Sustainable Urban Development
Forecasting and Appraisal

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Abstract

Achieving urban land use and transport systems that are sustainable in the long run poses a challenging problem to decision makers and planners. The Fifth Framework EU project PROSPECTS was aimed at providing the guidance cities need to tackle this challenge. The main output of PROSPECTS consists of three guidebooks, a Decision Makers’ Guidebook, a Methodological Guidebook and a Policy Guidebook. The guidance was tested, in case studies on real cities, by the partners of the project. This thesis reports on one such case study carried out in Stockholm.

The thesis consists of four main parts. The first part includes a summary of the guidance, but also some context and general background of the models and methods used. The intention is for the thesis to be self-contained, but to be brief on things that are readily available in the guidebooks. The main concepts are introduced, in particular a set of objectives that forms the basis for PROSPECTS appraisal of sustainability. Some of the theoretical foundations of the methods and models used are also outlined.

The second part contains the case study. The PROSPECTS approach is based on indicators measuring how well a strategy fulfills the set of objectives that describe sustainability. In order to do that, it is necessary to use models to predict the impact of a strategy. Two existing models, SAM-PERS and IMREL, were integrated specially for the Stockholm case study. PROSPECTS also suggests an appraisal framework to help in the decision process. The implementation of that framework is described, together with how an objective function is formed as a tool to rank strategies with respect to objectives. Using an objective function opens up the possibility of using formal optimisation to generate suitable strategies to test. In this thesis we have used a Response Surface Method to optimise the sustainability objective function.

Part III describes the estimation and calibration carried out as a part of the development of the integrated modelling package. The thesis’ fourth and final part provides some general experiences and also suggests some ideas for future research.
Acknowledgements

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I am especially indebted to the PROSPECTS team. The work in this thesis draws upon the experience and work of the members of that team. It has been a pleasure working together.

A nice working environment is of paramount importance, and by that I mean the people, not chairs, tables and stuff. My colleagues at the Unit for Transport and Location Analysis deserve all the smörgåsstända they can eat, for making TLA a great place to work. In particular I thank Staffan Algers and Lars Lundqvist for their many constructive comments at the final seminar. I am also grateful to Kerstin Pettersson for sharing her expertise on Stockholm’s transport network.

And finally, I would like to thank my friends and my family for their support. I think my parents deserve special mention for their encouragement, back when their ten-year-old son was convinced mathematics was the worst subject ever.

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Stockholm in November 2003
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1 Introduction

It is an increasing concern to decision makers, planners and the public that the way our cities are functioning is not sustainable in the long run. The threat of global warming from the emission of CO₂ into our atmosphere is perhaps what first comes to mind, but other things, more local in nature are also arguably not in line with what we mean by sustainability. Examples range from the local effects of transportation in the form of noise, accidents and local pollution to the increasing time people are wasting in their cars on congested roads or problems with segregation between communities in a city.

The work presented here was carried out as a part of the fifth framework project PROSPECTS. The main output of PROSPECTS consists of three guidebooks, a Decision Makers’ Guidebook (May et al., 2003), a Methodological Guidebook (Minken et al., 2003) and a Policy Guidebook (PROSPECTS, 2003). PROSPECTS was aimed to provide cities in Europe with guidance on how to plan their transport and land use systems for sustainability. It was recognised from the outset that it is necessary to analyse these two systems in an integrated approach as they are very much dependent on one another. The PROSPECTS approach to planning for sustainability encompasses the whole planning process, from defining the objective to monitoring and assessing the outcome of decisions. A logical structure identifying the key steps in the process is an essential part of the approach.

This thesis has its core in a case study carried out in Stockholm, testing the guidance of the guidebooks. Besides reporting the findings of the case study, is intended as a sort of companion document to the Methodological Guidebook (Minken et al., 2003), in the sense that it builds upon its guidance and provides some useful examples from an application of it. The structure reflects this. Part I gives an outline of the PROSPECTS approach to planning for and appraising of sustainability in the transport and land use system. We intend it to be self-contained, but some of the details are left out as they are readily found in other PROSPECTS documents. There is also a more general discussion on modelling and decision support tools used in the land use and transport context.

Part II details the case study carried out in Stockholm, giving examples of the practical considerations involved in applying PROSPECTS guidance. Part III deals with some development issues concerning the modelling tools used in the case study. In part IV we collect some general experiences from applying the PROSPECTS framework and provide some ideas for future work.

The appraisal framework was developed without having a specific modelling package in mind, in order to avoid our guidance on modelling being
too prescriptive. This flexibility in the evaluation framework, where it is usable with a wide range of modelling tools, also means that it is not tailored to any of them. Implementation requires adaptations to be made to the evaluation framework as well as to the modelling package. Some necessary considerations and assumptions will be addressed in this thesis.

In the Stockholm case study we have chosen to use an existing transport model and enhance its capabilities by pairing it with a land use model. We discuss some of our experiences from the development of the modelling package, which might be of some use for others in a similar situation.
Part I
PROSPECTS framework
2 Operationalising sustainability

2.1 Decision making context

Before going into the details of how to treat sustainability in a transport and land use context it is necessary to point out that the sustainability definition is to be used in a wider planning context. The decision making needs and practises of European cities were investigated in a survey of some 60 cities (May et al., 2001). This, together with more detailed discussions with six cities*, formed the basis for the logical structure we suggest.

We summarise some of the main points of the guidance available in PROSPECTS’ A Decision Makers’ Guidebook (May et al., 2003) below, but suggest reading the Guidebook for a fuller explanation. Three broad types of decision making was identified, vision-led, plan-led and consensus-led. These are seen as a kind of middle ground between a completely rational view of decision making at one end of the spectrum, and an approach of ”muddling through” at the other end†.

The vision-led approach depends on a leading person or group with a clear view of what the future should look like and what policy instruments are needed to get there. It is only a matter of implementing it. A plan-led approach starts out from problems to solve or objectives to reach. A structured procedure is used to compare different solutions and select the one performing best. A consensus-led approach resembles the plan-led approach, but consensus among all stakeholders is sought for some or every step of the process. May et al. (2001) reports that most commonly used in European cities is a mix of the plan-led and consensus-led approaches, followed by a mix of vision-led and plan-led.

The logical structure for planning suggested by PROSPECTS is intended primarily for plan-led decision making, but elements are useful if other approaches are in use as well. 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 lays out the groundwork for

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*Each PROSPECTS partner worked with a city. The cities were Stockholm, Edinburgh, Madrid, Helsinki, Vienna and Oslo.

†A rational view assumes that there is a best solution, and runs into difficulties with many stakeholders and conflicting preferences and objectives. The ”muddling through” involves no planning. Problems are solved as they crop up. There is no telling if such an approach moves in a direction towards sustainability, but is seems unlikely
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. We discuss this in section 2.5.

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 of this thesis.

Finally, the decisions should not be left without monitoring the implementation, and evaluation of the outcome, but that is outside the scope of this thesis.

2.2 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. As we shall see later, the PROSPECTS approach 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.

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 CO₂ 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 CO₂ case it means that we will have to derive the cost on the environment of emitting a kg of CO₂ 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.

2.3 Objectives

While a definition is a useful starting point to explain what we mean by sustainability, we need more detail to guide us in choosing a strategy for the future. The planning structure we suggested in the previous section starts out by specifying objectives. Our over-arching objective is a sustainable land use and transport system.

The following objectives were developed with input from the core cities. They were tested in a Europe-wide survey (May et al., 2001) where they were found to be legitimate aspects of sustainability in line with our definition.

- Economic efficiency
- Protection of the environment
- Liveable streets and neighbourhoods
- Safety
- Equity and social inclusion
- Contribution to economic growth
- Intergenerational equity

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. (United Nations, 2002, p. 9) which is well in line with the approach we have adopted in PROSPECTS.

2.4 Indicators

For practical purposes it is useful to divide the objectives into sub-objectives. Some suggestions for the first six objectives are offered in table 1. Each sub-objective can in itself 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-kilometers or person-hours spent on travel. There is a reason for that. They do not measure the level of achievement against any of the

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

Table 1: Objectives and sub-objectives (Minken et al., 2003)
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* 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. We will return to this matter in sections 4 and 8.1.

The Methodological Guidebook 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.

2.5 Strategy formulation

We would like to stress that we are concerned with appraising the extent to which strategies are sustainable, not single policy instruments. By strategy we mean a package of policy instruments. There are at least two compelling reasons for considering packages.

Sometimes two instruments can reinforce each other, or one instrument decrease adverse effects of another instrument. Finding such synergies becomes increasingly important as the focus in transport planning shifts, from providing enough roads, to include all aspects of sustainability.

It is often the case that there are barriers to implementation of an instrument. There are mainly four categories of barrier:

Legal and institutional barriers often arise from split responsibilities between different agencies of levels of government. There can also be direct legal barriers.

Financial barriers can be in the form of budget restraints on investment or on operation and maintenance costs. They can also come from constraints on how capital can be raised, or how revenues from other instruments can be used.

Political and cultural barriers include public opinion or pressure from special interest groups. It can also be a matter of cultural differences in public attitude to planning and enforcement.

*Note that vehicle-km can very well be an intermediate variable used for computing e.g. emission effects.
Practical and technological barriers. Sometimes management and administration of an instrument can be a barrier in itself, or finding the right technical solution to implement.

Packaging instruments into strategies can often help overcome barriers. One instrument can help finance another, or pairing an unpopular instrument with a more acceptable one can help sway public opinion. In this way a better overall strategy can be implemented than if each instrument was analysed separately. But instruments can also cancel each other out. The important point is that it is necessary to study policy instruments as packages, not individually.

It is also necessary to consider the long term aspect of planning for sustainability. Barriers we face today may well not be there a decade or two in the future. Technology and public opinion are two examples. Legal or institutional structures are also possible to change on the time scales we are dealing with. So while barriers are important, for the purpose of analysis it is useful to test what happens without them.

We make a clear distinction between strategies and scenarios. Simply put, the scenario is the things kept fixed, and the strategy is the things we change. The overall economic development and technological change will have to be part of the scenario, since it is not likely that the decisions in a single city will have enough impact on global development. But also the modelling tools used will influence what is considered scenario variables and what is considered to be part of the strategy. In traditional transport models land use was treated as a scenario variable. Different transport strategies were tested in fixed land use scenarios. By introducing a land use model the land use instead is affected by, and becomes part of the outcome of, implemented strategies. It also opens up for the possibility of a wider set of strategies that includes land use measures.

It can be of interest to test a strategy against more than one scenario to check whether it is robust or not. But, it is very important to use the same scenario if we want to compare different strategies.

2.6 Appraisal framework

We have now come to the point where we can discuss the appraisal framework PROSPECTS suggests (Minken et al., 2003, ch. 3). The reason for introducing a framework is to facilitate comparison between different strategies. In general it is necessary even if only one strategy is studied, since it must be compared to what happens in a do-minimum, or do-nothing, situation. Thinking in terms of strategies also introduces a lot of possibilities to combine instruments and the need for a structured way of studying the
combinations.

The first and most basic framework is to present indicators of goal achievement in a tabular form with one row for each indicator and a column for each strategy. This is where the levels discussed above comes in handy. Including more than one first level indicator per sub-objective would invite the risk of double counting, since a first level indicator should cover all important aspects of a sub-objective.

If there are no first level indicators, or they are deemed inappropriate, it is up to the planners and professionals involved to decide on the sufficient number of second or third level indicators. A presentation of indicators leaves the rest to the decision maker, as there is no formal criterion ranking the strategies. A drawback of this is that it leaves less of an audit trail. It is difficult to know what weights the decision maker put on different sub-objectives — even for the decision maker — since this is done subjectively.

The next thing you can do with an appraisal framework is to set target levels for certain indicators. Examples could be setting targets on air quality or preservation — or restoration if you will — of green areas. Setting targets is useful if there are compelling reasons for doing so. Medical evidence of harming effects of local pollutants is perhaps such a case. However, when setting many targets, there is always a risk that none of the strategies meet all of them. Conversely, it is also of limited use if the targets are met by a lot of strategies.

A further step in formalising the appraisal is to form a complete ranking of the strategies. If for instance many strategies fulfill a set of targets, we might be interested in some rule to help us decide which one of them to choose. It is done by forming an objective function. There are two main approaches in use in land use and transport appraisal, cost-benefit analysis (CBA), and multi-criteria analysis (MCA). Both formalisations share the advantage of setting explicit weights on different objectives. In a CBA the weights are set to reflect the stakeholders’ willingness to pay for (or the willingness to accept) the changes brought on by a strategy. In an MCA, on the other hand, non-monetary weights are set on the indicators of each objective, in order to study trade-offs between them. The PROSPECTS objective function, as we shall see in section 8.2, is based on a CBA, but with the option to include other indicators in an MCA fashion, or set targets on indicators (see section 9).
3 PROSPECTS in a Swedish planning context

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.

In a report the Swedish Institute for Transport and Communications Analysis (SIKA, 2000b) 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. We think that the PROSPECTS approach can help in this matter, since the objectives themselves are very much alike. The difference is mainly that of spatial scale. The Transport Policy Objectives were developed for the national level, while PROSPECTS is aimed at a regional level.

It is also worth mentioning that while the PROSPECTS framework might seem fearsomely complicated at first glance, in essence it is not much more complicated than an ordinary CBA. Planning authorities in Sweden have a long tradition of using CBA in general and transport models in particular, which means that thinking of sustainability in terms of objectives and an objective function should be relatively easy in the Swedish planning community.
4 Making forecasts

4.1 Modelling

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. Our approach to doing that requires that we in some way quantify the predictions. In its widest sense the term model can be used to describe any type of systematisation to recognise patterns. It can be the internal models we all have that makes us recognise a tree when we see it, or very abstract and mathematical models trying to describe and predict processes in the world around us. We will be concerned only with the latter here.

