diss. eth no. 28895

EMPIRICAL AND SIMULATION STUDIES ON PARKING IN SWITZERLAND

A thesis submitted to attain the degree of

doctor of sciences of eth zurich
(Dr. sc. ETH Zurich)

presented by

christopher michael tchervenkov

MSc. Microengineering,
École polytechnique fédérale de Lausanne

born on 14 January 1990
citizen of Canada

accepted on the recommendation of

Prof. Dr. K. W. Axhausen, examiner
Dr. M. Balać, co-examiner
Prof. Dr. D. Scott, co-examiner

2022

doi: 10.3929/ethz-b-000593365

The long and winding road

ABSTRACT

Parking is arguably the most important element of car travel; every car trip starts by interacting with a parked vehicle and ends with having to find a place to store the vehicle once again. As such, the proper understanding and management of parking within a city can play a major role in developing more efficient transport policies aimed at managing traffic and reducing car use and related externalities toward a more sustainable future. Although a widely researched topic, explicit consideration of parking is often still lacking from transport simulation frameworks, and thus so is its influence on travel behaviour. This begs the question: To what extent do the characteristics of parking supply shape mobility behaviour and how can we better integrate these insights into current transport simulation frameworks? This thesis tackles these questions through both empirical and simulation studies, on the basis of both large-scale survey and GPS tracking data.

The thesis starts with a simulation study exploring the potential reductions in parking demand in Zurich following the introduction and massive adoption of free-floating carsharing, highlighting that existing parking infrastructure can be better utilized.

Then, after examining the supply of parking across Switzerland and within Zurich and modelling how this depends on both socioeconomic as well as spatial factors, the impacts of employer-provided parking on commuting behaviour are studied. The results indicate that parking plays a significant role in commuting mode choice behaviour, and that policies encouraging Swiss employers to offer discounts on public transit subscriptions instead of company cars and free parking could prove beneficial in reducing the share of car trips to work.

Parking search traffic is often considered an important externality caused by the abundance of on-street parking within a city. The analysis of smartphone-based GPS tracking data shows that although parking search does exist in Zurich, it is substantially less than previous estimates, both for Switzerland and abroad, might suggest. The observed extent of parking search is influenced by the availability of on-street parking and cost of nearby parking garages, as well as by the familiarity of the driver with the area. On-street parking is observed to be overwhelmingly preferred to parking garages, with egress walking distance having the most substantial

effect on the choice of parking in a garage, followed by parking search distance and parking costs.

Based on the results of this empirical work, the last part of the thesis proposes an improved agent-based transport simulation framework capable of capturing the influence of the location, availability and price of different parking options on travel behaviour, thus providing first steps toward a valuable analysis tool with the potential to fuel future research on parking policy, both in Switzerland and abroad.

ZUSAMMENFASSUNG

Das Parken ist vermutlich eins der wichtigsten Elemente des Autoverkehrs: Jede Autofahrt beginnt mit dem Weg zu einem geparkten Fahrzeug und endet mit der Suche nach einem neuen Parkplatz. Daher kann ein verbessertes Verständnis der Parksituation in einer Stadt eine wichtige Rolle bei der Verkehrsplanung spielen und zu effizienteren Lenkungsmassnahmen führen, um den Verkehr zu regulieren, die Autonutzung und die damit verbundenen Externalitäten zu reduzieren und eine nachhaltigere Zukunft zu erreichen. Obwohl das Thema intensiv erforscht wurde, wird das Parken und damit sein Einfluss auf das Verkehrsverhalten in Verkehrssimulationen häufig nicht explizit berücksichtigt. Es stellt sich also die Frage: Inwiefern beeinflusst das Parkplatzangebot das Verkehrsverhalten und wie können wir diese Erkenntnisse besser in aktuelle Verkehrssimulationsmodelle integrieren? Diese Arbeit befasst sich mit diesen Fragen durch empirische und simulationsgestützte Studien auf der Grundlage von Umfrage- und GPS-Tracking-Daten.

Sie beginnt mit einer Simulationsstudie, welche die potenzielle Verringerung der Parkplatznachfrage in Zürich nach der Einführung und massiven Nutzung von Free-Floating-Carsharing untersucht und aufzeigt, dass die bestehende Parkplatzinfrastruktur besser genutzt werden könnte.

Nach einer Untersuchung des Parkplatzangebots in der Schweiz und in Zürich und einer Modellierung, wie dieses von sozioökonomischen und räumlichen Faktoren abhängt, werden die Auswirkungen der vom Arbeitgeber zur Verfügung gestellten Parkplätze auf das Pendlerverhalten untersucht. Die Ergebnisse deuten darauf hin, dass das Parken eine wichtige Rolle bei der Verkehrsmittelwahl spielt. Massnahmen sollten daher die Schweizer Arbeitgeber ermutigen, anstelle von Firmenwagen und kostenlosen Parkplätzen Rabatte auf ÖV-Abonnemente anzubieten, um den Autoverkehr zur Arbeit zu reduzieren.

Der Parksuchverkehr wird oft als wichtige Auswirkung des hohen Angebots an Parkplätzen in einer Stadt betrachtet. Obwohl der Parksuchverkehr in Zürich vorhanden ist, zeigt die Analyse der GPS-Tracking-Daten, dass er deutlich geringer ist als in früheren Studien geschätzt und wird durch die Verfügbarkeit von Parkplätzen auf der Strasse und die Kosten der umliegenden Parkhäuser sowie durch die Ortskenntnis des Fahrers beeinflusst. Parkplätze auf der Strasse werden mehrheitlich gegenüber Parkhäusern

bevorzugt, und die Entfernung zwischen dem Parkplatz und Zielort hat den grössten Effekt auf die Entscheidung, in einem Parkhaus zu parkieren, gefolgt von der benötigten Autodistanz, um dorthin zu kommen, und den Parkgebühren.

Basierend auf den Ergebnissen dieser empirischen Studien wird im letzten Teil der Arbeit ein verbessertes agentenbasiertes Verkehrssimulationsmodell vorgeschlagen, das die Auswirkungen des Standorts, der Verfügbarkeit und des Preises verschiedener Parkmöglichkeiten auf das Verkehrsverhalten erfassen kann. Damit werden erste Schritte zu einem wertvollen Analyseinstrument unternommen, welches das Potenzial hat, künftige Forschungen zur Parkplatzpolitik sowohl in der Schweiz als auch im Ausland zu unterstützen.

RÉSUMÉ

Le stationnement est sans doute l'un des éléments les plus importants des déplacements en voiture ; chaque trajet en voiture commence en se dirigeant vers un véhicule stationné et se termine par la recherche d'un nouvel endroit pour se garer. Par conséquent, une bonne compréhension et une bonne gestion du stationnement dans une ville peuvent jouer un rôle majeur dans l'élaboration de politiques de transport plus efficaces visant à gérer le trafic et à réduire l'utilisation de la voiture et les effets néfastes qui y sont associées en vue d'un avenir plus durable. Bien que ce soit un sujet largement étudié, les simulations de transport négligent souvent le stationnement, et donc son influence sur le comportement des voyageurs. La question se pose alors : Dans quelle mesure l'offre de stationnement influence-t-elle notre comportement en matière de mobilité et comment pouvons-nous mieux intégrer ces connaissances dans les modèles actuels de simulation de transport ? Cette thèse aborde ces questions par le biais d'études empiriques et de simulations multi-agents, sur la base à la fois d'enquêtes et de données GPS à grande échelle.

