Doctoral Thesis in Transport Science

Transport, Mobility, and Workplace Location: Models and Applications

FATEMEH NAQAVI

Stockholm, Sweden 2024
Transport, Mobility, and Workplace Location: Models and Applications

FATEMEH NAQAVI

Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy on Wednesday the 17th January 2024, at 9:30 a.m. in F3, Lindstedtsvägen 26, Stockholm.

Doctoral Thesis in Transport Science
KTH Royal Institute of Technology
Stockholm, Sweden 2024
To my loving family,
for encouraging resilience.
Abstract

Travel demand analysis is one of the core constituents of transportation studies. The required insight to maintain and develop a sustainable transportation system, in addition to learning from previous research globally and locally, is generated from studying the effects of previous policies, investigating future possibilities and potential outcomes, and describing the current situation. The objective of the thesis is to use urban modeling and decision support methods to contribute to the knowledge that improves decision making for a sustainable society.

In this thesis, three of the papers focus on implementation and application of a dynamic model of movement for prediction and forecast of workplace demand and accessibility, and for a trip chaining problem. This framework formulates movement through a Markov chain and solves it by using the Bellman equation which by the assumption of IID Gumbel error terms turns into a recursive logit, which reflects dynamic and directional nature of time in modeling movement. This approach is used for modeling a workplace choice model and accessibility to work (Paper 1), that is applied for workplace allocation in a scenario planning framework for urban development growth with a 2040 forecasted synthetic population (Paper 3), and a dynamic trip chaining model with flexible number of trips in the chain (Paper 4). The workplace location choice model is unique as it connects the land use and transport models in a framework that is consistent with random utility maximization approach while respecting forward-looking behavior of individuals and the dynamic and directional nature of time. This approach allows for evaluations of counterfactual scenarios in Paper 1 and in future workplace growth in Paper 3 for understanding the implications of workplace allocations under different urban planning scenarios in terms of travel behavior, with implied social segregation issues, workplace demand and distribution of welfare. When applied in a trip chaining context (Paper 4), the methodology allows for flexibility in number of trips in the chain, with the implication of creating the link between trip chaining problem and the marginal utility of time and the marginal rate of substitution not only for different trip purposes, e.g. work and leisure, but also for any other variables in the model, even in the absence of scheduling, which is novel in the literature of trip chaining and time valuation.

A fundamental aspect of the methodology that is used in this thesis revolves around the utilization of Multivariate Extreme Value (MEV) models. We explore the intricacies of these models in detail in Paper 2, and take one step against the convention by using a replicated nest in a multinomial setting. We discuss the empirical implication of retrieving exchangeability, when it is compromised. This approach gives a reminder to respect the complexity of error term in MEV models, while benefiting from the generality of its definition.
Travel time and costs are among the factors that impact transportation and land use interactions. In Paper 5, we address this interaction by exploiting a natural experiment to investigate green vehicle owners’ responses to phasing out of their time-varying toll exemption in Stockholm through comparison of data in 2012 and 2013, which were before and after this policy was implemented. The results show a significant drop in the total number of green vehicles that crossed the toll stations in 2013, and a significant shift to off-peak crossing time in the toll stations in 2013 compared to 2012.
Sammanfattning


En grundläggande aspekt av den metod som används i denna avhandling kretasar kring användningen av multivariata extremvärdesmodeller (MEV). I Artikel 2 utforskar vi dessa modeller mer i detalj och prövar en replikerad nästling, vilket inte tillhör praxis inom området. Vi diskuterar detta förfaringsätt utifrån modellteoretisk utbytbarhet (exchanceability). Denna ansats påminner om att hantera komplexiteten hos felstrukturen i MEV-modeller, samtidigt som man kan dra nytta av dess generalitet.
Acknowledgement

This work would not have been possible without the guidance and support of many individuals. I would like to express my sincere gratitude to my main supervisor, Muriel Beser Hugosson, for giving me this opportunity of learning and growth and supporting me through my journey. I thank Marcus Sundberg for two years of consistent support and sharing his insight and knowledge very patiently. I thank Anders Karlström for all the interesting lectures and helpful supervision meetings, and for sharing his rich and genuine curiosity which is rare to find elsewhere. I thank Emma Engström for her positive encouragements and her enthusiasm in work during the supervision process. I thank Oskar Blom Västberg for all his help and his positive attitude. I thank Joel Franklin for his persistence and commitment to work and supervision. I would like to thank Fariya Sharmeen and Maria Hákansson for their helpful feedback through the revision process, and finalizing the thesis. I would like to thank Christer Persson for his patience and help with my many questions. I thank Michele Simoni for his support especially towards the end.

I would like to thank our current and former administration staff, Therese Gellerstedt, Susan Hellström, Sofia Kroné Karlsson, Betty Jurdell, and Per Olsson for being good at their jobs, which makes our life easier, and also for being friendly, warm and supportive.

I am also thankful to my great friends and brilliant colleagues. First and foremost I thank my current officemate, Stephen McCarthy, for his commitment to our shared work and for all the interesting conversations, not just about modeling but also about languages, cultures and food, for his inclusive behavior and for reminding me that all achievements are worthy of celebration. I thank Robin Palmberg for all the fun conversations about work and life, and for his support during the first year of my PhD. I thank Tanay Rastogi, Joel Fredriksson, and Stephen for fun moments, either in the office kitchen or abroad in conference trips. I would like to thank my friend Maryam Sanaee, for our daily walks along the water that helped me clear my mind when I was writing the thesis. I thank my friends Zahra, Niloufar, Amanda, Esther, Dagni and Neva and all other colleagues and friends that provided support and fun moments and enriched my days.

Last but not least, I thank my family, especially mom and dad whose love and support is beyond time and space, which lightened my darkest moments. I thank my siblings for their support and kindness, and for reminding me of what matters. I thank Mehdi, for becoming my best friend and companion towards the end, and for his genuine generosity in understanding, care, and love. I thank him for making our small apartment feel like home. Thank you!
List of papers


_Published in Transportation Research: Part A._


_Presented at ICMC 2021; International Choice Modelling Conference._


_Presented at ERSA 2022; European Regional Science Association._
_Submitted to Journal of Transport Geography._


_Submitted to IATBR: International Conference on Travel Behaviour Research._

https://doi.org/10.32866/001c.88878

_Presented at VEHITS 2023; 9th International Conference on Vehicle Technology and Intelligent Transport Systems._
_Published in Findings._


Declaration of contribution

The ideas in all papers were jointly developed in discussion among Fatemeh Naqavi and co-authors. Fatemeh Naqavi was responsible for implementation, coding, analysis, writing, editing and reviewing for all papers under supervision of supervisors with the following qualifications:

In Paper 3, Fatemeh Naqavi had primary responsibility for estimation of the workplace location choice model, while co-authors had primary responsibility for application of the model. Writing a first draft was primarily the responsibility of the first author.

In Paper 4, co-authors had primary responsibility for writing the methodology section on Markov chains.
# Contents

## Part I - Introduction

1. **Overview and objectives**  
2. **Summary of contributions and limitations**
   1. Summary of contributions
   2. Summary of limitations
3. **Sustainable mobility**
4. **Transportation models**
   1. The four-step models
   2. Activity-based demand models
   3. SCAPER
   4. Intra-household mobility decisions
5. **Discrete choice models**
   1. Random utility models
   2. Exchangeability of alternatives in MEV models
   3. Elasticity
6. **Accessibility measures**
   1. ABA from SCAPER
   2. Applications
7. **Policy evaluation**
   1. Measures of welfare economics in transport
   2. Scenario planning context
      1. Urban development approaches
      2. Scenarios and conclusions
   3. Trip Chaining
      1. Valuation of time savings
      2. Trip chaining and VOT
   4. Congestion pricing

---

1
3
10
11
12
15
17
18
20
21
22
24
24
26
28
29
29
31
31
34
36
Introduction

1 Overview and objectives

The relationship between transport and land use is well recognized as a crucial aspect of transportation and urban planning and sustainable development. The interplay of transport and land use is such that changes or modifications in one, could have significant implications for the other. Understanding this dynamic is essential to the development of different land-use transport models, from the perspective of policymakers, planners, and researchers that aim to optimize land use and transport planning strategies for mobility efficiency while reducing congestion, and improving the livability of cities.

One departure point around the connection between land use and transport was developed in the 1930s, Christaller’s central place theory, which highlighted the spatial organization of economic activities and their dependence on transportation infrastructure. While this theory did not mainly focus on transportation, it acknowledged the significance of transportation in the size and distribution of central places in cities and the distribution of goods and services within a region that shapes the hierarchy of central places (see Getis and Getis (1966)).

The interaction of land use and transport forms the context to investigate accessibility. Hansen (1959) explained that higher accessibility of areas, which was measured in travel time or distance, influences attraction for land use activities, for example, residential, commercial, and industrial developments. He emphasized the importance of considering accessibility in land use and transport planning by providing empirical evidence that showed a significant connection between transportation accessibility and land use scenarios. From a similar and more comprehensive perspective, Hägerstrand (1970) explained how individuals can move in space and reach locations within their time budget through, thus introducing the space-time prism concept. Accessibility highly impacts the choices and opportunities that individuals face, from simple everyday choices, such as where to buy groceries, to larger and more transformative decisions such as workplace location choice. Accessibility could create or counteract social and economic issues, such as segregation, or car dependency.

Gravity models, and later the four-step models, were developed to model the relationship between land use and transport. Discrete choice theory and random utility framework is a work horse for models of spatial choice behavior and travel demand, and also used to forecast the behavior of actors such as investors, households, firms, or travelers (see Wegener (2004)). Discrete choice models are popular in transport
problems, partly due to the discrete nature of transport problems such as route choice, mode choice, destination choice, etc., partly for the ability of a disaggregated approach with socio-economics, and partly due to its microeconomic foundation. According to Acheampong and Silva (2015) that conducted a literature review on land use and transport modeling, the complex interaction among the land use and transport systems makes it very difficult to investigate and measure the impacts of these systems on each other in isolation empirically. Some variables that contribute to this complexity are socio-demographic, economic, and policy changes intrinsic to the observed structure of the land-use and transport systems.

Despite the diversity of questions that are posed in different papers in the thesis, all the papers contribute to the knowledge of developing and using urban models and decision support methodologies in a quantitative approach for more informed urban planning, aiming towards a sustainable society. One major link among research papers is shown on Figure 1, that reflects their relevance to Land Use and Transport Interaction (LUTI) models, in terms of research questions which are discussed in the next section. Another thread is the methodology that uses rationality based models to model behavior, travel demand and/or movement, and is used for prediction, forecast, and policy evaluation.

