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# Analysing Sustainable Urban Transport and Land-Use

## Modelling tools and appraisal frameworks

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To the memory of my father
Rolf Jonsson, 1944–2008

## Abstract

Sustainable development and climate change is high on the agenda for most cities around the world today. Urban transport is at the heart of these changes. Increasingly, it is recognised that not only is the emission of pollutants and greenhouse gases a problem, but also the detrimental effects of congestion and social exclusion. In order to address these issues, it will be necessary for cities to make strategic long term decisions regarding the future infrastructure and land use, not only in terms of what will be built, but also on measures that affect how these systems are used.

This thesis is focused on the decision support tools that we need in order to make well informed decisions. Models that predict the performance of future scenarios, and appraisal frameworks that help evaluate whether these outcomes are desirable or not. The first two papers experiment with different ways of bringing some aspects of sustainability into the appraisal frameworks used to analyse long term strategies. Paper I addresses intergenerational fairness, and Paper II focuses on the emission of greenhouse gases. Paper III develops a model, Scapes, that can help us to better understand the daily travel behaviour, through an activity based approach. By explicitly modelling space-time constraints, and travel time uncertainty in a microeconomic framework, we can get a better understanding of how people can respond to, and value, changes in the transport system. Papers IV and V describes a new integrated land use and transport model, LandScapes.

The policy implications from the studies in Papers I, II, and V are that it will be very difficult for Stockholm to reduce its emissions of $CO_2$. Particularly, predicted economic and population growth will inevitably lead to more transport. It is likely that a range of different policies will be necessary to solve that problem. At the same time, we must not forget that decreasing $CO_2$ emissions, although important, is not the only objective Stockholm has. To cope with the increasing travel demand from a growing population, it may well be necessary to build new infrastructure as well. This thesis does not prescribe any such relative valuation between conflicting objectives. It only helps bring them to the fore.

## Acknowledgements

At this point it is not easy to get excited about much of the material in this book. After revising the texts for the thousandth time it becomes somewhat more of a chore and less a celebration of creativity. I am, however, confident that when some time has passed the memories will be overwhelmingly positive.

One thing that I do get excited about, when I step back and take stock, is the fact that this process has been such an amazing learning experience. When I started working in this field I had only a fuzzy notion of the transport and land-use system as something that presented an interesting area to apply a vague interest in mathematical modelling. Over these last few years things like sustainable development, climate change, and increasing oil prices have moved firmly into the public consciousness, which makes analysing these things so much more rewarding. It is a privilege to work with something that people care deeply about.

I could not have done this on my own. I want to thank my supervisor, Lars-Göran Mattsson, for sharing his knowledge on the subject, and for his patience with my meandering way of reaching this point. But also for his and Lars Lundqvist's hard work building the stimulating environment at the division for Transport and Location Analysis. I would also like to thank my second supervisor Anders Karlström, for being interested in interesting things, and helping me discover them too. Staffan Algers has also been a great help, with his expertise in the art (and science) of model building. I thank all my colleagues, current and former, at TLA. You have provided not only invaluable help from time to time, but also interesting discussions on such a wide range of topics, from science to philosophy, or football; on things we know something about and on things we don't.

I would also like to thank other colleagues from around the world, in particular the project team around PROSPECTS. When I started out in the transport field, it was of great value to me to learn from such a varied and experienced group. I learned a lot.

Finally, I want to thank my friends and my family. For everything.

Stockholm, October 2008

Daniel Jonsson

# Contents

# 1 Introduction

The theme of this thesis is the tools used to provide support for strategic decisions regarding urban transport infrastructure. In some cases I have attempted to provide some answers on what needs to be done to move the current urban transport system towards sustainability. But more often the aim has been to improve upon the methods used to provide those answers.

Sustainable development and climate change have become kitchen table conversations for many people the last few years. This summer's high oil price was a reminder that the current reliance on cheap fossil fuel and car centric infrastructure is not necessarily going to be possible in the future. As a result there is a high interest among the public for these issues.

For the first time in history most of these people are living in urban areas, and there is no reason to believe that this trend will be reversed anytime soon (UNPFA, 2007), the decisions made in cities now will shape the future for a majority of humanity. It will be a challenge to transform these metropolitan regions into sustainable systems. This may seem to be an overwhelming task, and perhaps the best we can do is to try to make the best decisions we can in whatever local context we may find ourselves in.

The transport sector is key to this transformation. It is struggling with breaking its dependence on oil and at the same time providing the necessary services to support economic prosperity and escape social strife. Transport is responsible for a large, and more importantly, growing part of the global emissions of greenhouse gases. The way the infrastructure systems are structured shapes travel patterns, and the economic conditions affecting the people's travel behaviour is a complex system of, among other things, taxes, fees and regulations.

## Sustainable development

"Like it or not, ready or not, we have become the caretakers of this planet" (Trefil, 2004).

There is virtually no place left on the planet where humans have not had a major impact on the plant and animal life. In the more densely populated areas our built environment has profound effects on such things as rain run-off and ground water levels. Natural habitats are increasingly cut up into smaller and smaller pieces, while industrial agriculture and forestry lead to enormous mono-cultures.

In urbanisation there is also a potential for contributing to sustainability. It is clear that urbanisation is a powerful force for economic development, but the is also some evidence that urbanisation can contribute to poverty reduction (UNPFA, 2007). But, in terms of ecological sustainability the message is much more mixed. It is estimated that urban areas cover less than 3% of Earth's land mass, but in terms of ecological footprint (Rees & Wackernagel, 1996; Best, Giljum, Simmons, Blobel, Lewis, Hammer, Cavalieri, Lutter & Maguire, 2008), they consume resources from a much larger area. While cities are big contributors to environmental problems through their intensive resource use, they are also key to solving many problems (Martine, 2006). We must encourage urban growth that is resource efficient, and the challenge is to figure out what such growth looks like. To do that we need to adopt a systems view.

