, and to support a wider discussion in society on this topic. Papers I and III are backcasting studies which encompass the whole transport system. Paper III outlines an image of future Swedish transport by 2050, in which energy use per capita is reduced by 60%. This reduction is consistent with a 42% reduction in total global greenhouse gas emissions. Paper IV shows that total air travel by Swedes generates about 8.7 million tons of CO₂-equivalents annually. This corresponds to about 12% of total Swedish emissions. Considering the rapid growth in emissions, aviation is key to achieving overall climate targets. Paper V indicates that building high-speed tracks between Stockholm, Gothenburg and Malmö may yield emissions reductions of about 550,000 tons of CO₂-equivalents annually, if a life-cycle perspective is considered for all modes. However, this reduction is contingent on continuing growth of transport volumes, which seems difficult to reconcile with the images in Papers II and III. This might consequently be a 'second best' solution if a more radical break in transport growth is deemed unlikely due to external drivers.

The overall conclusion from this thesis is that improved vehicle technology and low carbon fuels are necessary, but not solely sufficient, to achieve long-term targets consistent with limiting global warming to two degrees. The growth in volume, especially of car and air travel and truck transport, must also be curbed. However, total travel volume can be maintained at 2005 levels if substantial modal shifts to cycling and public transport are achieved. Moreover, if conscious measures are taken regarding urban planning and the use of communications technology to replace travel, functional accessibility may increase considerably. The trend-breaking development needed to achieve climate targets requires a combination of different policy measures. Pricing of external effects, e.g. greenhouse gas emissions, is a key strategy and would involve ending aviation's exemption from carbon tax and value-added tax. Other possible pricing measures include differentiated charges for car travel in urban areas, km-charges on trucks and increased fuel taxes. However, to gain acceptance for pricing measures and maintain a well-functioning society, better alternatives with a lower climate impact are needed. Increased road capacity in urban areas usually increases car travel. Therefore, to achieve the targets set, strict prioritisation of investments in public transport, cycling and ICT infrastructure is needed, especially since public resources are limited. Another conclusion is that, for transport policies to be effective and not lead to sub-optimisations, it is necessary to consider the wider system delimitations explored in this thesis.

Sammanfattning

Denna avhandling handlar om vilka förändringar av transportsystemet som krävs om långsiktiga klimatmål ska kunna nås. Flyget ägnas speciell uppmärksamhet eftersom dess snabba ökning är mycket svår att förena med klimatmålen. Ett syfte med avhandlingen är att ge underlag för nutida beslut, speciellt sådana som gäller strukturer i samhället med lång livslängd. Det gäller bebyggelsestruktur, vägar, järnvägar och system för bränsleproduktion, men även fordonsflottor. Ett ytterligare syfte är att vidga föreställningen om möjliga transportframtid, i syfte att ge underlag för en bredare diskussion i samhället om vilka fördelarna och nackdelarna är med olika utvecklingar. Artiklarna I och III utgör backcastingstudier där hela transportsystemet behandlas. I artikel III presenteras en framtidsbild för det svenska transportsystemet år 2050 där energianvändningen per person har minskat med 60%. Detta är förenligt med en minskning av de globala utsläppen av växthusgaser med 42%. I artikel IV visas att utsläppen från den svenska befolkningens totala flygresande (inrikes och utrikes) år 2006 uppgick till 8,7 miljoner ton CO₂-ekvivalenter. Detta motsvarar 12% av de totala svenska utsläppen av växthusgaser från alla sektorer. Artikel V visar att ett bygge av höghastighetsjärnväg mellan Stockholm, Göteborg och Malmö (Europabanan) skulle kunna minska de årliga utsläppen med 550 000 ton CO₂-ekvivalenter per år, utifrån ett livscykelperspektiv. Denna utsläppsminskning är dock relaterad till ett referensscenario med en relativt kraftig ökning av transportvolymerna, en utveckling som synes svår att förena med framtidsbilderna i artikel II och III. Höghastighets järnväg kan således betecknas som en "näst bästa" lösning, som kan bli aktuell om ökningstakten för transportvolymerna inte bedöms kunna bromsas kraftigt.

Den övergripande slutsatsen från denna avhandling är att förbättrad fordonsteknik och större andel icke-fossila bränslen är nödvändigt, men att ökningstakten för främst bilresande, flygresande och lastbilstransporter också behöver brytas. Om en kraftig överflyttning kan ske till mer klimatvänliga transportslag, som cykel, buss och spårtrafik, så skulle dock det totala resandet kunna vara ungefär lika stort som det var år 2005. Med en medveten satsning på transporteffektiv samhällsplanering samt ett smart utnyttjande av IT för att ersätta en del resor med virtuella möten, så kan dessutom tillgängligheten till olika funktioner öka markant. För att åstadkomma de trendbrott som behövs om klimatmålen ska nås, krävs en kombination av olika styrmedel. Ekonomiska styrmedel är mycket viktiga, inte minst att flygets nuvarande undantag från klimatskatter och moms avslutas. Andra viktiga styrmedel är trängsel- och miljöavgifter för bilar i stadsområden, km-skatter för lastbilar samt i viss mån höjda koldioxidskatter. För att nå acceptans för dessa styrmedel samt bibehålla ett väl fungerande samhälle krävs dock, i vissa fall, bättre alternativ med låg klimatpåverkan. Eftersom ny vägkapacitet oftast leder till nygenererad trafik, är det viktigt att tillgängliga resurser konsekvent prioriteras till kollektivtrafik, cykel och informations- och kommunikationsteknologi.

List of papers

- I. Banister, D., Dreborg, K.-H., Hedberg, L., Hunhammar, S., Steen, P., Åkerman, J., 2000. Transport policy scenarios for the EU: 2020 Images of the Future. *Innovation*, 13 (1) 27-45.
- II. Åkerman, J., 2005. Sustainable Air Transport – On Track in 2050. *Transportation Research Part D: Transport and Environment*, 10 (2005) 111-126.
- III. Åkerman, J., Höjer, M., 2006. How much transport can the climate stand? – Sweden on a sustainable path in 2050. *Energy Policy*, 34 (2006) 1944-1957.
- IV. Åkerman, J. Climate impact of international travel by Swedish residents. Submitted to *Journal of Transport Geography*
- V. Åkerman, J., 2011. The role of high-speed rail in mitigating climate change – The Swedish case Europabanan from a life cycle perspective. *Transportation Research Part D: Transport and Environment*. In Press. doi:10.1016/j.trd.2010.12.004

1. Introduction

1.1 Background

This thesis examines how transport systems could be transformed to meet long-term climate targets. Limiting climate change to levels at which the negative impacts are tolerable will be a major challenge during the coming decades. The evidence from climate research during the years since the IPCC Fourth Assessment Report in 2007 (IPCC, 2007a) indicates that the situation is even more critical than was previously thought (The Copenhagen Diagnosis, 2009). There is a substantial risk that human greenhouse gas emissions will trigger positive feedbacks that might accelerate climate change out of control. Increased temperature as such is not the most important effect of climate change. For example, many of the more severe consequences are related to water. According to The Copenhagen Diagnosis (2009), the global sea level rise by 2100 may well exceed 1 meter. However, the impact of more frequent droughts on food supply might be even more significant. Food shortage might in turn trigger social unrest and possibly armed conflicts over water supply (Dyer, 2008).

In some respects the future transport systems outlined in Papers I-III may contribute to the solution of other major global problems in the coming decades. A case in point is the growing scarcity of oil. The point at which oil production will peak is uncertain, but it is not unlikely that the global community will face a rather drastic increase in oil prices during the next decade (Campbell and Laherre, 1998; Cleveland and Kaufmann, 2003; IEA, 2008; Aleklett et al., 2010). Most of the oil is used in the transport sector, which in 2004 gave rise to 23% of global energy-related greenhouse gas emissions (IPCC, 2007b), a proportion that is increasing.

Another global challenge is the preservation of ecosystems that deliver vital ecosystem services, e.g. food, water, fibre, fuel, climate regulation and disease regulation (Millennium Ecosystem Assessment, 2005). In this case there is a potential conflict with regard to future transport systems that meet long-term climate targets. For instance a rapid increase in the use of biofuels might endanger vital natural ecosystems, e.g. the Amazon rainforest. It should, however, be noted that exploiting natural ecosystems for bioenergy production might not even be very beneficial with regard to climate impact (Fargione et al., 2008; Searchinger et al., 2008). To minimise these conflicts, strong emphasis needs to be placed on reducing energy use in transport.

The transport sector accounts for about 40% of Swedish emissions of greenhouse gases, including international aviation and maritime transport (Åkerman et al., 2007). Globally, transport was responsible for 23% of global energy-related greenhouse gas emissions in 2004 (IPCC, 2007b). The main reason for the higher share for Sweden is that fossil fuels represent only a small fraction of electricity generation and heating of buildings in Sweden. Both in Sweden and globally transport is increasing its share of emissions. Aviation is of particular concern. The average growth rate of global air travel was 6.2% between 1972 and 2007 (Lee et al., 2009). This represents an eight-fold increase over that 35-year period. Greenhouse gas

emissions from aviation at present make up 4-5% of anthropogenic climate forcing, a proportion that is most likely to increase (Lee et al., 2009).

The policy formation process, the transport system and the climate system are all characterised by significant inertia and time lags. This means that the total time that elapses from the start of the policy formulation process until a physical change is brought about in the amount of global damage caused by anthropogenic emissions, may be very long. Different parts of the transport system have different degrees of inertia. The urban structure, primarily the building stock and transport infrastructure, takes 50-100 years or more to affect significantly. The introduction of new vehicles takes less time, but it still takes 15-20 years to develop passenger cars with evolutionary technology and to renew a major part of the fleet. If major technological advances are needed, as is the case with fuel-cell vehicles and electric vehicles, the process may take even longer. For aircraft the time lags are longer than for passenger cars. The total time from start of development of a new aircraft until the last in that series is retired is 40-65 years (IPCC, 1999). Revolutionary technology such as the flying wing or hydrogen aircraft will take even longer, since more basic research has to be done (Society of British Aerospace Companies, 2001). On the other hand, some behavioural changes may be comparatively swift, although the inertia in habits should not be underestimated. When congestion charges were introduced in Stockholm, car traffic into central parts of the city decreased by more than 20% almost immediately.

These substantial time lags have two major implications. First, they necessitate a long time perspective when analysing how climate targets might be achieved. Even the 40-50-year perspective that was used in Papers II and III might be on the optimistic side. Second, they mean that spatial structures and transport systems in 2050 will be shaped to a great extent by present policy decisions.

1.2 Aim and scope

The core research question in this thesis is how future transport systems can be made consistent with long-term climate targets. There are two overarching aims. The first is to provide scientific decision support for current transport policy-making, in particular with regard to structures with a high inertia, e.g. urban structure, roads, railways, fuel production plants and to some extent vehicle fleets. Critical choices are identified and analysed from a systems perspective. One key step entails making a technical assessment of future vehicle technologies and low carbon fuels (bottom-up) in order to draw conclusions on the combinations of transport volumes by different modes that could be consistent with postulated climate targets. Following that step, a limited set of internally consistent future transport systems is outlined with regard to organisation of activities in space and time, urban structure and localisation of destinations, use of IT to replace travel, public transport systems, etc. A key contribution of the thesis is demonstrating how these elements interact in a consistent and plausible way on a systems level, both quantitatively and qualitatively. An important issue is also how the outlined transport futures fit to external elements such as energy supply, global economic development, inevitable climate change and working hours. A

specific policy objective is to analyse the kinds of transport infrastructure that should be built if climate targets are to be met, and also the kinds of transport infrastructure that should *not* be built, recognising the fact that new infrastructure most often generates new travel or freight transport (SACTRA, 1994; ECMT, 1996; Transek, 2000). Within the transport system, special emphasis is placed on international aviation, since it has often been disregarded in national transport futures studies, and since the emissions from this segment are increasing rapidly.

The second overarching aim is to widen the perception of possible transport futures consistent with meeting climate targets, and to form a basis for a wider discussion in society on this topic. To accomplish this we have attempted to outline and present images of the future in which for instance urban structure, cycling and public transport networks, vehicle technologies, travel and consumption patterns, time regimes, etc., are integrated in internally consistent images of the future that achieve the climate targets set. These images, may, if considered attractive, increase public acceptance for necessary policy changes, e.g. pricing measures. One part of this aim comprises the internal work of outlining vivid and consistent images of future transport. The other part consists of spreading the results obtained to the outside world by means of seminars, conferences, popular articles, etc.

There were also more specific aims for each paper, which are described below.

Paper I: In this paper a backcasting approach was combined with external elements regarding the degree of co-operation at local, regional, EU and global levels. The aim of the paper was to construct images of future transport in EU-15 for 2020, that conformed to the principles of sustainable mobility. Environmental, regional development and efficiency targets were set at the EU level. Two strategic elements were elaborated on in the Images; (1) Improved vehicle technology and alternative fuels (2) decoupling transport growth from economic growth.