More specifically, research questions assigned to papers are summarized as follows:

- *Develop a workplace choice model and consequently a workplace accessibility measure, such that the spare time accessibility of individuals is maximized throughout a working day,*

- *Investigate exchangeability in Multivariate Extreme Value (MEV) models,*

![Figure 1: Papers’ relationships to the land-use and transport feedback cycle of Wegener (2004).](image-url)
• Evaluate policies for a workplace location-allocation problem in the Stockholm municipality.

• Introduce a dynamic trip chaining framework and valuation of time as an implication of the dynamic trip chaining, and

• Investigate the green vehicle owners’ behavioral change after phasing out the toll exemption in 2012.

The next section summarizes papers’ contributions and limitations to provide a more coherent understanding of the research in the thesis. Later, a literature review on the transport models is provided, and while explaining the gaps in the literature, our research is placed in the context, mainly from a transportation perspective.

2 Summary of contributions and limitations

2.1 Summary of contributions

The contributions of papers in the thesis fall broadly under three categories of theoretical (Paper 4), methodological (Papers 1, 2, 4), and applications, mainly for land-use and transport development and policy evaluation, (Papers 1, 3, 5). A summary of contributions are provided in the following.

Paper 1: Mobility constraints and accessibility to work: application to Stockholm

This paper investigates workplace accessibility in Stockholm through a workplace choice model within a space-time prism concept. We develop a model for workplace location, extending an activity-based demand model, SCAPE (Blom Västberg et al., 2019), which is formulated as a Markov decision process in a dynamic discrete choice framework. From the model we derive an accessibility measure, consistent with space-time constraints affecting the possibilities of individuals to engage in activities during spare time, which is explained in section 4.3. The accessibility measure thus incorporates individuals’ constraints in time, space, and resources. The results show that spare time accessibility is significantly linked to workplace accessibility (see section 6.1). Applications of the results show how space-time constraints, such as access to a car or having (young) children impact welfare measure. Applications of the results include (see section 6.2) the following.

- We investigate a hypothetical relocation of a large workplace (Karolinska hospital) with nearly 7000 workplaces to all other zones in Stockholm, and comparing the changes in welfare, in terms of Consumer Surplus (CS), compared to the current location of it.
- Demand analysis in two cases:
  1- Comparing the CS of the base scenario, to when people lose access to car. The results show that the central areas would have a higher CS, which extended along the metro lines.
  2- Calculating the odd ratio of workplace demand for higher income people to all people in the sample, which shows higher demand for northern part of the city with better transportation access. The results are informative to address social sustainability, in particular social segregation.
- Comparison of welfare measure for car-owners with and without an extra constraint, i.e. a child that needs to be dropped-off / picked-up at day care. The results show that individuals with the extra constraints have a higher CS, meaning that they are willing to pay more to keep their means of transport. To the extent that pick-up activities in the household is gender coded, the results are informative in terms of gender equality.

Paper 2: On Exchangeability in Multivariate Extreme Value models
In nested logit models (a.k.a., MEV models) IIA is relaxed by using the functional form of the error structure, which allows for flexibility of defining nests and does not dictate unique nests and parameters. However, common practice favors the structure with unique nests, which leads to overlooking the complexity of error structure and compromising exchangeability of choices.

In Paper 2 we use a numerical example in a multinomial setting to investigate implications of replicating nests with non-exchangeable alternatives. Although it is allowed and inherent in the definition of a generic MEV model, it is rarely implemented in practice. One take-away from this paper is a reminder that the functional form of the error structure is worthwhile to consider. The empirical finding, which was somewhat unexpected, was that replication of the nest was able to restore exchangeability and provide the same or better model fit, as compared with a non-exchangeable model definition. This is a result that may be of relevance for applied work, in which exchangeability from a theoretical and practical perspective is a desirable property, for example, in route choice problems or in stated preference (choice-based conjoint analysis).

Paper 3: Modelling scenarios in planning for future employment growth in Stockholm
The City of Stockholm is conducting a scenario planning exercise to explore where potential future office development should be planned: closer to the city centre as in the status quo, in peripheral hubs on the outskirts of the city, or dispersed throughout multiple neighbourhoods. To support this exercise, this paper models these three scenarios using a nested work location and dynamic activity-based scheduling model.
There are differences between SCAPER used in Paper 3 and Paper 1, which are newer traffic zones (1375 in Paper 3 compared to 1240 in Paper 1), including activity duration, change in the names of activity types (estimations are provided in the appendix of Paper 3), including values to reflect relationship between mode and activity type (McCarthy and Karlström, 2023).

We demonstrate how the model can be used in the scenario planning exercise. For instance, the following results are discussed (see section 7.2):

- High-income individuals have the highest welfare benefits and are over-represented as workers in all scenarios. Since 80% of the workplaces to be allocated are office jobs, they were categorized under the business-type sector. This could be a potential reason of this over-representation, which implies types of jobs that are going to be allocated matter in equity and environment considerations.

- Developing more central office space will likely reinforce existing geographical patterns of income inequality in Stockholm.

- Developing peripheral or dispersed office space, especially in the south of the city, will challenge these patterns.

Moreover, the model also illustrates a tension between the sustainability goals of equity and the environment (i.e. social and ecological sustainability). By taking advantage of existing transit infrastructure and congestion patterns, more central office development will result in lower vehicle kilometers travelled and lower car mode share for commuting than more peripheral or dispersed development.

**Paper 4: Recursive logit as a dynamic trip chaining model**

This paper introduces a recursive logit as a dynamic trip chaining model. We model mobility pattern through solving Markov chain using Bellman’s equation consistent with the recursive logit model definition. This formulation allows us to flexibly analyze trip chain. First, one of the challenges in trip chaining studies is inclusion of trips in the chain, such that including more than one trip other than the origin and destination in the chain, would create a complex trip chain. Our framework can include a flexible number of trips, up to an infinite number, in the chain. Second, our framework also creates a link between the time valuation and trip chain, allowing us to analyze the theoretical valuation of time in the context of arbitrary (potential infinite) trip chaining. Finally, from an applied point of view, implementing long trip chains provides computational challenges. We explore the approach of using control variate to speed up the computations, and demonstrate cases in which it does work well, and where it is less efficient, and compare it with importance sampling techniques. We investigate various properties that affects the computational efficiency of the CV
approach. In particular, the degree of correlation between the estimated expected value (EV) function and target EV, in addition to the logarithmic form of this measure.

**Paper 5: Responses to an Expiring Congestion Toll Exemption**

Stockholm established time-varying congestion pricing in 2007, and adopted a toll exemption as a temporary incentive for green vehicles (GVs) that ended in 2012. We examine the behavioral effects of phasing out the toll exemption by studying the change in cordon crossing events for GV morning commuters between May 2012 and May 2013, with a random sample of conventional vehicles (CVs) as control group. The results suggest (see section 7.4) a significant drop in the total number of crossings, a slight shift towards later journeys in the morning, and a reduction in the ratio of peak-toll period crossings to other ones.

### 2.2 Summary of limitations

This section starts with a reminder of the famous quote from the statistician, Box (1979) when he said, "All models are wrong, but some are useful."

There are general limitations that emerge due to model choice and type of data, which are inevitable and important to recognize. Examples are differences in data-driven versus theory-driven approaches, structural modeling versus treatment effect, and quantitative versus qualitative analyses. There is also one specific limitation in three of the papers, which is the absence of traffic assignment integration to SCAPER. We will below discuss these in turn.

A limitation of the theory-driven approach is the underlying assumptions. In the random utility maximization (RUM) approach, for example, the utility functions are maximized based on the *as-if* assumption. Axioms of rationality and preference which are the underlying constituents of RUM also follow a set of assumptions themselves, which often overlook the impact of bounded rationality, incomplete information, social and cultural factors when societies are not strictly rational, change in the preference, and non-transitivity (Hess and Daly, 2014).

Data-driven approach are known for their accuracy of predictions. Their estimations uses data with no prior assumptions which eliminates the modelers’ biases. This helps with model specification and identifying significant variables and their impacts. Despite higher accuracy of prediction, an agreed-upon limitation of data-driven approaches is the difficulty in interpretation of the results and estimated parameters, which might raises questions when policy evaluation is involved. Another limitation is hesitation of researchers and modellers to use them due to misconceptions and lack of recognition of its potential (van Cranenburgh et al., 2022).
Indeed, any combination of approach and data is possible, based on the problem. Examples are studies by my colleagues, for example, Amaani Jafer is using the same methodology (SCAPER) for big data, "an activity-based framework for reestimating a dynamic discrete choice model with anonymised mobile data", and Joel Fredriksson is using a data-driven approach for national travel survey data for "a neural network-based travel demand model". Each approach has limitations of its own, but also the distinct features that makes it useful.

Another categorization is structural modeling as opposed to treatment effect/natural experiments, where the former can used for counterfactual simulation and policy evaluation, at the cost of model assumptions. These different models might be different in terms of internal and external validity assessments. Internal validity is tested in experiments where there is a significant difference between the treatment and the control group. For theoretical research, the generated model could be applied to test how close are the behaviors predicted by the model to the actual human behavior (Druckman et al., 2011). External validity reflects the measure of usefulness of an inference. Inferences could be valid in some studies but not in others. There are two ways of testing external validity, through generalizing the findings to the whole population, or transport it to a sample from another population (Findley et al., 2021).

Examples of structural modeling would be Papers 1 to 4, with a RUM framework. Paper 5, on the other hand, investigates the effects of a change (congestion tax removal) among green vehicles’ users which is an example of treatment effect. The method selection in Paper 5, for the main part, is influenced by the available data. The findings of Paper 2, retrieving exchangeability and better model fit can be viewed from internal and external validity. Findings of Papers 1 and 3 indicate that our modeling approach is generalizable, while SCAPER would require re-estimation of parameters for another geographical location, although without any fundamental changes to the model structure.

Also, we note that our approach is quantitative, enabling statistical inference and interpretation of results. The qualitative approach may provide deeper knowledge and provide insights into individuals’ experiences, it might not facilitate the comparisons among choices in a systematic way. Unlike our approach, the qualitative method provides more in-depth understanding of experiences of users and contextual insights of their socio-economic environment, and identifies relevant patterns and variables (Clifton and Handy, 2003).

Finally, we should acknowledge that a major limitation in Papers 1, 3 and 4 is not to integrate traffic assignment with SCAPER. The travel times are not endogenous. This could be improved in two steps. First, one possibility is to iterate between SCAPER and MATSim (Multi-Agent Transport Simulation Toolkit) and use the converged static values (between days), and second, using dynamic assignment values that up-
3 Sustainable mobility

Transport and land use decisions directly impact mobility, accessibility, and subsequent opportunities, and consequently have a major impact on the quality of life. Therefore, a sustainable mobility system, that is not growing in congestion, pollution, and fuel consumption, while providing similar opportunities to travel for users is an aim to strive for (May, 2003). Moving toward sustainability would benefit from target objectives that are economically efficient, protect the environment, contribute to the liveability of cities and neighborhoods, improve safety and equity, contribute to economic growth, and hold intergenerational equity (Gallo and Marinelli, 2020; Hackl, 2018). This requires a logical structure for public decision making\(^1\) that uses a mix of vision-led, plan-led, and consensus-led approaches, to benefit from visionary individuals, professional planners, and undertaking actions. This research falls in the plan-led approach, which we follow in this thesis.