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.

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

the model. We shall see later that we are limited by the models from utilising the full potential of the PROSPECTS appraisal framework.

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 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, which is crucial to the PROSPECTS approach.

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. This is why we stress that the PROSPECTS appraisal framework and modelling examples should be thought of as only one part of a larger planning process.

4.2 Validation

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.

On the other hand, we cannot let transparency or democracy arguments dictate that models must be simple enough for everyone to understand them. We have to take it on faith that medical doctors and airplane engineers know what they are doing. No one in their right mind would require them to use only methods that everyone understands.

Lundqvist & Mattsson (2002) suggest a kind of a check-list for validating transport models:

- **Practical validation (system design and scope of application).** What is the system level? Which parts of the overall transportation system are included? Which mechanisms are endogenous and which are exogenous? What kind of resources (data, money, computers, competencies) have been and will be available? What kind of policy issues are and should be amenable to analysis. Is the system designed in a way that minimises the risk of unintentional misuse (data-checks, self-documentation, transparency, user-friendliness)?

- **Theoretical validation.** What is the theoretical foundation? Does the system use an equilibrium or dynamic approach? How are different submodels coupled to each other? Are the various causal relationships reasonably well modelled?

- **Internal validation.** How good are the models at reproducing the data on which they have been estimated (goodness of fit)? Are parameters of right sign and statistically significant? Is the responsiveness to changes in explanatory variables reasonable (sensitivity test)?

- **External validation.** Can the model system reasonably well reproduce other independent data (such as traffic counts if these data are not used for calibration)? Are elasticities of the model in accordance with what can be found in the literature? How well can the model system reproduce a future year (forecasting) or a previous year (backcasting)?

We try to answer the questions of the practical and theoretical validation in the general description of the models in section 7. The chapter on model development addresses the internal validation of the land use model. We have not attempted any explicit external validation.
5 Available tools

5.1 Theoretical foundations

Beside the general systems analysis view of modelling given in the previous section, we give an overview of the different theoretical fields that are commonly drawn upon in land use and transport modelling. There is no grand unified theory of regional science to fall back on and often ideas and inspiration come from more than one field. We will certainly not attempt a complete review here, but rather outline the main traditions we feel have some bearing on later, more technical sections. We give some suggestions of other reviews under the different sections below.

5.1.1 Urban economics

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 keep a certain utility level. More recent developments on using bid-rents to explain household behaviour include Martinez (1995) and Wadell (2000).

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, and also offer a historical background. 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 can be found in Bröcker (1995).

5.1.2 Gravity models

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. Our package is no exception.

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 broadens the theoretical base by approaching the problem from an information minimisation perspective.

5.1.3 Random utility econometrics

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 underpinning 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.
5.1.4 Network equilibrium

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; Kim, 1989; 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 is no longer 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.

5.1.5 Other 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. McNally (2000). Some operational activity based models exist e.g. ALBATROSS (Arentze & Timmermans, 2000) where the scheduling of a day’s 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, which also has impacts on validation.

5.2 Land use and transport interaction

The discussions in the previous sections have primarily dealt with transport models. There is widespread recognition, however, that land use and transportation should be studied together. 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 Batty (1994), Wegener (1994, 1998, forthcoming), Wilson (1998), or the meta-review in Klosterman (1994).

A distinct feature 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 day to day or faster. 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.
Part II
Case Study
6 Introduction

An important part of the PROSPECTS project was to test the methodology developed for sustainability appraisal in real cities. Each partner worked with a city to test some part of the guidance in the guidebooks. We applied a large scale transport and land use interaction model to Stockholm, which is an interesting city in many ways. It is the largest city in Sweden with, by Swedish standards, a very large commuting area around it. Increasing congestion problems together with an increasing interest in sustainability has opened up discussions on a range of policy measures. But, the planning situation in Stockholm is very complex, where it is difficult to reach consensus on strategic issues, something that perhaps better decision support tools might help alleviate.

There is a strong tradition in the planning community of using models as decision support tools. It means that data and models are available, and also that the planners are used to the type of studies we present here, including a healthy scepticism of model results.

For the purpose of this study we chose to integrate a transport model and a land use model. We chose the transport model, SAMPERS (Besar & Algers, 2002; Johansson Sveder, 2002), because it is a recently developed, state-of-the-art model. The land use model IMREL had been applied to Stockholm earlier with robust and reasonable behaviour (Anderstig & Mattsson, 1991, 1998). In-house knowledge of the models was obviously important as well, since we are putting them to a new kind of use.

We improve on previous decision support tools in several ways. SAMPERS and IMREL are in use today, but not together. Integrated tools for studying land use and transport are desirable when dealing with the long term future. We use an exact measure of user benefits in our welfare analysis instead of an approximation, with some caveats, see section 8.1.1. We use the PROSPECTS objective function to address long term sustainability, and finally we use optimisation techniques to generate and rank strategies.

7 Case study model package

In our modelling package the transport and land use system is represented by a collection of discrete choice models, representing the demand side of the housing, employment and transport markets, in which accessibility plays an important role. A network representation of the infrastructure represents the transport supply side. The supply of housing is in our model regulated by upper and lower bounds on the number of residents in each zone. The supply
of housing will affect the quality of a residential area since the attractiveness of a residential area is assumed to be inversely related to the housing density in the area. The model package uses an iterative process to find a state where both transport and housing markets are in equilibrium.

Even though the Stockholm model is rich in detail, it is conceptually fairly simple. There is essentially three sets of choices being modelled. One employment location choice, one household location choice, and a transport choice. Below we give a description of the models, but we leave some of the technical details for part III. The models themselves use SEK in 1997 monetary values internally, but in this thesis results are reported in euro, at the rate: $1€ = 9.2$ SEK.

7.1 SAMPERS

SAMPERS is a national transport model package. It was designed as a decision support tool for the Swedish National Road and Rail Administrations in their strategic infrastructure planning. It contains models at several spatial levels. There are models for international travel, domestic long distance trips and regional trips. Included in the package are tools for checking input data and analysing results. The analysis tools are CBA oriented, and indicators and results from them are very useful when assembling our appraisal framework.

We use the regional model in the package. In it the demand is subdivided into six travel purposes: Work, business, school, social, recreation and other trips. For each of them trip frequency, destination, mode choice and route choice is modelled. Like many present day transport models it is a model with four choice dimensions. The first three, trip generation, mode and destination choice, are represented by a nested logit structure. The route choice is found by iterating the discrete choice models with network assignment routines in EMME/2*. The assignment procedure finds the user equilibrium, where no individual can become better off by unilaterally changing behaviour, by solving an equivalent optimisation problem (Boyce & Daskin, 1997).

The transport system is represented by a network of road and public transport links connecting 99 zones in Stockholm county, stored in an EMME/2 databank. The 99 zone representation is a simplification from a more widely used 1240 zone representation. We opted for this simplification in order to decrease the overall run time of the model package. The necessity of doing so originates in the iteration between transport and land use, which leads to some 10-15 SAMPERS runs per SAMPERS/IMREL run.

*Information available from http://www.inro.ca
Zonal data on individuals and workplaces and other socio-economic details are kept in a separate database at a somewhat more disaggregate spatial level. It is based on Small Area Market Statistics (SAMS) data from Statistics Sweden, where Stockholm County is represented by 1240 zones.

### 7.2 IMREL

The land use model we use in our package is based on the mathematical formulation of the residential and employment model named IMREL in Andersstig & Mattsson (1991). The employment location model considers such things as accessibility to the labour force and dummy variables indicating if a zone contains large employers such as airports, universities or large hospitals. The housing location model takes employment location and accessibility into account while observing planning restrictions on the number of households in each zone. The spatial representation consists of 99 zones for Stockholm county, and the transport data used for accessibility measures is obtained from SAMPERS.

The author has developed a computer package programmed in Ox (Doornik,
specially adapted to be used together with SAMPERS. This IMREL version (IMREL 2.0*) relies on SAMPERS to export EMME/2 data in the form of text files. Socio-economic data on the other hand is read by directly accessing the SAMS database. Below we give a short description of the submodels.

7.2.1 Residential submodel

The residential submodel consists of a nested logit model derived from the assumption that the choice of residence is a combined mode and location choice of a random utility type. The deterministic part of the utility for an individual working in zone \( j \) of residing in zone \( i \) and using mode \( m \) when commuting to work is

\[
v_{ijm} = - \left( r_i + \mu \frac{H_i}{S_i} + a_m + b_m c_{ijm} \right)
\]

(7.1)

The first term, \( r_i \), is the rent level. The second term is the disutility associated with housing density and \( \mu \) is a parameter used to calibrate the location pattern to reproduce an observed pattern. \( \mu \) expresses how sensitive individuals are to housing density, given by the number of households \( H_i \) divided by available land for residential purposes \( S_i \). \( c_{ijm} \) is the generalised travel cost of mode \( m \), and \( a_m \) and \( b_m \) are estimated parameters, connected to mode. One worker per household is assumed.

Three modes are considered, car, public transport and a slow mode, which includes both cycling and walking. The generalised cost in the utility is a function of both time cost and monetary cost for the two motorised modes. The monetary car cost is simply proportional to travel distance. Since IMREL considers only work trips, we use equilibrium distance in the peak period, weighted at 0.14 €/km. Public transport cost is a weighted average of a monthly and a single fare.

Table 2 shows the values of time used. The estimates are the behavioural values from SAMPERS. We try to get as much consistency as possible between SAMPERS and IMREL, but there will inevitably be differences between the models. One example is a tax deduction car users can get under certain circumstances. SAMPERS takes it into consideration in its utility functions, IMREL does not. The total waiting time, for the public transport mode, is treated as a piecewise linear function, with different values of time for three different intervals. For the slow mode only the distance\(^1\) is

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*Code available from the author.

\(^1\)We assume that there is no congestion for slow modes so we use the shortest distance in the EMME/2 network, not equilibrium distances.
<table>
<thead>
<tr>
<th>Mode</th>
<th>Value of time [€/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car, total time</td>
<td>7.3</td>
</tr>
<tr>
<td>PT⁺, in-vehicle time</td>
<td>4.8</td>
</tr>
<tr>
<td>PT, auxiliary time</td>
<td>5.1</td>
</tr>
<tr>
<td>PT, total waiting time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>less than 30 minutes</td>
</tr>
<tr>
<td></td>
<td>between 30 and 60 minutes</td>
</tr>
<tr>
<td></td>
<td>more than 60 minutes</td>
</tr>
</tbody>
</table>

Table 2: Values of time used when weighting time and monetary together into a measure of generalised cost. Estimates from SAMPERS, 1997 monetary value. PT short for public transport.

considered, so the generalised cost is measured in kilometers.

The residential submodel in IMREL allocates the residents while observing planning restrictions consisting of upper and lower bounds (denoted $u_i$ and $l_i$) on the number of residents in a zone. But it is also a normative model because from the possible equilibria it chooses the one that maximises the aggregate expected utility of the system, or equivalently, the sum of consumer and producer surplus associated with the residential model, given by

$$V(H) = \sum_j W_j \log \left( \sum_i \left( \sum_m e^{-r^*_i(H)-\mu[m][\sigma_i]} \right) \right) + \lambda \sum_i H_i r^*_i(H)$$

(Anderstig & Mattsson, 1991) while observing $\sum_i H_i = \sum_j W_j$ and that $l_i \leq H_i \leq u_i$. $r^*_i(H)$ are the shadow prices or market clearing rents at the equilibrium, and $W_j$ is the number of workers in $j$. $\lambda$ is the logsum parameter from the nesting structure of the model. See also the estimation in section 13.

We see from the way the utility function is expressed, that the probability of choosing a residential zone is not dependent on the size of the zone. In behavioural terms it means that the individual chooses what zone to live in, not a specific house or apartment. An obvious enhancement to test would be to introduce another nesting level with a size variable, related to the number of available housing units in it.

### 7.2.2 Employment submodel

The employment location pattern is also modelled by a random utility model of the logit type. The utility function of locating in zone $j$, in equation (7.3),

\[ \text{The deterministic part. The usual assumptions on the distribution (IID, Gumbel) of the stochastic error term applies. See e.g. Ben-Akiva & Lerman (1985) for details.} \]
depends on accessibility to labour, $A_j$, and a number ($K$) of other indicators $I_{jk}$ of zonal attractiveness. $\rho_j$ is zone specific parameter that ensures that the number of workplaces stays within given planning restrictions.

$$v_j = \alpha A_j + \sum_{k=1}^{K} \beta_k I_{jk} + \rho_j$$  \hspace{1cm} (7.3)

Section 14 on estimation of the model describes the accessibility measure and the indicators we used. They included land area available for business purposes and dummy variables for extra attractive zones. The same argument applies concerning the possible inclusion of a size variable in this model as in the residential submodel.

It is necessary to point out that the employment model allocates an exogenously given number of workplaces, $W_{tot}$. Then the number of workplaces located in zone $j$ is given by

$$W_j = W_{tot} q_j = W_{tot} \frac{e^{v_j}}{\sum_n e^{v_n}}$$  \hspace{1cm} (7.4)

where $q_j$ is the probability of locating in zone $j$.

7.3 Integration

SAMPERS and IMREL differ largely in complexity and openness of architecture, since SAMPERS is a commercially developed package with an extensive user interface, while IMREL in this version, on the other hand, is a comparatively small program, without any user interface at all. This means that the IMREL code of course is the more flexible. We have built IMREL as a separate program, but tailored to be controlled from inside the SAMPERS interface where all the input parameters were specified.

The necessary communication between the two models is carried out through the two databases used for storing input data and results. Figure 4 shows how it is done. SAMPERS requires transport supply data in the form of time and cost matrices, stored in an EMME/2 databank and socio-economic data in MS-Access database tables. The results from SAMPERS are written back to the EMME/2 databank. IMREL reads its input data from the same sources, but its results are all written to the Access database.