## Systems analysis

Planning, in general, assumes that we are to some extent able to predict future impacts of our actions today. When we discuss long term sustainability we sooner or later will need to assess how well some objectives are met at some point far in the future. In this thesis we will be using mathematical models to do these forecasts and quantify the outcomes in terms of indicators that describe if we meet the objectives. It is useful to remember that the alternative to using mathematical models is not using no models at all. There are of course things that cannot be formally modelled, but even then, any predictions made are models too, only not as formalised.

Two things are necessary when it comes to assessing whether a strategy fulfils a set of objectives. One is the model of what effects a set of policies will have on the system. The other thing we need is an appraisal framework to be able to compare the outcome between strategies. The least we can expect from an analysis intended as decision support is that it compares what the likely results are from doing something with the likely effects of doing nothing.

But, objections have been raised against large-scale computer models. Lee (1973, 1994) warns that large scale models, often with many linked sub-systems, become 'black boxes' even to the modellers. There is not necessarily a theory explaining the behaviour of the whole model, only its sub-systems. He also warns that a comprehensive model tool that give the appearance of answering every question can lead to a too centralised, top-down approach to planning. Since it is unlikely that we can analyse systems as complex as cities with models that all stakeholders can readily know every detail about, the communication of assumptions, strengths and weaknesses of the models must be addressed through a robust planning process. This is why this essay starts out with an outline of the planning context in which the papers should be viewed.

### Organisation of this thesis

The rest of this introductory essay will try to set the context for the appended papers, and draw some collective conclusions from them. The main concern in this thesis is that the transport systems in our cities are not functioning in a sustainable way, and that long term planning is an integral part of addressing this problem. The next section will introduce some concepts on sustainability, and how they are related to urban planning.

Section 3 provides an overview of systems analysis. It is the guiding principle behind all the methods and models applied in the appended papers. It also briefly touches upon some of the assumptions inherent in the econometric methods used. Section 4 describes some of the more common modelling concepts used to analyse land use and transport interaction. The application of models to real world situations also usually reveals what interesting aspects are missed in the current model, and point to where future research could be directed. Section 2.2, in particular, is really something of a wish-list of things that we should do in terms of modelling and appraisal. Inevitably, when expressing these things in terms of research projects, it is necessary to limit the scope. Section 6 discusses the appended papers in light of the broad outlines in this essay.

# 2 Planning for sustainability

The problem of reshaping the transport sector is global, but the ways of tackling it differs from country to country, and from city to city. The planning approaches used have usually developed over time and are rarely formally prescribed, so they are often a mix of practises. In a survey of European cities (May et al., 2003), they were asked to indicate whether their planning approach was vision led, plan led or consensus led. What is clear is that most cities have some plan led element, what is often described as rational planning, in their approach. The appraisal frameworks discussed in this thesis takes this as a starting point. However, planning approaches with more focus on visions or consensus can also benefit from these methods.

The plan led approach takes its starting point in a clear view of what the objectives are. Problems can be identified, in terms of objectives that are not reached today or in some future scenario. They also may point to possible solutions. Sustainable development constitutes a complex set of objectives, sometimes in conflict with each other, which means that no single policy instrument can be expected to be the solution. Instead it is likely that what is needed is a combination of instruments, a strategy, is necessary, where the instruments help reinforce positive effects and mitigate negative impacts of the others.

Sometimes the rational planning approach is contrasted with a more incremental planning approach, more limited in scope. It is very tempting to try to find one single policy that solves the problem. The potential downside in the context of sustainability is that the limited scope may lead to a situation when the solution to one problem is counterproductive some other goal. And even if there is no such downside, there is the risk that you miss some other policy that may contribute to other objectives as well.

A consensus-driven planning method can be very powerful, because when a consensus is reached all actors will pull in the same direction. On the other hand, it can also be a very time consuming task, and it may even be the case that a consensus cannot be reached because of fundamental differences in values. This is of course an important democratic issue, but well outside the scope of this thesis. In any case, an open and flexible appraisal framework can contribute to the process by providing a common set of alternatives for discussion.

## 2.1 Decision making context

### 2.1.1 A logical structure

The logical structure for planning presented below was suggested by the European Union project PROSPECTS (May et al., 2003). It assumes a rational planning process, but it should not be viewed as exclusive. For example, in a more consensus oriented planning environment the logical structure can be used to identify steps where consensus is necessary. Figure 1 shows the interdependence of the key steps.

The starting point is to *specify objectives* and to specify *scenario assumptions*. The objectives help *identify problems* and suggest *possible instruments* to use to deal with the problems. Section 2.2.1 lays out the groundwork for specifying the objectives, which we do in section 2.3. It is likely there are *barriers to implementation*. By formulating *strategies*, packages of instruments, it is possible to overcome *barriers* and decrease negative impacts of instruments.

Since sustainability inevitably deals with the future, it is necessary to *predict impacts* of a proposed strategy. By applying an *appraisal framework* strategies can be measured against objectives. A framework is necessary to be able to *compare different solutions*. By formulating an objective function as a part of the appraisal we open up for a possible *optimisation*. The steps involving predicting impacts, appraisal and optimisation are the main focus