May (2003) provides a logical structure of recommendation for decision making that involves all elements of the plan-led approach, which consist of:

- a clear definition of objectives and indicators for now and future, through scenario evaluation for alternative futures in which alternative scenarios cover the objectives,
- suggested instruments and strategies in combination, to overcome the barriers that would emerge during implementation,
- investigating effects of these instruments or the overall strategies through a model, and their comparison through appraisal based on the objectives,
- find ways to improve the instruments or strategies either through the previous step, or optimisation techniques
- implementation of the preferred instrument or strategy and evaluation through regular monitoring that addresses changes in the problem and objectives

All these steps ensure a logical basis for the proposals and methodology assessment. Optimizing all objectives to achieve sustainable mobility to a feasible and possible extent requires trade-offs to adjust the current imbalance between improving the supply side of the transportation system and respecting and protecting the environment.

Defining clear objectives is possible through the investigation of indicators, e.g. a reduction in the number of accidents reflects an improvement in safety. An effective

---

\(^1\)Unless clearly stated otherwise, in the rest of the thesis, a decision-maker will refer to individuals and people on the demand side.
way of defining indicators is to have exhaustive indicators such that they cover multiple objectives, provide information and insight for decision-makers, and be sensitive to strategy changes (Gudmundsson, 2003).

Problem identification is crucial for identifying effective solutions, which helps communicate the abstract objectives. Problems could be categorized by consultation, objective analysis, and monitoring. Consultation is beneficial to identify current problems, while objective analysis addresses indicators and thresholds that represent the severity of the problems. Analyzing the problem severity is beneficial for current and future planning. Objective analysis and monitoring enable consistent comparison of issues across different areas and years, which results in the priority setting. Investigation of the impact of predicting solutions provides insight into potential improvements or drawbacks. This approach requires a comprehensive list of indicators that cover all objectives. The threshold setting is arbitrary and the problems should not occur below their values. If thresholds vary across indicators, the equivalence of different problems’ severity could emerge. This approach might show problems as symptoms, where investigating the cause analysis to determine suitable solutions is required.

Policy instruments are tools that help achieve objectives and solve problems in urban transportation. They include different methods such as infrastructure development, pricing policies, traffic management, and land use adjustments. These instruments can be implemented across the city, in specific areas, or at certain times. No single instrument can address all issues or fulfill all objectives, so effective strategies involve combining different instruments. Policy instruments influence transportation system performance by changing travel demand, transport facilities’ supply, and cost of new developments, or maintenance (see, for example, Bardal et al. (2020)).

Appraisal is a means for adopting an effective policy, where there are choices that require trade-offs. Appraisal is beneficial to understanding the severity of the problem, comparing different solutions and improving them, combining different instruments effectively, and evaluating how well a scheme has worked. A basic foundations of evaluating welfare within neoclassical economic framework is given by Karlström (2014).

This thesis follows the logical structure of the plan-led approach, as discussed above. In Sections 3 and 4 below, we will elaborate on the modeling approach that will be used.

4 Transportation models

Transportation models that integrate land use are crucial for creating more livable cities through optimized transport investments. They give insight into the direction of infrastructure growth, traffic management, pricing policies, and regulations, and the equity questions such as "who benefits?" from implementing transport policies,
and have a procedure to address "how much?". They have descriptive and predictive capabilities and are powerful tools for investigating travel behavior in a dynamic framework. This chapter is dedicated to a summary of the development of the transportation models, and contains a section about SCAPER, that is extensively used in the thesis.

4.1 The four-step models

The four-step model emerged as a comprehensive framework in transportation forecasting in the 1950s. The four-step models include trip generation, trip distribution, mode choice, and trip assignment. This model incorporates the gravity model, introduced by Stewart (1948), within its trip distribution step to effectively account for spatial interactions and to integrate land use and behavior considerations into transportation planning (e.g. McNally (2007)). While these models are primarily focused on forecasting and evaluating transportation demand, they also indirectly consider the reciprocal impacts of land use on transportation and vice versa. They recognize that land use characteristics, such as population, employment, and accessibility, influence travel demand and transportation infrastructure needs.

In the trip generation step, the number of trips generated or the demand is based on the land use characteristics, as well as land use patterns such as the distribution of residential, commercial, and industrial opportunities. Mukherjee and Kadali (2022) provides a review of modeling approaches used in the literature. They found that while socio-demographics, built environment, and land use characteristics had an impact on trip generation, land use characteristics had the most impact on the prediction of trip generation rates. They reported that the studies on trip generation are mainly conducted in developed countries while developing countries, not only have less research on the topic but are also expected to face significant land use changes in the near future.

In trip distribution, the land use structure and transportation infrastructure affect the number of trips between different locations. Areas with more opportunities or transportation options attract more trips. Besides the gravity model, another approach, inspired by intervening opportunities theory, uses distance as a surrogate for opportunities. Lenormand et al. (2016) found the gravity model excels in estimating commuting flows and maintaining network structure but struggles for long-distance predictions without detailed data for calibration.

Mode choice, often based on travel time and cost, can be influenced by land use characteristics. For instance, areas with mixed land use and good pedestrian infrastructure encourage active transportation modes. Discrete Choice Models (DCMs) typically investigate mode choice.
The traffic assignment model evaluates traffic flow through a road system, considering changes in land use like new workplaces or residential areas. This model relies on information from the previous steps in the four-step model and incorporates Wardrop’s user equilibrium principles, ensuring equal journey times for used routes. Wardrop’s principles state that journey times in used routes are equal and less than those on unused routes, with the average journey time minimized. Solving this is equivalent to solving the static user equilibrium assignment problem (Beckmann et al., 1956).

Limitations of the four-step models led to the development of the Activity-Based demand Models (ABMs). Rasouli and Timmermans (2014) counted these limitations as lack of integrity and complete independence among sub-model, and strong aggregate nature of the models. However, modern four-step models are more interdependent and in trip generation, distribution, and mode choice could be modelled simultaneously by multivariate extreme value models.

4.2 Activity-based demand models

Bhat and Koppelman (1999) provided a detailed discussion of the trip-based demand modeling and its limitations, which are, for example, the inability to include the scheduling problem, the absent link between the home-based trips and the non-home-based trips, and other behavioral inconsistencies.

As a response to these limitations, the family of Activity Based Models (ABMs) was developed. The ABM approach is based on the integration of the time-geography paradigm and human activity system analysis (Acheampong and Silva, 2015), while allowing for an integrated approach for modeling of land use and the transport system. In a disaggregated approach, modeling of individual decision making and socio-demographic variables in the problem formulation allows for behaviorally oriented analysis and objectives. Moreover, as applied in this thesis, it allows for a framework that it consistent with economic theory, providing a basis for appraisal, welfare and distributional assessment, see section 7.1.

Rasouli and Timmermans (2014) categorized the development of the ABMs into three groups of constraints-based models, utility-maximizing models, and computational process models, which are described in the following.

**Constraints-based models:** The objective of these models is to assess the feasibility of any given activity agenda in a specific space-time context. Input of these models are activity programs and durations that include geographical space and time. A combinatorial model would generate all possible activity sequences, such that the start/end time of activities creates enough time required to perform activities while respecting the sequence of activities.
Utility-maximizing models: Hägerstrand (1970) developed a conceptual framework, the space-time prism, that explains people’s limitations and possibilities of movement in time and space, with respect to distance, accessibility, and temporal constraints. This study was one of the first resources that contributed to the development of ABMs. The utility maximization models are aligned with the space-time prism, and emphasize the influence of constraints in individuals’ daily activity scheduling routines. Another category of models is using Random Utility Maximization (RUM) to investigate the preferences of individuals when selecting activity patterns. These models mainly have a nested structure, which has the possibility to address a range of questions (Rasouli and Timmermans, 2014).

Ettema (1996) categorized and evaluated the ABMs that were consistent with RUM, based on the insight that could be derived from them (see Ettema (1996), page 107-108). Some of the modeling approaches are joint logit models, simultaneous nested logit models, sequential (nested) logit models, prospective utility models, microeconomic time allocation models, and feasible pattern generation models. The difference between these models is how they range in choice definition, defining sequences of choices, and variable inclusion (Rasouli and Timmermans, 2014).

It should be noted that the an underlying assumption of the utility maximization models is the concept of rationality. As shown by Neumann et al. (1947) and Samuelson (1938a,b) and others, given the assumption of rationality, the decision-maker behaves as if it is maximizing a utility. Thus, the underlying assumption is not that the decision-maker is actually maximizing a utility. Instead, these models rely on the as-if assumption, assuming that the decision-maker is behaving rational. The axioms of rationality depends on the context, but they include for instance that the decision-maker has complete and transitive preferences.

Computational process models: These models are developed as a means to move away from the unrealistic assumptions of utility-maximizing behavior in decision-making by proposing rule-based models that reflect decision heuristics. The Albatros model system is known to be the perhaps most comprehensive model in this group (Rasouli and Timmermans, 2014).

4.3 SCAPER

In this thesis we use an ABM in the family of utility maximizing models, called SCAPER, which is building upon the work of Small (1982) and Rust (1986), and subsequently Karlström (2005) and Västberg et al. (2020). SCAPER adopts the scheduling approach of Small (1982). In this framework, individuals make the decision that maximizes their expected utility which is captured in a value function, and includes an immediate reward and the expected utility of the state that is the consequence of the choice. Formulating this transition is possible through a Markov chain. Assuming
that the unobserved portion of utility is Independently and Identically Gumbel Distributed (IID Gumbel) if solved by the Bellman equation, the Markov chain turns into a recursive logit. In a route choice context, Fosgerau et al. (2013) showed that a recursive logit over links is equivalent to an MNL over paths. In the context of our ABM, this means that generating day-path choices instead of starting choice calculation at every state, would simplify the estimation of the recursive logit. This is the approach adopted in SCAPER.

SCAPER is a dynamic discrete choice model that is consistent with random utility theory (Rust (1987), McFadden (1977)). The dynamic property is important, since it allows us to model time consistently in all choice dimensions. This is in contrast with most other previous models (Blom Västberg et al., 2019). For instance, the mode choice early in the day may be influenced by activity schedule later during the day, and vice versa. The direction of time is consistently respected in SCAPER.