7.3.1 Overview of a model run

1. Specify scenario. Economic and demographic development is specified in the SAMS database and infrastructure in the EMME/2 databanks.
2. Set policy instruments. See section 9.2 for details. This step could also include a car ownership model. In the PROSPECTS case study we have not done so, for technical reasons. Making sure that a parameter set in some part of the model was also set everywhere else proved to be one of the most challenging tasks in integrating the models. Adding the car ownership model would have meant another model where inconsistencies in parameter values could occur.

3. Run the transport demand model (the regional model in the SAMPERS package) and car network assignments to an equilibrium.

4. Run IMREL. This has four main parts
   
   - Read transport system data
   - Aggregate SAMS data
   - Run IMREL model
   - Disaggregate results into SAMS database

5. Compute indicators and objective function.

Iteration between 3 and 4 is carried out until an equilibrium is reached.

7.3.2 Aggregation and disaggregation

Some effort has been made to adapt SAMPERS and IMREL to work at the same level of aggregation for consistency and computational speed. Spatially this was done by aggregating the zonal system in the EMME/2 network.
<table>
<thead>
<tr>
<th>Data file</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car travel time</td>
<td>From network with congestion</td>
</tr>
<tr>
<td>Car distance</td>
<td>Distance matrix at equilibrium</td>
</tr>
<tr>
<td>In-vehicle time, PT</td>
<td></td>
</tr>
<tr>
<td>Auxiliary time, PT</td>
<td>Walking time on connectors</td>
</tr>
<tr>
<td>Total waiting time, PT</td>
<td></td>
</tr>
<tr>
<td>PT cost, cash</td>
<td></td>
</tr>
<tr>
<td>PT cost, monthly</td>
<td></td>
</tr>
<tr>
<td>Slow mode cost</td>
<td>Shortest distance</td>
</tr>
</tbody>
</table>

Table 3: Travel data exported from EMME/2 to IMREL. PT short for public transport.

used by the transport model (see section 15). The transport model uses detailed socio-economic stratification, while the land use model does not, which means that the data must be aggregated and disaggregated when transferred between them. When we aggregate the zonal system we lose some of the flow on the network, some of the inter-zonal trips becomes intra-zonal. To compensate we compared the flow on an aggregated and a non-aggregated network in the base year, and used the difference as extra volumes on the links.

**Punching EMME/2 matrices** Three EMME/2 macros write data from the EMME/2 databank to text files, in a standard EMME/2 format. These files are read directly by IMREL. The necessary variables are found in table 3. No aggregation is necessary in this procedure.

**Aggregation of SAMS data** In the SAMPERS package, economic and demographic data is stored in a MS Access database, coupled to SAMS zones. In Stockholm County there are 1240 such zones. SAMPERS then uses aggregation tables to sum the data to the desired zone system, on which the model will be applied. The same method is used by the program reading and aggregating SAMS data for IMREL. A program assembles an SQL* database query with the desired aggregation and data tables. The aggregation code is written as a dynamic link library (dll), linked into the IMREL code.

**Disaggregation of results** Before running the transport demand model again, the new land use pattern suggested by IMREL is transferred back to the SAMS database. The simplest solution to the problem of disaggregating IMREL results back to SAMPERS is to multiply each disaggregate zone

*SQL—Structured Query Language*
with the fractional change in the corresponding aggregate zone. It is not recommended though, because it can lead to a very strange behaviour, where the average income in the system changes with different spatial allocations.

We implemented an approach where people moved\(^*\) out of an aggregate zone are split up into socio-economic groups proportional to the shares the groups had in the zone before. These are drawn from the disaggregate zones in proportion to how many of that group there were in the aggregate zone in the previous iteration.

The land use model outputs a new location\(^\dagger\) pattern \(H_{I,n}\), at each iteration \(n\). \(I\) denotes the aggregate zones. We define the number of people moved out of an aggregate zone as \(M_I = |H_{I,n-1} - H_{I,n}|^+\), and the number moved into an aggregate zone as \(N_I = |H_{I,n} - H_{I,n-1}|^+\). We can note that this means that \(\sum_I M_I = \sum_I N_I\).

For every socio-economic group \(k\) we define

\[
M^k_I = \frac{M_I H^k_{I,n-1}}{H^k_{I,n-1}} \quad (7.5)
\]

The moved are collected into a pool for each socio-economic group \(M^k = \sum_I M^k_I\). Each pool is distributed to aggregate destination zones proportionally to the share that zone is of the total number moved, by letting

\[
N^k_I = \frac{N_I}{\sum_I N_I} M^k \quad (7.6)
\]

be those of group \(k\) moved to aggregate zone \(I\).

The socio-economic disaggregation of \(M_I\) and \(N_I\) to \(M^k_I\) and \(N^k_I\) is the important step. For technical reasons due to the way data is represented in SAMPERS we also disaggregate spatially to the finer zone-system. For each \(I\) we let

\[
M^k_i = \frac{M^k_i H^k_{i,n-1}}{H^k_{i,n-1}} , \ \forall \ i \in I \quad (7.7)
\]

\[
N^k_i = \frac{N^k_i H^k_{i,n-1}}{H^k_{i,n-1}} , \ \forall \ i \in I \quad (7.8)
\]

and the new disaggregate pattern becomes

\[
H^k_{i,n} = H^k_{i,n-1} - M^k_i + N^k_i \quad , \ \forall \ i \quad (7.9)
\]

\(^*\)It is important to remember that this is not people actually moving, like in a quasi-dynamic model. It is the change between two intermediary stages of finding an equilibrium. The mental image is useful, though, of moving people from one box to another.

\(^\dagger\)We describe the process for households. The workplace disaggregation works the same way.
The disaggregation procedure described above, preserves the number of people in each socio-economic group. But it is important to point out that the socio-economic disaggregation in equation (7.6) can have an unpredictable dispersing effect on spatial socio-economic patterns depending on the interactive procedure.

8 Appraisal framework

We discussed the role of an appraisal framework in section 2.6 from a theoretical viewpoint. We discussed the pros and cons of presenting indicators, setting of targets, and the forming of an objective function. In this section we will be somewhat more practical and describe how such a framework was implemented in the Stockholm case study.

We have outlined the modelling package used to make predictions of how strategies affect the transport and land use system. The appraisal framework is in this practical setting what takes data from model output and combines it into indicators, targets and objectives functions. Our modelling package delivers a snapshot image of the state of the transport and land use system for some year in the future. Since a strategy can involve policies implemented at more than one point in time we must also capture the development over time in some way. We do this by modelling, and computing indicators for two future years, 2015 and 2030.

8.1 Indicators

In this section we will look at the indicators we have used to measure achievement against each of the objectives we set in section 2.3. Remember we defined three levels of indicators in section 2.4. Ideally we would like to be able to find level one indicators for all objectives. Below we will discuss our choices of indicator for each objective in turn.

8.1.1 Economic efficiency

Cost benefit analysis is often used when appraising transport investments. It also forms the basis of the PROSPECTS objective function as it is a comprehensive indicator of economic efficiency, or a level one indicator by our definition. Economic efficiency is an attractive candidate because it is a complete ranking of the strategies. Of course, there is always the risk that by starting out from a CBA, the economic efficiency indicator will dominate the appraisal too much.
But let us look at it from another angle. If we make sure that we are satisfied with the other objectives in some way – we will return to that in 8.2 – for a set of strategies, it is reasonable that we pick the one that achieves what we want most efficiently.∗

SAMPERS comes with a CBA module for analysis of forecasts. We can retrieve much of the information we need for our appraisal framework from there, including e.g. the externality costs for pollution and accidents. Table 4 shows a so called social accounting table detailing the components of the economic efficiency indicator for a certain strategy at the year 2015. We will discuss each column in turn.

**Households, column (a)** The extent to which households are affected by a policy change is measured by *user benefits* or *consumer surplus*. The Methodological Guidebook discusses different ways of finding the user benefits in a transport and land use model (Minken et al., 2003, ch. 9). To summarise that discussion we would want to compute the consumer surplus, using an exact measure, at the top level of a correctly specified utility maximising model reflecting all aspects of the transport and land use system.

But unfortunately, since our model package consists of a collection of models, some choices will have to be made, of where to compute things and how. There are at least three different strands of this problem, that has affected the choice of a solution in the Stockholm case study.

The first is that we model land use and transport in several not fully consistent models, linked together by an iterative procedure. It means there is no single top level, describing the demand on all markets in terms of utility functions. Instead we have different models describing the demand on the transport market, housing market and employment market. IMREL models both land use and transport, with congestion effects in the housing market†. Benefits taken from IMREL would include transport benefits and disbenefits of dense living, but it is limited to only work trips and one household type, and we would have to use SAMPERS to find the user benefits of other trip purposes.

SAMPERS on the other hand has a very sophisticated segmentation of the population into socio-economic groups and models a range of different trip types. We believe that consistency between trip types with benefits

---

∗It is possible though, that people might disagree with the indicator itself. We will assume, however, that if all else is equal, a more efficient strategy is more desirable.

†They emerge from the disbenefit of housing density in eq. (7.1) and from imposing planning restrictions on the number of households and the number of workplaces in each zone.
Table 4: Example of a social accounting table detailing the economic efficiency indicator.

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>Households (a)</th>
<th>Firms (b)</th>
<th>Government (c)</th>
<th>External (d)</th>
<th>Row totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Public transp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Infrastructure*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Rolling stock*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Other*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>User benefits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Work</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Recreational</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Social</td>
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<td>0.00</td>
</tr>
<tr>
<td>School</td>
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<td></td>
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<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Business</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Producer surplus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Maintenance and other costs, road*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Toll revenue</td>
<td></td>
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<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Tax revenue</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Sub-total road</strong></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>Fares revenues</td>
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<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Maintenance*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Sub-total, PT</strong></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>External costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Accidents*</td>
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<td>0.00</td>
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<tr>
<td>Local air pollution*</td>
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<td></td>
<td>0.00</td>
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<tr>
<td>CO2*</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Column totals (M€)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

* changes in costs, change sign before adding to changes in benefits
from SAMPERS, outweighs the loss of effects from congestion in the housing market we would have had if we used IMREL.

In SAMPERS the default user benefit implementation uses the rule-of-a-half (ROH) similar to equation (8.1)

$$\Delta S(c_{ijm}) = \frac{1}{2} \left( \sum_{ijm} (T_{ijm}^A + T_{ijm}^R) (c_{ijm}^A - c_{ijm}^B) \right)$$  (8.1)

where $T_{ijm}$ is the travel demand from zone $i$ to zone $j$, by mode $m$. A and B corresponds to the situation before and after some policy change. $c_{ijm}$ is the corresponding generalised cost, assumed to consist of a monetary cost component, and a time component weighted by the so called value-of-time.

We can use equation (8.1) to illustrate the next thing to consider when dealing with user benefits. That is whether the user benefits calculated capture benefits originating from land use changes or not. As pointed out by Neuberger (1971), ROH may go amiss when the land use changes, see also Williams (1977). Or put in another way, when the transport demand, $T_{ijm}$ in equation (8.1), changes for reasons that do not show up in the generalised cost $c_{ijm}$. It is easy to see that the surplus $\Delta S = 0$ if the generalised cost remain unchanged between alternatives A and B.

But since we have a logit* model consistent with utility maximisation, the user benefit can be found directly by integration. In our case it is the well-known log-sum formula (McFadden, 1978). We then avoid some of the trouble adding anything, because the changes in zonal attractiveness that go into the demand calculation also show up in the consumer surplus. But, as Simmonds (2001) points out, changes in attractivity in the origin zone (given that we use log-sums from the transport model) do not show up, since they are not part of the utility function. It is not clear whether the iterative process between SAMPERS and IMREL solves this.

Standard ROH, equation (8.1), when we have this type of model is an approximation in two ways. First it is a linear approximation of the integral of the demand over the changes in cost and attractivity. This poses no problem if changes can be considered small. Secondly the generalised cost terms $c_{ijm}$ are approximations of the true integration variables.

From this it would seem beyond doubt that the ROH should be avoided when land use changes as it does in our case. There is, however, a situation where it could be reasonable to use ROH, and this is the third strand of the problem. We have a demand model estimated on some data set to reproduce

---

*Or more generally, a Generalised Extreme Value model (McFadden, 1978), see e.g. Ben-Akiva & Lerman (1985) or Train (2003) for introductions to random utility modelling.
behaviour, which implies a set of values of time, one for each socio-economic group. But often there is national guidance on what value of time to use in infrastructure appraisal. The reason can be that studies on values of time are carried out by other means, e.g. using stated preference methods. But there can also be a desire to treat all people in the system equally. Using the values of time implicit in the behavioural model, which is what we do when we use log-sums, means that people with high values of time – often groups with high income – would have a greater weight in the user benefit calculation.

But, using ROH to be able to use other values of time introduces an inconsistency between people’s behaviour and the benefit calculation. It could potentially lead to very counter-intuitive results. We believe that if equity issues are a concern, they should be addressed in some other way. An example could be to identify the vulnerable groups and set explicit weights on their user benefits.

**Firms, column (b)** The only firm we can identify with the current model package is the public transport operator. These are affected by fare revenue changes and changes in maintenance costs. The revenue is easily found from multiplying fare matrices with the public transport travel demand. Maintenance costs are computed line by line after the transport demand has been assigned to the public transport network.

The land rents from IMREL, r in eq. (7.2), are a possible addition as well. We have chosen not to include them at this point, because we do not know enough on how comparable the utilities are between SAMPERS and IMREL.