Paper II: This paper focuses on international aviation, which is a particularly problematic part of transport with regard to climate mitigation. The overall aim was to explore global aviation scenarios consistent with keeping global warming below two degrees, in order to indicate the magnitude of necessary changes to present trends. The approach used was backcasting. A more specific aim was to estimate the role that aircraft designed for lower speeds could play in such scenarios.

Paper III: In this paper images of future Swedish transport in 2050 consistent with long-term climate targets were outlined. Here as well, a backcasting approach was used. One aim was to give advice on present policy decisions, in particular with regard to structures with a high inertia, e.g. transport infrastructure and the built environment. Another aim was to provide a basis for public discussions on sustainable transport. An important element in this paper was to include international transport and thus use a system delimitation that would not arbitrarily (due to traditional statistics) exclude important transport segments. This kind of study had not previously been carried out for Sweden. It was partly based on Steen et al. (1997) and Åkerman et al. (2000).

Paper IV: The aim of this paper was to map the greenhouse gas emissions caused by international travel by Swedish residents in more detail than had previously been done (Paper III used less detailed estimates based on an older travel survey). It was shown that greenhouse gas emissions from international travel by Swedish residents amount to 12% of total Swedish emissions. These emissions are not accounted for in the official Swedish statistics or in the Kyoto Agreement.

Paper V: Since emissions from air travel are increasing rapidly despite technological improvements to aircraft and more efficient air traffic organisation, other mitigation options need to be explored. The aim of this paper was to analyse the potential climate benefit of building new high-speed rail tracks in regions similar to southern Sweden. A more specific objective of the study was to estimate the total direct and indirect changes in greenhouse gas emissions that would result if the proposed high-speed rail track called Europabanan were to be built. A rare approach used in this study was that it included not only direct emission changes associated with changed transport volumes and emission changes associated with construction of the new railway, but also other indirect emission changes, e.g. emissions associated with a reduced need for building and maintaining roads and airports, and for manufacturing cars.

The scope of this thesis is transport systems, with particular focus on international aviation. The more specific system delimitations used are discussed in section 2.1. The impact categories studied are mainly emissions of greenhouse gases and energy use. In Paper I, however, regional development targets and efficiency targets are treated explicitly. In building the image of the future in Paper III, other societal targets are also considered in an iterative way (see section 6.3). Energy use for fuel production is included in Paper III. In Paper V the emissions associated with production of fuels, manufacturing and maintenance of vehicles as well as construction, maintenance and operation of infrastructure are included.

Since transport is interlinked with most activities in society, and since meeting climate targets seem to require simultaneous changes to, e.g. technology, urban planning and behavioural patterns, the approach taken in this thesis is interdisciplinary.

Papers I-V of this thesis were written over a 10-year period. As mentioned, climate science has developed considerably in that period, and indicated that the climate system is more sensitive to greenhouse gas emissions than was assumed around the year 2000 (The Copenhagen Diagnosis, 2009). This means that the emissions cuts need to be greater in order to stabilise greenhouse gases at a level where the most detrimental effects of climate change can *probably* be avoided. For instance the target derived for greenhouse gas emissions from fossil fuels (all sectors) was 1.5 tons per capita in Paper III. In a later backcasting study comprising the Swedish energy and transport system (Åkerman et al., 2007), the corresponding target was 0.9 tons per capita.

The implication of this change is that the targets for greenhouse gas emissions in Papers I-III are somewhat less demanding than is now considered necessary. This means that the changes outlined in the images for 2050 in this thesis may be considered as the low end of

what needs to be achieved. That is, transport volumes and/or emissions per transport volume need to be somewhat lower than stated in Papers I-V of this thesis. This means that changing direction is even more urgent today and that the consequences, if no change of direction is made, will be worse than previously imagined.

1.3 Scientific context

Papers I-III constitute backcasting studies exploring how a transport system could be transformed in order to achieve (primarily) long-term climate targets, e.g. limiting global warming to two degrees. Paper I is based on research carried out within the EU 4th Framework Strategic Research Programme between 1996 and 1998 (Banister et al, 2000). Paper III is partly based on Steen et al. (1997) and Åkerman et al. (2000). Steen et al. (1997) outlined five Images of future Swedish transport in 2040, including international transport induced by Swedish residents. Two of these images achieved a 100% reduction in carbon dioxide, while the other three were consistent with a 80% reduction in overall Swedish emissions of carbon dioxide.

The following short review only covers normative (target-orientated) futures studies with the aim of exploring how transport could achieve demanding long-term climate targets (>approx. 25-year time horizon). These kind of studies were still quite rare in the 1990s. Notable exceptions were Naturvårdsverket (1996), Steen et al. (1997), Nijkamp et al. (1997) and Nijkamp et al. (1998) but none of these studies had the same features as Paper III (and partly Paper I) of this thesis. For instance, Naturvårdsverket (1996) used much less demanding targets for greenhouse gases and the time horizon was only 25 years. International transport was also excluded from that study.

In the 2000s, with the increased focus on climate change, normative futures studies became more frequent. Examples are OECD (2000), Rienstra et al. (2000), Åkerman et al. (2000), Banister et al. (2000), Topp (2002), Schade and Schade (2005), Robèrt and Jonsson (2006), Hickman and Banister (2007), TRANSvisions (2009) and Yang et al. (2009). Some of these studies are briefly discussed below.

Rienstra et al. (2000) outline four scenarios for European passenger transport in 2030.¹ One scenario is called Expected and might be considered a baseline scenario. The other three scenarios, which include climate policies, reach a carbon dioxide (CO₂) reduction of 81-94% between 1989 and 2030. However, behind these impressive reductions lie rather optimistic (if not unrealistic) assumptions regarding vehicle efficiency and the use of low carbon fuels. For instance, CO₂ emissions per kWh of fuel are reduced by more than 70% in these three scenarios. Furthermore, it is unclear to what extent international aviation is included.

The OECD project EST (OECD, 2000) explicitly used a backcasting approach. It featured the target that emissions of CO₂ should be cut by 80% between 1990 and 2030. Teams from nine countries carried out case studies for six different regions. Each team decided independently

¹ The figures for seventeen Western European countries are added to achieve the European average.

the emissions reductions that should be achieved by improvements in technology and how much from reductions in transport activity. This resulted in rather different assumptions. For instance car travel increased in Sweden, while it was reduced by more than 50% in Germany. A conclusion from this study was that vehicle technology and low carbon fuels contributed to between 40 and 50% of the total reduction in CO₂ emissions. The remaining reductions were achieved by transport avoidance, modal shift and increased occupancy/load factor.

In the VIBAT (Visioning and Backcasting for UK Transport Policy) project (Hickman and Banister, 2007), the target set was to reduce transport CO₂ emissions by 60% between 1990 and 2030. The approach used was rather similar to that adopted in Paper I (where Banister was lead author) and Paper III of this thesis. Two images of the future were outlined; *New market economy* and *Smart social policies*. The former focuses on technological improvements, while in the latter behavioural changes play a central role. The study devoted a comparatively large amount of effort to analysing policy paths. Eleven policy packages were designed and analysed with regard to their ability to cut emissions. The overall conclusion of the study was that a 60% reduction can be achieved by 2030 using a combination of strong behavioural change and strong technological innovation.

There are also futures studies focusing on climate targets that treat the entire energy system (supply and demand), of which transport is one part. Notable examples of energy futures studies are Lönnroth et al. (1979), Robinson (1996), Azar and Lindgren (2000), IPCC (2000), IEA (2003), Azar et al. (2003), IEA (2006), Åkerman et al. (2007), Nordic Council of Ministers (2007) and Höjer et al. (2011).

Azar and Lindgren (2000) outlined three scenarios for the Swedish energy system that achieved 50-75% reductions in carbon dioxide emissions by 2050. Regarding the transport sector, those authors relied heavily on the work by Steen et al. (1997).

IEA (2003) includes a global normative scenario to 2050 called *The SD Vision Scenario*, together with three exploratory scenarios. Three targets are used, relating to: (1) climate change mitigation, (2) energy security and diversification, and (3) energy access. The selected target for climate change did not state an emissions target but did instead call for 'a 60% share of 'zero carbon' sources in total world primary energy supply, by the year 2050'. Consequently the emphasis in the analysis is on energy supply rather than end-use in transport and other sectors.

In Paper IV an estimate is made of emissions caused by international travel by Swedish residents. This kind of study had not been performed in Sweden previously, although international travel by Swedes has been estimated according to older travel surveys (Frändberg, 1998; Frändberg and Vilhelmson, 2002). Travel surveys including international travel have been performed in several countries, for instance in the UK (Brand and Boardman, 2008), in Denmark (Danmarks Transportråd, 2001) and in Norway (Hoyer, 2000). Studies also estimating greenhouse gas emissions from that travel segment are rarer, an example being Brand and Boardman (2008).

Assessments covering building, maintenance and operation of railway infrastructure have been carried out by e.g. Uppenberg et al. (2003), Rozycki et al. (2003), Svensson and Eklund (2007), Schlaupitz (2008), Federici et al. (2009), Milford and Allwood (2010) and Botniabanan AB (2010). In Paper V a wider systems perspective is taken, that to our knowledge is novel. It includes emission changes due to modal shifts and newly generated rail travel, emission changes due to building, maintenance and operation of the new railway infrastructure, but in addition, an attempt has been made to estimate emission changes in the whole life cycle of the competing modes. This means that emission changes are estimated for; the increased need for manufacturing of rail vehicles, the decreased need for manufacturing trucks and cars and the reduced need for building and maintaining roads and airports.

1.4 Structure of this cover essay

This cover essay mainly takes the form of a synthesis, a format chosen in order to make it more readable as a monograph. Summaries of Papers I-V are contained in the abstracts of the individual papers. However, a condensed version of the aims, methods and key results of the individual papers is given in this cover essay, integrated in the thematic chapters. In Chapter 2 the approaches and methodologies used in this thesis/Papers I-V are presented and discussed. Chapters 3, 4, 6 and 7 are similar to the steps in a backcasting study, with Chapter 5 being a special focus area; *Aviation and climate change*. Chapter 6 outlines features of future transport systems meeting the climate targets and also contains a synthesis image for transport in 2050. Chapter 7 discusses appropriate policies in order to change direction towards transport systems consistent with limiting global warming to two degrees. Finally, Chapter 8 reconnects the findings to the aims of the thesis, presents some conclusions on the role of this thesis and identifies some topics that warrant future research efforts.

2. Methodological approaches

2.1 A systems perspective - Aiming for more appropriate system delimitations

A sub-aim of this thesis was to develop more appropriate system delimitations for analysing how to reduce the climate impact from transport. Most often the problem is that the system selected is too narrow, which means that the system may seem to cause less problems (e.g. emissions of greenhouse gases) than is actually the case. It also means that solutions proposed for this system may actually not decrease emissions as much as anticipated (if at all), if a broader more appropriate system delimitation is considered.

Due to the rapid globalisation of economic activities and tourism, the geographical system delimitation of a transport system is becoming increasingly crucial for the validity of policy conclusions. The proportion of passenger and freight transport that crosses national borders is continually increasing. In the Kyoto Protocol on greenhouse gas reductions, only domestic transport is included. This means that the majority of emissions from air and sea transport are not included. A political reason for this is that there is no unambiguous way of allocating these emissions to specific countries. However, since emissions from international air and sea transport are increasing faster than emissions from ground transport, this hampers the effect of the Protocol.

In Paper III we attempted to include emissions from international air and sea transport in the system analysed. The guiding principle was to use a consumption perspective where all transport generated by activities/consumption by Swedish residents was included. For passenger transport we included all travel made by Swedes according to the Swedish National Travel Survey 1999-2001, wherever it took place. For freight transport limited data availability called for some simplifications. All domestic freight transport was included. In addition, transport of import products by sea and air was included. Departures from the principle (due to limited data availability) were thus that transport in Sweden of export products was included and that domestic transport in other countries of products aimed for the Swedish market was excluded from the system considered. Although this delimitation is a mix of principles, it satisfies the basic requirement that, if generalised, the sum of emissions from all sub-systems equals the sum of total global emissions, in contrast to the Kyoto Protocol.

Another important system delimitation to be made is to decide whether indirect energy use and emissions should be included in the analysis, i.e. whether a life cycle perspective should be taken (Baumann and Tillman, 2004; Finnveden et al., 2009). Indirect effects of transport in this sense are those associated with manufacturing and maintenance of vehicles, construction, maintenance and operation of infrastructure, as well as production and transport of fuels. It has recently been pointed out that these indirect effects may be substantial and account for 20-50% of total energy use for transport (Jonsson, 2007; Chester and Horvath, 2009). In Paper III the only indirect effect included explicitly was production and distribution of fuels. In Paper V all indirect effects that are predicted to occur as a consequence of building the high-speed tracks Europabanan were considered. This study applied a simplified quantitative life cycle assessment (LCA), which was consequential in character.