SCAPER framework was outlined by Karlström (2005), An individual’s sequential decision-making process in a potentially uncertain environment is modeled as a finite horizon Markov Decision Process (MDP) for one-day activity and scheduling patterns. Jonsson et al. (2014) extended the MDP framework to an infinite horizon problem, incorporating all possible future activities, and interpreted the value function of the MDP as an accessibility measure. Similarly, Västberg et al. (2020) built an activity-based demand model that considers space-time constraints and dependencies on previous activities. The log-sum accessibility measure derived by Jonsson et al. (2014) is linked to microeconomic theory and trip-based demand models, which makes it applicable in the cost-benefit analysis as it is consistent with behavioral models of travel demand. The accessibility measure used in our model extends this approach by allowing for endogenous workplace choice, using the value function of the MDP as an accessibility measure among the input variables.

The SCAPER model differs from, e.g., Dong et al. (2006) and other activity-based models since it accounts for sequential decision-making in an uncertain environment without prior restrictions on feasible destinations or scheduling patterns. Constraints are primarily imposed in terms of transport, land use, and spatial-temporal considerations, such as mandatory activities or car availability, while the concepts of primary/secondary tours or available activity patterns are not used or endogenous.

SCAPER is based on random utility theory, assuming that individuals behave as if they aim to maximize their utility by planning their daily activities, considering their stay at home in the morning and evening, as well as their working hours during the day. Throughout the day, individuals can flexibly travel and engage in different activities, resulting in a sequence of trips and activities that form a daily activity-travel pattern. In addition, individuals are also constrained in space and time, which prevents them from selecting activities that exceed their time budget.

2It has been extended to multiple days and even infinite horizon by Västberg (2018).
In the SCAPER framework, the activity and scheduling decisions are formulated within the context of an MDP. A path throughout the day at stage \( k \) would give the individual an immediate utility \( u(x_k, a) + \varepsilon_k(a) \), entailing the utility of action \( a \) with the state variables \( x_k \) and unobserved component \( \varepsilon_k(a) \). The state variables include the time of the day, location, purpose of the previous action, duration of the current activity, previous mode of transport, and activity history. At any stage \( k \) the individual choice set includes activity, mode, and destinations. The state-dependent choice set \( C(x_k) = \{a_{k1}, ..., a_{kJ_k}\} \) with \( J_k \) alternatives, gives the available actions. The random utility component vector \( \varepsilon_k = [\varepsilon(a_{k1}), ..., \varepsilon(a_{kJ_k})] \) is assumed to be known by the individual at stage \( k \), but for future decision stages \( k \in \{k + 1, k + 2, ..., K - 1\} \) only the distribution is known.

Following a random utility maximization framework and using Bellman’s equation, the action that would maximize the individual’s sum of the immediate utilities in stage \( k \) and the expected utility for future stages is formulated as follows (Rust, 1987; Västberg et al., 2020):

\[
U^{\max}(x_k, \varepsilon_k) = \max_{a \in C(x_k)} \{u(x_k, a) + \varepsilon_k(a) + E_{\varepsilon_{k+1}}[U^{\max}(x_{k+1}, \varepsilon_{k+1})]\} \tag{1}
\]

where \( k \) is the order of states in a day, \( E_{\varepsilon_{k+1}} \) is the expectation over the \( J_{k+1} \)-dimensional vector \( \varepsilon_{k+1} \). The second term on the right-hand side of (1) is also known as the continuation value, and is deterministically given in the final stage, \( K \), by \( U^{\max}(x_K, \cdot) = v(x_K) \), where \( v(x_K) \) is exogenous. This utility is the utility of taking action \( a_k \in C(x_k) \), in state \( k \) and reflects the maximum immediate utility in the current stage \( k \) in the state \( x_k \) plus the expected utility for all future time periods. Assuming that the error vector \( \varepsilon_k \) is i.i.d Gumbel distributed with zero means, turns the formula into a recursive logit with log-sum as the expected values (Rust, 1987; Västberg et al., 2020):

\[
V(x_k) \overset{\text{def}}{=} E_{\varepsilon_k}[U^{\max}(x_k, \varepsilon_k)] = \log \sum_{a \in C(x_k)} e^{u(x_k, a) + E_{\varepsilon_{k+1}}[U^{\max}(x_{k+1}, \varepsilon_{k+1})]} \tag{2}
\]

where \( V(x_k) \) is the expected value that is calculated recursively by backward induction, starting from the final state \( x_K \). While the quantitative measure and formulation interpretation is similar to a nested logit (NL), the qualitative interpretation is different than NL, since SCAPER captures the expected values of the future activity pattern recursively throughout the day.

We take the value function at the beginning of the day that accounts for all this information, as a measure of spare time accessibility, which enables us to analyze individuals’ activity choices and travel behavior (see section 6.1).
4.4 Intra-household mobility decisions

Household members have access to similar resources, and distribute tasks among themselves and jointly participate in activities. These interactions impact mobility decisions among household members. Studies of consumer behavior, for the great part, treat household as one basic decision making unit (Ho and Mulley, 2015). There are two special issues that highlighted mobility decisions within the household by Bhat and Pendyala (2005) and Timmermans and Zhang (2009), which are summarized in the following.

Srinivasan and Reddy Athuru (2004) explored how households allocate maintenance activities, and if the activities were done individually or with others. They used a flexible mixed logit model on the 1996 San Francisco Bay Area activity-travel data set. Their study analyzed interactions within households and differences between households. Factors such as household role, gender, income, car availability, working status, and child presence/absence were found to be significant for participation in maintenance tasks. Bradley and Vovsha (2005) developed a comprehensive model for household activity engagement patterns in the Atlanta Regional Commission’s travel demand system for all household members simultaneously. Their model considered three layers of intra-household interactions, analyzing daily activity pattern choices, joint activity participation, and allocation of maintenance tasks. They found strong evidence supporting the benefits of joint activity participation for various household member combinations. They reported that their model returns realistic average observed individual patterns that are linked to others within the household. Gliebe and Koppelman (2005) focused on modeling intra-household interactions in the context of daily activity and tour patterns. They developed a structural discrete choice model that predicts the individual choices of full-day tour patterns, in parallel, for the two household decision makers, considering their joint selection of spatial interaction patterns. They used the 1989-1997 travel diary data from the Puget Sound Transportation Panel, and proposed a parallel constrained choice logit. Their results revealed the higher influence of workers, and women with very young children, in joint activity-travel decisions. Srinivasan and Bhat (2005) investigated the complexity of studying in-home and out-of-home activity interactions within households. They focused on how intra-household interactions impact the time spent by household heads on maintenance activities in nuclear families. They used regression equations and mixed-logit models on 2000 San Francisco Bay Area travel survey data to explore gender roles and resource constraints. They found that in-home maintenance activities are mainly done by non-working women, and car availability determines if out-of-home activities are done jointly or independently. Meister et al. (2005) used a genetic algorithm to model intra-household interactions in activity-travel patterns. They considered both individual characteristics and household structure, recognizing households as key decision-making units. Their utility-based approach considers the benefits de-
rived from activity schedules for individuals and households, factoring in travel costs, times, and constraints. Their approach used a pattern recognition technique that generates near optimal activity schedules for households. Kato and Matsumoto (2009) used a tobit-type model that considered the impact of children on time allocation in a nuclear family. The model considered time and budget constraints, and the occurrence of activities (if activities were performed or not), and compared those for a mega city and a local city in Japan, and concluded that the city size impacts time use patterns and significant factors. Wang and Li (2009) focused on household time allocation, including the impact of domestic helpers, and incorporated the influence of the cost of hiring helpers on time allocation. The methodology is similar to that of Kato and Matsumoto (2009). Roorda et al. (2009) proposed an integrated model that combines vehicle transactions, activity scheduling, and mode choice. They introduced the concept of "stress" which is the deviation from some expected or optimal state (Miller) to account for conflicts within households and model potential behavioral changes when facing long-term decisions with significant transaction costs. Their model provided a comprehensive framework for analyzing interactions in joint activity participation, vehicle allocation, and conflict resolution. Zhang et al. (2009) developed a novel household discrete choice model that incorporates heterogeneous group decision-making mechanisms through the integration of group decision theory and latent class modeling approach, which allowed various decision-making processes within the same framework. Their model can represent different types of household decisions, whether or not the decision-makers are known a priori. It is adaptable to different specified group sizes and provides flexibility in modeling a wide range of household choices. Arentze and Timmermans (2009) developed a need-based model for multi-day, multi-person activity generation within households. They introduced the concept of "potential" to measure how and how much activities satisfy the needs of the household and its members. They investigated the dynamics of altruism and selfishness within households by assigning weights to household and personal needs. Their model employed an exchange procedure to evaluate the influence of disagreement among household members, making joint decision rules consistent. They used dynamic micro-simulation to account for changing needs over time.

Picard et al. (2018) classified the intra-household approaches as unitary, or collective (Chiappori, 1988, 1992), where the first approach considers one decision maker in the household and assumes that regardless of who earns the money is spent the same way, and the household and interactions within members are considered a black box. This approach is the subject of criticism among researchers in family economics (de Palma et al., 2014). Collective models, on the other hand, recognize a bargaining process within household members and use concepts such as negotiation, altruism, repeated interaction, and Pareto optimality (Vermeulen, 2002; Browning et al., 2014). Picard et al. (2018) explained that while Pareto-optimality hypothesis seems relevant...
for decisions within the household, the assumptions of unitary models are usually rejected.

Considering intra-household decisions are important as the household members interaction could lead to a different response to policies. For example, couples’ departure time decision coordination could create more congestion on the road (De Palma et al., 2015). Picard et al. (2013) explored the value of time (VOT) for couples and concluded that for example, if the bargaining power is omitted, VOT for a 40-year-old French man is 20% overestimated and it is 15% underestimated for a French woman of the same age. Another factor that is relatively overlooked, is interactions within families that could impact women’s employment rate. Compton and Pollak (2014) reported a higher employment rate of women with young children when residing in proximity to mothers or mothers-in-law which could be a source of childcare.

Our modeling approach in this thesis considers the individuals’ movements and follows a space time prism approach that is consistent with RUM. However, a limitation of our approach is that it does not delve into interactions within the household or within families outside the household.

## 5 Discrete choice models

Discrete choice models (DCMs) are used to describe or predict the outcome when a decision-maker faces two or more discrete choices. These models are popular among transport modelers, as choices within transport questions are mainly discrete. Examples on the demand side are mode choice, route choice, activity purpose, workplace/residential location choice, or on the supply side, the urban development which could be location-allocation of workplaces or housing, or other facilities in different regions to address the demand. DCMs statistically relate the choice to the attributes of the decision-maker and the attributes of the alternatives that are available to the decision-maker. These models have a probabilistic approach that evaluates the probabilities of selection of different choices. The probabilistic approach reflects the lack of information or unobserved attributes, which would result in some stochastic error that is associated with each choice. Three sources of error are unobserved heterogeneity in alternatives, taste variation of decision-makers, and/or heterogeneous choice sets (Baltas and Doyle, 2001).