**Government revenue, column (c)** Our government revenue includes maintenance costs that depend on the flow on the links in the network, and change in revenue from fuel taxation. The fuel tax is one of our policy instruments and is discussed further under that heading.

**External costs, column (d)** Environment and accident costs are taken directly from the impact assessment modules present in the SAMPERS package. Impacts are proportional to vehicle-km with different factors for different link types. The factors, presented in table 5, are standard values by the Swedish National Road Administration reflecting a weighted average over several road types and surroundings. Costs for the environmental and accident externalities are ASEK* values (SIKA, 2000a), also in table 5.

---

*A Swedish review of cost estimates from transport*
<table>
<thead>
<tr>
<th>Factor</th>
<th>Description</th>
<th>Riban roads</th>
<th>Rural roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel consumption, l/vkm</td>
<td>0.059</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>NO₂, g/vkm</td>
<td>0.185</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>VOC, g/vkm</td>
<td>0.185</td>
<td>0.252</td>
<td></td>
</tr>
<tr>
<td>CO₂, g/vkm</td>
<td>140.3</td>
<td>171.7</td>
<td></td>
</tr>
<tr>
<td>SO₂, g/vkm</td>
<td>0.00058</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Accidents, #/million pkm</td>
<td>0.39</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Injured, #/accident</td>
<td>0.39</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO₂, €/kg</td>
<td>6.8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>VOC, €/kg</td>
<td>3.4</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>PM₁₀, €/kg</td>
<td>864</td>
<td>216</td>
<td></td>
</tr>
<tr>
<td>SO₂, €/kg</td>
<td>2.3</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Maintenance, €/vkm</td>
<td>2.9 × 10⁻³</td>
<td>2.9 × 10⁻³</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Factors and costs used in road transport effect calculations. vkm – vehicle kilometers; pkm – passenger kilometers. Costs are ASEK estimates.

In the Methodological Guidebook we argue that it is preferable with an approach where the road conditions are taken more into account. Our approach only distinguishes between urban and rural roads, with separate effect factors for each. It should be noted, though, that SAMPERS has been under extensive development since the version used in this study, and the impact assessment is one of the areas where the changes have been the greatest. We have not attempted any improvements specially for this study.

We have used a CO₂ externality cost from national guidance (SIKA, 2000a) which corresponds to 160 €/ton. The Methodological Guidebook discusses implementation of CO₂ (Minken et al., 2003, ch. 16) in some detail. The externality cost computation does not take any already internalised CO₂ cost into account.

8.1.2 Protection of the environment and safety

To the extent that the package can model these things they are included in the economic efficiency indicator.

8.1.3 Liveable streets and neighbourhoods

This indicator is very difficult to represent in the model package we use. Neither the transport nor the land use model take these kind of considerations into account. The actual geography of the zones is not represented in a way
that is useful to analysing impacts at this level of detail.

8.1.4 Equity

The methodological guidebook suggests some suitable indicators on equity. Were we only using SAMPERS we would have had the opportunity to use some of them, since it considers many different socio-economic groups and business sectors. IMREL on the hand does not, which means that it destroys that kind of disaggregate information during the course of iterating to an equilibrium. We are reluctant to draw any conclusions on equity other than purely spatial effects perhaps.

8.1.5 Contribution to economic growth

The Methodological Guidebook (Minken et al., 2003) suggests growth potential (SACTRA, 1999) as an indicator, but warns that the elements of this indicator are already included in our economic efficiency indicator. We do not put any more weight on the economic efficiency indicator to take this double role into account.

8.2 Implementation of the objective function

From section 2.6 we recall that there we have the option of using optimisation as a tool to sift through possible strategies in an efficient manner. In order to do that we need to assemble the indicators into an objective function. In Minken et al. (2002, ch. 6.2) and Minken et al. (2003, ch. 3.5) more detail is provided on the cost benefit and multi criteria analysis background to the suggested objective function.

We state the sustainability objective function as follows and explain it below

$$OF = \sum_{t=1}^{H} \alpha_t \left( b_t - c_t - I_t - \gamma_t m_t^{CO_2} \right) + \sum_{it} \mu_{it} y_{it}$$  \hspace{1cm} (8.2)

$b_t$ is benefit and $c_t$ is cost at year $t$

$I_t$ is investment

$m_t^{CO_2}$ is the carbon dioxide emissions in tons/year, and $\gamma_t$ cost per ton $CO_2$. The reason $CO_2$ cost is treated separately is that we might be interested in using different costs $\gamma_t$ for different years.

The sum of benefits minus costs and investment over the evaluation period, from the base year to the horizon year $H$, is discounted with the sus-
tainability adjusted discount rate given by

\[
\alpha_t = \frac{\alpha}{(1+r)^t}, \quad t = 1, \ldots, H - 1 \tag{8.3}
\]

\[
\alpha_H = \frac{\alpha}{(1+r)^H} + (1 - \alpha) \tag{8.4}
\]

where we call \( \alpha \) an intergenerational parameter and \( r \) is the discount rate.

The last term in equation (8.2) contains any indicators \( y_{it} \) with weights \( \mu_{it} \) that for some reason cannot be included in the CBA part, either because it cannot be expressed in monetary terms, or that it for some other reason does not belong to a CBA. Equity is such an indicator (see Methodological Guidebook (Minken et al., 2003, ch. 14) for more details). CBA is used in a loose sense here, since the discount factor \( \alpha_t \) does not behave quite like normally. We have not the last term of the Objective Function since the indicators our models can provide also are straightforward to include in the CBA part.

The approach above tries to follow the Chichilnisky (1996) approach, by adjusting an ordinary discounting procedure with a term representing the long term future. If we leave the \( \sum_{it} \mu_{it} y_{it} \) term out of the discussion for a while, we can see that if we set \( \alpha = 1 \) we get a normal discounting and the objective function reduces to the net present value with a fixed discount rate. If we on the other hand set \( \alpha = 0 \) the only thing remaining is the horizon year undiscounted. In other words, the first term of the OF is a weighted sum of a net present value discounted with the rate \( r \), and an undiscounted horizon year. The relative weight between them is the intergenerational parameter \( \alpha \).

Benefits are obtained from model runs at the base year 1997, year 2015 and year 2030. The intermediate years are interpolated from them. The same goes for costs and \( CO_2 \) emissions. Investments are calculated separately for each strategy. The linear interpolation between two arbitrary points in time, \( t_n \) and \( t_{n+1} \), can be expressed

\[
b_t = \frac{t - t_n}{t_{n+1} - t_n} b_{n+1} + \frac{t_{n+1} - t}{t_{n+1} - t_n} b_{t_n} \tag{8.5}
\]

*It is important that this linear interpolation is carried out before inserting \( b, c, \) and \( m^{CO_2} \) into the OF, since the multiplication with \( \alpha_t \) introduces a non-linearity.
9 Optimisation

Suppose we can form an objective function that forms a complete ranking of strategies. Our OF in equation 8.2 is an example. What we have then is essentially a constrained optimisation problem. Assume that \( \mathbf{x} = (x_1, ..., x_H) \) is a vector of policy instrument vectors over the time period from the starting year to the horizon year \( H \). \( \mathbf{X} \) is the set of possible instruments. Then the problem becomes

\[
\begin{align*}
\max_{\mathbf{x}\in\mathbf{X}} \quad & OF(\mathbf{x}) \\
\text{s.t.} \quad & \sum_{t=1}^{H} y_{it}(\mathbf{x}) \leq C_i \quad \forall i \in M \\
& y_{it}(\mathbf{x}) \leq C_{it} \quad \forall i \in M, \forall t
\end{align*}
\]  

(9.1)

where \( y_{it} \) is the level of indicator \( i \) at time \( t \) and \( M \) is the set of remaining indicators not included in the OF, but instead set as targets. \( C_i \) is a constraint on the sum of the indicator over the whole period, and \( C_{it} \) is a constraint for a specific year. The first type of constraint could be e.g. a constraint on total spending, while the second could be e.g. a maximum emission of some local pollutant at any time.

By setting constraints, and using the last term in equation (8.2) to account for un-monetised indicators, the framework allows for considerably more flexibility than a CBA, in terms of analysing trade-offs between different objectives. The simplified application of the framework we have attempted in this case study was focused on the intergenerational parameter.

By formulating sustainability as a formal optimisation problem like this we can apply formal methods of solving this problem as well. But, and this cannot be stressed enough, it is not a substitute for a robust planning process. An optimisation finds the best strategy given all the assumptions that are represented by the cost estimates in the CBA part, the intergenerational parameter \( \alpha \), weights on other indicators, and by the targets set.

9.1 Optimisation method

Since the modelling package used in this study is computationally cumbersome, with run times of 8-9 hours per objective function evaluation, we need an optimisation method that can give us as much information as possible with as few OF evaluations as possible. Using response surface methodology (RSM) where the OF values are fitted to a polynomial by regression has proven successful in similar studies in the past. Fowkes et al. use RSM in
successive steps to improve the response surface around the optimum. The Methodological Guidebook (Minken et al., 2003, ch. 18.2) also provides an overview.

Since we use an evaluation period of over thirty years, the optimisation problem would become too large to solve with the RSM method if we let an instrument be changed every year. But we have already decided that we represent the thirty year period by doing two model runs, at 2015 and 2030, and interpolating in between. The model we use works on the assumption that the model outcome represents an equilibrium state of the system where all policy interventions have had time to take full effect. So we are only able to model each policy instrument at two points in time. One sufficiently long before each modelled year for an equilibrium to form. So for each of the instruments discussed below we get two optimisation variables. The names we use, e.g. CarCost2015, corresponds to the year where the effects are modelled, not the actual implementation year.

The way we have treated the time dimension with a linear interpolation of costs as well as benefits in the objective function, is in a sense an implicit assumption that the instruments are introduced gradually, and that the effects also surface gradually.

9.2 Instruments, optimisation variables

For the purpose of optimisation policy instruments, land use, public transport service levels and fares, as well as new roads and light rail, are assumed to be under our control. Of course, in reality the responsibility is divided between many levels of administration.

It is worthwhile to step back and repeat the terminology here. From the planner’s point of view a policy instrument is some action intended to influence the transport and land use system in some way. In the model we try to represent that action as well as we can in model terms. We still call it a policy instrument. When we introduce the notion of optimisation we also start using optimisation terminology, which is why the instruments from here on also are called optimisation variables.

**Car cost**  The fuel price is considered an important policy instrument to influence car use. The policy instrument, or optimisation variable referred to in Table 6 is the overall cost of car use. Changes are effectuated through the fuel cost part of the overall car cost. The interpretation is that the decision maker can change fuel taxation and hence also affects government revenue. The do minimum value corresponds to the car cost at the base year. In the
optimisation it is allowed to vary from the base value up to twice the base value.

**Fare level and structure** Public transport fares are represented by two matrices, one for cash payment, the other for monthly tickets. A fixed share between the two is specified in advance. In the optimisation process the variable will be a percentage change from the do-minimum strategy. A potential sensitivity test would be to study changes in the spatial structure of the fares. The optimisation range is from 0.5 to 1.5 times the 1997 level do-minimum.

### 9.3 Possible extensions

The model system used in this study is set up to handle a few other instruments as optimisation variables as well, although time limitations excluded them from the study reported here.

**Infrastructure projects** Two infrastructure projects have been set up to be included in the optimisation as a discrete variable in the form of either build or not build. One is a major bypass motorway project. The other is a change in fare and operation structure of the rail system to make better use of interregional trains and tracks in regional transport. The projects are coded as separate scenarios in the EMME/2 networks.

**Urban road charging** Urban road charging is handled by an extra attribute on each link added to the overall cost of car travel in SAMPERS. The optimisation will not determine whether or not to implement a road charging scheme. Separate optimisations will be carried out with and without it. The optimisation variable, in the toll scheme case, is the overall level of toll, keeping the structure fixed.

**Overall public transport service level** The headway and speed can be changed in the PT line coding in EMME/2, using its network editing capabilities. Although it is possible to change individual bus and rail lines separately, for our strategic purposes it is enough to introduce an overall percentage change in headway common for all lines.

**Development densities** In IMREL it is necessary to specify upper and lower bounds on number of households and number of work places allowed in each zone. Since the available area for each of these purposes is fixed, it
Table 6: Initial experimental design. Objective function values computed with $\alpha = 0.1$

is equivalent to specifying minimum and maximum development densities. The lower bound is used as an optimisation variable in the inner city zones.

10 Results and analysis

10.1 Initial response surface model

The initial design was generated as a D-optimal* RSM design. It is an orthogonal experimental design where the design points are picked so that the standard deviation caused by the design itself is minimised with respect to a specified model type. In this case a model with linear, mixed and quadratic terms. Table 6 shows the initial design points and the corresponding values of the objective function.