A system delimitation that is commonly applied is to disregard other greenhouse gases than CO₂. For aviation this leads to an underestimation of climate impact by about 50%, according to current best knowledge (Lee et al., 2009), and imply that aviation appears less important than it is.

To sum up, three system expansions are explored in this thesis:

- Geographical, i.e. including international transport generated by a certain population.
- Life cycle, i.e. including vehicle manufacturing and maintenance, infrastructure construction, operation and maintenance and fuel production.
- Emissions, i.e. including emissions of NO_x and H₂O from aviation, which also contribute to climate change.

Figure 2.1 shows the influence of different system delimitations on the resulting greenhouse gas emissions.

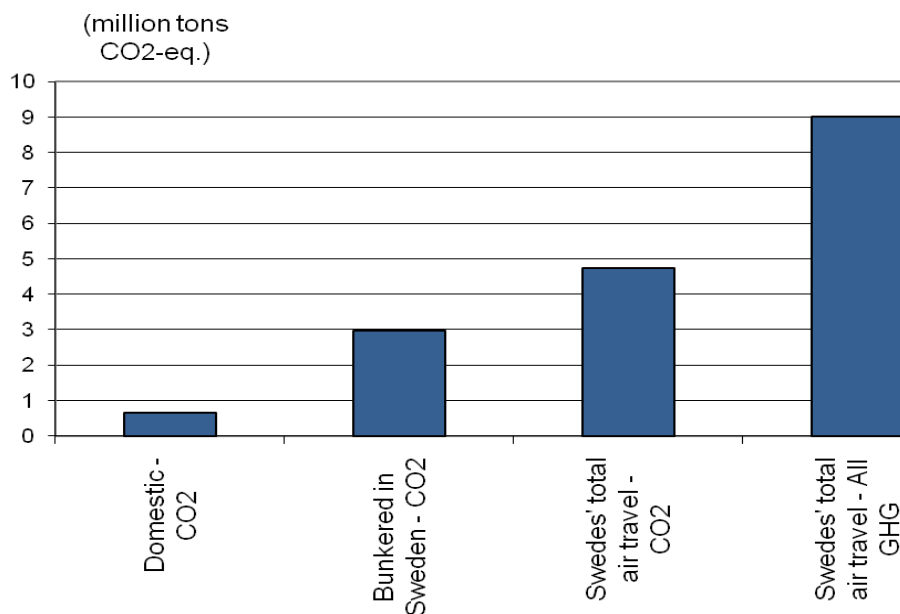


Figure 2.1: Effect of different system delimitations on the level of greenhouse gas emissions from ‘Swedish’ air travel in 2006. Sources: Own calculations based on Paper IV and Energimyndigheten (2009).

The first bar shows CO₂-emissions alone for domestic air travel in Sweden. The second bar shows CO₂-emissions from all fuel bunkered at Swedish airports. The third bar shows CO₂-emissions from all air travel by Swedes, domestic and international. And finally, the fourth bar shows all greenhouse emissions caused by air travel by Swedes. Emissions related to fuel production, aircraft and airports were not included in any of the delimitations in the figure. Even if these are comparatively small for aviation, their inclusion would still increase total emissions by 10-20%.

2.2 Futures studies

Futures studies can be divided into three main types corresponding to three fundamental questions: *What will happen?*, *What can happen?* and *How can a specific target be met?*. Figure 2.2 shows a typology developed by Börjeson et al. (2006), which is based on these questions. A similar typology has been proposed by for example Amara (1981).

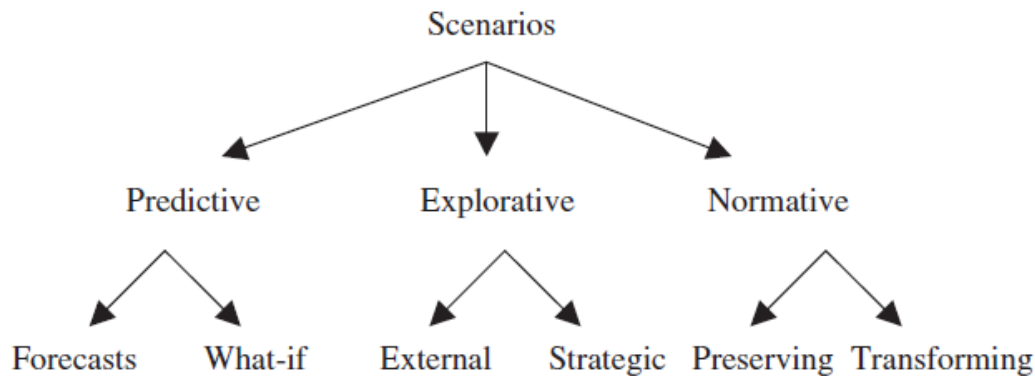


Figure 2.2: Scenario typology. Source: Börjeson et al. (2006).

Predictive studies provide answers to the question *What will happen?*. Forecasts try to identify the most likely outcome in a specific area. The aim is to give an actor (or actors) decision support in order to find a favourable strategy. What-if scenarios predict what will most likely happen given the occurrence of a specific event, external or internal. Examples of forecasts are weather forecasts or predictions of traffic volume development in a city. An example of a what-if scenario is a study of the consequences of implementing congestion charging in Stockholm.

However, the future is associated with a considerable amount of uncertainty. Therefore in many situations it is important to consider that several rather different developments are possible regarding the domain outside the control of the actor in question. This is when the situation is characterised by structural uncertainty (Dreborg, 2004). In such cases explorative scenarios may be appropriate. Explorative scenarios deal with *What can happen?*, i.e. external developments mainly outside the control of the actor in question. However, there is no clear distinction between internal and external factors, as there is often an area in which the actor (planning entity) has some influence but interacts with other influential actors (Van der Heijden, 1996). Factors that might be considered external to national transport policy (at least for smaller countries) include e.g. global energy supply, the price of oil, global economic development and vehicle technology development. In strategic scenarios some action/policy is added to the external scenarios. The external scenarios developed by Shell and RAND in the 1960s and 1970s were among the first of this type (Van der Heijden, 1996).

According to Dreborg (2004), important aspects in building external scenarios are that:

1. All scenarios must be relevant to the planning object.
2. The scenarios should be challenging.
3. The scenarios should be plausible.

The aim of building external scenarios is to identify the types of external developments that a successful policy/strategy must be able to cope with. Therefore the focus is not on the most likely development, contrary to predictive studies, but rather on developments that are particularly challenging. This means that 'worst case scenarios' are interesting. A house-owner who used a predictive study as a guide would probably not buy house insurance, as by far the most likely outcome is that the house will not suffer any other major damage. Still almost all house-owners do buy insurance. Correspondingly, the worst potential outcomes of climate change - runaway global warming that may trigger famines, major migration flows and possibly wars - are well worth considering, even if they are unlikely to materialise. This is the reason why debating the exact probability of severe consequences of global warming is of limited value.

The third category of futures studies answers the question *How can a specific target be met?* Preserving scenarios show how a specific target can be achieved by marginal changes to current trends and without questioning prevailing world-views. Transforming scenarios, on the other hand, are more appropriate if achievement of the targets set seems to require major changes to current trends and societal structures.² Backcasting is a typical transforming scenario approach and is discussed more thoroughly in section 2.3.

Combined studies

In practice, the three types of futures studies are sometimes combined. Most backcasting studies include some predictive/forecasting elements. For instance the demographic development is predicted in Papers I-III and the global supply of energy is predicted in Paper III. A kind of forecasting may also be used when investigating whether marginal changes in current trends are sufficient to reach the targets, as proposed by Höjer and Mattsson (2000). In Paper I the backcasting approach is combined with external elements. These concern the attitude towards co-operation at local, EU and global level, which was assumed to be out of the control of the users of the results, mainly EU transport officials. The backcasting element in Paper I mainly concerns the spatial and organisational structure of society, transport systems (infrastructure and vehicles) and travel and freight transport patterns. In a study closely related to this thesis (Åkerman et al., 2007), different developments in global energy supply were used as external elements.

² An alternative, and not infrequent, strategy is to adjust the targets so that a preserving scenario becomes suitable.

2.3 Backcasting

The main approach used in this thesis is backcasting (in Papers I-III). In accordance with Dreborg (1996), backcasting is referred to here as an approach rather than a methodology. This section starts with an attempt to identify some common features in different types of backcasting approaches. This is followed by a brief history of backcasting. Finally, the specific approach used in Papers I-III of this thesis is described.

Although there are different branches on the backcasting tree, there are some features that seem to be common to most, if not all, backcasting variants. A backcasting study answers the question *How can a specific target be met?* (Börjeson et al., 2006). It is concerned with a major (often societal) problem, the solutions to which require major changes to structures in society. The present climate change initiated by human activities, which seems to be one of the greatest challenges encountered by mankind, is a case in point. Often some dominant trends are part of the problem and need to be broken. Characteristic for a backcasting study is that images of the future³ are explored first and only in a subsequent stage is the focus shifted to the path between the images of the future and the present situation. However, the way in which those paths are analysed and the relative emphasis placed on paths and images of the future differ between studies.

A characteristic feature of backcasting – in the phase where images of the future are outlined – is the attempt to broaden thinking of possible futures beyond dominating world-views. It is to a great extent directed towards finding *trend-breaks* and possibly *alternative paradigms* that might be necessary in order to achieve the targets set. It may sometimes be that the very perceptions of what is possible may constitute major obstacles to real change (Dreborg, 1996).

The time horizon of a backcasting study depends on the structures in society that need to be changed in order to achieve the targets set and the inertia/lifetime of those structures. Since backcasting is mostly applied to major societal problems such as the unsustainability of energy and transport systems, it is common that physical structures with a high inertia need to be transformed. Therefore a rather long time horizon is often called for, typically 25-50 years or even longer according to Robinson (1990).⁴

In the mid seventies Amory Lovins proposed a new planning methodology as an alternative to the prevailing forecasts of ever increasing energy demand (Lovins, 1976, 1977). He called this method a “backwards-looking analysis”. This method was then renamed “energy backcasting” and further developed by John Robinson (1982, 1990).

Energy futures were the main subject of backcasting studies in the early years, e.g. Lovins (1976), Lönnroth et al. (1979), Robinson (1982) and Goldemberg et al. (1985). The attention

³ Robinson (1990) instead uses the term “scenario end-states”.

⁴ In the same paper he also mentions 20-100 years as suitable time perspectives.

paid to the concept sustainable development, following the Brundtland Report (WCED, 1987), has increased the interest in performing backcasting studies.

Several studies exploring the feasibility of reconciling transport with sustainable development have since been carried out, e.g. Naturvårdsverket (1996), Steen et al. (1997); Nijkamp et al. (1998), Höjer (1998), OECD (2000), Rienstra et al. (2000), Åkerman et al. (2000), Banister et al. (2000), Topp (2002), Paper II, Schade and Schade (2005), Paper III, Robèrt and Jonsson (2006), Hickman and Banister (2007) and Yang et al. (2009). Besides the early work of Amory Lovins (1976 and 1977) and John Robinson (1982, 1988 and 1990), methodological development have been carried out by e.g. Dreborg (1996 and 2004), Höjer and Mattsson (2000) and Quist (2006 and 2007).

Dreborg (2004) distinguishes between two types of processes that might be used for developing explorative scenarios and backcasting scenarios, the *think-tank model* and the *participative model*. In the former the work is carried out by a project team, while the latter may also involve citizens and other stakeholders. The participative model has been applied especially in Canada (e.g. Robinson, 1996) and in the Netherlands (e.g. Vergragt and Jansen, 1993; Weaver et al., 2000; Green and Vergragt, 2002), but also in Sweden (Holmberg, 1998; Dreborg and Åkerman, 2004). The backcasting studies in Papers I-III are of the think-tank model. However, in other studies made by the author, participative models with stakeholder reference groups have been used (Åkerman and Dreborg, 2004; Åkerman et al., 2007). In the former, politicians and civil servants from most municipalities in the Gothenburg region participated, while in the latter a reference group representing industry, national authorities and academics was used.

After this review and discussion of backcasting approaches, there follows a description of the variant of backcasting used in Papers II and III and to some extent in Paper I. This branch of backcasting is similar to most studies made in Sweden, and much inspired by the early work of Robinson, although there are important differences. The aims of a backcasting study as used in Papers I-III are to:

- (1) Provide scientific support for present policy-making on how to solve a major societal problem, e.g. how the transport system can be transformed to be consistent with long-term climate targets. The main focus is on decisions regarding structures with a high inertia, e.g. urban structures, roads, railways, fuel production plants and to some extent vehicle fleets.
- (2) Widen the perception of possible futures consistent with meeting (climate) targets and provide a basis for a wider discussion in society. The target group in this case is rather wide and may include policy-makers, civil servants, academics, industry, NGOs and interested citizens. A challenge is to communicate the results successfully to this heterogeneous target group. The results in this thesis have been presented to policy-makers at national and EU level and have received a fair amount of interest, although concrete impacts are hard to verify.