La thèse débute par une simulation visant à explorer les réductions potentielles de la demande de stationnement à Zurich suite à l'introduction et à l'adoption massive de l'autopartage en libre-service, démontrant ainsi que les infrastructures de stationnement existantes pourraient être utilisées de manière plus efficace.

Ensuite, après avoir évalué l'offre de stationnement dans toute la Suisse ainsi qu'à Zurich et modélisé comment celle-ci dépend de facteurs socio-économiques et spatiaux, les effets du stationnement fourni par les employeurs sur les déplacements domicile-travail sont étudiés. Les résultats indiquent que le stationnement au travail joue un rôle important dans le choix du mode de déplacement et que des politiques encourageant les employeurs suisses à proposer des réductions sur les abonnements aux transports publics plutôt que des voitures de fonction et des places de stationnement gratuites pourraient s'avérer bénéfiques pour réduire la part de déplacements en voiture vers le lieu de travail.

Le trafic induit par la recherche de stationnement est souvent considéré comme un problème important causé par l'abondance de places de stationnement sur rue dans une ville. Bien que ce type de trafic existe à Zurich, l'analyse des données GPS montre qu'il est nettement inférieur

aux estimations précédentes, tant pour la Suisse que pour l'étranger. Il est influencé par la disponibilité de places de stationnement sur rue et le coût des garages avoisinants, ainsi que par la connaissance du quartier par le conducteur. Le stationnement sur rue est largement préféré aux garages, la distance entre le lieu de stationnement et la destination finale ayant l'effet le plus important sur le choix de se garer dans un garage, suivi par la distance de déplacement en voiture requise pour y accéder et le coût du stationnement.

Sur la base de ce travail empirique, cette thèse propose finalement une approche de simulation multi-agents améliorée, capable de tenir compte de l'influence de l'emplacement, de la disponibilité et du prix des différentes options de stationnement sur le comportement des voyageurs. Cette approche constitue un premier pas vers un outil d'analyse ouvrant la voie vers de futures recherches sur la politique de stationnement, tant en Suisse qu'à l'étranger.

ACKNOWLEDGEMENTS

Having the courage to start, enjoying the ride and knowing when to stop.

Life is about taking risks, not being afraid of failure and trying something new. This is what I did over five years ago when I decided to join IVT and start a PhD. I knew very little about the group, or about transport planning at all for that matter, but I was curious and wanted to learn more about a field that I think can truly shape society. This was the first risk on my part, not knowing what I was getting myself into. It was also a bit of a gamble on Prof. Axhausen's part. Thank you for your trust and support and for giving me a chance to learn and be a part of the group.

Life is also about enjoying the moments. Enjoying the moments with colleagues and friends. Enjoying the long brainstorming sessions, the evening mensa dinners, the stressing over the next wave of MOBIS emails and the all-nighter before the TRB deadline. Enjoying a beer or more by the Limmat or at Alumni, the Winter Seminars in Tyrol, the weekend escapades to Belgrade and Ticino and the next conference to exchange with colleagues from around the world. Thank you Felix, Joe, Schatzi, Maxim and all the others for sharing all these moments over the past five years. And thank you Miloš and Sebastian, not only for this but also for all you did to help me have the grit to persevere.

Life is also about friends and family. Merci à vous, Marc, Sarah, P-O, Marie, J-P, Frank, P-A et tous les autres qui ont su être là pour moi – malgré la distance, ou grâce à la proximité. Thank you all. And especially, thank you mom and dad, Jen, Babchi, Gigi, Uncle and Baba for all your love and support over the years.

But most importantly, life is about knowing your limits and when to stop. When enough is enough. When one more line of code, one more simulation run, one more model or one more analysis for one more conference or paper won't change anything. It's about being content and appreciating what you have and what actually is important.

Amalia. Merci pour tes encouragements, ton soutien et ton amour inconditionnel pendant toutes ces années. Tu as été mon roc et je n'y serais jamais parvenu sans toi à mes côtés. Je t'aime!

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ARE	Swiss Federal Office for Spatial Development
BFS	Swiss Federal Statistical Office
CHF	Swiss franc
Covid-19	Coronavirus disease 2019
GPS	Global Positioning System
IVT	Institute for Transport Planning and Systems
MATSim	Multi-Agent Transport Simulation
MOBIS	Mobility Behaviour in Switzerland
MPE	Marginal probability effects
MTMC	Swiss Mobility and Transport Microcensus
OSM	OpenStreetMap
PT	Public transport
RP	Revealed preference data
SP	Stated preference data

1 INTRODUCTION

The transportation sector is a large contributor to overall CO_2 emissions, representing 34% of emissions in the USA, 28% in the European Union and 41% in Switzerland (Thalmann and Vielle, 2019). A large share of these emissions are due to private motorized road transport, i. e., the private car. According to the most recent report on the external costs and benefits of transport published by the Swiss Federal Office for Spatial Development, 45% of transport-related CO_2 emissions are due to private motorized road transport (ARE, 2022). When additionally accounting for other forms of external costs (e. g., air pollution, noise, accidents, etc.), 56% of all transport-related externalities are imputable to private car usage.

So why do people still choose to travel by car? More often than not, it is simply the most convenient mode available to travel from one place to another due to a combination of several factors, e. g.,

- it is the cheapest option,
- it is the quickest option,
- it is the most comfortable option,
- the traveller is carrying large objects,
- there are no other alternatives, etc.

As a result, a lot of effort has been directed at either making alternative modes more attractive (e. g., by improving public transport comfort, quality and connectivity, reducing travel times and prices, improving cycling and pedestrian infrastructure) or by increasing the generalized cost of car travel (e. g., by implementing various forms of road pricing).

But what about parking?

Parking is arguably the most crucial element of car travel. Every car trip starts and ends with walking to and from a parked vehicle and every single car needs to be parked somewhere when not in use. This realization signifies that the proper understanding and management of parking within a city can play a major role in managing traffic and reducing car use and related externalities.

1.1 WHY IS PARKING IMPORTANT?

Parking has a very specific relationship with traffic in downtown areas for different reasons and if not managed properly can have harmful effects on travel. It is still widely considered an important part of urban design to provide minimum parking requirements for new developments. Increasing unpriced parking supply to meet future demand, however, takes away valuable space from people and gives it to cars. These vehicles are used for only small portions of the day and, therefore, end up standing on these parking lots for long periods of time.

The increase of parking supply also attracts more car users (McCahill *et al.*, 2016), thus increasing car travel and causing negative environmental effects. Increasing parking supply in downtown areas has negative effects on the urban environment, discourages the use of active modes and reduces the economic success of business districts (Manville and Shoup, 2005; McCahill and Garrick, 2010; Voith, 1998). The land that is taken by parking could be otherwise used to increase the quality of life in urban areas by providing green spaces or higher concentrations of amenities. This would, as a consequence, encourage walking, cycling and public transit.

Searching for parking in downtown areas is yet another negative consequence of poorly managed parking supply. In a review of several studies on parking search, Shoup (2006) concludes that between 8% and 74% of the total traffic in downtown areas is caused by cruising for parking, for an average of 30% corresponding to an average search time of 8.1 minutes. Shoup argues that large quantities of free on-street parking and mispriced parking garages are the main causes of parking search traffic in downtown areas, further causing congestion and negative externalities.