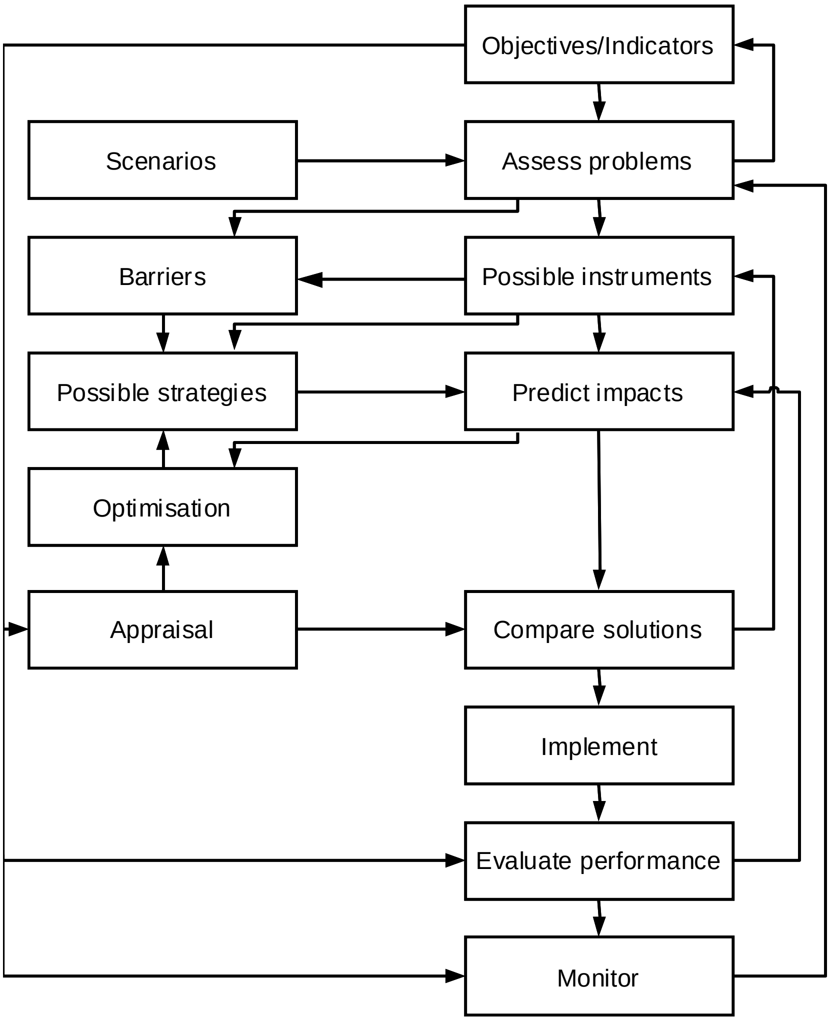

**Figure 1:** A logical planning structure. The key steps are described in greater detail in the Decision Makers' (May et al., 2003) Guidebook and the Methodological Guidebook

of this thesis.

Finally, the decisions should not be left without *monitoring* the implementation, and *evaluation* of the outcome even though this thesis does not cover these issues.

## 2.2 Operationalising sustainability

### 2.2.1 Some definitions

Most recognise the Brundtland Commission's (1987) *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* as a basic definition of sustainability. But, inevitably, the term 'needs' will have different meanings for different people. It is also perhaps not apparent how future generations should be treated.

We build upon Chichilnisky (1996) and Heal (1998) in our efforts to build a useful framework in the land use and transport context. Chichilnisky develops a formulation of intergenerational equity from two axioms which in non-mathematical terms says that the appraisal method should not ignore any generation far in the future, but neither should it ignore the welfare of the present generation. Or in Chichilnisky's terms, there should be neither a 'dictatorship of the present' nor a 'dictatorship of the future'.

Heal summarises sustainability in terms of three axioms

- A treatment of the present and the future that places a positive weight on the very long run
- Recognition of all the ways in which environmental assets contribute to economic well-being
- Recognition of the constraints implied by the dynamics of environmental assets

and suggests the Chichilnisky formulation as a candidate to deal with the first of the axioms. The second addresses the problem that traditionally economic valuation of environmental assets is derived only from consumption of the asset, not from existing stock. The third deals with the case when an asset is renewable or otherwise change over time.

Assets, or *capital*, are usually divided into three types, *natural capital* such as natural resources, bio-diversity, or clean air; *man-made capital* in the form of machines or infrastructure; and *human capital* which is the knowledge and skills of the population. One interpretation would be that development that increases, or keeps constant, the total stock of capital, i.e. the sum of the three types, is sustainable in the long run. This interpretation (*weak* sustainability) assumes that the three types are perfect substitutions for each other. Another interpretation requires a non-decreasing stock of natural capital. This view, *strong* sustainability, grown out of environmental concern, singles out the natural capital, but the same argument could possibly be applied to the other two as well. It is of course introduced because perfect substitution is a very strong assumption.

A variation on strong sustainability is to require non-decreasing stocks of some set of *critical* natural capital. The appraisal framework from Paper I (Jonsson, 2008a) allows for setting constraints on critical capital. There is actually nothing to stop a user from setting constraints e.g. on all natural capital, but we argue that then there is an obvious risk that there are no solutions that meet all constraints. If that happens, the appraisal framework does not help very much. The backcasting inspired framework of Paper II (Robèrt & Jonsson, 2006) explicitly takes a target on future emissions of greenhouse gases as the starting point.

In an effort to clarify what we mean by sustainability we have adopted the following definition of sustainability in an urban transport and land use system:

> A sustainable urban transport and land use system
>
> - provides access to goods and services in an efficient way for all inhabitants of the urban area,
> - protects the environment, cultural heritage and ecosystems for the present generation, and
> - does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage.

Some comments on this definition: First of all, our object of study is the urban land use and transport system. There will inevitably be decisions at the local level that have global implications, with perhaps $CO_2$ emissions as the prime example. While our strategies should minimise negative global impacts we have to limit the interactions with the rest of the world in our analysis. In the $CO_2$ case it means that we will have to derive the cost on the environment of emitting a kg of $CO_2$ from some other global analysis or get it from literature.

The first point in the definition is straightforward, but we would like to emphasise the word *all*, which should be interpreted as requirement on some measure of equity within the population. The second point raises the issue of protecting non-renewable, or slowly regenerating, resources. The resources can be both natural or man-made. The third point has two important messages. There should be a measure of balance or equity *between generations*, and the welfare measure used should include valuation of the natural environment and cultural heritage not only as they are consumed, but also derived from the existing stock.

There are also geographical differences. In a country like Sweden, the congested streets of the largest cities and the long distances of remote rural areas present very different conditions. Even within an urban area there is a tension between city centre and suburb. In this paper we will focus on personal travel in urban areas, and often use the term transport to describe this subsystem, but an obvious extension is to use the same methodology to study regions with other geographical features. Goods transport and logistics are an important factor in reaching a more sustainable transport system, but that is outside the scope of this dissertation.