An argument for using the long time-perspective that backcasting enables is that the preference order of policy measures is dependent on how demanding the long-term (climate) targets are. This is due to lock-in effects, among other things. An example relates to investments in railways. If only moderate volumes of travel and freight are to be shifted to rail, the best strategy might be to improve existing lines with additional sidings, etc. However, if a much higher shift to rail is envisaged at the point of decision, new lines need to be built anyway, and in this case improving existing lines (apart from regular maintenance) first would be a waste of resources.⁵ The development of urban structures provides another example. It might be possible to achieve modest climate targets by a combination of somewhat sprawled urban structures in combination with much improved vehicle technology and increased use of low carbon fuels. If, however, it is then discovered by novel climate research that emissions of greenhouse gases need to be reduced more than previously anticipated, the urban structure, which takes decades to change, constitutes a detrimental lock-in.

Since backcasting studies usually address major societal problems, an interdisciplinary approach is preferable. Figure 2.3 shows the different steps in the backcasting approach as it is used in Papers I-III of this thesis. These are explained more thoroughly in the following text.

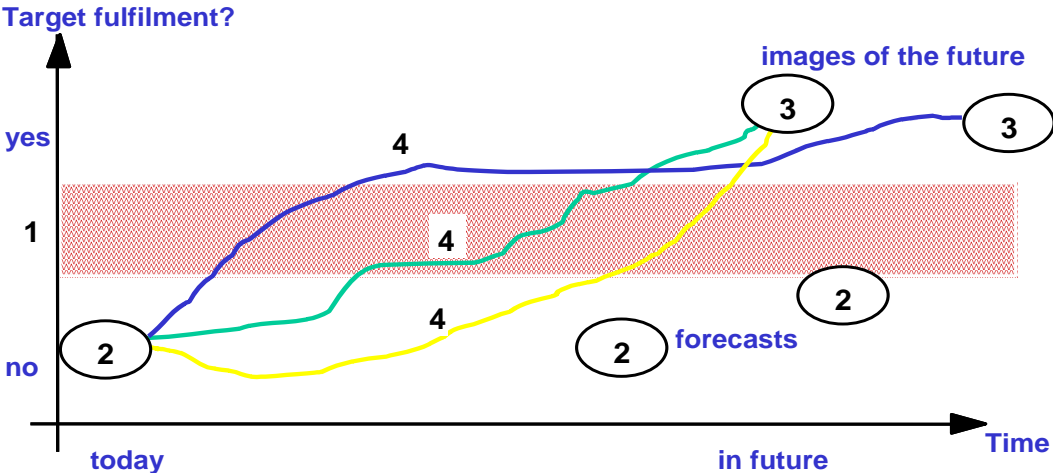


Figure 2.3: The four steps in the backcasting approach applied in this thesis. The steps are explained in the text below. Source: Developed from Höjer and Mattsson (2000) and Steen and Åkerman (1994).

Step 1. Identification of problem and target setting

In this step the problem is formulated and targets are set. The system to be studied is delimited regarding, e.g. geographical and sectoral scope. If a subsystem (e.g. the transport system) of the system relevant for the problem is to be studied, some subdivision of the overall target needs to be made.

⁵ The emissions and energy use associated with additional construction works also have to be accounted for. A key issue is how much transport is sufficient, given economic and social objectives.

Step 2. Analysis of whether targets could be reached by marginal changes to present trends

If it is found in this step that the problem might be solved by moderate changes in existing trends, e.g. technical improvements under development, the problem considered turns out not to be a major problem needing a shift of paradigm. In this case the subsequent steps may be left out. In this step forecasting methods are often used. If it seems that the target levels could be reached by marginal changes to existing trends, there is no need to proceed with steps 3 and 4. In practice, the result of this step is often known, or strongly suspected, when the study is started.

Step 3. Outlining of images of the future achieving the targets

The selection of images of the future is probably the most critical step in the whole backcasting process, at least in the school developed at KTH and FOI. The images must all achieve the targets while being as attractive as possible in other respects. However, attractiveness is a subjective matter and that is one reason for outlining images with rather different features. In practice the generation of images of the future is performed in an iterative process. Structured brainstorming is often used to create draft images. These might be further elaborated on and then presented to a reference group containing stakeholders. The comments collected are then used to improve the images. Another reason for the iterative process is that fulfilment of other societal targets than climate change (relating to environment, health, economy and social matters) and general attractiveness need to be considered. This might, if possible, require an update of the images in order to better take these other criteria in account, while still achieving the main targets. Due to the focus on trend-breaks and structurally different futures – which is unknown territory for many participants in public discussions – it is particularly important that the assumptions behind the images (regarding technology, transport volumes, etc.) are transparent, so that they can be discussed and criticised. ‘Black boxes’ should be avoided. It is important to present the images in a way that enables public discussion, since this may be regarded as one of the aims of backcasting studies. As with explorative scenarios a key aim, and challenge, is to outline futures that are internally coherent and plausible.

Step 4. Strategic decisions and paths to the images

This step involves analysis of how developments at present could be turned in a direction indicated by the images of the future. The need for trend-breaks and ways in which these may be initiated are analysed. The need for combining different kinds of policy measures is discussed. Of key interest are strategic decisions regarding long-lived structures with a high inertia, in this thesis especially transport infrastructure, urban structure, buildings and fuel production systems, but also vehicle fleets. The inertia in these structures means that their characteristics in 2050 are shaped by present decisions to a great extent. Furthermore, these structures are partly predetermined by the images of the future, so the degree of freedom regarding different paths from the present to the images is limited.

Some interpretations of backcasting include outlining a detailed path from the present to the images of a future 25-50 years away. I do not take this view as the future will always bring surprises and, where possible, a flexible strategy is to be preferred. However, as mentioned, many important decisions concern structures that only change slowly. In these cases flexibility is not an option, and instead these structures need to be robust in order to cope with rather different future developments that are external to the system under consideration. For transport and climate change this means that urban structures and transport infrastructure should be able to achieve what are currently judged to be sufficient climate targets, but also to be able to achieve the possibly more demanding targets derived from future improved knowledge of the climate system. Another aspect of the robustness is that the infrastructure should be able to resist such consequences of climate change that are inevitable, e.g. sea level rise and an increasing frequency and severity of storms, etc. However, this is mainly outside the scope of this thesis.

Backcasting as interpreted in this thesis contains both qualitative and quantitative elements. In many regards it is difficult to make quantifications of the distant future, even in backcasting studies that assume policy intervention in order to reach the targets set. At the same time there is an urgent need for at least a quantitative skeleton to connect to, when discussing such quantitative matters as limiting greenhouse gas emissions. There is otherwise a risk that e.g. actors that gain from preserving current trends and paradigms will refer to 'technical fixes' in a vague and unsupported manner. In the backcasting approach in this thesis, an attempt is made to strike a balance by using a transparent spreadsheet model where assumptions on fuels, specific vehicle emissions and transport volumes are clearly specified. The qualitative description of the images of the future and paths to these should reflect the coherent trend-breaking futures and connect to the quantifications.

Backcasting is an overarching approach which may encompass several different more specific methods or tools. In Papers I-III a bottom-up approach was used for technology assessment, including desk-top research, spreadsheet modelling and expert interviews. All attempts to assess future technology are associated with considerable uncertainties. An advantage with the bottom-up approach applied in this thesis is that it can explicitly consider revolutionary changes in technology. Furthermore, resource constraints such as competition for productive land can be accounted for.

3. Climate targets and the uncertain future

3.1 Limiting climate change to tolerable levels – the two-degree target

According to recent climate research, developed countries need to reduce greenhouse gas emissions per capita by 80-95% between 2000 and 2050 in order to limit global warming to two degrees. In addition 'To stabilize climate, a decarbonised global society - with near zero emissions of CO₂ and other long-lived greenhouse gases - needs to be reached well within this century.' (The Copenhagen Diagnosis, 2009). There is no abrupt change happening at exactly two degrees of global warming, but the projections are that the severe consequences will increase more rapidly above two degrees and that the risk of uncontrollable feedback loops will also increase. Given the potentially devastating consequences of a worst-case scenario, a risk averse strategy according to the precautionary principle is appropriate (Hansson and Johannesson , 1997). The Copenhagen Diagnosis (2009) also emphasise that emissions need to start decreasing rather soon. Figure 3.1 shows three alternative emission trajectories consistent with the two-degree target. As can be seen, it is the accumulated emissions that matter, and a slow start will call for very large (not to say unrealistic) annual reductions in the end of the period. Furthermore, even if such a trajectory could be realised the risk would be greater, since positive feedback loops may be catalysed if emissions do not start to decrease very soon. It is thus not evident what time perspective is appropriate: 100 years as is most often used, or a shorter period in order to avoid initiating natural positive feedback loops and thus possibly crossing dangerous thresholds.

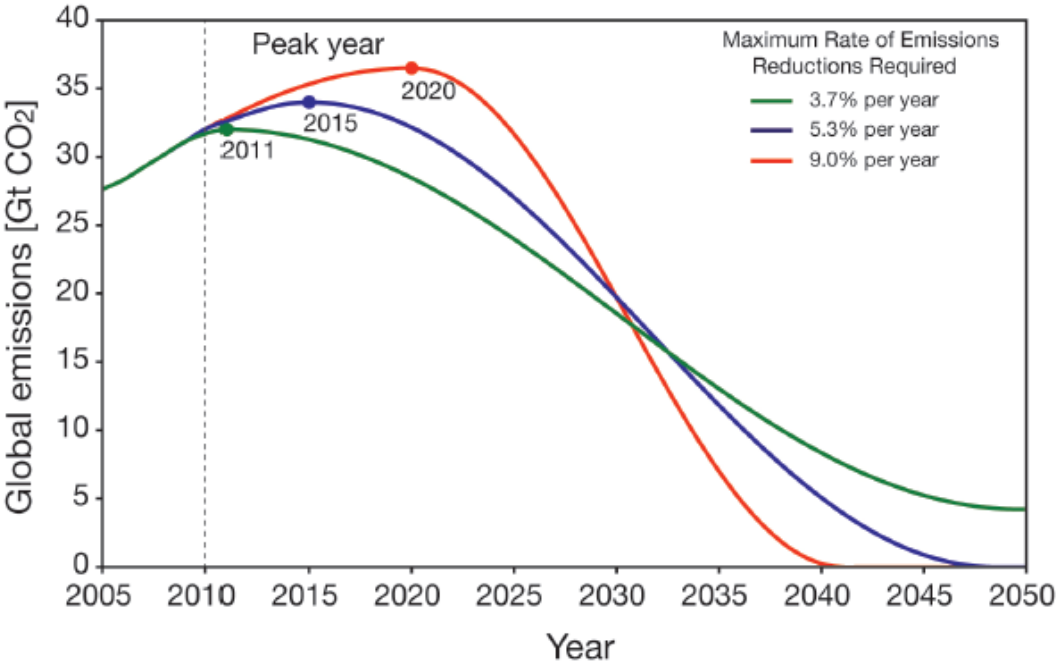


Figure 3.1: Three emission trajectories that entail a 67% probability of limiting global warming to two degrees. Source: WBGU - German Advisory Council on Climate Change (2009).

In addition to the time lags in the policy formation process and the transport system, including the built environment, there are substantial time lags within the earth/climate system (Hansson and Johannesson , 1997).

3.2 How to select target level for a sub-system

It is not evident how to deduce from an overall target the target of a sub-system such as the transport sector. In Paper III an unchanged proportion of energy use for transport is assumed. In Paper II two levels are used for global aviation, an unchanged proportion and a doubled proportion.

It is sometimes stated that specific targets should not be set for sectors such as transport, but that only an overarching target should be set. The economic argument is that flexible market mechanisms should be used as these will automatically allocate emissions reductions in the most effective way, which cannot be known beforehand. This may sometimes be a valid argument, at least when emissions reductions can occur rather quickly. However, this is not the case for transport, which in many aspects is characterised by significant inertia. It is not a wise strategy to base long-term investments in buildings and transport infrastructure on the current price of greenhouse gas emissions. Therefore, long-term futures studies (such as those in Papers II and III) may be an appropriate tool for supporting such strategic decisions. These may incorporate technical/economic assessments of future end-use technologies in all sectors, as well as assessments of low carbon energy supply. A key consideration in this context is that energy and emissions reduction potentials do not always follow linear patterns. Achieving small to moderate energy efficiency gains might be more cost-effective in the building sector, while more substantial changes might be easier in the transport sector due to the much faster renewal of vehicles compared with renewal of the building stock.

4. The role of vehicle technology and low carbon fuels – will this be sufficient to achieve climate targets?

4.1 Potential for improved vehicle technology

Assessments of the potential for vehicles with lower energy use were performed in particular in Papers II and III, with updates on long-distance transport in Papers IV and V. A report by Steen et al. (1997), on which Paper III is partly based, included a short review of radically new concepts. Among the concepts considered were electric trucks using a catenary system, airships, flying cars, Personal Rapid Transit and dual mode systems like the Danish RUF concept. It was concluded that none of these new vehicle concepts would be able to make a major contribution to a sustainable transport system, although some, like PRT and electric trucks, might constitute complements in specific niches. Therefore development of existing vehicle concepts will be the main technological path. This is especially the case when a 40-50 year perspective is considered, given the inertia in infrastructure and vehicle fleets. Perhaps the most radical change that we foresee is the anticipated (partial) electrification of road transport in the form of ‘conventional’ hybrids⁶, plug-in hybrids and all-electric cars.