In summary, parking has a great effect on the urban landscape as well as urban dynamics. It influences people's travel behaviour and travel choices. When it is plentiful, it favours more car usage at the expense of walking, cycling and public transport, and takes away valuable space from people. When it is incorrectly priced, it additionally encourages people to excessively search for a free parking space, further increasing negative transport externalities. Thus, it is an element of transport behaviour and planning with substantial repercussions that deserves adequate consideration.

1.2 RESEARCH GOALS

Given the previously highlighted importance of parking to overall car travel, the main objective of this thesis is to study parking through both observed behaviour and simulations. Agent-based transportation models have been developed over the past few decades, in contrast to four-step models, notably to address the need to model complex interactions between individuals. MATSim (Horni *et al.*, 2016) is such a multi-agent transportation simulation framework. It consists of both a synthetic population of agents, each with a preferred daily travel plan and socioeconomic characteristics obtained from census data, and a detailed transportation network. These agents are then iteratively simulated on the network, interacting with each other and causing each other delays. The results of the previous iteration are fed into the next, creating a feed-back loop where the agents can modify their plans accordingly. The simulation is terminated once equilibrium is reached, that is when the overall behaviour stabilizes, ultimately providing departure and arrival times, as well as the transport mode and route used, for all agents in the simulated population. This framework is particularly useful in the context of modelling parking, where competition for a scarce resource such as space induces traffic and congestion.

However, in order to build such models, a greater understanding of parking supply in Switzerland and its influence on travel behaviour needs to be established. The Institute for Transport Planning and System (IVT) at ETH Zurich conducted a large-scale GPS tracking survey in autumn 2019 (Molloy *et al.*, 2021a). This large GPS dataset, along with other surveys, will be used as the basis for answering the following research questions.

- What is the current supply of parking in Switzerland, and more specifically in the city of Zurich?
- Which factors influence the availability of parking at home and work in Switzerland?
- What effect does parking at work provided by employers have on Swiss commuting behaviour?
- What factors influence the choice of where to park in Zurich?
- To what extent is parking search present in Zurich, and if so, what are its influencing factors? Can any patterns be observed?

The answers to these questions will then be integrated into an agent-based transport simulation for a more accurate representation of travel behaviour, as parking is often not considered in such models. The ultimate objective is to include a data-driven parking behaviour model, which in turn influences mode choice, within an agent-based transport simulation framework. This will in turn allow the study of future transport planning policies and scenarios related to parking.

1.3 OVERVIEW OF THE THESIS

This thesis tackles the above research goals across the following chapters.

Chapter 2 contains a literature review on different aspects related to parking, and focuses on the impacts of parking provisions on travel behaviour, the estimation of parking location choice, parking search and mode choice models as well as their integration into agent-based simulations.

Chapter 3 briefly describes the state of the art in agent-based transport simulations using MATSim, how it deals with parking and its limitations, as well as the MATSim scenario for Switzerland. Chapter 4 follows up with a first MATSim case study examining the effects of carsharing on parking in Zurich.

Next, the main data sources used throughout this thesis are presented in Chapter 5. Chapter 6 focuses on parking supply, first exploring parking at home and work in Switzerland, and then publicly accessible parking in the city of Zurich. Chapter 7 examines the specific case of parking availability at work within the context of fringe benefits and their impact on commuting behaviour. Chapter 8 examines the issues of parking search and parking type choice using GPS data.

Chapter 9 presents the integration of the parking-related findings from the previous chapters within the MATSim scenario for Switzerland, while Chapter 10 concludes.

2

LITERATURE REVIEW

Parking is a crucial element of car travel and as such has been a widely researched topic. The following chapter reviews some of the work on parking, focusing mainly on parking supply and its effect on travel behaviour, parking location choice, parking search and resulting mode choice models as well as transport simulation frameworks considering parking.

2.1 PARKING SUPPLY AND EFFECTS OF TRAVEL BEHAVIOUR

Mobility tool ownership plays an important role in mode choice behaviour (Simma and Axhausen, 2001), and the impact of parking, as an enabler for car travel, cannot be neglected. Based on data from 44 world cities (Kenworthy *et al.*, 1999), Manville and Shoup (2005) compute that, on average, 31% of the land area in central business districts is devoted to the sole function of parking a vehicle. Previous research has shown that abundant parking supply in cities attracts more car users and thus encourages more car use (McCahill *et al.*, 2016), discourages the use of active modes and reduces the economic success of business districts (Voith, 1998; Manville and Shoup, 2005; McCahill and Garrick, 2010).

Despite this, minimum parking requirements are still an important part of urban planning regulations in many cities. Residential parking provision have a major impact on travel behaviour, as they tend to increase vehicle ownership and use. Using data from the American Housing Survey, Manville (2017) estimates the effect of parking included in the rent or housing price on household vehicle ownership. Manville concludes that households with such bundled parking are 50% to 75% less likely to be vehicle-free, and that bundled parking encourages driving among commuters who own vehicles.

Millard-Ball *et al.* (2022) conducted a survey among 2,700 households from San Francisco's housing lottery programs[1] to measure how both residential parking provisions and the surrounding built environment

1 These programs are designed to give low-income households a better chance at living within the city. A government-mandated portion of units within new residential developments are made available at below-market-rate prices, and low-income households can apply to lotteries which then randomly allocate these units.

impacts travel behaviour and economic outcome. Their results show that increased residential parking affects travel behaviour by inducing more car ownership and driving while reducing the use of public transport, regardless of public transport accessibility. However, this additional parking does not have an effect on employment outcomes.

In many countries, taxation policies encourage employers to offer employees fringe benefits instead of increasing their wages. By providing mobility-related fringe benefits to their employees, employers can thus influence their daily mobility choices. Parking is a common fringe benefit offered by employers and also has a major impact on travel behaviour. In the US, 87% of employers offer free parking (Society for Human Resource Management, 2014) and 95% of employees who drive to work have a free parking space available (Brueckner and Franco, 2018). According to the Swiss Federal Statistical Office (BFS), a more modest 58% of Swiss employers offer parking (BFS, 2010). Nonetheless, these parking subsidies encourage increased car usage and ultimately urban sprawl (Brueckner and Franco, 2018). In a review of several empirical studies on the effects of employer-paid parking on mode choice, Willson and Shoup (1990) show that between 19% and 81% fewer employees drive to work when having to pay for parking. Using the results of a multinomial logit model estimated on travel diary data from Portland, Oregon, Hess (2001) shows that 62% of commuters would drive to work in the presence of free parking. More recently, Christiansen *et al.* (2017) model the effect of free parking at both home and work on mode choice based on travel survey data from Norway, concluding that restricting free parking at the workplace is an effective measure for reducing car trips to work.

However, parking is not the only mobility-related fringe benefit offered by companies. Company cars are also a popular fringe benefit offered by employers and make up a substantial share of the passenger vehicle fleet: about 50% of new car registrations (Naess-Schmidt and Winiarczyk, 2010) and about 12% of the total passenger vehicle stock (Shiftan *et al.*, 2012) in Europe in 2008. Many employers offer a company car to at least some of their employees, e. g., 56% of companies in Switzerland in 2010 (BFS, 2010). In the Netherlands, nearly 10% of employees have a company car (Gutiérrez-i Puigarnau and Van Ommeren, 2011). However, only certain groups of employees might receive a company car; Macharis and De Witte (2012) report that the majority of company car users in Belgium are male (70%) and in their 30s (39%). Not only are these vehicles often provided to employees at an advantageous rate, some of the variable costs, such as fuel, insurance or parking, might also be subsidized by the employer. Given that car availability influences car usage, one might expect these employer benefits to influence travel behaviour, encouraging car use, more car trips and more kilometres travelled. Indeed, multiple studies show that the annual mileage of company cars, mainly driven for professional and commuting purposes (Macharis and De Witte, 2012), tends to be higher than that of privately-owned cars (Macharis and De Witte, 2012; Cornelis *et al.*, 2007; Ramaekers *et al.*, 2010; Metzler *et al.*, 2019).