## 2.3 Objectives and indicators

The Swedish Government introduced an objective to guide the transport sector, in a government bill (prop. 1997/97:56). It states that transport policy should ensure an economically efficient and long term sustainable transport provision for individuals and businesses all over the country. It is further defined in a set of Transport Policy Objectives

- Accessibility: The transport system shall meet the basic transport needs of individuals and the business community.

- Quality: The transport system shall provide transport with a high level of quality for individuals and the business community.

- Safety: The long term goal is that there should be no deaths or serious injuries from accidents.

- Environment: The transport system shall be adapted for a good living environment for all, where the natural and cultural environment is protected from damage, and an efficient use of resources is promoted.

- Regional development: The transport system shall promote a positive regional development by reducing differences in development opportunities in different parts of the country, and by reducing disadvantages of long transport distances.

- Equal opportunities: The transport system should provide equal opportunities for women and men.

|  | Objective |  | Sub-objective |
|---|---|---|---|
| 1 | Economic efficiency | 1.1 | Economic efficiency in land use and transport markets |
| 2 | Protection of the environment | 2.1 | Reduce energy use and avoid climatic change |
|  |  | 2.2 | Reduce local and regional pollution |
|  |  | 2.3 | Protection of valuable areas (green areas, cultural heritage sites) |
|  |  | 2.4 | Avoid urban sprawl |
|  |  | 2.5 | Reduce fragmentation (of settlements and habitats) |
|  |  | 2.6 | Protect vulnerable areas |
|  |  | 2.7 | Reduce noise |
| 3 | Liveable streets and neighbourhoods | 3.1 | Increase freedom of movement for vulnerable road users |
|  |  | 3.1 | Achieve positive external effects on social, cultural and recreational activity |
| 4 | Safety | 4.1 | Reduce traffic accidents |
| 5 | Equity and social inclusion | 5.1 | Accessibility for those without a car |
|  |  | 5.2 | Accessibility for the mobility impaired |
|  |  | 5.3 | Equity and compensation to losers |
|  |  | 5.4 | Economise on taxpayers money |
| 6 | Contribution to economic growth | 6.1 | Create a potential for economic growth |

**Table 1:** Objectives and sub-objectives (Minken et. al., 2003)

In a report the Swedish Institute for Transport and Communications Analysis (SIKA) (SIKA, 2000) develops the Transport Policy Objectives in terms of targets. The report points out that this does not solve the problem of trading off the different objectives against each other.

As a part of the PROSPECTS project the objectives in Table were developed with input from discussions with planners and decision makers in six European cities. They were tested in a Europe-wide survey (May et al., 2003) where they were found to be legitimate aspects of sustainability in line with our definition.

In this context it is also worth noting that the Implementation Plan from the World Summit on Sustainable Development in Johannesburg in 2002 says, under the heading of *Changing unsustainable patterns of consumption and production*, that we should

> promote an integrated approach to policy-making at the national, regional and local levels for transport services and systems to promote sustainable development, including policies and

> planning for land-use, infrastructure, public transport systems and goods delivery networks, with a view to providing safe, affordable and efficient transportation, increasing energy efficiency, reducing pollution, reducing congestion, reducing adverse health effects and limiting urban sprawl, taking into account national priorities and circumstances. (WSSD, 2002)

Each sub-objective in Table 1 can be represented by one or more indicators. The Methodological Guidebook (Minken et al., 2003, ch 3.3.2; Appendix II) offers suggestions on indicators for all of them. It is necessary to choose the appropriate indicators to use in each case, since some indicators sometimes measure the same thing and using them all would lead to double counting.

Missing from the list are some traditional indicators such as mode shares, vehicle-kilometres or person-hours spent on travel. There is a reason for that. They do not measure the level of achievement against any of the objectives we have set. They are more like proxies for the indicators we suggest and including them might bias the decision by double counting of effects. By using e.g vehicle-km[1] as an indicator we might end up focusing on reducing car traffic instead of reducing the negative impacts of car use. It is a distinction that possibly can lead to very different strategies.

Chosen indicators should be computable from model output. It is obvious that we need models to predict impacts of strategies in terms of indicators. What is less obvious is whether a specific model represents the system well enough that the computed indicator makes sense. Minken et al. (2003) discusses three levels of indicator. Level 1 is when an indicator forms a comprehensive measure of achievement against a sub-objective in Table 1. E.g. a cost benefit analysis is by definition a measure of economic efficiency. Level 2 is a quantified indicator related to a sub-objective. Level 3 is a qualitative assessment of a sub-objective.

With a concept as wide as sustainability is, there of course exist many other definitions and suggested indicators. Jeon & Amekudzi (2005) provides a detailed overview of many others.

# 3 Systems analysis and modelling

As I mentioned above, there are two levels to evaluation whether some policy is a good idea or not. We need to be able to predict what will be likely to

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[1] Note that vehicle-km can very well be an intermediate variable used for computing e.g. emission effects.

happen when the policy is introduced, and we need some kind of measure if that outcome is desirable or not. The discussions on sustainability above outlines the aspects of appraising the outcomes. Let us now turn to some methods of predicting the outcome of policies.

We begin with a very general description of what modelling is, from a systems analysis point of view (e.g. Quade, 1985), illustrated in Figure 2. Consider that we want to study a real world system, R in the figure. The reason can be either that we want to better understand the processes that drive R, or that we want to predict what happens to R if we introduce some changes to it. When we are concerned with sustainability issues, it is obvious that we cannot expect to be able to carry out experiments to see what happens. It would be a slight comfort to people in the lowlands in Holland and Bangladesh sitting around in boats a hundred years from now, that we wanted to experiment with emitting more $CO_2$ to see what happened. Instead we build a model.

When we construct a formal model, F, we have to determine what the important features of R are. A good model works the same way a good caricature does. It brings out the important characteristics without adding every little detail. The features are represented by specifying variables, by specifying functional forms for relationships between the variables. We also have to specify the system's boundaries. However much we want to we cannot build a model of everything. We use the term *coding* to denote the process of representing R in mathematical formalism, creating F. This is where the perhaps most important step in systems analysis comes in. Defining the boundaries of the system.