The two main DCMs, logit and probit models, mainly differ in the assumption of the error term distribution. Logit model assumes a Gumbel distribution, while probit model assumes a normal distribution for the error terms. There is one significant downside to the probit model, which is the unavailability of a closed-form solution for integrals of the multivariate normal density function, meaning they must be calculated numerically (Horowitz, 1991).
5.1 Random utility models

Following the axiomatic as-if approach, the key assumption for choice models is that the individuals are rational, including adhere to preference axioms (Samuelson, 1938a,b) which results in behaving as if they want to maximize their utility. In a random utility model (RUM), if an individual (or a decision maker) faces a choice among $J$ alternatives, where each alternative provides a utility (or profit) $U_j$ for $j = 1, ..., J$, the individual would choose alternative $i$ if and only if $U_i > U_j \forall j \neq i$.

Econometric models of population choice behavior were first modeled from distributions of individual decision rules by McFadden et al. (1973). He introduced logit models as a tool for this measurement through different consumer choice problems, such as choice of geographical location and migration, occupation, choice of mode, and destination for shopping travel.

The choice set which contains the set of alternatives is assumed to have these three characteristics: alternatives are mutually exclusive from the decision maker’s perspective; alternatives are exhaustive, meaning that all possible alternatives are included; and the number of alternatives are finite.

McFadden et al. (1973) introduced the logit models as follows. Assuming that an individual has a vector of observed attributes $s$, and choice set with $J$ alternatives ($j = 1, 2, ..., J$) described by vectors of attributes $x$, the utility function would be:

$$ U = V(s, x) + \varepsilon(s, x), $$

where $V$ is the deterministic or observed part of the utility function that reflects the "representation" taste of the population, and $\varepsilon$ is the error term that is unknown to the researcher and reflects the individuals’ idiosyncrasies in tastes for the alternative with attributes $x$. McFadden explained that utilities are treated as random variables, which reflects the lack of information on the part of the observer about the attributes of alternatives and/or decision-makers, rather than a lack of rationality (Manski, 1977; McFadden, 1976).

The $\varepsilon$ for different alternatives are assumed to have independently and identically Gumbel distributions (i.i.d. $\sim$ Gumbel). Given these assumption, the choice probability is then given by

$$ P(x|s, B) = \frac{e^{V(s, x)}}{\sum_{y \in B} e^{V(s, y)}}, $$

where $V$ is the deterministic utility, a.k.a. "utility indicator" of "representative" taste (McFadden et al., 1973).

---

3Jeremy Bentham started the systematic study of consumer motivation and well-being in 1789. McFadden (2014) discuss the historical development of utility theory.

4For a textbook exposition, see, e.g., Train (2009)
Given weak complementarity, the thus defined multinomial logit model then follows the Independence of Irrelevant Alternatives (IIA) property. According to the IIA property, the ratio odds of choosing any pair of alternatives are independent of any other alternative.

\[ \frac{P(x)}{P(y)} = \frac{e^{V(x)}}{e^{V(y)}} \]  

(5)

This follows as the error components are assumed to be uncorrelated. In much applied work, this is a strong assumption, and Ben-Akiva (1973) introduced a new structure for the travel demand model, the family of nested logit model, which was originally developed for travel demand and extended to residential location choice (McFadden, 1977).

In the formulation of McFadden (1977), the nested logit model is defined by a generating function \( G(y_1, ..., y_J) \), which is non-homogeneous-of-degree-one of \( (y_1, ..., y_J) > 0 \), where for \( i = 1, ..., J \):

\[ \lim_{y_i \to \infty} G(y_1, ..., y_J) = +\infty \]

with the assumption that for any distinct \((i_1, ..., i_k)\) from \(\{1, ..., J\}\),

\[ \frac{\partial^k G}{\partial y_{i_1} ... \partial y_{i_k}} \begin{cases} \geq 0 & \text{if } k \text{ is odd} \\ \leq 0 & \text{if } k \text{ is even.} \end{cases} \]  

(6)

Then the choice probability for \( i = 1, ..., J \) is given by

\[ P_i = e^{V_i} \frac{G_i(e^{V_1}, ..., e^{V_J})}{G(e^{V_1}, ..., e^{V_J})} \]  

(7)

which is consistent with utility maximization. The special case of

\[ G(y_1, ..., y_J) = \sum_{j=1}^{J} y_j \]  

(8)

where \( y_i = e^{V_i} \) degenerate into the standard the MNL model with the error components being independent and identically Gumbel distributed terms.

A nested logit model with disjunct subsets can be defined by a functional form of \( G \) as follows:

\[ G(y) = \sum_{m=1}^{M} \alpha_m \left( \sum_{i \in B_m} \frac{1}{y_i^{1-\sigma}} \right)^{1-\sigma} \]  

(9)

where nests \( B_m \subseteq \{1, ..., J\}, \cup_{m=1}^{M} B_m = \{1, ..., J\}, \alpha_m > 0, \text{ and } 0 < \sigma_m \leq 1 \). \( \sigma \) is interpreted as an index of similarity of the unobserved attributes between alternatives (see McFadden (1977)). Note that the value of \( \sigma \)s for the nests naturally should be
tested against 1 to test against a null hypothesis of independent error terms (see Train (2009)).

5.2 Exchangeability of alternatives in MEV models

As discussed above, the logit model with IID Gumbel distributed error terms may suffer from IIA property. To relax IIA assumption, McFadden et al. (1978) introduced the family of nested logit models, which we would refer to as Multivariate Extreme Value (MEV) models in this section. As discussed above, the correlation of the error terms is scaled and reflected in the nest dissimilarity parameter (log-sum parameter, or scale parameter) which is an index of dissimilarity of error terms of alternatives in the nest. Koppelman and Wen (2000) introduced paired combinatorial logit models, where every pair of alternatives has a nest with a dissimilarity parameter. Wen and Koppelman (2001) later introduced the GNL models, which allowed for calculating the amount to which extent each choice belonged to a nest, which is captured in the allocation parameter, \( \alpha \). They also introduced Paired GNL, which includes nests of all pairs of alternatives with scale and allocation parameters. The substitution pattern reflects not only the error term correlation structure but also which alternatives are exchangeable within the generating function. A byproduct of exchangeability is symmetry of choices within the same nest in the probability function. Exchangeability is a restrictive assumption, implying a symmetric choice preference, which has been further investigated more in the logistic regression in literature.

Brathwaite and Walker (2018) addressed class imbalance for multinomial settings. They introduced a new class of closed-form finite-parameter multinomial choice models. These models, which they referred to as logit-like models in their study, included the multinomial scobit model. They showed that the binary scobit model, developed by Nagler (1994), is a special case of logit-like models. One example of a transport-related choice problem where there is class imbalance is a route choice problem where taking the same route in different directions returns different probability values (see Li et al. (2023)). This condition arises when the traveler perceives route features in a large network, where it is practically not feasible for the traveler to make an informed decision about the route choice.

In Paper 2, we investigate the error structure and retrieve exchangeability by adding a replicated nest in the generating function of paired GNL. The improvement in the log-likelihood would reflect how well these correlations are captured, and consequently how well the predictive power of the model is. The functional form of the error structure in MEV models allows for flexibility in defining nests, eliminating the need for unique nests and parameters. However, common practice often leans towards a structure with unique nests, potentially overlooking the intricacies of the error structure and compromising the exchangeability of choices. In Paper 2, we explore the implications of replicating nests with non-exchangeable alternatives. While
this approach is permitted and inherent in the definition of a generic MEV model, it is rarely put into practice. A key takeaway from our study is a reminder of the importance of considering the functional form of the error structure. Interestingly, our empirical findings reveal that replicating nests can restore exchangeability and provide a model fit equal to or better than a non-exchangeable model definition. This result holds particular relevance for applied work, where achieving exchangeability is a desirable property from both theoretical and practical perspectives. This is especially pertinent in scenarios such as route choice problems or in stated preference studies (choice-based conjoint analysis).

5.3 Elasticity

The IIA reflects the substitution pattern, which could manifest as changes in elasticities. Elasticity measures the responsiveness of the probability values for one choice due to changes in attributes of the same alternative (elasticity) or other alternatives (cross-elasticity). If for an individual, alternative $i$ with attribute $z_i$ have a probability of $P_i$, the elasticity formula has the form (Train, 2009):

$$E_{iz_i} = (\frac{\partial P_i}{\partial z_i})(z_i / P_i)$$

$$= \frac{\partial V_i}{\partial z_i} P_i (1 - P_i)(z_i / P_i)$$

$$= \frac{\partial V_i}{\partial z_i} z_i (1 - P_i).$$

(10)

With the assumption of the linear $z_i$ in the utility, $\frac{\partial V_i}{\partial z_i}$ would be the parameter (coefficient) $\beta_z$ and the formula would be $E_{iz_i} = \beta_z z_i (1 - P_i)$.

The formula provided above is for MNL, and does not include any nesting structure for error correlations to relax IIA property across the nests. The elasticity values for GNL models are given by Wen and Koppelman (2001), which is:

$$E_{iz_i} = \sum_m P_{m} P_{i|m} [(1 - P_i) + (\frac{1}{\mu_m} - 1)(1 - P_{i|m})] \beta_z z_i$$

(11)

for $i$ in one or more common nests ($m$). The elasticity values in Paper 2 for smaller values of the dissimilarity parameter show more sensitivity, as choices show more correlations in the error terms. The elasticity density graphs show more dispersion as the models’ complexity increases, which reflects more explanation power, and this is also reflected in the log-likelihood values. Overall, Paper 2 suggests that other than interpretation difficulties, adding replicated nests could retrieve exchangeability, relax IIA, maintain rationality axioms, and improve goodness of fit, and the possibility of doing so may not be overlooked.
6 Accessibility measures

One of the main functions of transport studies is creating and improving access. Accessibility overcomes physical, social, and political distance, while it contributes to freedom of choice (Hall, 1983). Accessibility could measure how much freedom an individual has to engage in different activities within their surroundings (Burns, 1980; Hall, 1983). The first well-known conceptualization of accessibility through studying human activity was introduced by Hägerstrand (1970), and is known as the time-space or time-geography. His method takes time as a third spatial dimension and treats the geographical space as a 2D map, which makes it possible to locate things and people in geographical places at any given time in unity, while reflecting the spatial and temporal constraints. He counted three forms of constraints. Capability constraints that reflect human performance limits such as sleeping and eating, or the speed limit; coupling constraints that make people be in a specific place at a specific time, e.g., work; and authority constraints that limit the time and space that people can visit. Hall (1983) showed that accessibility depends on the performance of the transportation system and the outcome of the destination activity. He also showed that randomness and uncertainty impact accessibility.