Public transport discounts are another benefit often offered by employers to make themselves more attractive and reduce commuting by car. In their study assessing the impact of employer-subsidized transit passes or parking on commuter mode choice within the Atlanta metropolitan area, Ghimire and Lancelin (2019) report that employees who were provided with subsidized transit had a 156% higher odds of commuting to work by transit. More recently, Busch-Geertsema *et al.* (2021) studied the example of the German state of Hesse, which introduced a free public transport ticket for all state employees. They analyzed data from before and after the new policy and report substantial increases in public transport use for both commuting as well as other trip purposes.

While most of the aforementioned studies focus on the behavioural impacts of different mobility-related fringe benefits individually, little work has been undertaken to model the impacts of multiple fringe benefits jointly. Hamre and Buehler (2014) use multinomial logistic regression to model the mode choice behaviour of commuters in the Washington, DC area given free car parking provisions, public transportation benefits and the availability of showers, lockers and bike parking at work. They show that transit-, cycling- and walking-related benefits translate in a decreased likelihood of commuting to work by car; however, these effects are offset if free parking provisions are also provided. Bueno *et al.* (2017) report similar effects when modelling the impact of mobility-related fringe benefits on commuter mode choice in the New York-New Jersey region. Shin (2020) shows that parking provisions and transit benefits respectively increase and decrease the likelihood of commuting to work by car and that transit benefits are effective in reducing overall car travel in the Puget Sound region around Seattle.

In the European context, both descriptive analysis and local case studies on the impact of mobility-related fringe benefits have been conducted. For example, Cairns *et al.* (2010) analyze the effect of parking management as well as transit, cycling, walking and carsharing incentives on the share of employees who commute by car and report an average 18% decrease in commuter driving across 20 UK employers, though no models are estimated. Vanoutrive (2019) estimates a regression model to better understand the impact of public transport, cycling and carpooling incentives on the share of single-occupancy car trips to work in Belgium, albeit for the specific case of Brussels Airport and the seaports of Antwerp, Bruges and Ghent.

In summary, abundant parking provisions, whether they be dedicated space at home, provided along with other benefits at work or publicly available within the city centre, encourage increased car use along with the associated negative externalities. However, it remains to be seen which factors influence the supply of parking at home and work in Switzerland, and how the latter affects commuting behaviour.

2.2 PARKING LOCATION CHOICE AND PARKING SEARCH

Searching for parking in downtown areas is yet another negative consequence of poorly managed parking supply. In a review of several studies on parking search conducted between 1927 and 2001, Shoup (2006) concludes that between 8% and 74% of the total traffic in downtown areas is caused by cruising for parking, for an average of 30% corresponding to an average search time of about 8 minutes. Shoup proceeds by presenting a simple model to explain how drivers choose between on-street parking and parking garages given the parking costs, parking duration, search time, fuel cost, number of people in the vehicle and value of time spent searching. On the basis of this model, Shoup argues that large quantities of cheap on-street parking and mispriced parking garages are the main causes of parking search traffic in downtown areas, further causing congestion and negative externalities, and thus concludes that the price of on-street parking should equal that of parking garages in order to eliminate cruising traffic.

In their review on parking search, Polak and Axhausen (1990) emphasize the importance of parking search in understanding overall parking behaviour. The choice of where to park is a complex process, involving not only both the driver's personal preferences and prior knowledge about the parking supply, but also the current availability of parking as well as traffic conditions. Drivers who are well informed of the parking supply at their destination will likely have a clear location in mind, given the purpose of their trip and their personal preferences, whereas those with little previous experience will only have a vague idea. However, the uncertainty in parking availability brought on by high demand for parking, especially in the peak hour, signifies that even the most well informed driver cannot be certain that their desired parking location will be available upon arrival, and therefore might anyway be forced to search for a free parking space. This uncertainty causes drivers to attempt different strategies when searching for parking, e. g., always driving to the same nearly certain location, first driving to the destination to assess the current parking occupancy before starting to search, driving directly to the nearest parking garage, etc.

After reviewing a set of 7 previous revealed preference studies on parking location choice behaviour, Axhausen and Polak (1991) present two parking type choice models estimated using stated-preference data collected from Birmingham, United Kingdom, and Karlsruhe, Germany. The models differentiate between up to 5 different parking type alternatives, each described by their respective access, search and egress times as well as parking cost. The model results suggest that search time is valued differently from access (i. e., driving) time, and thus should be considered separately both when estimating parking choice models as well as mode choice models.

In a similar fashion, Hess and Polak (2004) collected stated preference data in order to estimate a mixed multinomial logit model to analyze parking type choice behaviour. Like Axhausen and Polak (1991), they find that a significant heterogeneity exists in the valuation of the different time-related parking components and additionally that behaviour differs across different trip purposes. More recently, Chaniotakis and Pel (2015) conducted a stated preference experiment and estimated parking choice models while considering the uncertainty in both search times and parking occupancy levels. Their results show that the uncertainty in parking availability plays an important role in parking location choice.

Since Shoup (2006), there have been a few more empirical studies on parking search, although estimates on the share of cruising traffic vary. Using data from the Dutch National Travel Survey, van Ommeren *et al.* (2012) estimate the average cruising time to be 36 seconds, and argue that this is due to the similarity of on-street and off-street parking prices in the Netherlands. They also find cruising to have both spatial (higher in cities) and temporal (peak in the morning) patterns and to increase with both travel and parking duration as well as with shopping and leisure trips. On the other hand, Lee *et al.* (2017) estimate an average cruising time of between 13 and 16 minutes in a busy commercial district in Brisbane, Australia, based on an intercept survey. Hampshire and Shoup (2018) estimate that 15% of the traffic in central Stuttgart is cruising for parking, with a peak just before noon.

The aforementioned parking choice and parking search studies provide only a snapshot of the literature on the topic. Young *et al.* (1991) review earlier work on the development of parking location choice and mode choice models. In their extensive review on on-street parking search, Brooke *et al.* (2014) identify the main factors influencing on-street parking behaviour, namely search time, cost, parking policy, and socioeconomic characteristics. They also summarize the main modelling methods which have been used when studying on-street parking search and suggest future research directions.

More recent development of technologies such as navigation devices and smartphones capable of collecting GPS or other location data have allowed for conducting new parking search data collection and analysis. Kaplan and Bekhor (2011) propose a conceptual methodological framework for the joint modelling of parking location and search route choice, using both self-reported and GPS data. Montini *et al.* (2012) used a smartphone-based GPS tracking study to understand parking search behaviour in both Zurich and Geneva, Switzerland. Parking search trajectories were extracted from the GPS data within a 800 m radius around the final parking location. Their results show that although cruising depends largely on the area within the cities and increases in denser areas, it is not substantial, with 80% of the observed cruising lasting under 4 minutes. However, their results cannot be linked to the driver's socioeconomic information or trip purpose, as neither is available for the dataset.