Tables 4.1 and 4.2 from Paper III show the estimated potential for reduction of fleet average energy use by 2050. The energy use assumed for electric cars in 2050 is on the optimistic side given conditions for driving in Sweden, e.g. a substantial need for heating. As concluded in Paper II, slower aircraft with a cruising speed of 640-700 kph may achieve a 25% lower energy use of 0.25 kWh/passenger-km by 2050. The potential for cars not using electricity from the grid⁷ may be achieved by either a fuel-cell hybrid or an efficient diesel hybrid. Although fuel-cell cars may be the ultimate solution for long-distance driving, many substantial barriers need to be overcome.

⁶ Like Toyota Prius.

⁷ In the table somewhat incorrectly labelled “Car combustion mode”, since it also includes fuel-cell cars.

Table 4.1: Potential to reduce energy use per passenger-km. Occupancy and speed are assumed to be unaltered, except for an increase in occupancy from 70 to 74% for aviation. Source: Paper III

	kWh/passenger- km, 2000	Potential change by 2050	kWh/passenger- km, 2050
Car, combustion mode, 1.25 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

Table 4.2: Potential to reduce energy use per ton-km. Load factor and speed are assumed to be constant. For light trucks there are no statistical data available on goods carried, but total energy use and emissions of carbon dioxide are known. Source: Paper III

	kWh/ton-km, 2000	Potential change by 2050	kWh/ton-km, 2050
Lorry (<100 km)	0.70	- 40%	0.42
Lorry (>100 km)	0.25	- 30%	0.17
Light lorry (<3.5 tons)	-	- 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

4.2 Potential for low carbon fuels

The future global supply of bioenergy is dependent on many uncertain variables (Åkerman and Åhman, 2008). Biofuel production will strongly compete for land with food production and the preservation of ecosystems which deliver vital ecosystem services, e.g. food, water,

fibre, climate and disease regulation (Millennium Ecosystem Assessment, 2005). Furthermore, recent research indicates that carbon emissions from the soil when natural land is converted into farmland may offset a substantial part of the benefits of replacing fossil fuels by biofuels (Fargione et al., 2008; Searchinger et al., 2008). It is also the case that the climate benefit per unit biomass is greater if bioenergy replaces coal in electricity and heat production than if it is used to produce vehicle fuel (Åkerman and Åhman, 2008).

In Paper III the global potential of renewable energy was estimated to be 72 PWh by around 2050. This can be compared with the two energy supply scenarios provided by Åkerman et al. (2007), which included 62 and 107 PWh of renewables, respectively. The main difference concerned biofuels, which amounted to 25 PWh in the lower scenario and 80 PWh in the higher. Global bioenergy use in 2005 was about 14 PWh (IEA, 2006). The proportion of transport fuels derived from renewables was assumed to be 50% in the image of sustainable transport in 2050 in Paper III.

4.3 Conclusions

In Papers I-III the conclusion was that improved vehicle technology and increased supply of low carbon fuels are necessary, but are not sufficient on their own to achieve the long-term targets (see Figure 4.1). The growth rates of car, air and truck transport also have to be curbed. This is illustrated by Figure 4.1, which is taken from Paper III.

It can be seen from Figure 4.1 that although energy use per passenger-km and ton-km is approximately halved by 2050, the total energy requirement is about the same as in 2000, and consequently far from the target level. The reason is that transport volumes are forecast to double during this period. However, a combination of much improved technology and transport volumes similar to those in 2000 would nearly reach the target level, as illustrated by the third column in Figure 4.1. Moreover, it should be noted that in Paper III the energy target for 2050 corresponded to 1.5 ton CO₂ per capita, while recent research indicates that global emissions need decline to well below 1 ton CO₂ per capita by 2050 (The Copenhagen Diagnosis, 2009).

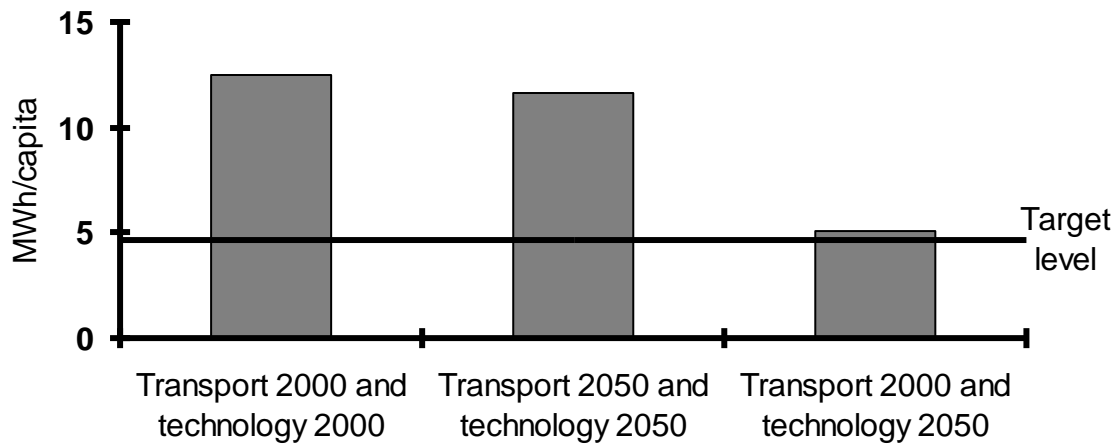


Figure 4.1: Energy use in the transport sector. The left-hand column indicates present-day (2000) energy use for Swedish transport. The middle column builds on a reference case for 2050 but with much improved technology. The right-hand column indicates a case with the transport volume of 2000 in combination with hypothetical realisation of the technology potential in Tables 4.1 and 4.2. The diagram also shows the assumed target level for sustainable energy use in the transport sector, 4.6 MWh/capita. Source: Paper III.

5. Aviation and climate change – A key challenge

5.1 Air travel and greenhouse gas emissions

Air travel has increased at a rapid pace both globally and for Swedish residents during recent decades. Between 1980 and 2007 the number of passengers departing from Swedish airports increased by a factor of four, as shown in Figure 5.1. Two temporary breaks in the long-term increase can be discerned. One was caused by the economic recession in the early 1990s and the other was a consequence of the terrorist attacks in the US on 9 September 2001. In 2006 total air travel by Swedish residents amounted to 34 billion passenger-km, or 3700 km per capita and year (Paper IV). This is nearly a quarter of total travel by Swedish residents in that year. Nearly 90% of the air travel consisted of international flights. The travel in 2006 can be compared with that in 1994, which amounted to 20.3 billion passenger-km (Frändberg, 1998). This means that average growth rate was 4.4% between 1994 and 2006 despite the significant downturn following 9 September 2001. In 1994, two-thirds of air travel was for leisure purposes and one-third was business travel (Frändberg, 1998). However, these relative proportions are rather uncertain, not least since business and leisure purposes may be combined on the same trip.

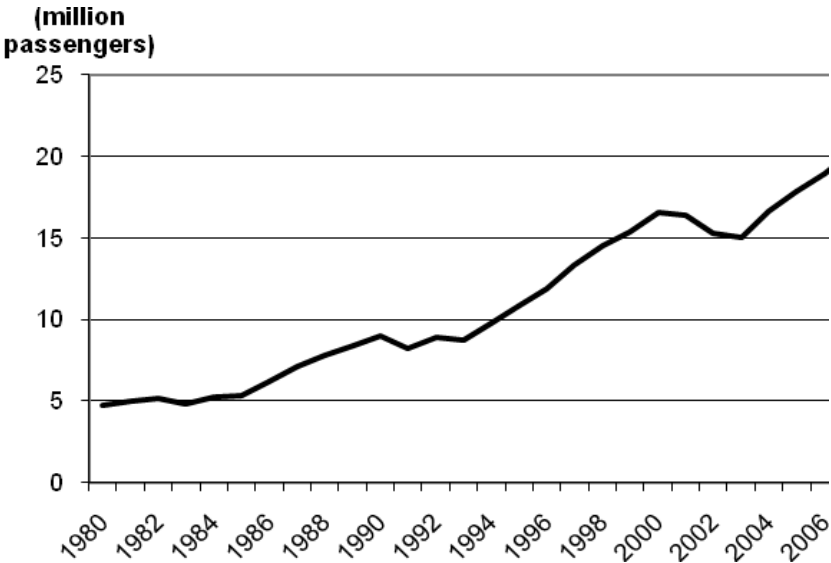


Figure 5.1: Departing and arriving passengers in international traffic at Swedish airports 1980-2007. Source: SIKA (2008).

Air fuel is also used for military purposes and for air freight. In 1992 military aircraft used between 13 and 18% of global air fuel, but that proportion is projected to diminish to 3% by 2050 (IPCC, 1999). It should be noted that this decrease may mask the increase in emissions from civil aviation. The respective emissions for passenger and freight within civil aviation are not evident, since a substantial (although uncertain) proportion of air freight is carried by passenger aircraft (Paper II). In 2005, total global passenger air travel amounted to 3990

billion passenger-km and total global air freight to 142 billion ton-km (SIKA 2008). If it is assumed that each passenger causes as much emissions as 160 kg of freight (Paper IV), passenger transport represents 82% of the emissions from civil aviation.

Table 5.1 shows the destinations that contributed most to air travel by Swedes in 2005 (Paper IV). Statistics on passengers departing from Swedish airports indicate that travel to Thailand doubled in only two years between 2005 and 2007. This means that Thailand today may well be the destination generating most travel by Swedes.

Table 5.1: The countries contributing most to international travel by Swedes in 2005. Except for travel to Finland, aviation is the totally dominant mode. Source: Paper IV.

International travel by Swedes by destination (Billion p-km)	
Spain	4.2
United States	2.4
Thailand	2.3
Greece	1.4
UK	1.2
Finland	1.1
Italy	0.9

Regarding the climate impact of aviation it is important to note that it is not only caused by emissions of carbon dioxide. At the altitudes where most of the emissions occur, 10-12 km, emissions of nitrogen oxides and water vapour also contribute to climate change. The level of these impacts is uncertain, but the best scientific understanding indicates that the total climate impact from aviation, measured as Global Warming Potential during 100 years (GWP-100), is 1.9-2.0 times the impact of carbon dioxide alone (Lee et al., 2009).

Aviation currently is responsible for 4-5% of global energy-related climate impact, if an uplift factor of 1.9 is used (Lee et al., 2009). For Sweden the proportion is higher. The emissions from domestic and international air travel by Swedish residents in 2006 amounted to 8.7 million tons of CO₂-equivalents, which is 12% of total Swedish emissions from all sectors of society (Åkerman et al., 2007; Paper IV). In comparison, all passenger cars in Sweden caused emissions of 12 million tons. Aviation thus already makes up a significant proportion of greenhouse gas emissions, especially in industrialised countries. What is even more serious, however, is the rapid growth rate. If no substantial changes to current policies are realised, a doubling of greenhouse gas emissions from aviation might occur within 25 years, despite the fact that aircraft are becoming ever more fuel-efficient. Such a development would imply that emissions from aviation alone will exceed the total emissions limit for all sectors in society before the year 2050 (Anderson et al., 2006).

As recognised by the above, scrutiny of system delimitation is particularly important in the case of aviation (and for sea transport). Figure 2.1 in section 2.1 shows how emissions differ for different definitions of 'Swedish' air travel. It can be added that if a shorter time perspective than 100 years is used – which may be justified in order to avoid triggering positive feedback loops in the climate system – the climate impact might correspond to much more than 8.7 million tons of CO₂-equivalents.

5.2 Mitigation options.

Improved technology making aircraft more fuel-efficient is very important and different technology options are analysed in Paper II. It is concluded that the introduction of more radical aircraft configurations, e.g. the flying wing, probably has the highest ultimate potential for reducing fuel consumption, but the development of such aircraft is associated with large uncertainty. A less risky strategy would be to opt for a high-speed propeller aircraft with a cruising speed which is 20-25% lower than for a conventional turbofan aircraft. Such an aircraft would entail a 56% cut in carbon dioxide emissions per passenger-kilometre compared with the year 2000, i.e. 25% lower than the state-of-the art conventional aircraft in 2050 (Paper II). More efficient organisation of aircraft movements may eventually yield about 10% lower emissions, but this is a one-time reduction (IPCC, 1999).

Synthetic air fuel (kerosene) made from biomass is under development and some large-scale production plants may be constructed world-wide in the decade to come (Vera-Morales and Schäfer, 2009). However, as discussed in Paper III bioenergy supply is limited. Although there are considerable uncertainties involved, bioenergy will most likely only suffice to cover a minor part of global transport energy demand (Åkerman et al., 2007; Paper III). It should also be noted that air fuel made from biomass does not reduce the emissions of NO_x and H₂O, which together make up nearly half the total climate impact from aviation.