Geurs and Van Wee (2004) reviewed the usability of accessibility measures in evaluations of land use and transport changes. They counted four different components of land use, transport, temporal, and the individual to account for distribution of opportunities, travel time and other travel characteristics, transport infrastructure, time of the day and time budget, and other factors such as car access, physical ability, and skills that fit the opportunities in the surroundings. They named four different perspectives on measuring accessibility measures as follows. Infrastructure-based measures are used for the analysis of network congestion or travel speed, location-based measures that reflect the level of accessibility to spatially distributed activities, person-based measures that follow the time-geography concept, and utility-based measures for calculating (economic) benefits that people get from access to spatially distributed activities.

In a study, Halden (2011) explained that accessibility is a broad and complex concept, and this could cause confusion. Accessibility is usually a secondary focus of government policy, compared to mobility and service quality (e.g. better and more healthcare, education, employment). He explained that accessibility in passenger transport defines "each of reaching or being reached" in terms of who, where, and how (Baradaran and Ramjerdi, 2001). These three factors include the subject/object of access, the activity source of supply in terms of land use or people, and separator factors such as time, cost, or information among other things. There are distinctions in defining accessibility between people, places, or connections. Accessibility in passenger transport can be understood from two perspectives: origin accessibility, which
relates to how easily individuals or groups can reach a defined set of one or more opportunities, and destination accessibility, which focuses on how a given destination can be reached from a set of different origins. The inconsistency in these definitions has led to confusion in measuring accessibility. Organizations dealing with people or services often simplify accessibility using factors such as distance, while transport planning has concentrated on the travel part, without considering the social, (e.g. disability discrimination legislation) or human aspects (e.g. physical disability, or car ownership) unless required by regulation or market demands.

Halden (2011) clarified that mobility, often linked to individual rights and freedoms, is measured by traveler characteristics or behaviors, but it doesn’t necessarily mean improved accessibility. Accessibility, on the other hand, emphasizes the potential for interaction, which is aligned more closely with the purpose of transportation to satisfy the individuals’ derived demands by enabling social and economic interactions.

A fundamental aspect of accessibility entails the opportunity to participate in a wide range of activities and the ability to reach different workplaces, which are widely recognized as central constituents of this concept (El-Geneidy and Levinson, 2006; Miller, 1999; Levinson, 1998).

The activity-based accessibility (ABA) measure, as discussed by Ben-Akiva and Bowman (1998a), addresses individuals’ preferences for engaging in a variety of activities, combining activities through trip-chaining, and satisfying activities without travel. This measure can consider taste heterogeneity among individuals, combine different types of trips into a unified measure, and provide a quantifiable assessment of the different impacts of accessibility on important population segments, according to Dong et al. (2006). Furthermore, the concept of ABA measures takes information from activity-based models to investigate its influence on longer-term land-use variables such as residential and workplace choices, as Shiftan (2008) explained. Econometric activity-based demand models incorporate activity and travel scheduling decisions, as well as origin-to-destination matrices, which allow ABMs for the examination of trip-based, tour-based, and daily schedule models (see Ben-Akiva and Bowman (1998a)). These model systems are based on hierarchies of decisions and are modeled using nested logit models (Ben-Akiva and Bowman, 1998b).

There are different variables that influence activity and travel decisions, such as household activity decisions, which could vary due to household size, age and gender, and children in the household. Designing hierarchical structures that align with the hierarchy of component models for the decision process, makes the scheduling hierarchy of the lower level dependent on the outcomes of higher levels. This approach represents the dynamics of decision-making interdependencies among different decision levels (Ben-Akiva and Bowman, 1998b).
6.1 ABA from SCAPER

We already described SCAPER in section 4.3. The expected value function gets the form $V(x_k)$ in Eq. (2) and at the first state $x_0$, when individuals are by assumption at home, captures the expected value of all future activity patterns recursively throughout the day, and depends on the location, activity history, and characteristics of the individual, including home and work locations. For an individual $n$ that lives in zone $i$ and goes to zone $j$ to work, this expected value is what we refer to as the \textit{spare-time accessibility} measure:

$$A_{ni} \overset{\text{def}}{=} V(x_0). \quad (12)$$

The spare time accessibility measure $A_{ni}$, as defined in Equation (12), allows for evaluating the impact of applying changes on both individual-level constraints and system-level attributes such as travel times and costs. Individual spare time accessibility depends on factors such as home and work locations, car availability, and temporal constraints, and we take advantage of this relationship by analyzing the influence of space, time, and resource constraints on workplace choice. We use a nested structure, where on the top level we use the spare time accessibility, which encompasses the information explained earlier, and at the lower level is the number of workplaces and opportunities in four different sectors and one for others. We interpret the logsum measure of this nested work location model, as a workplace accessibility measure, and investigate what it could reflect. Some of the current applications are the ability to calculate workplace location allocation benefits in terms of consumer surplus (see Paper 1 and Paper 3), car dependency in terms of willingness to pay, and segregation in terms of the difference for workplace demand that could potentially create social segregation.

6.2 Applications

Accessibility is a useful tool for selecting locations for urban development and traffic and congestion management, and serves as an indicator for the evaluation of urban life such as segregation, car dependency, and location benefits. These three indicators are investigated in our research.

One application of workplace accessibility is to evaluate appropriate cites for developments (Halden et al., 2000). The welfare measures of counterfactual scenarios could be investigated through calculation of consumer surplus (CS) that potential workers across the city would experience from allocating a workplace. We have investigated how the location change in a large workplace, Karolinska Hospital with 7073 work opportunities, would change the CS compared to its current location. Intuitively, the central zones had higher values of CS.
Car dependency is characterized by high per capita car travel, car-oriented land use, and limited transport alternatives (Litman and Laube, 2002). While car-dependent individuals have a preference for car-based travel driven by habit and intention (Lucas and Jones, 2009), not having a car can result in transport disadvantage, potentially leading to limited access to essential services and social exclusion (Pickup and Giuliani, 2005; Hassan, 2016). This exclusion arises due to differences in access to social activities, and employment (Preston and Rajé, 2007). There are clear links between restricted mobility, reduced accessibility, and social exclusion. Motives for car use include instrumental, e.g. speed limit, or convenience, and symbolic and affective, e.g. power and superiority, with car usage levels being related to these motives (Steg, 2005). Child-related travel constraints contribute to car dependency, especially among families with children in less urbanized areas Oakil et al. (2016a,b). In Paper 1 we address the effect of one extra time-space constraint, having to pick up/drop off children at daycare, on the car-dependency of car users. The results show that individuals with one more extra constraint, have a higher willingness to pay to use their car.

Social segregation and unequal accessibility to services and the labor market are known issues in Sweden (Legeby, 2010). The interplay of segregation in urban life and public spaces is equally as important as housing segregation. Qualitative studies show that individuals in segregated Swedish suburbs that are feeling socially excluded, value opportunities for urban interactions (Lilja, 2002). Workplace accessibility indicates where people spend their time in workdays and how urban life is influenced (Legeby, 2010). Job accessibility impacts the long-term unemployment for low-skilled workers, especially when car access is limited (Korsu and Wenglenski, 2010). Public transit partially mitigates car-less household segregation but falls short of achieving equitable
accessibility (Grengs, 2001). In Paper 1, we have addressed segregation, by showing that higher income people are more likely to choose workplaces in the northern part of Stockholm, which also has more frequent public transport, and is not separated from downtown by water. We also investigated a counterfactual scenario where individuals with car ownership in base scenario lose their access to car to reach the workplace (Karolinska hospital). The results show higher CS in central parts of the city with an extension along public transport lines.

7 Policy evaluation

In transport studies, a common tool for policy evaluation is using welfare economics, consistent with a neo-classical microeconomic framework in which it is assumed that individuals are rational, and therefore behave as-if they are utility maximizers. Thus, a common approach for policy evaluation, when the RUM framework is present, is to use monetary measures to quantify changes in consumer welfare.

7.1 Measures of welfare economics in transport

There are two components that influence policy evaluation, the financial value and the consumer’s surplus (Bergstrom (1990), Stoll et al. (1987)). The financial value entails the value that the consumer is paying for a service or good, which is rarely the same as the price that the consumer is willing to pay. The difference between the gross value and the financial value is known as the consumer’s surplus (Bergstrom (1990)). The consumer surplus is the net utility change in monetary terms.

There are two types of consumer surplus, depending on the consumer’s demand function: the Marshallian and the Hicksian. Alston and Larson (1993) explained that the term consumer surplus conventionally refers to the Marshallian consumer surplus. It is worth noting that this measure was originally formulated by French engineer J. Depuit in 1850, to get the amount of subsidy for a bridge construction (Ng, 2003). There are four measures that refer to Hicksian consumer surplus, which are compensating variation, equivalent variation, compensating surplus, and equivalent surplus. These values are also known as the "exact welfare measures". The common values could be described briefly as follows (Bates, 2006).

- Compensating variation is the adjustment (or compensation) required in income to restore the consumer’s original utility after a change and provides a monetary measure of the overall impact on individual welfare.

- Equivalent variation is the adjustment in income that changes the utility of the consumer to the level that would happen if the event had happened. Equivalent variation represents the maximum amount of money an individual would be
- Compensating surplus measures the net change in consumer surplus after a policy change. It reflects the difference between what consumers are willing to pay and the actual price paid for a good or service. Compensating surplus considers changes in consumer welfare but doesn’t include the compensation needed to restore welfare to its original level.

- Equivalent surplus measures the total welfare change experienced by the consumer due to the policy change, including both the changes in consumer surplus and the compensation required to restore individuals to their original welfare level. Equivalent surplus quantifies the overall net gain or loss in welfare and provides a comprehensive measure of the total welfare impact.

Alston and Larson (1993) explained that there is a trade-off of bias and precision between Marshallian and Hicksian welfare measures. The Hicksian measure has a lower bias, but that comes at the price of a potential variance increase. The Marshallian demand and the Hicksian demand could be related through the Slutsky equation, which entails the income effect and the substitution effect. The income effect reflects the change in demand for a good or service, when the income changes and prices are constant, while the substitution effect reflects the change in consumer demand due to changes in relative prices of goods, given the income is constant (Varian (2014), chapter 8).

McFadden implemented the random utility models in transportation decisions, and further used them in the cost-benefit analysis (see McFadden et al. (1973), McFadden (1974), McFadden (1981)). According to McFadden (1998), by assuming that the consumers are rational and behave as if they are utility maximizers, an evaluation of a change in the utilities could be achieved through the calculation of the consumer surplus (CS) attached to the change, where mean CS is a measure of consumers’ welfare. The consumer surplus for an individual is the change in the utility value in monetary terms. For a population, it is a difference in the expected values (log-sum
measures) between different scenarios divided by the marginal utility of income, or cost parameter. This conversion from expected utility to monetary unit is possible and straightforward if the model is linear in the utility of income or cost. We assume that the marginal utility of cost is linear in SCAPER and therefore in the workplace choice model (Paper 1), which makes the policy evaluation possible for Paper 1 and Paper 3 through the calculation of the log-sum measure for different scenarios. Our approach is aligned with the literature provided by De Jong et al. (2007) about the use of log-sum measure as a welfare measure.