Using GPS data from 97 car trips collected in the city of Turnhout, Belgium, van der Waerden *et al.* (2015) investigate both the temporal and spatial aspects of parking search behaviour. They report an average parking search time of 1 min 18 s, accounting for approximately 14% of the total travel time. They also analyze which factors impact the use of certain streets over others during the parking search process, and find that the choice of a particular street segment is influenced by the distance both to the city centre and the nearest parking facility, the presence of retail, and the cost of parking. However, given the very few observations, this study cannot be considered representative.

Weinberger *et al.* (2020) examine parking search behaviour in San Francisco and Ann Arbor using both vehicle- and smartphone-based GPS data. The authors define cruising as the difference in length between the observed trajectory mapped to the road network (Millard-Ball *et al.*, 2019) and the shortest path once a driver first enters within a 400 m radius around their destination. Their results show that parking search occurs in less than 6%

of vehicle trips and accounts for less than 1% of vehicle travel. However, the data are anonymized and thus lack socioeconomic information. Also, for the vehicle-based data, information on the trip destination is not available. Using the same data from San Francisco, Millard-Ball *et al.* (2020) derive a dynamic programming model which distinguishes between parking search, i. e., the time required to actively find and park in a vacant space, and cruising, i. e., the excess travel due to parking search. Their model indicates that drivers are willing to park in more convenient parking spaces further from their destination when parking is perceived as scarce and that in certain cases, this can even reduce vehicle travel. In other words, although drivers always travel a positive distance while searching for parking, the excess cruising distance due to parking search can be null or even negative when parking is hard to find.

Passenger vehicles are not the only ones to experience cruising. Dalla Chiara and Goodchild (2020) analyze commercial vehicle cruising time using GPS data from a sample of 2,900 trips performed by a fleet of commercial vehicles in downtown Seattle. They estimate that commercial vehicles cruise 2.3 min per trip on average, corresponding to 28% of total trip time, and that these cruising times are influenced by urban infrastructure.

Using enriched GPS data from more than 48,000 car trips in the Region of Attica, Greece, Mantouka *et al.* (2021) estimate survival models to identify the factors that impact parking search duration. The time of day of the performed trip appears as the most significant factor, while trip duration, trip length and land use at the destination also play a significant role. The authors additionally present their methodology for detecting parking search in real-world trajectory data, based on computing the distance between each trajectory point and the final destination and taking the first local minimum within 400 m of the destination. This provides an alternative approach to other radius-based methods (Montini *et al.*, 2012; Weinberger *et al.*, 2020).

GPS data collection for the analysis of parking search behaviour has gained traction in the last decade, allowing for more spatially and temporally detailed analysis and insights. Yet, none of the reviewed parking search GPS studies control for socioeconomic attributes when determining which factors most influence parking search behaviour, mainly due to the lack of such information. To fill this gap, this thesis will examine how such socioeconomic information might affect parking search behaviour in general within the city of Zurich, on the basis of recently collected GPS data for Switzerland (Molloy *et al.*, 2021a).

2.3 MODE CHOICE MODELLING CONSIDERING PARKING

The previous section focused solely on how drivers' choice of parking location and search behaviour is influenced by not only their own preferences, but also by the characteristics of their trip, their destination and parking supply. However, in order to fully understand and model the impact of parking on the overall transportation system, it is important to also consider its effect on mode choice.

Policies affecting parking can indeed have an impact on mode choice, and many previous travel behaviour studies have investigated the effect of different components of parking on modal choice. In an early review of 19 mode choice models, Feeney (1986) found that only five incorporated parking cost as a separate variable, 13 included it in the overall travel cost while one omitted it altogether. He also noted that few models considered parking search time but several used excess or walking time to the destination. All of the models considered excess time as more important that in-vehicle time. The review by Young *et al.* (1991) comes to similar conclusions: some models include parking cost as a separate variable while other incorporate it into the driving costs, and few models consider parking search time separately from driving time. Axhausen and Polak (1991) however suggest that parking search and egress time should be integrated into mode choice models as separate variables, as they are valued differently than driving and access time.

Since then, further progress has been made on including different parking characteristics (e. g., cost and time components) into discrete mode choice models. Hensher and King (2001) collected stated preference data from car drivers and public transport users in the central business district (CBD) of Sydney. Respondents were asked to choose between 6 choice alternatives: park in one of 3 locations within the CBD, park outside the CBD and then use public transport to reach the CBD, switch to public transport altogether, or forego the trip to the CBD entirely. The parking locations within the CBD differed in terms of operating hours, price, and egress time to the final destination. The authors then estimate a nested logit model for mode and parking choice in order to evaluate the behavioural response to parking supply and prices. The results indicate that the sensitivity to parking prices is higher than for driving costs and travel time, and the authors conclude that it is by far the best policy instrument for reducing car travel into and parking in the CBD.

Weis *et al.* (2012) used stated-preference data collected in Switzerland to estimate both a multinomial and mixed logit model for mode and secondary location choice. Their results show that parking costs, search times and type have a significant effect on mode and secondary location choice in Switzerland, and that the willingness to pay to reduce parking search decreases with an increase in activity duration. The authors therefore suggest that policy measures aimed at changing these parking characteristics might be efficient in influencing both modal split and location choices, instead of large infrastructure investments.

Using revealed preference data from the Swiss Mobility and Transport Microcensus (MTMC) enriched with open-source parking data, Burchard (2021) estimated a multinomial logit model for mode choice including parking for the city of Zurich. The results indicate that parking costs do have an influence on mode choice behaviour; however, the model shows a lower goodness-of-fit when parking costs are included. This is likely due to the method used for imputing parking costs for such revealed-preference data.

Weis *et al.* (2021) present the results of mode choice models estimated on combined RP/SP data collected at the Swiss national level from repeated studies in 2010 and 2015 and find the willingness-to-pay indicators to be stable between 2010 and 2015 (for a more detailed report, see Weis *et al.* (2017)). Included in the models are parameter estimates for both parking search time and costs, the latter differentiated by trip purpose, with the estimated parameter being only slightly more negative for education and shopping trips.

2.4 TRANSPORT SIMULATIONS INCLUDING PARKING

In order to capture the complex spatial and temporal interactions between travellers on real-world transportation networks considering parking, several transport simulation models which explicitly integrate parking have been developed over the years. Axhausen (1989) developed a discrete-event simulation of activity chains including parking behaviour. In the proposed model, drivers search for vacant parking space of their preferred type until a specified parking search time limit is reached, after which they extend their search into nearby network elements and also search for other types of parking.

Benenson *et al.* (2008) developed the multi-agent, spatially explicit PARKAGENT model for city parking as an ArcGis application applied to Tel

Aviv, focusing solely on the parking process of commuters returning home in the evening. Parking search is modelled as follows. Drivers first assess the parking occupancy within a defined radius around their destination. Then, for each free parking space en-route to their destination, the driver evaluates whether it should park or continue its search given the estimated occupancy. If the driver reaches the destination without having parked, it searches for the next free space within a limited acceptable distance.

The cellular automaton model SUSTAPARK (Spitaels *et al.*, 2009; Steenberghen *et al.*, 2012) simulates not only the parking search process but also the city-wide effect of parking on the entire transportation system in the case of Leuven, Belgium. However, as with PARKAGENT, the model is not capable of capturing behavioural changes such as modal choice or adjustments to daily travel plans resulting from changes in parking policy.