The causality of R, i.e. if we do *this* to R *that* will happen, has its counterpart in F in the mathematical logic of the model. After we have let the logic run its course we must use some caution when we interpret, or *decode* the results from the model. To use the caricature analogy again, you can recognise the person, but it would be unwise to use the caricature as decision support for plastic surgery. The point here is that when interpreting results it is important to remember what simplifications were made, and what effects it actually can represent, to avoid drawing conclusions outside the scope of the model. To push the analogy even further, a good caricature avoids adding to much detail to the background as well, which is why setting the boundaries of the system is so important. We shall see later that we are limited by the models from reaching measuring all the things we laid out in the previous section on sustainability.

There are several advantages of using mathematical models and computers in decision support tools. Mathematics forces preciseness in assumptions and the assumptions are possible to check by others. Computer models

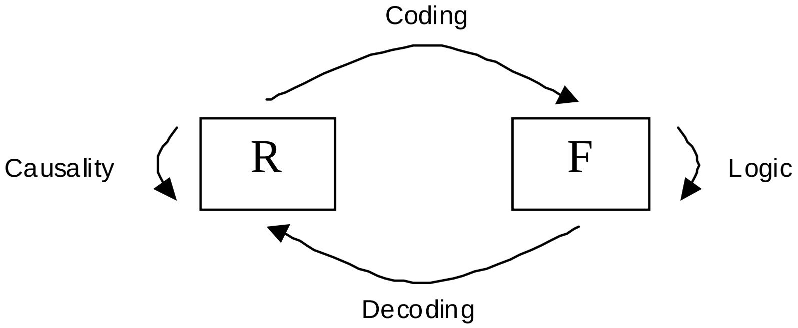

**Figure 2:** Coding and decoding: R is a real world system, F its formal counterpart (Karlqvist, 1999)

can contain huge amounts of data, and models made by different people with different skills and backgrounds. Models often help uncover gaps in our knowledge about a system, either because we do not understand certain mechanisms or that data is missing. A well made model is supposed to answer ”what if” questions. What happens to the system if a certain strategy is implemented. But what is even more powerful, is that many different strategies can be investigated.

## 3.1 Positive or normative?

In economics and related fields models and theories are sometimes classified into *positive* or *normative*. The former concerns *what is* while the latter *what should be*. There is a deeper epistemological debate whether a positive economics really is possible, but it is very much outside the scope of this thesis. However, it is useful to remember the warnings of Myrdal (1953), that economic models are riddled with assumptions that may sometimes confuse facts and judgements.

Throughout the papers in this thesis, the assumption has been that the models do not necessarily tell us that people are utility maximising. It is enough for our purposes that their decision making processes make them behave *as if* they were utility maximisers. The purpose of our models is to say something about behaviour in the aggregate, not on the individual level.

There is a more practical level of the positive/normative division, though. It is perhaps difficult to know whether a model contains hidden value judgements, but some things are explicitly normative. From the point of view of using models to produce decision support there will inevitably be value judgements involved. As far as possible these belong to the appraisal framework, if for no other reason, because then the decision maker knows where to find them. The remaining hidden values will to some extent be a matter of trust between the modeller and the other stakeholders.

Consider, for instance, a cost benefit analysis of some transport infrastructure change. Ideally, the valuations used for the various impacts and benefits are the true social costs of each. However, in practise, there may be disagreements on what should be included or not in these costs, or how to estimate them. It means that someone will have to make a judgement call on these valuations.

It is often a problem communicating results from large scale models to decision makers or the public. The results are often distrusted because the model is too complicated in the eyes of the decision maker. With a simple model it is easier for the non-professional to have an opinion on assumptions and behaviour. With a complex model it is more a matter of trusting the modeller. A way of earning that trust is to validate the model. Lundqvist & Mattsson (2002) discusses this in the context of national transport models.

# 4 Land use and transport interaction

The interaction between land use and transport is both obvious and very complex. The obvious part is that there is interaction and interdependence. The transport arising from people getting to work depends on where they live and where their jobs are located. The transport flows from food distribution will depend on where it is produced, where food is sold, and where people's kitchens are located. In this way it is possible to identify many such cases where there is an obvious connection between land use (or location) and transport. But the complexity of the issue also becomes apparent fairly quickly, because it is equally obvious that the locations of food sellers depends on the transport system around it, and that the spatial distribution of jobs will be uneven, with many jobs located where the transport system provides easy access. So, the question becomes what causes what, and how much?

A distinct feature of the of the urban land use and transport system is that different processes, or sub-systems in modelling terms, operate on very different time scales. Wegener (1998) identifies nine such sub-systems:

- Very slow change: Networks, land use
- Slow change: Workplaces, housing
- Fast change: Employment, population
- Immediate change: Goods transport, travel behaviour.

- Very slow to immediate: Environment

Infrastructure networks take years to build and last for decades. Land use patterns tend to be slow to change since any new development or change in use is determined by the surrounding land use. Industrial sites do not mix well with housing etc. Buildings for workplaces and housing also last a long time, sometimes even longer than roads and other infrastructure, but conversion between different uses can react to changes in demand at a faster rate than the actual turn-over of buildings. The firms and people using the buildings change even faster, as firms open and close, and people go through different stages in their lives. From a land use and transport perspective, goods transport and travel decisions are immediate effects.

The urban environment feature changes on vastly different time scales, e.g. an oak forest can take centuries to grow, while the noise levels at a city intersection can vary from hour to hour. Often environmental effects are modelled as effects originating from one of the other eight subsystems. It is perhaps beyond the scope of land use and transport models to also include interaction between different environmental processes, but an open model system can provide useful data for other models.

## 4.1 A web of models

Many research traditions have tried to analyse how urban development and transport work. Different relationships have been focused on depending on the the viewpoint of each.