A regression model of the objective function is formed with linear and quadratic terms, where the insignificant terms are removed one by one, until all parameter estimates are significant (backward elimination). The regression routine re-codes the values of the factors so that they all range from -1

*Design Expert 6.0 from Stat-Ease was used to generate and analyse the design. See e.g. http://www.itl.nist.gov/div898/handbook/pri/section5/pri521.htm for a description of D-optimality
<table>
<thead>
<tr>
<th>Factor</th>
<th>Coefficient Estimate</th>
<th>Standard Error</th>
<th>95% CI Low</th>
<th>95% CI High</th>
<th>Actual Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>327.15</td>
<td>0.82</td>
<td>325.05</td>
<td>329.26</td>
<td>-781.45</td>
</tr>
<tr>
<td>A-CarCost2015</td>
<td>105.46</td>
<td>0.33</td>
<td>104.62</td>
<td>106.30</td>
<td>192.38</td>
</tr>
<tr>
<td>B-PTFare2015</td>
<td>-44.85</td>
<td>0.32</td>
<td>-45.68</td>
<td>-44.03</td>
<td>-11.97</td>
</tr>
<tr>
<td>C-CarCost2030</td>
<td>153.10</td>
<td>0.35</td>
<td>152.20</td>
<td>154.01</td>
<td>910.76</td>
</tr>
<tr>
<td>D-PTFare2030</td>
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<td>0.33</td>
<td>-60.06</td>
<td>-58.39</td>
<td>6.93</td>
</tr>
<tr>
<td>B²</td>
<td>5.63</td>
<td>0.70</td>
<td>3.83</td>
<td>7.43</td>
<td>22.53</td>
</tr>
<tr>
<td>C²</td>
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<td>-42.55</td>
<td>-176.24</td>
</tr>
<tr>
<td>D²</td>
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<td>0.83</td>
<td>-22.42</td>
<td>-18.15</td>
<td>-81.14</td>
</tr>
<tr>
<td>AB</td>
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<td>0.44</td>
<td>3.50</td>
<td>5.78</td>
<td>18.55</td>
</tr>
<tr>
<td>BC</td>
<td>-25.10</td>
<td>0.78</td>
<td>-27.12</td>
<td>-23.09</td>
<td>-100.41</td>
</tr>
<tr>
<td>CD</td>
<td>6.15</td>
<td>0.64</td>
<td>4.50</td>
<td>7.80</td>
<td>24.59</td>
</tr>
</tbody>
</table>

Table 7: Regression model of the objective function with \( \alpha = 0.1 \)

In Table 7 we show parameter estimates with confidence intervals in coded factors, and estimates for actual factors.

Using a numerical optimisation routine included in Stat-Ease we find that the maximum of the objective function is at CarCost2015 = 2, PTFare2015 = 0.5, CarCost2030 = 2, PTFare2030 = 0.5 (or in a shorter form \( \mathbf{x} = (2, 0.5, 2, 0.5) \)). That is, doubling car costs to 2015 and keeping it there, and halving public transport cost until 2015 and keeping it there. The predicted maximum value of the objective function is \( OF = 645 \text{ M€} \).

The optimisation method calls for more model runs around the optimum to increase the resolution of the model around that point. We have not done so, because our optimum lies on the edge of our feasible area. In a model estimated and calibrated against some baseline scenario there is always a limit to how far from that scenario it is possible to venture, before the results become meaningless. We believe that going further than twice the cost for car travel is not useful. There is also a feasibility argument. A doubling of the overall car cost corresponds to a very large tax increase.

### 10.2 Adjusted response surface

The model was applied to the predicted optimum point \( \mathbf{x} = (2, 0.5, 2, 0.5) \), and the appraisal framework yielded an objective function value of 629 M€. It is somewhat lower than predicted by the regression model, but greater than the other design points in Table 6. We do a new regression including the new point, using the same method of backward elimination of regression coefficients. The estimates are shown in Table 8.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Coefficient Estimate</th>
<th>Standard Error</th>
<th>95% CI Low</th>
<th>95% CI High</th>
<th>Actual Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>326.59</td>
<td>4.91</td>
<td>315.47</td>
<td>337.70</td>
<td>-791.68</td>
</tr>
<tr>
<td>A-CarCost2015</td>
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<td>1.97</td>
<td>97.87</td>
<td>106.77</td>
<td>204.64</td>
</tr>
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<td>B-PTFare2015</td>
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<td>2.24</td>
<td>-49.17</td>
<td>-39.05</td>
<td>9.56</td>
</tr>
<tr>
<td>C-CarCost2030</td>
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<td>895.72</td>
</tr>
<tr>
<td>D-PTFare2030</td>
<td>-59.92</td>
<td>2.06</td>
<td>-64.57</td>
<td>-55.27</td>
<td>19.15</td>
</tr>
<tr>
<td>C^2</td>
<td>-43.75</td>
<td>3.51</td>
<td>-51.70</td>
<td>-35.80</td>
<td>-174.99</td>
</tr>
<tr>
<td>D^2</td>
<td>-17.37</td>
<td>4.99</td>
<td>-28.66</td>
<td>-6.08</td>
<td>-69.49</td>
</tr>
<tr>
<td>BC</td>
<td>-16.30</td>
<td>3.46</td>
<td>-24.12</td>
<td>-8.47</td>
<td>-65.18</td>
</tr>
</tbody>
</table>

Table 8: Regression model with adjusted design. The objective function computed with $\alpha = 0.1$

### 10.3 The optimum strategy

We have argued that our sustainability objective function will point us in the direction of a long term sustainable strategy. We will investigate the optimal strategy our optimisation has delivered and see if it seems sustainable. Tables 9 and 10 show the details of the economic efficiency indicator for the two modelled years.

The first thing we notice is that the two are fairly much alike, which makes sense. The transport systems in 2015 and 2030 are not very different. The 2030 transport system has a somewhat higher capacity, but that is probably balanced by the larger population.

If we look at the result from 2015 we see that we have a user benefit of $-113.75 \text{ M€}$ in total, summed over all the trip types. On the other hand, we have an increase in tax revenue of $206 \text{ M€}$. This suggests that some of the negative impact of the increased car cost is offset by the decrease in public transport fare.

Work trips and 'other' trips show large effects, which is to be expected. 53% of all car trips are work trips and 26% are in the 'other' category. Making car travel more expensive will obviously have a large impact on them. The relatively large impact on business trips, which constitute only 2% of the total number of trips, stems from the fact that this category has a car share of 67%.

We see that the user and producer surpluses are negative, while government revenue and external benefits are positive. For this to be a useful strategy, it is obvious that how the government revenue is channelled back into the system is very important. We leave the decision on how government revenue should be used an open question. Examples could be to decrease
other taxes or use it to fund the increased public transport costs. It would probably require an analysis with a wider scope than the land use and transport system in order to ensure efficiency in the allocation. We have assumed that there is no shadow price on public funds, i.e. that one euro in the government’s lockbox is of equal value to one euro in an individual’s pocket. Equity considerations would also play an important role in determining how to redistribute the revenue.
### Annual cost and benefit

<table>
<thead>
<tr>
<th>Year</th>
<th>Households (a)</th>
<th>Firms (b)</th>
<th>Government (c)</th>
<th>External (d)</th>
<th>Row totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Public transp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Infrastructur</strong></td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Rolling stock</strong></td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Other</strong></td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Sub-total</strong></td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>User benefits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Work</strong></td>
<td></td>
<td>-39.03</td>
<td>-39.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Other</strong></td>
<td></td>
<td>-44.56</td>
<td>-44.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Recreational</strong></td>
<td></td>
<td>-14.23</td>
<td>-14.23</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Social</strong></td>
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<td>-2.53</td>
<td>-2.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>School</strong></td>
<td></td>
<td>-0.81</td>
<td>-0.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Business</strong></td>
<td></td>
<td>-12.58</td>
<td>-12.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Sub-total</strong></td>
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<td>-113.75</td>
<td>-113.75</td>
<td></td>
</tr>
<tr>
<td><strong>Producer surplus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Maintenance and other costs</strong></td>
<td></td>
<td>-9.91</td>
<td>-9.91</td>
<td></td>
</tr>
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<td></td>
<td><strong>Toll revenue</strong></td>
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<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Tax revenue</strong></td>
<td></td>
<td>206.17</td>
<td>206.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Sub-total road</strong></td>
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<td>0.00</td>
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<tr>
<td></td>
<td><strong>Fare revenues</strong></td>
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<td>-61.61</td>
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<td></td>
<td><strong>Maintenance</strong></td>
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<td>19.96</td>
<td>19.96</td>
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</tr>
<tr>
<td></td>
<td><strong>Sub-total, PT</strong></td>
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<td>0.00</td>
<td>0.00</td>
<td>-81.57</td>
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<tr>
<td><strong>External costs</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Accidents</strong></td>
<td></td>
<td>-10.13</td>
<td>-10.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Local air pollution</strong></td>
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<td>-8.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>CO2</strong></td>
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<td>-37.74</td>
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<tr>
<td></td>
<td><strong>Sub-total</strong></td>
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<td>0.00</td>
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<tr>
<td><strong>Column totals (M€)</strong></td>
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<td></td>
<td><strong>-113.75</strong></td>
<td></td>
<td>-81.57</td>
<td>216.08</td>
<td>55.95</td>
</tr>
</tbody>
</table>

* changes in costs, change sign before adding to changes in benefits
### Table 10: Details of the economic efficiency indicator for 2030. The table shows the difference between the optimal strategy \( x = \{2, 0.5, 2, 0.5\} \) and the do-minimum \( x = \{1, 1, 1, 1\} \)

<table>
<thead>
<tr>
<th></th>
<th>2030</th>
<th>2030</th>
<th>2030</th>
<th>2030</th>
<th>2030</th>
</tr>
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<tr>
<td></td>
<td><strong>Households (a)</strong></td>
<td><strong>Firms (b)</strong></td>
<td><strong>Government (c)</strong></td>
<td><strong>External (d)</strong></td>
<td><strong>Row totals</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Infrastructure</strong></td>
<td><strong>Public transp.</strong></td>
<td><strong>Roling stock</strong></td>
<td><strong>Sub-total</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>User benefits</strong></td>
<td><strong>Work</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>Investment</strong></td>
<td><strong>Sub-total</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>User benefits</strong></td>
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<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>Producer surplus</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>Maintenance and other costs, road</strong></td>
<td><strong>192,69</strong></td>
<td><strong>0,00</strong></td>
<td><strong>192,69</strong></td>
<td><strong>0,00</strong></td>
<td><strong>192,69</strong></td>
</tr>
<tr>
<td><strong>Toll revenue</strong></td>
<td><strong>-10,32</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>-10,32</strong></td>
</tr>
<tr>
<td><strong>Tax revenue</strong></td>
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<td><strong>192,67</strong></td>
<td><strong>0,00</strong></td>
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<td><strong>0,00</strong></td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>192,69</strong></td>
<td><strong>0,00</strong></td>
<td><strong>192,69</strong></td>
<td><strong>0,00</strong></td>
<td><strong>192,69</strong></td>
</tr>
<tr>
<td><strong>Fare revenues</strong></td>
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<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>-74,71</strong></td>
</tr>
<tr>
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<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>26,27</strong></td>
</tr>
<tr>
<td><strong>Sub-total, PT</strong></td>
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<td><strong>-100,98</strong></td>
<td><strong>0,00</strong></td>
<td><strong>0,00</strong></td>
<td><strong>-100,98</strong></td>
</tr>
<tr>
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<td><strong>-7,79</strong></td>
<td><strong>-37,81</strong></td>
<td><strong>-55,82</strong></td>
</tr>
<tr>
<td><strong>Accidents</strong></td>
<td><strong>-10,23</strong></td>
<td><strong>-7,79</strong></td>
<td><strong>-7,79</strong></td>
<td><strong>-37,81</strong></td>
<td><strong>-55,82</strong></td>
</tr>
<tr>
<td><strong>Local air pollution</strong></td>
<td><strong>-37,81</strong></td>
<td><strong>-0,00</strong></td>
<td><strong>-0,00</strong></td>
<td><strong>-0,00</strong></td>
<td><strong>-37,81</strong></td>
</tr>
<tr>
<td><strong>CO2</strong></td>
<td><strong>-55,82</strong></td>
<td><strong>-55,82</strong></td>
<td><strong>-55,82</strong></td>
<td><strong>-55,82</strong></td>
<td><strong>-55,82</strong></td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>-104,21</strong></td>
<td><strong>-104,21</strong></td>
<td><strong>192,69</strong></td>
<td><strong>55,82</strong></td>
<td><strong>43,33</strong></td>
</tr>
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</table>

* changes in costs, change sign before adding to changes in benefits
<table>
<thead>
<tr>
<th></th>
<th>Do-min</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. distance[km], shortest</td>
<td>18.1</td>
<td>18.1</td>
</tr>
<tr>
<td>Avg. distance[km], congested</td>
<td>22.3</td>
<td>21.5</td>
</tr>
<tr>
<td>Avg. travel time[min]</td>
<td>33.7</td>
<td>30.7</td>
</tr>
<tr>
<td>Avg. speed[km/h]</td>
<td>39.7</td>
<td>42.0</td>
</tr>
<tr>
<td>Avg. density[residents/ha]</td>
<td>12.6</td>
<td>12.6</td>
</tr>
</tbody>
</table>

**Table 11:** Effects on average distance and time to CBD. Average weighted with number of residents. Situation in 2015.

<table>
<thead>
<tr>
<th></th>
<th>Do-min</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. distance[km], shortest</td>
<td>17.1</td>
<td>16.9</td>
</tr>
<tr>
<td>Avg. distance[km], congested</td>
<td>21.2</td>
<td>20.3</td>
</tr>
<tr>
<td>Avg. travel time[min]</td>
<td>32.9</td>
<td>29.2</td>
</tr>
<tr>
<td>Avg. speed[km/h]</td>
<td>38.8</td>
<td>41.9</td>
</tr>
</tbody>
</table>

**Table 12:** Effects on average distance and time to CBD. Average weighted with number of workplaces. Situation in 2015.

The strategy has some, but fairly limited, effects on location. The difference between the two strategies only amounts to about 1 percent of the number workplaces and slightly less than that (0.7%) of total number of residents. A simple measure of centralisation is the average distance and travel time to the central business district (CBD). Table 11 shows an average of residents distance and travel time to the CBD* weighted with the number of residents in each zone. In table 12 the weights used were the number of workplaces. We see that for workplaces we have a centralising effect, since the average shortest distance goes down, while no such effect is discernible in the residential case. We can note, however, the effect congestion has. In the land use model the accessibility measures that govern location choice are based on work trip conditions, where congestion is present. We see that in these terms, i.e. congested time and distance we have a centralising effect.