MATSim (Horni *et al.*, 2016) is a modular multi-agent transportation simulation framework, in which a synthetic population of agents, each with a daily travel plan, are iteratively simulated on a detailed transportation network, interacting with each other and causing each other delays. Based on the results of previous iterations, agents can then modify their plans accordingly (e. g., in terms of mode and route choice) until equilibrium is reached. The MATSim framework has already been utilized for large-scale transport simulations including parking. Scherr *et al.* (2020) developed a complete microscopic travel demand model, including population synthesis, activity-based demand generation and agent-based traffic flow simulation, the latter based on the MATSim framework. However, parking is considered in the simulation only by means of a zone-based parking cost model.

Waraich and Axhausen (2012) implemented a parking choice model for selecting one from a set of parking spaces located near an agent's destination within a MATSim agent-based transport simulation for the city of Zurich. The model was calibrated to match parking count data; however, it omits the parking search process. The model was subsequently used to simulate a dynamic pricing scheme (Waraich *et al.*, 2013) as well as study the impact of parking price policy on free-floating carsharing (Balać *et al.*, 2017a) in Zurich. However, given that the model neglects the parking search process, it is unable to capture the resulting traffic and congestion impacts.

To remedy some of these limitations, Bischoff and Nagel (2017) implemented a random parking search logic into the MATSim framework and applied the simulation model to Berlin. More realistic parking search strategies, including the one proposed in PARKAGENT, have since then been implemented and integrated into the framework (Kolomatskiy *et al.*, 2020).

However, the logic of these models are mainly based on heuristics and not calibrated to observed data.

Recent work has been directed at pairing discrete choice models with MATSim in order to facilitate the calibration of the model and improve the match to observed data (Hörl *et al.*, 2019b). However, these new models have yet to include parking-related variables. Therefore, the ultimate goal of this thesis will be to include parking within the MATSim discrete mode choice framework developed by Hörl *et al.* (2019b), based on empirical insights, to produce a data-driven agent-based transport simulation including parking for the city of Zurich.

3

AGENT-BASED TRANSPORT SIMULATIONS

Before diving into the details of understanding and simulating parking in Switzerland, it is important to first present the state of the art in agent-based transport simulation considering parking-related behaviour using the MATSim framework. The following chapter starts by presenting the multi-agent transport simulation MATSim as well as its main elements. Then, the current state of the art in terms of parking simulations within the MATSim framework, along with its limitations, is presented. Next, the MATSim scenario for Switzerland, based on the eqasim framework which links MATSim to the world of discrete choice models, is briefly discussed. Finally, a conclusion on how each of these different aspects can be improved with regards to parking is provided.

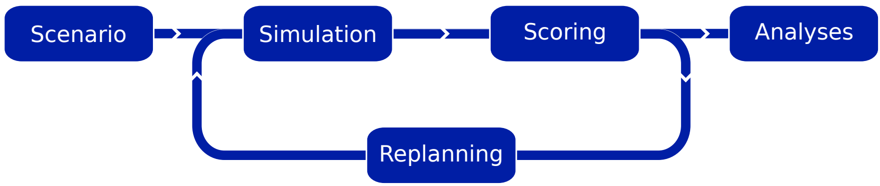
3.1 MATSIM IN BRIEF

Four-step models have traditionally been the standard approach for modelling transportation systems, forecasting demand and evaluating policy measures and infrastructure investments. However, as these models focus on aggregate flows, they are unable to capture the interactions between individuals and resulting emergent behaviour.

Agent-based transportation models, e. g., CEMDAP (Bhat *et al.*, 2004), SimMobility (Adnan *et al.*, 2015), POLARIS (Auld *et al.*, 2016), SUMO (Lopez *et al.*, 2018), or MATSim (Horni *et al.*, 2016), have been developed over the past few decades to overcome some of the limitations of such traditional four-step models, namely to address the need to model interactions between individuals. This aspect has become ever more crucial today, as many different competing and complementary transportation services now exist simultaneously; they are often highly dynamic and therefore require modelling on very short time-scales. In recent years, the multi-agent transport simulation MATSim has been extensively used in case studies to explore the potential demand, operational requirements and system-wide effects of a variety of new mobility services, e. g., carsharing (Balać *et al.*, 2017b, 2019a; Tchervenkov *et al.*, 2019), bikesharing (Becker *et al.*, 2020), unmanned aerial vehicles (Balać *et al.*, 2019b) and automated vehicles (Spieser *et al.*, 2014; Maciejewski and Bischoff, 2018; Fagnant and Kockelman, 2018; Hörl *et al.*, 2019c,a).

MATSim is an iterative simulation framework designed as a co-evolutionary algorithm. The basic components of the simulation process are outlined in Figure 3.1 in what has become colloquially known as the MATSim loop.

FIGURE 3.1: The MATSim loop



SCENARIO A MATSim simulation always starts with a scenario, which contains the basic elements required to run a full MATSim simulation. There are two main components required to build an agent-based transportation scenario: mobility demand and supply.

The demand is comprised of a *synthesized population*, namely a set of *agents* characterized by their *attributes* and their *plans*. A plan is an activity chain describing an agent's typical schedule during an average working day. It also contains information on the desired times and locations at which the agent wishes to perform these activities and on the trips linking one activity to the next. The attributes describe the socioeconomic condition of the agents and provide information on the transport modes that they can access. Agents are grouped into *households*, which are also characterized by additional attributes.

The transport supply consists typically of a road and public transport network. Information concerning transit schedules are required as well, and the road network can be additionally supplemented with information on *facilities*, that is the places where an agent can perform an activity.

SIMULATION Each agent's daily plan is simulated on the transportation network using the computationally efficient queue-based approach. Each link on the network is represented as a first in, first out queue, characterized by two parameters: storage capacity, which defines the number of vehicles that can physically be stored on a link at the same time, and flow capacity, which specifies the rate at which vehicles can be processed by, i. e., travel along, the link. Each new vehicle entering a link is added to the end of the queue, and the vehicle at the head of the queue may only move on to the next link if 1) the travel time specified by the link's flow capacity has elapsed and 2) the next link has enough remaining storage capacity. It is in this way that MATSim is able to capture the interaction between individual vehicles as they travel across the network, generating congestion for other travellers.

SCORING After having simulated each agent's daily plan on the network, the experienced plan is scored based on the utility provided to the agent. A simulated plan's score S_{plan} is expressed using the Charypar-Nagel utility function

$$S_{plan} = \sum_i S_{act,i} + S_{trip,i} \tag{3.1}$$

as the sum of the score $S_{act,i}$ of each activity i and the score $S_{trip,i}$ of the subsequent trip. The score of each activity is typically expressed as a linear combination of scores which depend on the arrival time and actual duration of the activity, while the score of the subsequent trip is similar to what one would expect in a mode choice model

$$\begin{aligned} S_{trip,i} = \beta_{ASC,m} & \\ & + \beta_{travelTime,m} \cdot x_{travelTime} \\ & + \beta_{distance,m} \cdot x_{distance} \\ & + \beta_{cost} \cdot x_{cost} \end{aligned} \tag{3.2}$$

with $\beta_{travelTime,m}$ and $\beta_{distance,m}$ the mode specific travel time and distance parameters, β_{cost} the cost parameter and $\beta_{ASC,m}$ the alternative specific constant for the selected mode m. The attributes x are obtained from the simulation iteration, while the β parameters are to be specified by the user. More complex formulations of the scores of both the activity and trip utility can be defined in the code depending on the use case, e. g., when considering new transport modes or new policy measures. The score S^k which is ultimately stored for the plan for iteration k is

$$S^k = \alpha S_{plan} + (1 - \alpha) S^{k-1} \tag{3.3}$$

where S_{plan} is the score for the plan simulated by the mobility simulator, S^{k-1} is the previously stored score and α is the learning rate. This new score is then stored within the agent's memory, which typically can hold up to 5 plans, although this is configurable.