Urban economics has its beginnings in von Thünen's (1826) land rent analysis, where he explains differences in land rent and crop choice by relating them to the distance to market. Alonso (1964) developed the theory to a more urban setting. A central concept here is that of bid-rent, which is the maximum amount a household can pay for a piece of land given that they need to travel, and keep a certain utility level. More recent developments on using bid-rents to explain household behaviour include Martínez (1992) and Waddell (2002).

Mainstream economics has been relatively unconcerned with the spatial dimension. Krugman (1993) explains the differences between how trade theory and urban economics view the world, and what they could learn from each other. Fujita, Krugman & Venables (1999) develop these ideas, explaining location choices using models of monopolistic competition and scale economies. See also Fujita & Thisse (1996). The transport, housing and labour markets in transport and land use models have usually been treated as separate from the rest of the economy. Some attempts have been made to put the transport and land use into a general equilibrium setting. An example of such a spatial computable general equilibrium model (SCGE) can be found in Bröcker (1995). SCGE is often the method of choice for models of goods transport.

From the needs of transport engineering to cope with quickly growing cities there grew a modelling tradition based on spatial interaction. Hansen's (1959) model was inspired by an analogy to gravity, where the households tended to gravitate toward employment. The residential pattern was a function of accessibility to employment. The term gravity model is still very much in use. In Lowry's (1964) model we can see the use of many gravity type models of different sectors of the urban system linked together, which is a very common feature in today's integrated land use and transport model. The models used in this thesis are no exceptions.

A reason why gravity modelling is still in business is that it was possible to arrive at from other assumptions than the somewhat ad-hoc gravity analogy. Wilson (1967) introduced a statistical justification. His example concerns the problem of trip distribution in a system subdivided into zones. A known number of departures, or trip *origins*, are to be connected to an also known number of arrivals, or trip *destinations*, given some known measure of impedance between zones (distance or time or some combination of them) and a known aggregate cost for the system as a whole. He shows that these constraints together with some natural statistical principles give rise to a trip distribution of the type seen in gravity models. The method is analogous to entropy maximisation in statistical mechanics. The trip distribution of Wilson's gravity model is the most probable in the same sense that the air molecules of a room are spread approximately even over the whole room. Snickars & Weibull (1977) further broaden the theoretical base by approaching the problem from an information minimisation perspective.

Where the gravity approach relies on reproducing system behaviour at an aggregate level, the random utility approach starts out from behaviour at the individual level. McFadden (1973) applied ideas from experimental psychology to a transportation setting deriving the real work-horse of econometric models, the multinomial logit, and extending it to the more general General Extreme Value (GEV) model class (McFadden, 1978). With the random utility approach the transport models were given a micro-economic foundation, and robust and efficient methods of parameter estimation could be developed. The economic under-pinning of the random utility models (RUM) is also important for consistency when we want to do welfare analysis. For welfare analysis in RUM see also e.g. McFadden (1978) and Karlström (1999).

Anas (1983) and Mattsson (1984) show that the distinction between gravity models and random utility models often only is superficial, in the sense that the multinomial logit model is derivable from both principles of entropy and random utility maximisation. It is often the case that scholars using aggregate data use the terminology of gravity modelling and users of disaggregate data formulate the model in random utility terms.

## 4.2 Trip based transport models

Gravity models and RUM have traditionally been used in a transportation setting envisioned as a four step process. While it used to be distinct steps, in state-of-the-art models it should be regarded as four choice dimensions.

- *Trip generation* predicting the number of trips originating in each zone.
- *Trip distribution* allocating destinations for each trip.
- *Mode choice* determining modal split in the system.
- *Route choice* assigning the flow of trips on the transportation network.

The three first are commonly dealt with in a nested logit model, with one or more nests representing each step. The fourth is usually treated as a separate problem, but combined models including all four exist (Wegener, 1986; Lundqvist, 1998; Hanley & Kim, 1998). The route becomes important because of congestion in the system. More travellers on a link in the network, leads to an increase in travel time for all travellers on the link.

The solution algorithms ensure that the flows adjust to an equilibrium where no-one can become better off, in terms of generalised travel cost, by unilaterally changing their behaviour. This is called a Wardrop (1952) user equilibrium, which is also equivalent to the more well known Nash equilibrium. In a system with no congestion effects this would also coincide with the systems optimum where the total cost is minimised. In the presence of congestion this may longer be true, since travellers make their decision based on the inconvenience they experience, and not on the extra inconvenience they cause the other travellers. Congestion pricing aims at closing this gap.

## 4.3 Land-use models

Many early modelling approaches, such as Lowry (1964), and McFadden (1978) were concerned with the location choices involved in the forming of a city's spatial pattern. But, perhaps because land-use planning tends to be more decentralised and fragmented, the field has been dominated by transport demand modelling, with transport and land-use models rarely being used in practical application.

Of the many operational models that exist most have some element of random utility theory to explain the actions of households and other actors in the system. For reviews see e.g Chang (2006), Hunt, Kriger, & Miller (2005), Batty (1994), Wegener (1994, 1998, 2004), Wilson (1998), or the meta-review in Klosterman (1994).

## 4.4 Activity based approaches

Models and methods developed to solve the transportation problems of the 1950's through to the 1970's when the primary goal was to provide enough infrastructure, tend to run into some difficulty today when the focus has shifted to sustainability. Perhaps most evident is the trouble of representing the impact of new types of policy instruments. We can take pricing measures intended to decrease congestion in a city as an example.

Let us say that we introduced a scheme where the cost was high during the morning and afternoon peak hours, but low in between. Traditional four step models immediately run into two problems. The first is they seldom treat the choice of departure time at all, and if they do the statistical, ”faceless” treatment of people have trouble dealing with the various constraints faced in this choice, e.g. fixed or flexible work hours, children's school hours etc. The second problem is in the network assignment step, where a dynamic departure time requires other methods than user equilibrium (Ran & Boyce, 1996).