A further option is to tailor each flight path to the specific atmospheric conditions at that time, in order to reduce the climate impact from NO_x and H₂O. Although such flight paths would often be at lower altitudes and thus increase fuel burn and emissions of CO₂, they appear to entail a significant theoretical potential to reduce the overall climate impact of aviation (Fichter et al., 2005; Rädcl and Shine, 2008). However, there are substantial practical barriers that need to be overcome. First, much research and development is needed in order to identify flight paths which entail a lower climate impact. This is a complex task, since atmospheric conditions are under constant change. The second task is to construct economic incentives in such a way that it actually leads to realisation of this potential, since altering flight paths in this way would entail a penalty in terms of fuel burn and/or flight time.

It can be concluded that improved aircraft technology, biofuels and optimised air traffic organisation are not sufficient, but that in addition the rapid increase in air travel needs to be curbed if the two-degree target is to be met (Anderson et al., 2006; Macintosh and Wallace, 2009; Paper II; Paper III).

A key fact in this context is that international aviation at present is exempt from all kind of taxes; CO₂-tax, energy tax and value added tax (VAT). The EU has decided that flights departing from EU territory should be included in the EU emissions trading system from 2012. Even if the price for emission rights then increases by a factor of four, aviation would still pay less for emissions than road transport and would in addition be exempt from VAT.

Virtual meetings can replace some business travel. The potential impact on emissions from such use of IT is indicated in Paper II. Replacement rates like those envisaged in Paper II (about half of all business trips) would probably require the spread of virtual communication habits and pricing of aviation emissions.

For leisure travel, which to a large extent is driven by a desire to experience other cultures and climates, it is hard to see any potential for replacement of trips by IT-services in the foreseeable future. For this travel segment there is a need to reduce travel distance by air by shifting to less remote destinations, to reduce the frequency of trips and/or to shift to modes with less climate impact, e.g. rail (Papers II, III and V).

5.3 High-speed rail

The results of Paper V indicate that introducing high-speed rail links between the three largest cities in Sweden would entail a total life cycle emissions reduction (including emissions caused by high-speed rail infrastructure) of about 0.55 million tons of CO₂-eq. annually by 2030. Nearly 60% would come from a shift from truck to freight trains on the old tracks. The emissions reduction from shifting passengers from air to high-speed rail would amount to 0.20 million tons annually. These figures can be compared with the emissions from total Swedish domestic aviation, which amounted to about 0.9 million tons in 2006, or the emissions from total world-wide air travel by Swedes, which amounted to 8.7 million tons CO₂-eq. in 2006.

So is it a good idea to build high-speed railway lines in countries like Sweden, if a climate perspective is considered?⁸ The answer is not evident but can be discussed with the help of the matrix in Table 5.2. The two alternative and rather different mobility paradigms shown are *Continued globalisation of travel and freight* and *Local and regional focus*. The latter would entail a rather distinct break in the present transport growth and imply constant or slightly decreasing overall travel and freight transport volumes. If the most severe effects of climate change are to be avoided, developed countries need on average to be much closer to *Local and regional focus* than *Continued globalisation of travel and freight*, as indicated by Papers I-III. If such a state were to be realised, Table 5.2 shows that the best strategy would probably be not to build new high-speed rail infrastructure, since volumes of car and air travel and truck transport would be reduced by other means, e.g. high tax on emissions, use of virtual meetings and transport efficient spatial structures. In this case the emissions caused by

⁸ There have been several cost-benefit analyses made on Europabanan, some yielding a net loss and some giving a net benefit.

building the new high-speed rail infrastructure would also be avoided.⁹ If, however, high-speed tracks are not built and the actual outcome turns out to be closer to *Continued globalisation of travel and freight*, then we would face the worst outcome, since air travel and road transport would increase rapidly and there would not be sufficient capacity in the railway network to shift more than a minor part of this to rail. The policy-maker deciding on whether to build new high-speed rail infrastructure, i.e. the Swedish Government, has only a limited influence on the mobility paradigm. So, if it does not seem likely that a major break in transport growth will occur, and if the worst case is to be avoided, then building new high-speed rail infrastructure might be a kind of “second best solution” from a climate point of view. An additional advantage is that it would enhance acceptance for necessary increases in emission taxes.

Table 5.2: Outcomes with regard to climate consequences of combining different strategies of high-speed rail investment with paradigms for mobility

Mobility paradigm Strategy	<i>Continued globalisation of travel and freight</i>	<i>Local and regional focus</i>
<i>High-speed rail investment</i>	Medium	Medium
<i>Only efficient use of existing tracks</i>	Worst	Best

⁹ In practical transport policy-making in Sweden a gross amount of funding for transport infrastructure is first decided on by the Government. Only in the second step is the allocation made between, mainly, road and rail investments. This means that generally speaking, if a rail investment is abandoned it tends to be replaced by road investments with the same costs (at least if no alternative attractive rail investments are at hand) and the same likely magnitude of emissions.

6. Future transport systems meeting climate targets

6.1 Introduction

A common misconception, although quite natural, when discussing alternative futures is to make comparisons with the present situation. The images of the future in Papers I-III might seem very different to the present and especially to a business as-usual development to 2050. However, the alternative, to postpone action, might well involve rather abrupt changes to society later on in a much shorter time period, leading to social disruptions and considerable economic losses (Stern, 2006; Dyer, 2008; The Copenhagen Diagnosis, 2009). The aim of futures studies such as those presented in this thesis is instead, recognising the significant inertia in systems under consideration, to prepare for gradual changes that start in the present and thus may be realised over a longer time period, typically 40-50 years.

An important part of the concept sustainable development concerns distributional issues. Intergenerational distribution is assumed to be implicitly considered in the climate targets themselves, e.g. the two-degree target. Whether future generations are given their proper weight by using this target is outside the scope of this thesis (although of course an important issue). Intragenerational distribution is considered explicitly in Papers I-III by allowing all global citizens an equal proportion of energy supply or emissions quota to meet the target explored. Such a hypothetical situation would still mean that countries with much renewable energy resources per capita, e.g. Sweden, would be better off since they could benefit from exporting some of this renewable energy. Another unresolved issue concerns the fact that industrialised countries already have a developed infrastructure and modern building structure in place. This might actually be an argument for giving industrialised countries a smaller emissions allocation per capita than developing countries.

The synthesis image of a Swedish transport system in 2050 that is sketched in section 6.2 is mainly based on Paper III, although there are influences from the other Papers as well as from Åkerman et al. (2007). The synthesis image is mainly described in qualitative terms, but quantitative assumptions on transport volumes and specific energy use etc. can be found in Paper III. The image in Paper III is consistent with a global annual energy use of 13.9 MWh per capita and emissions of 1.5 tons of CO₂-equivalents per capita. Energy use in the transport sector amounts to 4.6 MWh per capita, in the image.

6.2 Features of future transport systems meeting the targets

There are four main ways of reducing greenhouse gas emissions from transport:

Technological (mainly)

- Lower energy use per passenger-km or ton-km for each mode of transport (e.g. more energy-efficient vehicle technology)
- Lower carbon intensity of fuels (g CO₂/kWh)

Behavioural

- Shifts to modes with lower carbon emissions
- Reduced volumes of transport (fewer passenger-km or ton-km in total)

Of the four ways of reducing emissions outlined above, having more energy-efficient vehicles is probably the single most important measure. Assessments of the future potential for improved vehicle technology are included in all papers in this thesis. The technological developments assumed in the synthesis image described in this section are found in section 4. Having said this, however, one of the main conclusions is that improved technology and low carbon fuels on their own are not sufficient to achieve emissions reductions consistent with reaching the two-degree target. It is also the case that within the present transport paradigm – continuing growth of transport volumes in particular for car, air and truck – emerging problems, e.g. climate change, are most often responded to by attempting to find ‘technical fixes’. Although technical progress within the more emission-intensive modes (car, air and truck) may also be associated with implementation problems, they are still inside the dominant paradigm and thus more easily managed. This is the reason why comparatively much emphasis in this thesis is placed on the latter two ways of reducing emissions, which are directed towards limiting the volume of car and air travel and truck transport.

The travel and freight patterns may be seen as a combination of (1) preferences/values of travellers (citizens) and (2) the boundaries made up of spatial and organisational structures as well as options regarding means of transport. The former refer for instance to preferences with regard to health, security, community values, consumption patterns and willingness to take measures to mitigate climate change. The latter is defined broadly here and includes localisation of functions (residential areas, workplaces, shops, schools, restaurants, sport facilities, theatres, green areas, etc.), transport infrastructure, vehicle supply but also organisational structures (e.g. working hours, timing of cultural and sport events, etc.).

An important aspect permeating the images of the future is to shift the planning paradigm from enabling increased mobility to enabling increased *functional* accessibility, as discussed in Paper III. 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, e.g. seaside resorts with enjoyable climate, or when the activity of travelling itself is valued highly. 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 – but that is inherently valued negatively. There is, however, not a clear distinction between these two types of travel, since for instance commuter travel by comfortable trains may offer good opportunities to use travel time. Even car travel in congested areas may for some people entail a substantial positive value in itself. (Lyons and Urry, 2005) Many structures of society, e.g. location of home and jobs and organization of work, are characterised by a substantial inertia. This implies that a sudden external event, like drastically higher oil prices, in the short term will mainly lead to a decrease of desired travel. In the long term the spatial and organisational 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*. The former refer to the possibility (with regard to time and cost) to reach certain geographical areas or spots, regardless of what services are located there, and the latter refer to the possibility to access functions/services. Focusing on *functional accessibility* opens up for alternatives like access via information technology or decentralisation of services. (Paragraph adapted from Paper III).

Passenger transport from the image in Paper III is shown in Figure 6.1, where the width of the bars indicates energy use per passenger-km. The improvement by 2050 is assumed to be according to potentials estimated in Table 4.1. It can be seen that total travel per capita in the image for 2050 that meets the target level is much lower than in the reference scenario for 2050, but about the same as for 2000. The synthesis image for 2050 in Boxes 1-3 is broadly consistent with Figure 6.1.

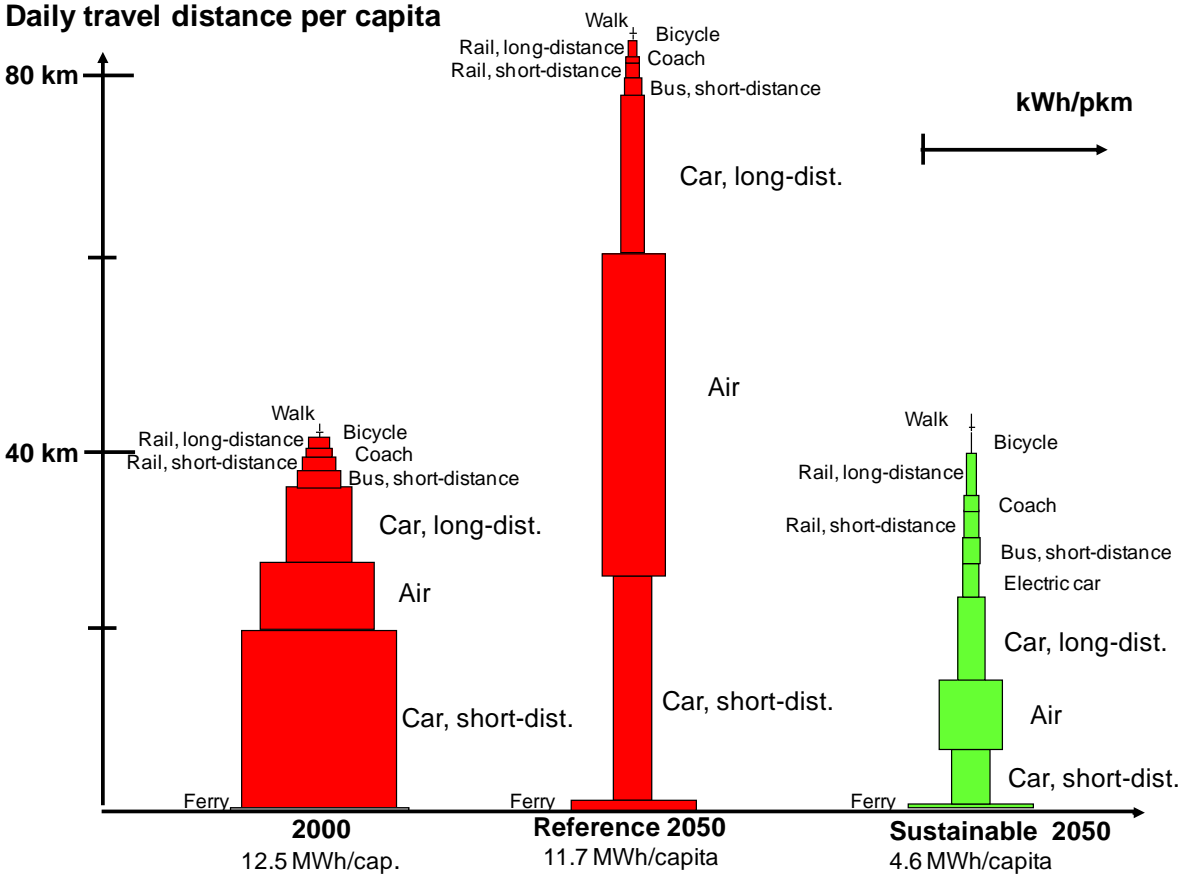


Figure 6.1: Daily per capita travel in the three cases; 2000, Reference 2050 and Sustainable 2050. Reference 2050 does not include any additional demand management. The width of each box corresponds to the energy use per passenger-km, and thus the area of the boxes represent the energy used for each mode. Source: Slightly refined version from Paper III.