For more details on scoring in MATSim, the reader is invited to consult Nagel *et al.* (2016).

REPLANNING After scoring, all agents must select a single plan from their memorized set of experienced and scored plans to be simulated during the next iteration. These are typically selected probabilistically following a logit formulation based on the plan scores. A small random share of agents (usually 10%) are then allowed to modify their selected plan, i. e., to replan, across different dimensions: departure time, route and mode choice. The dimensions can be modified using different strategies, e. g., random mutations of departure times or modes, least-cost path for routes, etc. Once all agents have their selected (and modified) plan, a new simulation iteration is ready to start.

ANALYSES Once the simulation has reached equilibrium, e. g., the scores or mode shares have stabilized, the simulation output is ready for analysis. MATSim generates a logbook of all the events that occur during the simulation in the form of an event file, containing the information of, e. g., when an agent starts or ends an activity, enters a vehicle or a link, etc. These events can further be processed and analyzed to provide insights and indicators for relevant transport policy studies.

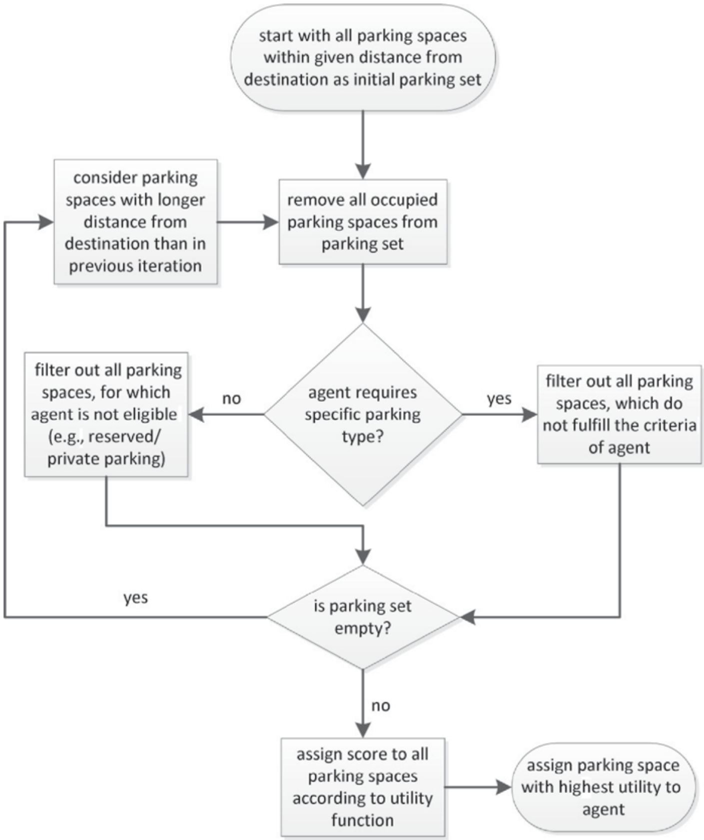
3.2 PARKING IN MATSIM

In its most basic form, MATSim does not consider parking; vehicles magically appear when travellers wish to depart from their origin activity and subsequently disappear once they arrive at their destination, the burden of having to actually find a vacant parking spot being left to the omnipresent God that is the mobility simulator which in turn stores the vehicle in some infinitely large parking garage in the skies of sorts. This is a reasonable approximation in areas where parking is both cheap and abundant, but no longer applies in urban contexts where demand is high and parking is usually both expensive and scarce. Two independent contributions have been implemented in an attempt to address these parking limitations in MATSim: parking choice and parking search.

3.2.1 *Parking choice*

A parking choice model for MATSim, which considers parking supply, walking distance and parking fees, has been implemented by Waraich and Axhausen (2012) as a post-processing step after the mobility simulation. At the end of each simulated car trip, an agent is required to decide on where to park its vehicle. This parking location choice is modelled using the algorithm depicted in Figure 3.2.

FIGURE 3.2: MATSim parking choice algorithm



Source: Waraich and Axhausen (2012)

Agents typically have preferences or are required to use certain types of parking (e. g., for disabled persons, electric vehicles, etc.) and may also not be allowed to use certain parking spaces (e. g., reserved or private parking spaces). The algorithm filters all available parking spaces within a certain distance to the destination which fulfill these preferences and restrictions and rank them in terms of utility considering both the cost of parking and walking distance. The parking location that maximizes this utility is then selected by the agent. During scoring, the agent's plan is then evaluated considering this additional parking utility, which in turn allows the agents to adapt their plans while considering parking supply and costs.

While this approach is able to capture the effects of parking availability and costs on travel behaviour, the model neglects the parking search process and as such is unable to capture the resulting traffic and congestion impacts of parking within a city.

3.2.2 *Parking search*

To remedy some of the limitations of the parking choice model presented in Section 3.2.1, Bischoff and Nagel (2017) implemented a first parking search model into the MATSim framework. More realistic parking search strategies, including the one proposed in PARKAGENT, have since then been implemented and integrated into the framework (Kolomatskiy *et al.*, 2020). Unlike the parking choice model, which acts as a post-processing step after the simulation, the parking search model is directly implemented within the mobility simulation, such that agents make decisions on whether to park or to continue driving at each new link within the network en route to their destination. Unlike the traditional MATSim approach, in which an agent can either be travelling or performing an activity and a car trip consist of a single leg, this approach considers 5 distinct simulation states: 1) walk from location to parked car, 2) unpark car, 3) travel to destination, including parking search, 4) park car and 5) walk from car to destination. As a result, car trips now consists of three legs (walk, car, walk) and two parking activities. As for the travel and parking search logic, three different versions have been implemented to date and integrated within the MATSim framework:

RANDOM SEARCH In this approach, agents start by driving directly to their final destination, at which point parking search begins. Agents then perform a random walk along neighbouring links until they find a vacant parking space.

BENENSON This approach is the MATSim implementation of the PARK-AGENT model developed by Benenson *et al.* (2008). Unlike the random walk approach, in which parking search only starts after first reaching the destination, here drivers first assess the parking occupancy while approaching their destination after having entered a pre-defined observation radius. Within this observation radius, the link whose end node is closest to the final destination is selected as the next to visit. Then, once the driver is within a closer search radius, it evaluates, for each new vacant parking space, whether it should park or continue its search given the estimated occupancy. If the driver reaches the destination without having parked, it searches for the next free space within a limited acceptable distance.

DISTANCE MEMORY This search logic is similar to the random walk search logic in that agents first travel to their final destination. If there is a vacant parking space on the destination link, the agent parks there. Otherwise, the agent select the next link as the one whose end node is closest to its destination among all outgoing links. If there is a vacant parking space, the agent parks there, otherwise it memorizes this link and then selects a new link to search among all the new outgoing links, excluding those it has already searched. If all outgoing links have been searched, the next link is selected randomly.

These implementations all suffer from the same limitation: they do not differentiate between different parking types nor do they consider the monetary cost of parking and thus cannot capture how these aspects influence both parking and mode choice behaviour.