We saw in table 9 that a large part of the surplus of 76 M€ of the strategy in 2015, comes from a decrease in externality costs that amounts to 56M€. In fact, in 2030 (table 10) the whole surplus¹ can be attributed to decreased externality costs. Let us investigate this a bit further. Table 13 compares CO₂ emissions (in ktons) for the do-minimum strategy and the

---

*It should be noted that this measure is not an accurate description of average travel times and distances of the whole system, since it includes only the one destination, the city centre.

¹Remember that since we use the exact measure of user benefits, congestion externalities are included in the user benefit.
<table>
<thead>
<tr>
<th>Domin</th>
<th>Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car</td>
</tr>
<tr>
<td>Urban</td>
<td>-26.4</td>
</tr>
<tr>
<td>Rural</td>
<td>0.7</td>
</tr>
<tr>
<td>Total</td>
<td>-25.7</td>
</tr>
</tbody>
</table>

*Table 13:* CO₂ levels of the do-minimum strategy and optimum strategy compared to 1997 levels, in ktons. 2015 situation.

<table>
<thead>
<tr>
<th>Car, drive</th>
<th>Car, pass.</th>
<th>PT</th>
<th>Bicycle</th>
<th>Walk</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-19</td>
<td>-4</td>
<td>22</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
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<td>1</td>
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<td>Visit</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>School</td>
<td>-14</td>
<td>0</td>
<td>4</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Business</td>
<td>-5</td>
<td>-2</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>-14</td>
<td>-5</td>
<td>17</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 14:* Percentage difference in total number of trips between optimal and do-minimum strategies, in year 2015.

optimum strategy with 1997 levels. For both strategies there are decreases in emissions from cars on urban roads. The emissions from public transport goes up, also for both strategies. The difference is that for the do minimum the sum is an increase of CO₂ emissions with 27.7 ktons over 1997 levels, while the optimum strategy means a decrease of CO₂ emissions by 203.7 ktons. The largest effects are on rural roads, which is reasonable, since the increased tax would make long distance travel by car expensive.

We can also look at the differences between the two strategies with respect to some transport indicators. In table 14 we see that the total number of trips is about the same, which means that the trip generation is not affected very much by the policies. But we can see a mode shift, with the largest effects for work trips. This is likely due to the fact work trips dominate peak travel, and that the difference between the car mode and the second best alternative, i.e. the public transport mode, is smaller in the peak period than in the off peak period.

In tables 15 and 16 we note that the total travel decreases. Measured in distance it is a 9% decrease. Travel time decreases slightly more measured in percent than the distance for the car mode. This is probably because the congestion decreases as well. Tables 17 and 18 illustrate the same effects of decreasing congestion but in terms of the average time and distance per
<table>
<thead>
<tr>
<th>Car, drive</th>
<th>Car, pass.</th>
<th>PT</th>
<th>Bicycle</th>
<th>Walk</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>-36</td>
<td>-12</td>
<td>20</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>-34</td>
<td>-23</td>
<td>10</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Recreational</td>
<td>-34</td>
<td>-24</td>
<td>9</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Social</td>
<td>-39</td>
<td>-20</td>
<td>11</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>School</td>
<td>-32</td>
<td>2</td>
<td>3</td>
<td>-4</td>
<td>-3</td>
</tr>
<tr>
<td>Business</td>
<td>-17</td>
<td>-9</td>
<td>4</td>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td>Total</td>
<td>-34</td>
<td>-20</td>
<td>15</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Table 15:** Percentage difference in total travel distance [pkm] between optimal and do-minimum strategies, in year 2015.

<table>
<thead>
<tr>
<th>Car, drive</th>
<th>Car, pass.</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>-38</td>
<td>-16</td>
</tr>
<tr>
<td>Other</td>
<td>-35</td>
<td>-25</td>
</tr>
<tr>
<td>Recreational</td>
<td>-35</td>
<td>-26</td>
</tr>
<tr>
<td>Social</td>
<td>-39</td>
<td>-22</td>
</tr>
<tr>
<td>School</td>
<td>-32</td>
<td>-2</td>
</tr>
<tr>
<td>Business</td>
<td>-21</td>
<td>-14</td>
</tr>
<tr>
<td>Total</td>
<td>-36</td>
<td>-22</td>
</tr>
</tbody>
</table>

**Table 16:** Percentage difference in total travel time between optimal and do-minimum strategies, in year 2015.

person.

### 10.4 Response surface

Let us see what information can be gleaned about the objective function itself. By differentiating the estimated objective function and using the estimates in table 8 we get the marginal rate of change in the objective function with respect to the optimisation variables (see table 19). Obviously, these would be zero if the optimum was an inner solution.

But it is perhaps even more intuitive to show these things by plotting some response surfaces. In figure 5 we have plotted the car cost against PT fare in 2015. The two variables in 2030 are kept fixed at the optimum. We can see that the slope in car cost is steeper, suggesting that a decrease in car cost is more expensive than an increase in public transport fares, with respect to the objective we have set. We see that the same holds for 2030.

We can also get an indicator of the temporal behaviour of our model and appraisal method. Figure 6 shows a plot of car cost in 2015 against car cost in 2030. It suggests that from our sustainability point of view the longer term cost is more expensive to decrease. It contradicts the elasticities somewhat,
<table>
<thead>
<tr>
<th></th>
<th>Car, driver</th>
<th>Car, pass.</th>
<th>Publ. trp.</th>
<th>Bicycle</th>
<th>Walk</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>-3.4</td>
<td>-1.2</td>
<td>-0.4</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.9</td>
</tr>
<tr>
<td>Other</td>
<td>-2.4</td>
<td>-1.8</td>
<td>-0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.9</td>
</tr>
<tr>
<td>Leisure</td>
<td>-4.0</td>
<td>-3.1</td>
<td>-0.5</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-1.5</td>
</tr>
<tr>
<td>Visit</td>
<td>-3.6</td>
<td>-1.9</td>
<td>-0.4</td>
<td>-0.1</td>
<td>-0.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>School</td>
<td>-1.9</td>
<td>0.1</td>
<td>-0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Business</td>
<td>-2.4</td>
<td>-1.4</td>
<td>-0.5</td>
<td>-0.1</td>
<td>0.0</td>
<td>-1.8</td>
</tr>
<tr>
<td>Total</td>
<td>-3.3</td>
<td>-2.1</td>
<td>-0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

**Table 17:** Differences in average travel distance between do-min and optimum, measured in kilometers. Situation in 2015.

<table>
<thead>
<tr>
<th></th>
<th>Car, driver</th>
<th>Car, pass.</th>
<th>Publ. trp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work</td>
<td>-5.3</td>
<td>-2.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Other</td>
<td>-3.9</td>
<td>-3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Leisure</td>
<td>-5.8</td>
<td>-4.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Visit</td>
<td>-5.1</td>
<td>-3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>School</td>
<td>-2.9</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Business</td>
<td>-4.4</td>
<td>-3.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>-5.1</td>
<td>-3.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Table 18:** Differences in average travel time between do-min and optimum, measured in minutes. No travel times are computed for slow modes. Situation in 2015.

but it is necessary to keep in mind that the elasticities are computed at the boundary point, which by the look of the surface in figure 6 seems fairly close to a global optimum where the elasticities would be zero. Later, in section 10.5 we will investigate how this behaviour changes with different assumptions on the intergenerational parameter \( \alpha \).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Cost 2015</td>
<td>0.65</td>
</tr>
<tr>
<td>PT Fare 2015</td>
<td>-0.10</td>
</tr>
<tr>
<td>Car Cost 2030</td>
<td>0.52</td>
</tr>
<tr>
<td>PT Fare 2030</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

**Table 19:** Elasticities of the response surface.
Figure 5: Response surfaces, 2015 variables and 2030 variables respectively. It is easy to see that the solution is more sensitive to Car Cost than to Public Transport Fare for both years.
Figure 6: Response surface of CarCost2015 versus CarCost2030.
<table>
<thead>
<tr>
<th>Policy instruments</th>
<th>2015</th>
<th>2030</th>
<th>Outcome</th>
<th>OF ( (\alpha=0.1) )</th>
<th>OF ( (\alpha=0.2) )</th>
<th>OF ( (\alpha=0.3) )</th>
<th>OF=NPV ( (\alpha=1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car Cost PT Fare</td>
<td>2</td>
<td>0.5</td>
<td>0.5</td>
<td>629 [M€]</td>
<td>905 [M€]</td>
<td>1181 [M€]</td>
<td>3111 [M€]</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>2</td>
<td>0.5</td>
<td>545 [M€]</td>
<td>698 [M€]</td>
<td>851 [M€]</td>
<td>1922 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1.5</td>
<td>0.5</td>
<td>517 [M€]</td>
<td>787 [M€]</td>
<td>1056 [M€]</td>
<td>2945 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>2</td>
<td>1</td>
<td>482 [M€]</td>
<td>673 [M€]</td>
<td>863 [M€]</td>
<td>2196 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>400 [M€]</td>
<td>663 [M€]</td>
<td>926 [M€]</td>
<td>2770 [M€]</td>
</tr>
<tr>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>327 [M€]</td>
<td>468 [M€]</td>
<td>609 [M€]</td>
<td>1597 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>0.5</td>
<td>316 [M€]</td>
<td>384 [M€]</td>
<td>452 [M€]</td>
<td>931 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>281 [M€]</td>
<td>496 [M€]</td>
<td>711 [M€]</td>
<td>2215 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>257 [M€]</td>
<td>272 [M€]</td>
<td>287 [M€]</td>
<td>393 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>256 [M€]</td>
<td>512 [M€]</td>
<td>767 [M€]</td>
<td>2557 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>216 [M€]</td>
<td>185 [M€]</td>
<td>155 [M€]</td>
<td>-62 [M€]</td>
</tr>
<tr>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>200 [M€]</td>
<td>334 [M€]</td>
<td>469 [M€]</td>
<td>1409 [M€]</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>150 [M€]</td>
<td>358 [M€]</td>
<td>566 [M€]</td>
<td>2021 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
<td>99  [M€]</td>
<td>62  [M€]</td>
<td>25  [M€]</td>
<td>-236 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>71  [M€]</td>
<td>76  [M€]</td>
<td>81  [M€]</td>
<td>116 [M€]</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>55  [M€]</td>
<td>109 [M€]</td>
<td>163 [M€]</td>
<td>543 [M€]</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
<td>30  [M€]</td>
<td>117 [M€]</td>
<td>205 [M€]</td>
<td>819 [M€]</td>
</tr>
</tbody>
</table>

Table 20: List of strategies and the corresponding objective function value, ranked by the objective function with \( \alpha = 0.1 \). The columns following have \( \alpha = 0.2 \), \( \alpha = 0.3 \) and \( \alpha = 1 \). The last corresponds to a discounted net present value (NPV) with a fixed discount rate.

### 10.5 Sensitivity analysis

In table 20 we rank the strategies of the adjusted design (table 8) by the objective function value used in the optimisation. In the three rightmost columns we provide values of the objective function where we use other values of the intergenerational parameter \( \alpha \). Setting \( \alpha = 1 \) means putting no weight on the undiscounted long term year, and the objective function reduces to an ordinary fixed rate discounted net present value (NPV).

What we can notice is that the ranking of strategies is different for the four versions of the objective function. In table 21 we show models with the same set of parameters for various values of \( \alpha \), with computed elasticities for all four response surfaces. It is perhaps not surprising that when we increase \( \alpha \) we get surfaces more sensitive to changes in 2015 and less sensitive to changes in 2030.

We can also study the response surface model for the objective function where \( \alpha = 1 \). Optimising over that surface suggests an optimum at \( \mathbf{x} = (2, 0.5, 2, 0.92) \). The SAMPERS/IMREL model was applied to two points near that suggested optimum to refine the response surface. The results are shown
### Table 21: Estimated parameters for different values of \( \alpha \). All parameters were significant. The elasticities of the response surface are computed at the optimum solution. They are non-zero since the optimum is on the boundary.

<table>
<thead>
<tr>
<th>Factor</th>
<th>( \alpha = 0.1 )</th>
<th>( \alpha = 0.2 )</th>
<th>( \alpha = 0.3 )</th>
<th>( \alpha = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-791.68</td>
<td>-1128.90</td>
<td>-1466.13</td>
<td>-3826.69</td>
</tr>
<tr>
<td>A-CarCost2015</td>
<td>+204.64</td>
<td>+413.39</td>
<td>+622.14</td>
<td>+2083.39</td>
</tr>
<tr>
<td>B-PTFare2015</td>
<td>+9.56</td>
<td>+4.40</td>
<td>-0.76</td>
<td>-36.88</td>
</tr>
<tr>
<td>C-CarCost2030</td>
<td>+895.72</td>
<td>+1055.23</td>
<td>+1214.74</td>
<td>+2331.32</td>
</tr>
<tr>
<td>D-PTFare2030</td>
<td>+19.15</td>
<td>+189.46</td>
<td>+359.77</td>
<td>+1551.94</td>
</tr>
<tr>
<td>( C^2 )</td>
<td>-174.99</td>
<td>-209.27</td>
<td>-243.55</td>
<td>-463.51</td>
</tr>
<tr>
<td>( D^2 )</td>
<td>-69.49</td>
<td>-155.27</td>
<td>-241.05</td>
<td>-841.51</td>
</tr>
<tr>
<td>BC</td>
<td>-65.18</td>
<td>-116.27</td>
<td>-167.36</td>
<td>-524.00</td>
</tr>
<tr>
<td>Elasticity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( E_A )</td>
<td>0.65</td>
<td>0.91</td>
<td>1.05</td>
<td>1.34</td>
</tr>
<tr>
<td>( E_B )</td>
<td>-0.10</td>
<td>-0.13</td>
<td>-0.14</td>
<td>-0.18</td>
</tr>
<tr>
<td>( E_C )</td>
<td>0.52</td>
<td>0.35</td>
<td>0.27</td>
<td>0.09</td>
</tr>
<tr>
<td>( E_D )</td>
<td>-0.10</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

### Table 22: Extra runs to test NPV optimum.

<table>
<thead>
<tr>
<th>Policy instruments</th>
<th>2030</th>
<th>Outcome</th>
<th>( \text{OF}(\alpha=0.1) )</th>
<th>( \text{OF}(\alpha=0.2) )</th>
<th>( \text{OF}(\alpha=0.3) )</th>
<th>( \text{OF}(\alpha=1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Car Cost} )</td>
<td>Car Cost</td>
<td>PT Fare</td>
<td>[M€]</td>
<td>[M€]</td>
<td>[M€]</td>
<td>[M€]</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>1</td>
<td>564</td>
<td>836</td>
<td>1109</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>2</td>
<td>0.9</td>
<td>548</td>
<td>819</td>
<td>1090</td>
</tr>
</tbody>
</table>

in table 22. It turns out that they are not better than \( x = (2, 0.5, 2, 0.5) \), and including them in the regression only confirms that.