The first problem is explicitly being addressed by the activity based modelling approach, where an attempt is made to model the activity pattern over a whole day or week. Activity based models often trace their ideas back to Hägerstrand (1970), who pointed out that statistical modelling in regional science overlooks the fact that if a person is at a certain location one moment she cannot be at a totally different location the next. Given that a person needs to be at home or at work at regular intervals, there is only a limited volume of space-time available to that person. These constraints have a profound impact on location and transportation choices. Considerable research efforts have been invested in this approach, see e.g. Algers et al. (2005), or McNally (2000). Some operational activity based models exist e.g. ALBATROSS (Arentze & Timmermans, 2000) where the scheduling of a days activity is explicitly modelled, or the Portland model in which the RUM framework has been extended to take a day's activities into account (Bowman & Ben-Akiva, 2001).

One promising solution to the second problem mentioned above is dynamic simulation of the transportation network. Micro-simulation is not only an option for solving the network assignment problem, but it is also a choice for modelling location and employment decisions, that shows some promise (TRANSIMS, 2003; Nagel & Raney, 2003). It has a downside, that it shares with many activity based models, that the methods of estimation and calibration are not well developed. Random utility models have also moved towards microsimulation as a way of overcoming computational problems involved when the nesting structure gets complex and the number of alternatives grows (Vovsha, Bradley & Bowman, 2005).

# 5 Reflections on the appended papers

The papers of this thesis are all attempts to address some problem or develop some idea from the previous sections. The first two papers (Jonsson, 2008a; Robèrt & Jonsson, 2006) use existing modelling tools, but experiment by using innovative appraisal frameworks to analyse some aspects of sustainability. The first tries to address intergenerational fairness, and the second is focused on $CO_2$ targets.

The third and fourth papers concern model development. Paper III (Jonsson & Karlström, 2008) is an attempt to put a microeconomic foundation to an activity based model (ABM). ABM may well become necessary to be able to analyse many new transport policies, where departure times, and time constraints are important. The fourth paper (Jonsson, 2008b) describes a model system that addresses the problem that transport policies often are analysed without taking long term land use effects of the transport policy into account. The fifth paper (Jonsson, 2008c) is the first attempt to use the model developed in Paper IV for the same kind of analyses that were done in Paper I and II. It shows, among other things, the power of being able to tell *when* things happen, not only what and where.

## 5.1 Paper 1: Analysing sustainability in a land-use and transport system

Paper 1 addresses a fundamental concern associated with long term sustainability. Usually sustainability is described as having three parts, economic, ecological, and social. But even more central, and spanning these three, is the concept of fairness between the people living now and future generations. While economic and, at least some, environmental impacts of urban policy are considered when projects are evaluated, the intergenerational fairness is often lost because of a requirement to do a cost-benefit analysis (CBA). Since CBA uses discounting it is inherently biased such that the impacts on current generations will be more important to the final evaluation, than will the impacts that happen far in the future.

The results show a slightly different ranking of strategies for the sustainability objective function. This has less to do with the objective function, and more to do with using a static model where we will get a really good representation of when costs and benefits show up. Also, if we e.g. would assume that costs of global warming would be higher in the future than they are today, it would also change things.

The methods used in Paper 1, developed as a part of the EU project PROSPECTS is an attempt to address the intergenerational fairness issue, and at the same time use optimisation methods to find an optimal set of policies. The intergenerational fairness is inspired by the approach of Chichilnisky (1996) As discussed in Section 2.2 above, it fulfils an attractive set of axioms: A sustainable outcome should be neither a dictatorship of the present, nor a dictatorship of the future. It is treated in the urban policy setting by adding an non-discounted horizon year, representing the far future, to the net present value. Or more precisely, the objective function that we optimised was a weighted sum of the net present value of the whole evaluation period and a non-discounted horizon year.

The approach was tested on a full-scale transport model SAMPERS, used together with a land-use model IMREL. To compute the PROSPECTS objective function the model system was applied twice, once for the year 2015, and once for 2030. Because the model system is computationally demanding, each such evaluation of the objective function takes a long time. A response surface method, where an orthogonal experimental design was used to plan what combinations of policies to test, turned out to work really well. The possibility to plan computer experiments in advance is extra useful when each model run requires manual preparation.

## 5.2 Paper II: Assessment of Transport Policies toward future emission targets

Paper II also experiments with combining the transport model SAMPERS with an innovative framework to evaluate the outcome of policies. The framework is inspired by backcasting, which is a very useful method of analysing scenarios of the future. The backcasting viewpoint is to take future situations where the planning targets are fulfiled as the starting point. Combining this with forecasting models, which we use to fill in the paths from today to those future states, is an excellent way of making sure that the future scenarios are consistent with what we know of travel behaviour through these transport models.

The study presented i Paper II considers what it would take for Stockholm to reach their long term goal in terms of greenhouse gas emissions. The results show that even with quite sharp policies in place it will be necessary that half of automobiles must be powered by $CO_2$ neutral energy sources.

The discussion on the potential for mobility management services, becomes even more urgent in light of recent spikes in oil prices combined with increases in food prices partly driven by the demand for bio-fuels. Also troubling reports on the viability of some bio-fuels as methods of reducing $CO_2$ emissions contribute to this picture.

## 5.3 Paper III: SCAPES - A dynamic microeconomic model of activity scheduling

Paper III demonstrates a prototype of a microeconomic approach to model activity scheduling. A model of this kind would be really useful when assessing the welfare impacts from such things as travel time uncertainty, or flexible working hours. Other things, like departure time choice and within-day replanning can also be studied. These issues become more and more interesting as cities around the world are reaching a point when it is not possible to build more infrastructure to cope with peak demand. Instead demand management policies are increasingly considered. Current models of demand are limited when it comes to analysing these things, since they rarely include departure time explicitly.

The approach we propose is based on formulating each day as a Markov Decision Problem. It hinges on the assumption that there are a large, but limited and tractable, number of states an agent can be in each day. The Markov property requires that the agent does not need to remember the path used to reach the current state. All necessary information to be able to decide where to go next should be contained in the state itself, and in the values attached to the potential states reached after a choice is made.