Short-distance travel

Short-distance travel (less than 100 km one-way) at present makes up about 60% of total travel volume measured as passenger-km and 39% of greenhouse gas emissions from Swedish transport (Åkerman et al., 2007; Paper III). Car travel is responsible for the majority of these emissions. Although there is considerable potential to improve the energy efficiency of vehicles and increase the use of low-carbon fuels, it was concluded in section 4 that transport volume growth of the most energy-intensive and polluting modes also has to be curbed. However, this does not mean that other modes may increase in an unlimited way. In order to reduce the need for car travel, important means are to transform spatial and organisational structures and improve climate-benign ways of getting access. A key aim is to reduce the length of trips. This also has a positive secondary effect in that it improves the competitiveness of walking and cycling. An obstacle for reduced car travel is that about two-thirds of costs for a private car are fixed, which means that public transport has to compete with one-third of the total cost for car travel. Therefore an important strategy is to improve possibilities in cities to do without a privately owned car, but still have easy access to pool or rental vehicles when necessary. This may at the same time reduce total household expenditure and increase incentives for choosing public transport or cycle transport. Reducing the need for privately owned cars, is only an option in cities, since there will be no alternative to privately owned cars in the countryside and in small municipalities. Box 1 below presents an image of short-distance travel in 2050. This image is mainly based on Paper III, but with influences from the other Papers.

Box 1: Synthesis image of short-distance travel in 2050 consistent with climate targets

Generally there has been a trend of growing concern about the local neighbourhoods. Cities now in 2050 are structured around high quality public transport networks with especially dense areas around public transport nodes. The increased population density has been achieved by using already exploited land, e.g. such that formerly was used for industries, harbours or as parking space. A new way of organising knowledge-based work (which has increased its relative proportion by 2050) has emerged. Many people work in network organisations in which employees are not necessarily working at the same offices, but are connected via high-quality communication technology wherever they are. Many people have chosen to work at telecottages situated in local centres close to their homes. This in combination with more specific measures has increased cycling by more than a factor of four compared with the situation in 2010. The local centres also constitute nodes in the public transport system, which to a great extent relies on electric propulsion, e.g. rail transport and trolley buses. The supply of liquid and gaseous fuels is rather scarce due to the competition for productive land that has intensified since 2011. The increased population in the local centres in the daytime has in turn made these centres more vivid in terms of shops, restaurants, cultural events, etc., which has caused a positive upward spiral. Functional accessibility has increased, while travel volumes have decreased. The fact that few if any external shopping centres have been added since 2010 also contributes to this development.

Furthermore, car sharing and rental services are now widespread and there are cars available in almost every block. This development was accelerated around 2015 when businesses and public bodies realised that sharing cars with households could reduce costs significantly. This has increased the convenience of not having a private car and enables users to book a vehicle well suited to each specific aim that may occur. There are a wide range of vehicles available, from small electric scooters and small cars to long-distance station wagons and small trucks. In addition to reducing the kilometres driven by car, car pooling also reduces the use of unnecessary large and fuel-intensive cars.¹⁰ Since users pay the full cost each time they use a pool vehicle, public transport is often competitive if the specific characteristics of a car, e.g. the ability to transport a lot of luggage, are not needed. This trend has been stimulated by extensive use of differentiated GPS-based km-charges/taxes in urban areas. Another element that contributes to the possibility to do without a private car now in 2050 is the home delivery services common in this image. Available space in cities for different modes is an important parameter that affects travel speed. There is now less space for cars in cities, and more for cycling and public transport, compared with the first decades of the 21st century. There is another important synergy here. The reduced need for owning a car has decreased the car fleet even more than car travel. This has reduced the need for parking space, which releases space that can be used to increase the density of dwellings and workplaces, without sacrificing green areas. Per capita travel by car is almost unaffected in rural areas, but have declined by 40-50% in cities with more than 100 000 inhabitants.

Long-distance travel

Long-distance travel by Swedish residents (trips longer than 100 km one-way) makes up about 40% of travel in terms of passenger-km and 33% of greenhouse gas emissions from transport (Åkerman et al., 2007; Papers III and IV). As can be seen from the *Reference scenario 2050* in Figure 6.1 long-distance travel is increasing faster than short-distance travel. This applies especially for air travel, which may well be more than four times higher in 2050 compared with today, if measures are not applied to curb that growth. Although such growth rates need to be broken, long-distance transport (in particular aviation) may increase its *share* of total transport emissions in the images in Papers I-III. This is partly a consequence of the deliberate effort to reduce “structurally enforced travel” in these images. Box 2 outlines an image of long-distance travel in 2050. This image is a synthesis, drawing on images from Papers I-III and with some additional features from Åkerman et al. (2007). Travel volumes are broadly similar to those in the scenario *Sustainable 2050* in Figure 6.1. This means that air travel is at the same level as in 2000, but that it needs to be decreased by approximately 25% from the level in 2010.

¹⁰ Private cars are often chosen in order to cope with the most demanding case, for instance when a family travels to a summer cottage with a lot of luggage. The same car is then used for commuting by a single person.

Box 2: Synthesis image of long-distance travel in 2050 consistent with climate targets

Now in 2050 business travel by air has been reduced by one-third compared with the year 2000, by using video and telephone conferences in situations where people have already met face-to-face. Although increasing climate concern contributed somewhat, the main driver for this development was that businesses came to the conclusion that they could save a lot of money by using virtual meetings instead of air travel. That aviation since around 2022 also has to pay the same taxes – climate tax and value added tax – as other modes, has been an important catalyser for this development.

Leisure travel by air has increased by 20% compared with 2000, but this still means a small decrease from the 2010 level. The proportion of travel by trains has increased substantially in Scandinavia as well as to Northern Europe. For travel within southern Sweden transport by aviation is almost zero. There are daily direct connections with night trains from Stockholm to cities such as Brussels, Amsterdam, Zurich and Berlin. Trains leave Stockholm around 8 p.m. and arrive at final destination between 7 and 10 a.m. in the morning. Generally less distant destinations for leisure travel are chosen and the trend towards shorter duration of trips in the early 21 century has now been reversed. The longer duration of trips has also been enabled by more flexible and, on average, reduced working hours. The emission charges and VAT now levied on aviation is a key driver. There was a rather fierce debate in the EU around 2020 before aviation was withdrawn from the EU Emission Trading System and the cost of emissions was raised, by means of taxes, to the same level as for road transport. Southern Europe and Northern Africa have taken market shares from Asia, regarding leisure travel. New highly efficient ECO-liners are often used for travel to these destinations. These aircraft are 20-25% slower than conventional aircraft but reduce energy use by 25% compared with the best ‘fast’ aircraft in 2050 (Paper II). Spending vacations in summer cottages in Sweden has also gained in popularity. Car is still the preferred means of travel for these purposes, but in many cases pool cars or rental cars are used.

Freight transport

Freight transport generated by consumption by Swedes represents 28% of greenhouse gas emissions from transport if international transport is included (Åkerman et al., 2007; Paper III). The current growth rate for freight transport is higher than for short-distance travel but lower than for air travel. Box 3 presents a synthesis image of freight transport in 2050, which is based on the image in Paper III.

Box 3: Synthesis image of freight transport in 2050 consistent with climate targets

Truck transport per capita has decreased by 30% since the year 2000, while rail freight has increased by 12%. Sea transport has decreased by one-third. This development is in stark contrast to the considerable growth rate at the turn of the century, especially regarding truck and sea transport. Flows of products with a low cost/weight ratio, such as basic food, fuels and building materials, are transported shorter distances. The trade in this kind of goods makes a relatively small contribution to the economy, but represents a large proportion of freight transport volumes. Products with a high cost/weight ratio, e.g. electronic equipment, vehicles, etc., now in 2050 are still to a large extent traded on the global market, as are products such as coffee, wine and bananas. However, a significant increase in 'glocal production' has been achieved since the turn of the century. Glocal production means that while company management and product development may be centralised, physical production may be decentralised 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. An overall dematerialisation of society (e.g., through lighter and more durable products) has also contributed to the reduction in freight transport. There are a couple of drivers that have contributed to the rather radical trend-break that has led to this structure for freight transport in 2050. Global pricing of the externalities of freight transport has been important, not least for ocean transport of low-value goods. Transport of oil has decreased substantially, but has partially been counteracted by an increase in transport of bioenergy. The increased interest in locally produced goods, in particular food, has also contributed. The rapid economic growth in China and the rest of South-East Asia has diminished the wage difference compared with Europe. This has led to lower freight volumes from China and instead higher volumes from the new 'low-wage' regions, mainly Africa, resulting in shorter average distances for sea transport.

The system of distributing everyday commodities has largely changed in character. Many of these commodities are ordered via computer networks, and small efficient hybrid trucks 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. The market share for external shopping centres has diminished.

Rail transport is characterised by considerable economics of scale both for passenger and freight transport, which, somewhat paradoxically, implies that the less society deviates from the current paradigm of increasing transport volumes, the more important rail becomes. In Paper I, rail freight is thus more important in Image 2, where rapid growth in long-distance freight transport has continued, than in Image 1, which is characterised by more local lifestyles and a greater willingness to pay for locally produced goods.

6.3 Synergies or conflicts with other societal targets?

The images of the future outlined in Papers I, II and III seem to contain several positive secondary effects with regard to other societal targets. Part of the iterative process of backcasting involves trying to achieve this, provided that the main climate target is not

compromised. The urban environment will be less polluted, less noisy and generally offer a better living environment. Speed limits are kept low mainly to allow people, not least children, to survive 'mistakes' in the traffic environment. Since most cars driving in urban areas have some kind of electric or hybrid drive, the lower speeds also reduce energy use. The increase in cycling and walking (partly to public transport stops/stations) contributes significantly in a pro-active way to better health and lower costs for healthcare. Cycling accidents may increase in absolute terms, but this negative effect is much smaller than the positive health effect of more cycling.

A potential conflict that needs to be handled is that the focus on denser cities may put greater pressure on green areas. In many major cities, e.g. Stockholm, there is great potential for using already exploited areas, e.g. former industrial areas, harbours and, given the reduced car dependency, road space and parking areas.

7. Conclusions for current policy-making

An overall conclusion from this thesis is that improved vehicle technology and low carbon fuels are necessary, but not sufficient on their own, to achieve long-term targets consistent with limiting global warming to two degrees. The growth in volume, especially of car and air travel and truck transport, also needs to be curbed. This conclusion is strengthened by the even more demanding climate targets that recent climate research has identified (The Copenhagen Diagnosis, 2009). Although major changes thus are necessary regarding e.g. modal choices and general travel patterns, etc., the average accessibility to different functions is better in the future transport system outlined in Paper III compared with today. This holds in particular for those people who today have the lowest accessibility, e.g. those without a car of their own.

There is considerable uncertainty regarding the potential for bioenergy, especially on a global scale. Biofuel production will strongly compete for land with food production and the preservation of ecosystems which deliver vital ecosystem services, e.g. food, water, fibre, as well as climate and disease regulation (Millennium Ecosystem Assessment, 2005). An important factor is the potentially substantial negative effects from changes in land use. If natural ecosystems are turned into farmland for energy crops, it may take decades before there is any climate benefit, due to the substantial initial carbon release from the soil (Fargione et al, 2008; Searchinger et al., 2008). It is also the case that a unit of bioenergy yields a higher climate benefit if it replaces coal in a power plant than if it is used for making vehicle fuels. The conclusion is that only a limited proportion of current fossil fuel use in transport can be replaced by biofuels, even when second generation fuel production becomes available on a large scale. It is thus a risky strategy to rely heavily on the large-scale introduction of biofuels. At least as much effort must be devoted to reducing the need for physical travel and freight transport and achieving modal shifts, as well as stimulating more energy-efficient vehicles and driving styles. Having said this, there is still a need for research in, and demonstration of, the second generation of biofuels, and of hydrogen systems including fuel-cells. Hydrogen faces many hurdles and may not play a significant role for decades to come. Still it may finally be an important fuel for long-distance transport, and due to the significant inertia in sub-systems involved, there is a need for far sighted preparations.