## 11 Conclusions

The purpose of the case study we have seen here was to test PROSPECTS methodology on an operational land-use and transport model. In this section we offer some tentative conclusions from the tests.

First we would like to point out that the optimisation method turned out to be very suitable for our type of model package. The model we use takes a long time to run, and require a fair amount of manual input. Using an experimental design makes it easier to plan model runs efficiently. Response surface methods also provide very useful sensitivity information, in a visual and intuitive way.
We can only draw limited conclusions on the results from the optimisation itself. What is immediately apparent is that the suggested sustainability objective function ranks strategies differently from an net present value function using an ordinary fixed discount rate. The initial model design suggested that the NPV would have a different optimum than the OF with $\alpha=0.1$, but subsequent tests with the model package showed that the boundary point was still optimal with NPV. But the differences in parameters and elasticities suggest that if the optimisation was to be continued outside the boundary we would arrive at a different optimum.

The full potential of the optimisation method was never tested since our optimum was situated on the boundary of our feasible region. The optimum strategy we found to be to raise the fuel tax and lower the public transport fares by half. But it also includes fairly large negative user benefits, indicating that the strategy would probably be unpopular, unless the revenue were used to cushion that effect somehow.

The main challenges have been to implement the policy instruments and indicators. We chose to use log-sums to compute the user benefits, which turned out to work fine, after some initial programming trouble.
Part III
Modelling package development
12 Introduction

We described the model package in section 7. The models were chosen because they already were tried and tested in Stockholm. But using SAMPERS and IMREL together prompted some adjustments to the models. IMREL and SAMPERS share some basic characteristics. Both are random utility models, and both model work trips. In SAMPERS it is to forecast travel demand, an in IMREL it is a measure of accessibility affecting choice of locations. SAMPERS is estimated on a recent and comprehensive data material (Beser & Algcrs, 2002; Johansson Svedcr, 2002; Beser Hugo.sson, 2003). To repeat the same with IMREL was not feasible for this kind of study. Instead IMREL was calibrated against SAMPERS, to produce as much consistency between the two models as possible. This is described in the next two sections.

Using the two models together in an iterative process means that it becomes necessary to take steps to decrease run times. The EMME/2 network representing the supply side of the transport market was aggregated from a 1240 zone system to one with 99 zones. The method is described briefly in section 15.

13 Residential sub-model, RES

13.1 Model formulation

The residential submodel is a nested logit model derived from the assumption that the choice of residence is a combined mode and location choice of a random utility type. The deterministic part of the utility, consists of an individual’s observable cost of residing in zone \(i\), commuting to work in zone \(j\), by mode \(m\). It is given by

\[
\nu_{ijm} = -\left(\omega_i + \mu \frac{H_i}{S_i} + a_m + b_m c_{ijm}\right)
\]  

(13.1)

The first term is a zone specific constant. The second term is the disutility associated with housing density and \(\mu\) is a parameter used to calibrate the location pattern to reproduce an observed pattern. \(c_{ijm}\) is the generalised travel cost (see section 7.2), and \(a_m\) and \(b_m\) are estimated parameters connected to mode.

Depending of the assumptions we make on the random utility terms we get the probability that a worker in zone \(j\) will live in zone \(i\) and commute
by mode $m$ either as

$$p_{im|j} = \frac{e^{-\omega_i - \mu \frac{H_i}{S_i} - \lambda \hat{c}_{ij} m} e^{-a_m - b_m e_{ijm}}}{\sum_i e^{-\omega_i - \mu \frac{H_i}{S_i} - \lambda \hat{c}_{ij}} \sum_m e^{-a_m - b_m e_{ijm}}} \tag{13.2}$$

where

$$\hat{c}_{ij} = -\ln \sum_m e^{-a_m - b_m e_{ijm}}$$

which is a model with mode choice conditional on residential location choice, or

$$p_{im|j} = \frac{e^{-a_m - \lambda \hat{c}_{jm}} e^{-\omega_i - \mu \frac{H_i}{S_i} - b_m e_{ijm}}}{\sum_m e^{-a_m - \lambda \hat{c}_{jm}} \sum_i e^{-\omega_i - \mu \frac{H_i}{S_i} - b_m e_{ijm}}} \tag{13.3}$$

with

$$\hat{c}_{jm} = -\ln \sum_i e^{-\omega_i - \mu \frac{H_i}{S_i} - b_m e_{ijm}}$$

where instead the residential location choice is conditional on the mode choice. Which of the models to choose is determined by the parameter estimation.

### 13.2 Parameter estimation

The parameters are estimated with a maximum likelihood approach, using a general maximisation package. It is described in some detail below.

Given the number of observed trips $N_{ijm}$ $i, j$ and $m$ denoting the same things as in section 13.1, the likelihood function has the following form*\(^*\)

$$L = \prod_{ijm} p_{im|j} N_{ijm} = \prod_{jm} p_{m|j} N_{jm} \prod_{ijm} p_{ijm} N_{ijm} \tag{13.4}$$

where $p_{im|j}$ is given by equation (13.3), which is a pre-distribution modal split model. If the structure from equation (13.2) is used, the indices $i$ and $m$ are switched in equation (13.4).

Earlier experience, (Anderstig & Mattsson, 1991; Lundqvist & Mattsson, 1992), suggested that models with residential location choice conditional on the mode choice (eq. (13.2)) was to be preferred to avoid counter-intuitive cross-elasticities of the choice probabilities. This case proves to be no exception. The model using the structure in (13.3) shows the desired inclusive

*Missing indices from $N_{ijm}$ means they have been summed over, e.g. $N_i = \sum_j \sum_m N_{ijm}$

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value $0 < \lambda < 1$. A value in this interval ensures that this particular problem is avoided. The choice of the pre-distribution modal split also determines the way the accessibility measure used in section 14 is derived.

For the chosen structure the log-likelihood function becomes

$$
\ln L = \sum_{jm} \ln p_{m|j} N_{jm} + \sum_{ijm} \ln p_{i|jm} N_{ijm}
$$

$$
= \sum_{jm} N_{jm} \left( -a_m - \lambda \bar{c}_{jm} \ln \sum_m e^{-a_m - \lambda \bar{c}_{jm}} \right)
$$

$$
+ \sum_{ijm} N_{ijm} \left( -\omega_i - \mu \frac{H_i}{S_i} - b_m c_{ijm} + \bar{c}_{jm} \right)
$$

or rewritten

$$
\ln L = -\sum_m N_m a_m + (1 - \lambda) \sum_{jm} N_{jm} \bar{c}_{jm} - \sum_j N_j \ln \sum_m e^{-a_m - \lambda \bar{c}_{jm}} \tag{13.6}
$$

$$
- \sum_i N_i \omega_i - \mu \sum_i \frac{H_i}{S_i} - \sum_{ijm} N_{ijm} b_m c_{ijm}
$$

The log-likelihood function is maximised with the MaxBFGS algorithm included in the Ox programming language (Doornik, 1999). The process is speeded up considerably if an analytical gradient is provided. It has the components

$$
\frac{\partial \ln L}{\partial a_m} = -N_m + \sum_j N_j p_{m|j}\tag{13.7}
$$

$$
\frac{\partial \ln L}{\partial b_m} = -\sum_{ij} N_{ijm} c_{ijm} + \lambda \sum_j N_j \sum_i c_{ijm} p_{i|jm}
$$

$$
+ (1 - \lambda) \sum_{jm} N_{jm} \sum_i c_{ijm} p_{i|jm}\tag{13.8}
$$

$$
\frac{\partial \ln L}{\partial \omega_i} = -N_i + \lambda \sum_j N_j \sum_m p_{m|jm} + (1 - \lambda) \sum_{jm} N_{jm} p_{i|jm}\tag{13.9}
$$

$$
\frac{\partial \ln L}{\partial \lambda} = -\sum_{jm} N_{jm} \bar{c}_{jm} + \sum_j N_j \sum_m p_{m|jm} \bar{c}_{jm}\tag{13.10}
$$

$$
\frac{\partial \ln L}{\partial \mu} = -\sum_i N_i \frac{H_i}{S_i} + \lambda \sum_j N_j \sum_{im} \frac{H_i}{S_i} p_{i|jm}
$$

$$
+ (1 - \lambda) \sum_{jm} N_{jm} \sum_i \frac{H_i}{S_i} p_{i|jm}\tag{13.11}
$$
The components of the gradient which are zero at optimum, are helpful in understanding the model since they in some sense reflect the various requirements we set on the model generated pattern (terms with a positive sign), to reproduce the observed pattern (terms with a negative sign). Equation (13.7) requires that the model reproduces the mode split, equation (13.9) that the total number of residents in each zone is reproduced.

The last component, equation (13.11), is of some additional interest. It is always equal to zero in a doubly constrained model making it impossible to estimate \( \mu \) together with \( \omega_i \). To see this we rewrite the two last terms of equation (13.11). In a doubly constrained model

\[
\lambda \sum_i \frac{H_i}{S_i} \sum_{jm} N_j p_{im|j} = \lambda \sum_i \frac{H_i}{S_i} N_i \tag{13.12}
\]

and

\[
(1 - \lambda) \sum_i \frac{H_i}{S_i} \sum_{jm} N_{jm} p_{i|jm} = (1 - \lambda) \sum_i \frac{H_i}{S_i} N_i \tag{13.13}
\]

We address the problem by estimating the model in two steps. First a singly constrained model is estimated, which is equivalent to setting \( \omega_i = 0 \) above. The resulting \( \mu \) is then used as a constant when estimating the rest of the parameters in the doubly constrained model.

### 13.3 Data

The model is estimated using OD-matrices for the three modes, model generated for a base case situation in 1997. Corresponding travel impedance measures are obtained by assigning a 1997 travel demand to an EMME/2 network. Land area used for housing purposes is based on real estate taxation data 1998.

The car travel impedance consists of the terms

- Distance, at equilibrium
- Travel time, congested

and public transport of

- Monetary cost, avg. of cash and monthly
- In-vehicle time
- Auxiliary time
- Total waiting time

Slow mode uses a shortest distance matrix from the EMME/2 network. Times are in minutes, costs in SEK.

13.4 Results

The resulting models are presented in tables 23 and 24. The first showing the singly constrained model used to obtain an estimate of $\mu$, and the second the doubly constrained model, where $\mu$ is kept constant.

The differences between the models are small, which suggests that the value of $\mu$, calibrated in the singly constrained model makes sense in the doubly constrained model. It may be noted that the generalised cost parameters, as well as the logsum parameter $\lambda$ are larger in the doubly constrained case, indicating that it is somewhat more sensitive to the costs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{public}$</td>
<td>-0.0282</td>
</tr>
<tr>
<td>$a_{slow}$</td>
<td>-0.0640</td>
</tr>
<tr>
<td>$b_{car}$</td>
<td>0.0342</td>
</tr>
<tr>
<td>$b_{public}$</td>
<td>0.0529</td>
</tr>
<tr>
<td>$b_{slow}$</td>
<td>0.270</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.737</td>
</tr>
<tr>
<td>$\mu$</td>
<td>-0.0427</td>
</tr>
</tbody>
</table>

$\ln L = -3.0227 \cdot 10^6$  
$\rho^2 = 0.122$

Table 23: Singly constrained residential model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{public}$</td>
<td>-0.190</td>
</tr>
<tr>
<td>$a_{slow}$</td>
<td>-0.131</td>
</tr>
<tr>
<td>$b_{car}$</td>
<td>0.0349</td>
</tr>
<tr>
<td>$b_{public}$</td>
<td>0.0565</td>
</tr>
<tr>
<td>$b_{slow}$</td>
<td>0.286</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.876</td>
</tr>
</tbody>
</table>

$\ln L = -2.870 \cdot 10^6$  
$\rho^2 = 0.183$

Table 24: Doubly constrained residential model where $\mu = -0.0427$ is used. The zone specific constants $\omega_i$ are not shown here.
14 Employment sub-model, EMP

14.1 Model formulation

The probability, \( q_j \), that a workplace is located in zone \( j \) is assumed to be of a logit form i.e.

\[
q_j = \frac{\exp(\alpha A_j + \sum_{k=1}^{K} \beta_k I_{jk} + \rho_j)}{\sum_j \exp(\alpha A_j + \sum_{k=1}^{K} \beta_k I_{kj} + \rho_j)} \tag{14.1}
\]

where the probability depends on accessibility to labour, \( A_j \), and a number (\( K \)) of other indicators \( I_{jk} \) of zonal attractivity. \( \rho_j \) is zone specific parameter that ensures that the number of workplaces stays within given planning restrictions. The accessibility measure

\[
A_j = \ln \sum_m \left[ \left( \sum_i H_i e^{-a_m-b_m c_{ijm}} \right) \left( \sum_i e^{-a_m-b_m c_{ijm}} \right)^{\lambda-1} \right] \tag{14.2}
\]

is based on the notion that the employer will compensate the employee for commuting costs. The derivation of this accessibility measure from a random utility assumption is found in Anderstig & Mattsson (1991). The parameter \( \lambda \) is the logsum parameter estimated in the residential sub-model. The formulation is dependent on whether equation (13.2) or (13.3) is chosen. The one above is based on equation (13.2).