7.2 Scenario planning context

There is a broad range of existing scenario methods as tools in urban planning, that are used for urban developments. The following three approaches are known to be the main scenario planning approaches (Abou Jaoude et al., 2022):

- the predictive (forecasting), which predicts the most likely future in a short time-frame,
- the normative (visioning and backcasting): which includes generating a desirable scenario, which encompasses a set of shared goals and embodies values of stakeholders and citizens, and analyzing pathways and strategizing to achieve that scenario through regulations and measurable targets, and avoiding undesirable futures (Holmberg, 1998; Robinson, 1990; Hopkins, 2001; Van der Helm, 2009), and
- exploratory scenario planning, which tries to understand the external sources of uncertainties and forces, and design systematic solutions and robust strategies to mitigate challenges (Bradfield et al., 2005; Chakraborty et al., 2011).

One straightforward way of constructing images of the future is by using a systematic method of selecting scenario axes (van’t Klooster and van Asselt, 2006). There are three perspectives towards defining scenario axes, which are scenario axes as:

- backbone, which considers axes as the fundamental forces that frame the future,
- building scaffold, which allows the axes to be removed and developed for more integrated scenarios. The axes are considered a heuristic to position scenarios with sufficient divergence, and
- foundation, which accepts that axes are chosen from a set of driving forces, based on the different weights of social arguments in a systematic process. This approach is more flexible for interpretation of the axes, since they are selected intentionally. However, the axes could not be removed as they form the foundation of scenario building.
7.2.1 Urban development approaches

There are two "classic" approaches to the development of the city in the urban planning literature: urban sprawl, that e.g. discussed by Gordon and Richardson (1997), and urban compactness which was a counter-response from Ewing (1997). These two approaches are the two different ends of the development spectrum (Ewing et al., 2015).

Ewing (1997) defined sprawl in terms of leapfrog or scattered development, commercial strip development, and large expanses of low-density or single-use development. And later expanded the definition to any development pattern that created poor accessibility and a lack of functional open spaces. The definition of compact development in his view was on the contrary: strong centers, mixed land uses, medium to high density, good accessibility, and permanent open spaces. Ewing et al. (2015) acknowledged sprawl has numerous dimensions and advised identifying particular dimensions of development. Tsai (2001) introduced a division within the compact versus sprawl continuum, establishing two separate axes: mono- versus polycentric and centralized versus dispersed development. Different types of developments have different impacts on travel behavior and mode share (Schwanen et al., 2001; Kitamura et al., 2003; Levinson and Kumar, 1994; Schwanen et al., 2003), and also different effects on different groups of workers (Jun, 2020).

The research question in Paper 3 develops around the current urban development approach in the City of Stockholm, using the two axes that distinguish compact and sprawl developments as Tsai (2001) introduced as the two scenario axes that separate scenario quadrants.

7.2.2 Scenarios and conclusions

Stockholm has long followed a centralized workplace development pattern, which is reflected in its transportation system converging at the central station. However, planners are now considering newer urban development ideas for greater proximity between workplaces and residences. While future office construction may not significantly change workplace distribution, the choice of development patterns remains important in shaping future urban investments. The allocation of around 35,000 new jobs is envisioned for each scenario, with an 80% focus on the business sector. These jobs are distributed across zones, approximating real-world scenarios. The scenarios are shown in Figure 4 and are described as follows:

- "Status Quo": central and concentrated developments align with the historical pattern in Norra Djurgårdstaden and Söderstaden,
- "Dispersed Development" that maintains centralization but spreads development across neighborhoods like Brommaplan and Årstaberg,
- "Peripheral Hubs" that take a decentralized but concentrated approach, concentrating on Kista, Älvsjö, and Skärholmen.

Decentralized and dispersed growth is considered less plausible from an implementation point of view, and therefore is not investigated here.

The modeling approach uses an integration of SCAPER and the workplace choice model from Paper 1. We investigate different scenarios through the welfare benefits that they offer for different working groups, and the travel behavior.

The results show that while the scenarios tried to distinguish between polycentric and dispersed development, the model suggests that the outcomes were less distinct. All scenarios were in favor of high-income groups, highlighting the importance of the type of jobs over their geographical distribution. The results show that where people choose to live depends on the workplace locations, potentially impacting income distribution and spatial segregation. Dispersed or polycentric development could lead to greater income diversity in historically low-income areas. This would raise a conflict regarding the environmental outcomes. Concentrated employment patterns tend to reduce car use and vehicle kilometers traveled (VKT), and promote environmentally friendly transport. A polycentric model would require transit investments to prevent

![Figure 4: Map of new jobs added in each scenario. Scenario bubbles are scaled to the number of new jobs added. Expected 2040 employment and Stockholm City (see Paper 3).](image-url)
increased car commuting. This analysis also highlights the importance of non-work activities influenced by workplace locations, potentially reducing the central city’s dominance for shopping and other activities, if jobs are provided in combination with shopping and recreational peripheral hubs.

### 7.3 Trip Chaining

Understanding the travel demand and people’s behavioral patterns in interaction with transport services for demand forecast takes the primary focus in many studies. Early transport models did not consider interdependencies among different non-home trip links. Trip chaining evolved to address this complexity in travel behavior, as the link between people’s spatial and temporal movement. Modeling trips within a trip chain with more than one trip besides the origin and destination has been a challenge and referred to as complex in the literature (Strathman and Dueker, 1995). The first trip chaining models were developed on the assumption that trip chaining was raised from household decisions, which included travel patterns, order of decision making, and travel mode (Adler and Ben-Akiva, 1978). This justifies the inclusion of trip chaining behavior in travel forecasts.

The different variables that impact the trip chaining formulations include a flexible number of trips in the chain, modes of transport, household structure, socio-demographics (age, income, gender, education level), density of population and employment, and being chronologically consistent (Goulias and Kitamura, 1991; Bhat, 1997; Ballis and Dimitriou, 2020; Bricka, 2008; Bautista-Hernández, 2020). The chaining nature of recursive logit and its consistency with RUM, makes it an attractive modeling approach for trip chaining and transition probabilities (Thill and Thomas, 1987). Our trip chaining formulation approach is explained in section 7.3.2.

#### 7.3.1 Valuation of time savings

Central to transport economics is the concept of time and its value. Indeed, the core expected benefit of many transportation projects is travel time savings (see, for example, section 7.4). Time has qualities that makes it distinct from money: for example, it is difficult to save and must be allocated, and all individuals have the same time budget. It has been long recognized by economics that time cannot simply be treated as money; however, most analyses of the marginal utility of time take place in a static framework in which time is treated like money subject to certain constraints (see, e.g., DeSerpa, 1971).

The first formulation of time as a commodity was introduced by Becker (1965). He postulated the idea of final goods, that directly induced satisfaction and formed the utility function, and took market goods and preparation time as necessary inputs. He considered work time as the whole time budget (constraint) in a period minus
preparation-consumption time, which meant that consumption needed time that could be spent on working and gaining money. So, the first value of time in the literature was equal to wage rate (Jara-Díaz, 2007). This was followed by the addition of work time to the utility function (Johnson, 1966), which changed the VOT as wage rate plus the marginal rate of substitution of work and income. Johnson (1966) explained that this value reflects the value of leisure and it was equal to the value of travel time. Later, Oort (1969) included the travel time in the utility function, which introduced a perception of the value of travel time to the utility. This addition meant that a reduction in travel time could create more leisure or work.

DeSerpa (1971) explained that consuming goods requires a minimum time assignment and introduced a new constraint that connected goods and time in the utility function. He formulated the value of time allocation as follows:

\[
L = U(X_1, ..., X_n, T_1, ..., T_n) +
\]

\[
\lambda (Y - \sum_{i=1}^{n} P_i X_i) +
\]

\[
\mu (T^o - \sum_{i=1}^{n} T_i) +
\]

\[
\sum_{i=1}^{n} K_i (T_i - a_i X_i)
\]

(13)

where \( K_i \geq 0, i = 1, ..., n \) and \( \mu, \lambda > 0 \), and

- \( X_i \) is the quantity of the \( i \)th consumption good,
- \( T_i \) is the time allocated to the \( i \)th good,
- \( (X_1, ..., X_n, T_1, ..., T_n) \) is the bundle of goods and their allocated time,
- \( Y \) is income,
- \( P_i \) is the money price of \( i \)th good,
- \( T^o \) is the length of the decision period,
- \( a_i \) is the institutionally determined minimum amount of time required to consume one unit of \( X_i \). An example is the time for having a meal or the driving time based on the speed limit. These are time consumption constraints which are different than time resource constraints.

The necessary conditions for maximization with these specifications would be: for \( i = 1, ..., n \)

\[
Y = \sum_{i=1}^{n} P_i X_i
\]

(14)
\[ T^\circ = \sum_{i=1}^{n} T_i \] (15)

\[ U_i = \lambda P_i + K_i a_i \] (16)

\[ U_{n+i} = \mu - K_i \] (17)

\[ K_i(T_i - a_i X_i) = 0 \] (18)

which is either \( T_i = a_i X_i \), or \( K_i = 0 \). The partial derivatives of the utility function with respect to \( X_i \) and \( T_i \) are reflected in the subscripts \( i \) and \( n+i \). \( \mu \) and \( \lambda \) are shadow variables for the marginal utility of money and time respectively. So, the marginal rate of substitution which is commonly interpreted as VOT would be \( \frac{\mu}{\lambda} \). This value is also referred to as the value of time as a commodity. It shows how much an individual is willing to trade time for money when consuming goods. The time in this context indicates working time, which is equated with wage rate. Another concept is the value of time as a resource which is the value of extending the time period, equivalent to \( \frac{\mu}{\lambda} \). This value takes the substitution rate of time and any activity, and is not limited to wage-earning activities, and reflects that time is not only used for work. The last concept is the value of saving time in activity \( i \), which is given by \( K_i = \frac{\mu}{\lambda} - \frac{\partial U}{\partial T_i} \). This value indicates the time allocated within an activity \( i \). He defined "leisure" as the sum of all activities that take more time than strictly necessary. The value of time savings for these activities is zero, and the value of time allocated (VOT as a commodity) is equal to \( \frac{\mu}{\lambda} \), the resource value of time, or the value of leisure.

Truong and Hensher (1985) formulated the travel utility function based on money, time, and technological constraints, which are the minimum required time for doing an activity such as speed limit, combining Becker’s and DeSerpa’s utility functions. Bates (1987) argued that the indirect utility function in mode choice is not directly linked to the resource value of time but rather the value of reallocating time to leisure, making negative values impractical. Jara-Díaz (2007) emphasized including the value of changing consumption patterns and rescheduling activities in utility. Schmid et al. (2019) clarified that the subjective value of time savings encompasses the willingness to pay for time reduction, monetary equivalence for reallocating time, and the monetary value of reduced utility when time is assigned to travel.