In Paper III we develop a prototype model that shows that the method is workable. The main conclusion from the experiments is that the agents show reasonable behaviour with surprisingly little calibration. The most important result for future research activities that the model implies a value of time that varies with the state the agent is in, e.g. by time of day. It is, however, quite some way to go before a model of this kind could be operationalised. The first hurdle to overcome is to estimate the model. The introduction of a random utility term in each choice of action during the day means that we can use known methods for the estimation. But the model is still a very complex network of choices, which means that estimating it will probably be quite a challenge.

From the perspective of land-use and transport interaction, it is likely that accessibility measures derived from models with a better representation of the space-time constraints that people face could better explain what development makes people dependent on cars and what promotes walking, cycling, and transit use. Another area where models of this kind would be very useful is in analysing reliability, because their ability to estimate the welfare effects of having to re-plan the schedule because of an unexpected event.

## 5.4 Paper IV: LandScapes – A transport and land use model of Stockholm

Paper IV describes the new model system LandScapes. The main difference with earlier, similar models used in Stockholm, is that it is dynamic, in the sense that changes in land use patterns develop over time, interacting with the transport system along the way. It also integrates housing location decisions and transport decisions by using the same set of agents for both choice situations. This is useful for future welfare analyses.

The transport system is modelled using a fairly traditional approach. The travel demand is modelled as a multidimensional choice of trip frequency, mode, and destination choice. The demand is assigned to a multi-modal transport network using network equilibrium assignment. At equilibrium between transport demand and supply, we can compute accessibility measures for all agents. These are then used as an input for the land use models.

The land use models use the accessibilities as an explanatory variable in the location choices, together with other properties of the zones where location is possible. The employment location model locates employment based on accessibility and the available land zoned for non-housing purposes. In this version of LandScapes, there is no endogenous construction of commercial floorspace depending on where demand is high. Instead, the employment can be constrained to upper and lower limits, set exogenously.

Each year a subset of the population is moving, determined by moving probabilities that depend on their socio-economic properties. These moving individuals want to locate where accessibility and other attractiveness is high, and where prices are low. But, there is a limited supply, consisting of houses vacated by other people moving, and new construction. The demand and supply each year is brought to an equilibrium by solving a system of equations in prices.

## 5.5 Paper V: Policy application and validation of the transport and land-use model LandScapes

Paper V reports on the first policy applications of LandScapes. Two questions are at the forefront in these applications. First a few comparisons against traffic counts and other data available before and during the congestion charge trial carried out in Stockholm in 2006. The evaluation data available from the congestion charge trial is an excellent opportunity to test the model's short term adaptation to a change.

Furthermore, LandScapes is applied to a few long term strategies. The question is how big the impact is from having land-use and transport interacting over time. A related question is how much potential is there to use land-use planning to affect transport outcomes. The strategies have been designed to have some relevance to current planning in Stockholm, but the purpose has not been to evaluate them fully. Rather, they serve as an illustration of the potential impacts from each strategy, since the details of each strategy may need more elaboration.

The results from the policy applications show that LandScapes does well in replicating the short term results from the congestion pricing experiment carried out in Stockholm in 2006, on measures like vehicle kilometers, mode shares, and the changes on inner city streets due to the congestion charges.

The long term results show off the power of tracking changes over time. It is clear that if Stockholm is to grow as fast in the future as it has in the past, there is little chance that transport or land use policies can curb $CO_2$ emissions in the medium term, by themselves. It reinforces the message from Paper II, that a technological shift towards climate neutral fuels will be necessary. Land use planning will have some impact, though. A more dispersed, multi-centric, land use will have positive effects on user benefits, which in our case is directly tied to accessibility, but will inevitably increase car use as well.

# 6 Conclusions

Papers I and II has their main focus in trying out new appraisal frameworks. In Paper I it is the PROSPECTS attempt to treat intergenerational fairness, and in Paper II we experiment with a backcasting inspired framework. There are, however some clear policy messages as well. From Paper I we get the clear message that from a sustainability point of view we should increase fuel taxes. It also suggest that combining that with an increase in transit frequency is even better. The optimisation method used in Paper I also gives us sensitivity information that of those two policy dimensions, the fuel price is the more effective policy.

The model development papers, Paper III and Paper IV, offer less in terms of policy conclusions. On the other hand, from a research point of view they highlight many new avenues of future research because, in the process of building new models, you come to realise where the shortcomings of the current approach are. The models of both papers offer improvements in welfare analysis. In Paper III it is the by giving the planning of activities (and the travel they induce) a microeconomic foundation. In Paper IV it is the common treatment of individuals in both transport and housing choices.

The strongest message from Paper II is that if we want to be on track to reach the long term goal of no carbon dioxide emissions in Stockholm in 2050, we need to have replaced at least 50 percent of vehicle energy use with completely $CO_2$ neutral energy sources. This is on top of other measures that reduce car traffic, such as a substantial increase in fuel taxes.

Paper V confirms these findings nicely. In it only a few policies were tried, but from them the only scenario that led to decreased emissions of $CO_2$ per capita was an increase in fuel price. And it only slows the increase in total emissions in Stockholm, since the population in the metropolitan area of Stockholm is expected to continue to grow.

There are many interesting directions future research can take from here. The most obvious is to continue to refine the models presented in Papers III and IV. In particular, the model in Paper IV, is still in its early stages, where many improvements are relatively straightforward to implement. The scenarios presented in Paper V represent a first look at the kind of results LandScapes can produce, but these can be developed further, together with the planning community in Stockholm. It would also allow us to compare and contrast the results with other approaches already used in the planning process. With the Scapes model in Paper III the first thing would be to estimate the model on some sample of individuals. With better parameter estimates, the model could provide very interesting answers on how travellers valuation of time varies with the time of day, and in how travel time uncertainties are valued.

In summary, this thesis contributes to the research on the tools for modelling and appraising transport and land use policies. The studies underline the great challenge cities face in trying to move towards sustainability. Population growth and economic growth are powerful drivers of more travel, and it is likely that many different policies used together will be needed to limit the negative impacts of that travel. But, ultimately, these decisions are in the domain of the political process. Research, such as the work presented in this thesis, can hopefully help making better informed decisions.

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