Air travel is a particularly problematic area. Domestic air travel in Sweden only makes up 1-2% of total Swedish greenhouse gas emissions from all sectors. However, if international air travel by Swedish residents is included, the proportion for air travel increases to about 12% or 8.7 million tons of CO₂-equivalents annually (Paper IV). Even more problematic from a climate perspective is the growth rate of emissions. If the reference scenario for 2050 in Paper III were to be realised, greenhouse gas emissions from aviation alone would exceed the total emissions allowed for all sectors in society if climate targets were to be achieved.

The key to curb the volume growth of car travel, air travel and truck transport, and to achieve lower emissions per vehicle-km, is to make these modes pay the full price for the

negative externalities they cause.¹¹ However, to make that an acceptable political strategy, it is also important to improve alternative ways of reaching accessibility (OPTIC Deliverable 1, 2010). The *extent* to which alternatives have to be improved depends on e.g. the specific transport context and the public notion on what constitutes a sufficient accessibility. A combination of different kinds of policy measures is needed (Banister et al., 2000; Åkerman et al., 2000; OPTIC Deliverable 1, 2010; Paper III). In Paper III four types of measures were distinguished due to main purpose (they are not mutually exclusive):

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

1b. Measures which improve existing environmentally-benign alternatives.

2. Measures which limit the volume of the transport modes having the most negative externalities (in particular with regard to climate change).

3. Measures which reduce specific emissions and energy use for the respective transport modes or which increase the use of low carbon fuels.

Measures aimed at only reducing specific emissions, such as subsidies on fuel-efficient new cars or funding of research into more efficient vehicles, are important but, as shown in section 4, not sufficient to achieve the targets. Therefore, measures of type 2 are the key to achieving the targets, and these measures also influence specific emissions. However, to gain political and public acceptance for such measures and maintain a well functioning society, it is often necessary to complement pricing measures with measures that improve alternative ways of getting access (types 1a and 1b).

What is needed, given the urgency of climate change as shown in section 3, is a twofold strategy. It is necessary to immediately start to reduce emissions, but also to start transforming structures with a high inertia, the latter being crucial to reach the major emissions reductions needed in the long run. It is thus important to recognise the considerable inertia in both the transport system (including infrastructure and the built environment) and the climate system. It often takes 50-100 years to significantly affect the structure of urban areas and the networks of infrastructure, and even the renewal of vehicle fleets may take 20 to 50 years.

This also means that there is little room for mistakes, e.g. regarding infrastructure investments. Regarding the chronological order, it is best if measures of type 1a and 1b are implemented just before measures of type 2, so that citizens and businesses have a reasonable means of getting functional access. Often, however, satisfactory alternatives are already at hand or the purpose of travel is not that important. In such cases, measures which limit the

¹¹ For climate change it is difficult to quantify negative externalities. The outcomes are uncertain and there is a risk for rather severe consequences. In such cases society must take a stand on what risks to take and this is done by setting a target, i.e. in this case postulating that global warming should not exceed two degrees. From this target a "shadow price" on CO₂-emissions might be calculated, that is, a price that would lead to achieving the target.

volume of the more harmful transport modes, e.g. pricing measures, could be implemented right away (Åkerman et al., 2000). This seems to be applicable to a large proportion of air travel. At present aviation (and sea transport) is exempt from all taxes on fuel.

At the overarching policy and planning level, it is crucial to accomplish a paradigm shift in planning, from mobility to *functional accessibility* (Paper III). Transport is but one means, albeit the most important, to get accessibility to different functions. Taking departure in such a paradigm shift, four mutually supporting elements of a policy strategy for urban transport/communications might be identified: (1) An urban planning strategy that focuses on high density of dwellings and work places around public transport nodes, and short distances to shops, schools, sport and cultural facilities etc. (2) Improving the competitiveness of cycling and public transport, in particular rail transport.¹² The previous element of urban planning is an important prerequisite for this, in order to achieve attractive and efficient public transport. (3) Supporting virtual communication techniques such as videoconferencing and social media in order to replace part of commuting and business travel. (4) Pricing measures such as charges/taxes on road transport differentiated according to time, place and emission characteristics of vehicles. Such a deliberate strategy might reduce the demand for structurally enforced travel (commuting, service and shopping travel). This would leave room for somewhat increased leisure travel, although not by air (Paper III).

The future is uncertain and will bring surprises. Therefore policy strategies that are either *flexible* or *robust* are necessary (Paper III). For structures like the built environment and transport infrastructure, a flexible strategy is not possible (except in some cases where investment may be postponed for a while). Instead, a cautious, robust, strategy is needed in order to avoid structures leading to detrimental lock-ins with regard to mitigating climate change. The precautionary principle is well applicable in such cases. There are several reasons for avoiding, or at least postponing, investments in new infrastructure that lower the cost (in terms of money and time) of the more energy-intensive and polluting modes of transport, e.g. car, air and truck. The main reason is that in all but a few cases in Sweden, the infrastructure capacity for these modes is already sufficient to handle the transport volumes that are consistent with achieving the two-degree target (Åkerman et al., 2007; Papers I-III). In the future image for 2050 in Paper III, total car travel is reduced by 32% compared with 2000. Since it is difficult to replace car travel in the countryside, the reduction need to be 40-50% in cities.

Furthermore, increased road capacity in urban areas almost always leads to increased car travel (SACTRA, 1994; ECMT, 1996; Transek, 2000). One misconception that sometimes appears in this context relates to the proportion for public transport. The *proportion* for public transport is strictly speaking irrelevant for environmental targets. If substantial investment is made in *both* road infrastructure and rail infrastructure, as two consecutive Swedish governments (one left-wing and one right-wing) have done since 2002, the proportion for

¹² Personal Rapid Transit might in some cases be a complement.

public transport tends to remain about the same. The main consequence is then that *both* car travel and travel by public transport increase and so do emissions. Only by shifting travel *from* car to public transport and cycling can emissions be reduced. To achieve that, a rather strict prioritisation of investments in public transport, cycling and ICT infrastructure is needed, especially since public resources are limited. Furthermore, all infrastructure construction in itself leads to significant energy use and emissions of greenhouse gases.

At the time of completing this thesis, much hope rests on the deployment of electric cars, not least plug-in hybrids, which are multi-purpose vehicles in contrast to battery electric cars with limited range. On policy level the alleged near-term success of the electric car is sometimes used to justify increased road capacity in urban areas. In the image of the future for 2050 in Paper III and in image 1 and 3 in Paper I, cars with electric drive play a significant role. However, both the speed of penetration to the vehicle fleet and the environmental benefits of electric cars are often exaggerated in the present public debate. Even in Sweden marginal electricity will not be carbon neutral for decades to come, since Sweden is connected to the grids of other European countries such as Denmark and Germany. The indirect emissions associated with manufacturing and maintenance of cars also need to be taken into account. They amount to 5-10 ton CO₂ per conventional car (Paper V), and the figure is even somewhat higher for plug-in hybrids. Furthermore, electric cars need the same space for driving and parking as conventional cars, a fact that tends to lead to sprawling cities and increased transport distances.

Although the costs of plug-in hybrids will decline as the technology matures, it is important to note that even in the long run plug-in hybrids will be significantly more costly to produce than comparable conventional cars. The reason is that in addition to the combustion engine, they also have an electric engine and a battery pack. The implication of this is that for them to be competitive without subsidies, a substantial increase in fuel price is needed. It is also important to note that short-distance car travel at present stands for only 35% of Swedish transport emissions, including international transport, and that this share is diminishing (Åkerman et al., 2007; Paper IV). This is mainly due to the rapid increase in air travel and freight transport by truck and ship.

One key policy issue to address is that international aviation – as well as sea transport¹³ – is exempt from taxes on greenhouse gases, energy taxes and value added tax (VAT). This is a significant distortion compared with road transport and the situation urgently needs to be remedied. The inclusion of aviation in the EU Emission Trading System from 2012 will likely only involve small increases in costs for emissions (Wit et al., 2005). The exemption from VAT on international aviation is not often noted, but is about as important to terminate as is

¹³ For sea transport the policy situation is slightly more complex. Short distance sea transport to some extent compete with truck transport, which is worse from a climate perspective. Therefore it is important that truck transport is made to pay its full costs before (or at the same time) taxes are levied on short distance sea transport. For intercontinental sea transport a CO₂-tax could be levied rightaway, if only the substantial practical barriers could be overcome.

the exemption from tax on greenhouse gases. For domestic aviation in Sweden there is a VAT of 6%. This is, however, much lower than the general VAT of 25%, which is levied on most goods and services, including cars and their fuel. Although making aviation pay the full costs is a crucial issue, it is also important to improve alternatives to air travel, e.g. virtual meetings and fast rail connections.

As concluded in section 5.3 investing in high-speed rail in Sweden is not the best conceivable solution with regard to climate change. If it is judged feasible to bring transport growth to a halt or reduce growth rate considerably, there is limited value of building high-speed rail. One reason is that at least in sparsely populated countries such as Sweden, the purpose of building a high-speed rail track is largely to increase capacity for rail freight on the old tracks.¹⁴ On the other hand, if the current mobility growth is only affected marginally, high-speed rail tracks seem to be a fairly good option from a climate perspective. This might then be called a “second best solution”. An additional advantage of investing in high-speed rail is that it would enhance acceptance for necessary increases in emission taxes for aviation and road transport.

Given the amount of air travel consistent with the climate targets, there is no need for expanding airport infrastructure in Sweden. The development of slower aircraft might reduce energy use by 25% and greenhouse gas emissions even more. Development of such aircraft might be stimulated for instance by procurement synchronised by the EU.

Finally, 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 general. A green tax reform where increased taxes on emissions and resource use are used to reduce other taxes, e.g. labour taxes, may be a viable alternative for combining effectiveness and acceptance of policies.

¹⁴ If a parallel track is to be built anyway, the extra cost of building a high-speed track is comparatively small.

8. Final remarks

One of the two overarching aims of this thesis was to provide better knowledge for current policy decisions on how the transport system can be transformed in order to comply with the target to limit global warming to two degrees. Particular focus was placed on structures with a high inertia, e.g. urban structure, roads, railways, fuel production plants and to some extent vehicle fleets. The main conclusions for current policy are presented in section 7.

The second overarching aim was to widen the perceptions of possible futures, in order to form a basis for a wider discussion in society. This ideally requires more space than is allowed in journal papers and has therefore also been investigated by more extensive reports in Swedish (Steen et al., 1997; Åkerman et al., 2000; Åkerman et al., 2007). To achieve both these aims, the results have been communicated in many ways to policy-makers, businesses, the academic community and the public. For instance, they have been presented at seminars hosted by the Swedish parliament, at seminars hosted by the European parliament and at a hearing held by the Swedish Commission for reduced oil dependency¹⁵.

An additional aim of the present work was to develop more relevant system delimitations than are commonly applied. Attempts were made to estimate and include international travel and freight transport in the system analysed. Another example of adjusted/expanded system boundaries is found in Paper V, where indirect emissions associated with fuels, vehicles and infrastructure were included. An important case relates to the introduction of electric cars. Taking the wider, more appropriate, systems perspective, it turns out that the climate benefit of electric cars, although still significant, is lower than is often assumed. These cases show that considering wider system boundaries than is presently common, is necessary for transport policies to be effective and not lead to sub-optimisations.

Regarding acceptance for the changes suggested in this thesis, a move towards a transport system consistent with climate targets will require significant changes to the structures and organisation of existing societies. This will probably not happen without conflicts. Some of the strong actors in today's society have contributed to the climate problems and may need to reassess their business. Some of the ingrained habits of households also need to be changed. However, given recent evidence on climate change it seems that a wait and see strategy will entail considerably more severe social and economic consequences (Stern, 2006; Dyer, 2008; The Copenhagen Diagnosis, 2009). Future images of transport, as outlined in this thesis, also seem to encompass substantial secondary benefits in terms of more liveable cities, better health, reduced household expenditure and, in some cases, more efficient businesses. Finally, a determined effort to make transport more energy efficient and less dependent on fossil fuels, will leave us all in a much better position when oil get scarce and prices soar.

Essential knowledge already exists – in this thesis and in many other sources – on how to start transforming the transport system in line with climate targets. There is no excuse for

¹⁵ With the Swedish prime minister participating. Held on 17 February 2006.

policy-makers to lose time if they are interested in fulfilling the target they have themselves agreed upon (the two-degree target). Having said that, there is evidently more research needed. Here I have only mentioned some knowledge gaps that I encountered while writing this thesis. Indirect emissions and energy use are only considered to a limited extent here (mainly in Paper V) and are usually ignored in current policy-making. It would be interesting to combine a full life-cycle perspective with a backcasting approach. How to limit the rapid increase in long-distance freight is a particularly difficult task, which has only partially been addressed in this thesis. Finally there is a need for more specific advice on how effective and acceptable transport policies could be designed. One such project is the currently running EU-funded project OPTIC (Optimal Policies for Transport In Combination), in which the author participates.

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