14.2 Data

The data set is compiled from two sources. The majority of the data used comes from SAMS 98, a database used by SAMPERS. Land area, and land area for employment purposes, are retrieved from real estate taxation data from 1998. The number of workplaces in each zone is also compiled from SAMS 98.

14.3 Results

This type of multinomial logit model is readily estimated using commercial software packages. The one used in this case is Alogit. Table 25 presents the estimated model.

Some additional terms were introduced (those called \( \beta_k I_{jk} \) in eq. 14.1) to correct for phenomena that accessibility alone cannot explain. Stockholms inner city has a disproportionately large concentration of businesses and therefore employees. The inner city dummy variable captures this. The model is
<table>
<thead>
<tr>
<th></th>
<th>Estimate</th>
<th>t-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility</td>
<td>0.884</td>
<td>364.1</td>
</tr>
<tr>
<td>Area</td>
<td>0.101·10^{-3}</td>
<td>116.6</td>
</tr>
<tr>
<td>Extra attraction dummy</td>
<td>1.190</td>
<td>416.2</td>
</tr>
<tr>
<td>Inner city dummy</td>
<td>1.572</td>
<td>462.3</td>
</tr>
<tr>
<td>Ring dummy</td>
<td>0.644</td>
<td>69.7</td>
</tr>
<tr>
<td>Arlanda dummy</td>
<td>1.543</td>
<td>158.9</td>
</tr>
<tr>
<td>(\ln L)</td>
<td>(-2.875\cdot10^6)</td>
<td></td>
</tr>
<tr>
<td>(\rho^2)</td>
<td>0.177</td>
<td></td>
</tr>
</tbody>
</table>

Table 25: Employment location model.

very sensitive with respect to what zones are considered inner city. The best solution seems to be to use only the innermost zone as inner city and introduce a ring of zones around it as a second dummy.

A dummy variable is also introduced to take care of Arlanda airport, since its location is not determined by accessibility to the labour force. An extra attraction dummy is included for other large employment centres, such as universities, hospitals and commercial centres.

15 Aggregation of the network

Planners in the Stockholm area have used an EMME/2 base network with 1240 centroids/zones for a long time. SAMPERS uses that network as its standard, but the iterative procedure we use it takes too long to run. By decreasing the number of zones we can decrease the run time for both the demand model, and for the network assignment. We do lose some flow on the network though, since the traffic between zones that are merged will disappear. We countered that somewhat by using the difference in flow between the two networks for the 1997 base year as a fixed extra flow on the links in order to reach approximately the same level of congestion.

The zones were merged to a system of 99 zones used in earlier IMREL studies (Anderstig & Mattsson, 1998), but the original network was kept intact. What was changed was the connectors between the zones and the network. An initial connector layout was produced by an expert* with many years of experience of working with the EMME/2 network in Stockholm. The experience proved crucial, since both too many and too few connectors can cause problems. To few and the resulting flows become too concentrated to

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*I would like to extend my thanks to Kerstin Pettersson at Inregia for the network aggregation work and for teaching me how to use the EMME/2 tools.
the largest routes, and too many and there is the risk that some route that was originally only connected to a small zone becomes connected to a large one, resulting in unreasonably large flows.

The connector layout was then calibrated by adjusting the length and connection node. It was calibrated first to reproduce the average distance, and then the average travel time. Both distance and time were aggregated using the original trip pattern (origin-destination matrix) as weights. Extra care had to be taken with the public transport network. It was necessary to add additional connectors to balance the increased size of the zones.

The network was also checked against network flows at some key points, especially the highly congested bridges over lake Mälaren. They turned out to be reasonably in line with model results and with experience from the planning community. We did not attempt any validation against traffic counts.

16 Concluding remarks

The way this particular version of IMREL has been developed and calibrated has been largely determined by the context in which it was used. A growing concern is planning for the transport system to take its share of the responsibility of reaching a sustainable society. Since sustainability analyses demand a long run view of the transport system, it becomes necessary to also take land use changes into account.

Furthermore, it is desirable to use as good a representation of the transport system as possible in the analysis. A reason for this is that a comprehensive transport model is responsive to a wide range of policy instruments, and more likely to capture synergies between instruments. Some instruments may only contribute to sustainability when packaged together with others.

It may be pointed out that the estimation of parameters in this paper is perhaps not an estimation in the usual sense, but rather more like a calibration of IMREL to be as consistent with SAMPERS as possible.

Since most sustainability definitions includes intra- as well as intergenerational equity, the perhaps most serious shortcoming of this IMREL version is the fact that it has only one household type, a one person – one job household, working in one type of workplace, to be able to do proper equity analyses socio-economic groups, different household types and an employment market with more than one sector in it would be desirable.
Part IV
Experiences for the future
17 Sustainability and the PROSPECTS framework

In this licenti ate thesis we have tested an approach to planning for sustainability suggested by the PROSPECTS project. It is an approach that takes a rational view on planning. A problem or objective is identified and different solutions are evaluated with respect to how we they solve the particular problem or reach the objective. There is an implicit assumption that we can predict the outcome of strategies.

We use an objective function to compare different strategies. We have argued that if targets are met by many strategies, we can use those extra degrees of freedom to find the best solution that meet the targets, but it requires an objective function that ranks the strategies. There is considerable flexibility in the framework. We have used the parts of it that we have been able to, with respect to modelling capabilities and time constraints. It is a strength, that in its simplest form, the framework does not require very much more than an ordinary CBA or MCA, which means that for many cities a first step towards using PROSPECTS guidance need not be that big. But of course, to really address sustainability, all the seven objectives from section 2.3 must be adequately included in the appraisal framework.

To some it might seem overly technical to condense the information in many indicators into one number. But, what is often overlooked is that if the indicators are presented and the decision-maker chooses, there are still implicit weights involved. It is probably a good idea to experiment with weights and costs in the context of the larger planning process. It could for instance be useful do several optimisations with different weights, corresponding to e.g. a green view, an equity view and an efficiency view. The sensitivity analysis we attempted by checking different values of the intergenerational parameter $\alpha$ is an example. In this case it turned out that the optimum was the same, but that is probably due to the constraints we have set. Differences in the estimated response surface indicate that the optima would not be the same.

A main concept in the approach we have used is that strategies, not individual policy instruments, should be considered. It is possible that synergies between instruments can improve the solution or help overcome barriers. In table 26 we compare two pure strategies with the combined strategy of the optimum. We can see that the optimum is better in all four versions of the objective function, in this case roughly equal to adding the pure strategies.

We have used a response surface method to search the policy space for the best strategy. Essentially it means that instead of optimising the function
directly, which would take too long, we use regression to construct a simpler functional form and optimise on that instead. And perhaps even more useful is the sensitivity information we get on the response surface, shown in table 19 and figures 5 and 6.

18 Experiences from the programming work

18.1 Logic, content and style

The information content of a modelling package like the one we used in this study is considerable. Oftentimes different skills are necessary in different stages in the lifetime of a model package. We found during work with our package that eh problems we faced had many similarities with the design of web services.

In the early days of website design the whole site was built by a person or a team skilled in coding html. As more information was added and the visual capabilities of browsers became more advanced it became necessary to include people with skills in writing and editing text and in visual design. Today’s web services are even more complex, with database back-ends, interactivity, and advanced layout.

A useful concept from the web industry is to separate logic, content and style. Take a news site as an example, where the content consists of articles provided by journalists and reporters. They should be able to use appropriate tools (e.g. word processing software) for writing and editing text, and not have to worry about how a browser renders it on screen. The people responsible for layout are not supposed to have to edit each and every article. Their job is to decide how a generic article, in terms of headlines, body text etc., is presented to the reader. The logic of a news site could e.g. be that only subscribers have access to some of the content.

So, where do our land use and transport interaction models fit into this? Well, we can imagine a similar separation, where we down at the bottom have

<table>
<thead>
<tr>
<th>Policy instruments</th>
<th>Outcome</th>
<th>OF</th>
<th>OF</th>
<th>OF</th>
<th>OF=NPV</th>
</tr>
</thead>
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<td>OF=0.2[M€]</td>
<td>OF=0.3[M€]</td>
<td>OF=M=NPV[M£]</td>
<td></td>
</tr>
<tr>
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<td>2</td>
<td>0.5</td>
<td>629</td>
<td>905</td>
</tr>
<tr>
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<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>124</td>
<td>182</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>520</td>
<td>748</td>
</tr>
</tbody>
</table>

*Table 26: A comparison of two pure strategies with the optimum strategy.*
the content, in the form of databases describing the system. It is the socio-economic data, as well as the network. The logic layer obviously consists of the models. Think of a model as an object that retrieves data from the database, does some computation and returns the output data to the database. In the same way we can view the style, or presentation, layer as some object or program that gets data from the database and presents it in a spreadsheet or map form.

The great advantage of separating things is that we can use the appropriate tools for each task, as there is really no reason to reinvent software already available. The most important factor here is the database. By using some standard database system with ODBC* support, e.g. MySQL, Access or Microsoft SQL Server, you get interoperability with other software almost out of the box†. The point is that if the data is available, you can use Excel for spreadsheet tasks, SPSS or something similar for statistics, your GIS (Geographical Information System) of choice for spatial representation, and more or less any programming language you like for the things that are not available.

18.2 GIS

Geographical Information Systems deserve a separate comment. They could have been brought up in section 5 on available tools, but that section was more focused on theoretical background. GIS is more a technical toolbox to facilitate the use of spatial data. While the GIS packages that are available often encompass all three aspects of logic, content and style, the one they truly excel in is the presentation. Often they are designed to be hooked up to a database backend, and the user is often required to do some programming for everything except fairly basic analysis. From a researchers point of view this is not necessarily a bad thing, if the focus of a package is that it should be easy to extend instead of trying to include everything out of the box, which of course is not possible.

18.3 SAMPERS/IMREL

A general observation regarding the SAMPERS/IMREL package we have used is that it is not detailed enough for some of the policy analyses we would like to do. One example is that the spatial representation of the network is too aggregate to be useful in a study of the interaction between walk/cycling

---

*Open Database Connectivity

†I am talking about Windows based software here. If you use Linux/Unix you have probably figured these things out yourself already
and the other modes. Another is the lack of socio-economic segmentation in IMREL.

But on the other hand, it is already too slow to allow other than very basic optimisations. A very interesting direction would be to adapt the models for running on parallel processors. The potential is large, since the logit structure is relatively easy to parallelise.

A sketch planning model was developed and tested in PROSPECTS (Pfaffenbichler & Emberger, 2003) to try to model the urban system on a strategic level quickly enough to facilitate more elaborate optimisations. There is a sketch-version of SAMPERS available as well, where some socio-economic detail has been traded for increased speed. Had that model been available at the time this work was started, it would have been the obvious choice, since IMREL does not use that socio-economic detail anyway.

19 Future research

This licentiate thesis is only a beginning in the work of investigating and testing the PROSPECTS sustainability appraisal framework with integrated land use and transport models. There are many interesting directions further work could take from here. The objective function used is essentially a CBA corrected for intergenerational equity. We have not attempted to take advantage of the possibilities the framework provides, in terms of setting targets/constraints, or including indicators of other objectives in the objective function. Because of this it is not really possible to say that the appraisal we have attempted really deals with sustainability. Rather, it is one step towards that goal, where we have taken intergenerational equity into account. Further work, involving discussions with different stakeholders would be necessary to make sure this approach reflects a general view of sustainability. It would also require more sensitivity tests and a more thorough analysis of the behaviour of the objective function.

There were several reasons for this. One was the inability of the modelling package to produce useful indicators of other objectives, such as equity considerations between different socio-economic groups, or spatial effects on a detailed level such as noise and other things related to livable streets and neighbourhoods. But also ecological effects, e.g. on bio-diversity, from the land use and transport system is desirable to include somehow.

These limitations of the modelling package are of course things that further work could help alleviate. Some are even addressed already by the continuing development of SAMPERS that has been carried out since this study began. The other things require some development of the land use
model.

The second main reason why only selected parts of the appraisal framework were implemented was that integrating two models and a new appraisal framework proved fairly technically complex. To involve more indicators and optimisation variables would have increased that complexity. But having arrived at some useful results with this simple set-up, there are some relatively straightforward follow-up studies that can be done.

More policy instruments can be included in the optimisation. Section 9.3 describe some instruments that the model package already is prepared for. Naturally this increases the size of the optimisation problem, as well. Earlier experience (Minkel et al., 2003, ch. 18.2) suggests \( n = 2c + d + 5 \) as a rule of thumb of how many initial runs are necessary to set up a response surface. \( c \) is the number of continuous variables and \( d \) the number of discrete variables (e.g. infrastructure projects).

In this study we have used a fixed valuation of emitted CO\(_2\) following national guidance. There are two alternatives that could be interesting to study. The first is to use an increasing cost over time, reflecting a desire to not only halt but also reverse the emissions of CO\(_2\) in the long run. The other alternative is to set a target level of CO\(_2\) emission as a constraint in the optimisation. It would yield an interesting shadow price of CO\(_2\), reflecting the cost of reaching the target.

The optimisation problem is essentially an optimal control problem. We have formulated it with a cut-off point at a horizon year. The original formulation by Chichilnisky does not. An interesting research direction would be to investigate how dynamic programming techniques could be employed in solving the problem in the infinite horizon case.
References


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