To properly assess the marginal utility of time, we need to account for its particular nature. Time is dynamic and directional. We live in a world created by the consequences of our earlier decisions, and the decisions we take now will influence our future. Using a dynamic framework for time, we can examine the impacts of these previous decisions and the potential effects on future states when making a decision.
7.3.2 Trip chaining and VOT

The methodology of formulating the trip chaining is similar to that of SCAPER, which is explained under the SCAPER section. The trip chaining is modeled through modeling movement. Assuming that movement manifests in a chronological order, it could be modeled as a Markov chain. Solving the Markov chain through the Bellman equation, and assuming the IID Gumbel error terms for immediate rewards would form a recursive nested logit over choices, that could be solved as an MNL through paths that contain sets of choices for the trip chain.

The chain is home-based, meaning that it starts and ends at home. The first trip is the first non-home stop (an activity could be happening at home zone, but not at home), and the last trip is home. There are two approaches that we have explored to solve the trip chaining problem and estimate the parameters in a very simple trip chaining model:

- using sampling methods to narrow down the choice set, and
- using eigenvalues in linear algebra, and differential equations to solve the trip chaining problem for the converged transition probability values.

Both approaches allow for a flexible number of trips in the chain, and have the potential to include socio-demographics, as the model is consistent with RUM. The limitation of these models is computational efficiency, due to the network size that creates the destination choice sets. At every stop in the chain, the individual has 1240 zones to choose from. Extend this to a couple of thousand individuals in the sample, and the problem is already large even with just one variable such as travel time.

The first approach, which is explained in Paper 4 uses Important Sampling (IS) to reduce the choice set, and represent a more realistic decision making behavior while improving the computation’s efficiency. While IS is an unbiased estimator, it has a variance to the actual value, which at every step in the trip chain would stack up as the chain progresses. We tried to integrate the IS estimator with a regression estimator or Control Variate (CV) to reduce variance as well. This showed improvement in a simple MNL, as the correlation between the assumed function and the target function has increased. However, in the recursive logit case, there was no improvement compared to the IS estimator, but rather a divergence from it towards higher values of variance that started as the trip chain progressed, and therefore did not contribute to the improvement of estimation.

The second approach, which is explained in more detail in Paper 4, uses linear algebra and differential equations to solve the Markov chain using the eigenvalues for stationary states. The formulation is provided for a general case where the future is discounted, and also solved for when the discount factor is set to 1. The Markov chain can take an infinite number of trips in the chain, before reaching home (absorbing...
This formulation revealed an implication of the trip chaining, i.e. the effect on the marginal utility of time, that stems from the trip chaining process itself, even in the absence of scheduling. The value of time in a trip chaining context has not been investigated to our knowledge.

In our research, we assume that the trip chain starts and ends at home (absorbing states), and there could be flexible (or infinite) numbers of trips in the chain among zones (non-absorbing or transient states). To clarify this relationship with the future discount, if we are interested in the marginal utility (\( v \) s.t. \( v_i = V(s_i) \)) change to one travel time, say \( T_{ij} \), with all other variables entering the reward function fixed, we show that:

\[
\frac{\partial v}{\partial T_{ij}} = (N\beta)_{i} P_{ij} \frac{\partial R_{ij}}{\partial T_{ij}}
\]

(19)

where

\[
N\beta \overset{\text{def}}{=} (I - \beta P)^{-1},
\]

(20)

\( \beta \) is the discount factor, \( P \) is the transition probability matrix for the reward function that allows the movement from one state to the next, \( R \) is the reward function for moving from state \( i \) to \( j \), or the immediate utility. Equation (19) holds for \( \beta < 1 \), where \( (N\beta)_{i} \) is column \( i \) of \( N\beta \). The Equation (19) can be reduced to a vector times scalars since all elements of \( \frac{\partial R}{\partial T_{ij}} \) are zero except \( \frac{\partial R_{ij}}{\partial T_{ij}} \). Setting \( \beta = 1 \) in Equation (20) for transient states would result in the equation for a future with no discount. The entry \( N_{ij} \) of fundamental matrix \( N \) represents the expected number of times visiting transient state \( s_j \) when starting from state \( s_i \).

Taking these equations as the core of analysis of marginal utility changes to one single travel time, results in a more general formula (for \( \beta = 1 \)):

\[
\frac{\partial V(s_k)}{\partial t_{ij}} = \alpha_{TT} N_{ki} Q_{ij}
\]

(21)

where \( Q \) is the probability matrix for transition from state \( i \) to state \( j \) for transient states, and \( \alpha \) is the travel time parameter. This formula allows for a comparison of Marginal Rate of Substitution (MRS) for work and leisure trips. This value for the value function at home state would be:

\[
MRS_{wk,ls}^{V} = \frac{\partial V(s_h)/\partial t_{h,wk}}{\partial V(s_h)/\partial t_{h,ls}} = \frac{Q_{h,wk}}{Q_{h,ls}}
\]

(22)

which in our data is 3.08, and is a ratio of the average of \( Q_{h,wk} \) to the average of \( Q_{h,ls} \). If the trip actually takes place, the change of travel time in the trip and in the return trip would contribute to the MRS as follows:
\[
MRS_{wk,ls}^U = \frac{\partial U(s_{wk}|s_h) / \partial t_{wk,h} + \partial U(s_{wk}|s_h) / \partial t_{h,wk}}{\partial U(s_{ls}|s_h) / \partial t_{ls,s} + \partial U(s_{ls}|s_h) / \partial t_{s,ls}} \\
= \frac{1 + N_{wk,h} Q_{h,wk} + N_{wk,wk} Q_{wk,h}}{1 + N_{ls,h} Q_{h,ls} + N_{ls,ls} Q_{ls,h}}
\]

which includes the effects of expected future travel as well. The immediate utility of travel (1s in the equation) would have a higher impact on the \( MRS_{wk,ls}^U \). In this case, \( MRS_{wk,ls}^U = 1.028 \).

The research in Paper 4 aims to incorporate time as an endogenous factor in the trip chaining model, in the absence of a scheduling framework, while not including time as a variable, and create the link between the marginal change in utility function and time as an implication of the dynamic nature of the trip chaining process.

One limitation in this research is forming the transition probabilities. While the current paper only includes the travel time of Car, including two trip purposes already enlarges the transition probability matrix significantly. Including other modes or other variables could be challenging when defining transition probability matrices for different states. Another challenge is including the scheduling framework. Blom Västberg et al. (2019) solved the recursive logit in the context of AMBs, while allowing for the activities to end in the middle of a state time period. This might not be very straightforward in the context provided in our research with the current formulation.

### 7.4 Congestion pricing

This section focuses only on the Stockholm congestion pricing practice, and does not provide information on the general history, methodologies, or comparison of different cases of pricing schemes in other cities or countries.

In 2006, Stockholm City introduced a seven-month trial of congestion charges and in August 2007, reintroduced them on a permanent basis. The purpose was to decrease congestion in the city center, increase accessibility, and reduce environmental impacts (Karlström and Franklin, 2009). The scheme consisted of a cordon that surrounded the central city and car owners were charged a toll that varied by the time of the day, and later complemented by public transport extensions, including new bus lines, additional capacity on commuter trains and subways, and more park-and-ride facilities (Eliasson et al., 2008). The public transport extension started in August 2005, and consumed more than half of the budget for the congestion pricing scheme (1400 MSEK of 2000 MSEK), to add 200 new buses and 16 new bus lines as an alternative to move from the surrounding Stockholm to the inner city. This difference in time of implementing the public transport extension and toll congestion helped to clarify the differences in behavioral responses to each piece (Eliasson et al., 2008), although it coincided with
fuel price increase. Travel surveys showed the extension did not encourage more than few car drivers to switch to public transport, i.e., less than 0.1% of drivers that stopped crossing the cordon during the day when the congestion tolls were in effect. Franklin et al. (2016) reported that other adaptation strategies could be switching destinations, or decreasing trip frequencies, possibly by combining trip purposes, and increasing trip chaining.

The traffic reduction after the congestion pricing trial in 2006 was around 22%, and around 20% after the reintroduction in 2007, both compared to 2005. Previous studies have found that the charges have been effective in reducing traffic across the cordon, leading to substantial reductions in congestion within and around the city (Hamilton et al., 2014). Stockholm used the congestion prices as one of the incentives to purchase green vehicles (GVs), also referred to as alternative fuel vehicles, or clean cars, which fall under the description explained by Hugosson and Algers (2012). Examples of other incentives are lower fuel cost, and national purchase subsidy for GVs of 1000 euros among other things. In a short period, GVs were exempt from charges. During the trial in 2006, 2% of the vehicles were GVs, while in 2008 this share increased to 14%, accounting for one-third of all cars sold in Stockholm in 2008. The overall increase of GVs from 2005 to 2008 was 23% (Börjesson et al., 2012). Most GVs are reported to be taxis (2.6% of 14%), and company cars (8.2% of 14%), while only 3.2% of crossings were by private GV owners.

The exemption of GVs was in effect up to and including July 2012 for vehicles that entered in the Swedish Road Traffic Registry prior to 1 January 2009. Since 2009, there was a successive phasing out of the exemption of GVs. The toll exemption of GVs completely phased out in August 2012. Since then, the congestion charging system in Stockholm has remained largely unchanged.

While there are numerous studies that investigated the congestion pricing case in Stockholm over the years (see e.g. Karlström and Franklin (2009); Börjesson et al. (2012); Eliasson et al. (2008)), it has not been examined how the GV owners changed their behavior after the removal of tax exemption. In Paper 5, we carry out a natural experiment to answer this question.

The Swedish Transport Agency administers Sweden’s congestion pricing systems and uses automated number plate recognition technology for billing car owners. During toll hours, this system continuously collects data, which is then linked to the vehicles’ registration information and stored for billing and reporting purposes. For our current research, the agency provided a data set containing anonymized records of all identified GVs and a random sample of CVs. While the vehicle identification numbers were encrypted for privacy, a consistent encryption key was used to enable comparisons between similar 2-week periods in records from 2012 and 2013. This allowed us to measure changes in crossing behaviors for the same vehicles. The data collection was carried out on working days between May 23rd and June 4th in both 2012 and
2013, from 6:30 am to 6:30 pm. We have three main findings from comparing data in 2013 to 2012, which were:

1. a significant drop in the total number of crossings (33%),
2. a slight shift towards later journeys in the morning, and
3. a reduction in the ratio of peak-toll period crossings to crossings in other times.

References


Tsai, Y.-h. (2001). *Travel-efficient urban form: A nationwide study of small metropolitan areas*. University of Michigan.