3.3 THE SWITZERLAND SCENARIO

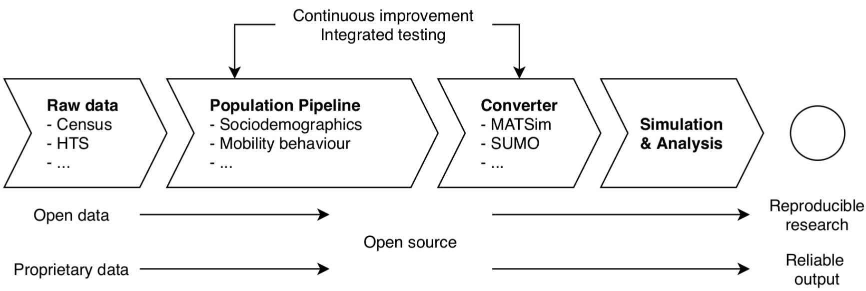
This section presents the basic elements of the current MATSim scenario for Switzerland, which is constructed around the eqasim framework. The eqasim framework was developed by Hörl and Balać (2021a) in an effort to generate agent-based transportation models which can be both reproduced and validated by others researchers. The framework combines a pipeline of different algorithms to generate agent-based transport simulation scenarios with the MATSim discrete mode-choice extension (Hörl *et al.*, 2019b) to then simulate transport behaviour within a given study area.

3.3.1 *Population synthesis*

Figure 3.3 shows the general outline of the eqasim population synthesis pipeline. It is a generic and modular software package allowing the chaining of several algorithms which process the raw data from several open data sources to ultimately produce the necessary input for running a MATSim simulation, namely the transportation demand and supply.

Based on the synthetic population pipeline previously developed by Bösch *et al.* (2016), Hörl (2020) applied the eqasim pipeline to the case of Switzerland. A complete technical documentation of the synthetic population generation pipeline for Switzerland is further described by Tchervenkov *et al.* (2022).

Figure 3.3: Eqasim population synthesis pipeline



Source: Hörl and Balać (2021a)

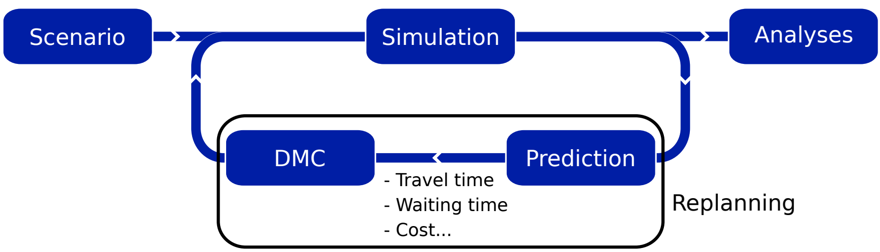
In brief, population synthesis begins by selecting a random share of households present in the Swiss census depending on the desired sample size (e. g., 10% of households for a so-called 10% sample). Next, each sampled individual is matched to an observation from the Swiss household travel survey (HTS) using a statistical matching procedure. In doing so, activity chains from the HTS, that is a list of trip purposes connected by trips with a given transport mode, are attached to census individuals. Locations are then determined for each activity: work municipalities are first drawn from mode-specific origin-destination matrices for which precise locations are then sampled from the Swiss enterprise registry, while secondary locations are assigned using the relaxation–discretization algorithm proposed by Hörl and Axhausen (2021). The generated synthetic population, complete with household- and person-level attributes and detailed activity chains at precise locations connected by trips using different travel modes, is converted to the format expected as an input to the MATSim framework.

Given that the Swiss HTS provides information for parking availability at home and work, at least for some respondents, these could in principle be carried over to the synthesized population during the matching procedure. However, given that a synthesized household's attributes are altered during matching, and that a synthesized person's workplace is later reassigned during location assignment, the household and person characteristics likely no longer correspond to those of the original respondent. Thus, what is missing is a sufficient model for parking availability at both the home and work location, dependent on their characteristics, which can be used to impute these attributes for the entire synthetic population. Also missing is additional information within the MATSim scenario on the locations of publicly accessible parking.

3.3.2 *Discrete mode choice*

In addition to providing a structured pipeline for reproducible population synthesis, the eqasim framework also modifies the elements contained within the MATSim loop. In this refined eqasim loop, shown in Figure 3.4, the scoring and replanning steps have been replaced by a prediction and discrete mode choice step, which are combined into a new replanning step.

FIGURE 3.4: The eqasim loop



As with the conventional MATSim, a random share of agents are still selected after the mobility simulation for replanning. However, unlike the conventional case where the plans are randomly modified before being simulated again, here the procedure is more controlled. First, feasible tours are constructed for each agent's daily plan considering the availability of different mobility tools as well as other constraints (e. g., cars must follow the agent throughout the tour). Then, these tours are routed across the transport network based on the predicted attributes (e. g., travel times, waiting times, costs, etc.) observed in the mobility simulation from the previous iteration. Finally, the mode combination for a given tour is probabilistically selected using a multinomial logit formulation. For Switzerland, the individual utilities for each mode are defined as in Equations (3.4) to (3.7)

$$\begin{aligned} u_{car} = \beta_{ASC,car} \\ &+ \beta_{travelTime,car} \cdot x_{travelTime,car} \\ &+ \beta_{travelTime,car} \cdot \theta_{parkingSearchPenalty} \\ &+ \beta_{travelTime,walk} \cdot \theta_{accessEgressWalkTime} \\ &+ \beta_{cost} \cdot \left(\frac{x_{euclideanDistance}}{\theta_{averageDistance}} \right)^{\lambda} \cdot x_{cost,car} \end{aligned} \tag{3.4}$$

$$\begin{aligned} u_{pt} = \beta_{ASC,pt} \\ &+ \beta_{numberOfTransfers,pt} \cdot x_{numberOfTransfers,pt} \\ &+ \beta_{inVehicleTime,pt} \cdot x_{inVehicleTime,pt} \\ &+ \beta_{transferTime,pt} \cdot x_{accessEgressWalkTime,pt} \\ &+ \beta_{accessEgressTime,pt} \cdot x_{accessEgressTime,pt} \\ &+ \beta_{cost} \cdot \left(\frac{x_{euclideanDistance}}{\theta_{averageDistance}} \right)^{\lambda} \cdot x_{cost,pt} \end{aligned} \tag{3.5}$$

$$\begin{aligned} u_{bicycle} = \beta_{ASC,bicycle} \\ &+ \beta_{travelTime,bicycle} \cdot x_{travelTime,bicycle} \\ &+ \beta_{age,bicycle} \cdot \max\left(0, a_{age} - 18\right) \end{aligned} \tag{3.6}$$

$$\begin{aligned} u_{walk} = \beta_{ASC,walk} \\ &+ \beta_{travelTime,walk} \cdot x_{travelTime,walk} \end{aligned} \tag{3.7}$$

Parameters β and λ are estimated from survey data, whereas attributes x are estimated from previous simulation iterations and θ are calibration constants added to improve model fit.

With regards to parking behaviour, the critical issue with the above discrete mode choice formulation for Switzerland is that both parking search time and access/egress walk are predefined constants, i. e., they are independent of the actual supply and demand of parking, whereas parking costs are excluded from the model altogether. In order to model parking behaviour within the eqasim framework, all these parking-related attributes should be estimated from previous simulation iterations and explicitly appear in the utility function for the car alternative within the discrete choice model.

3.4 CONCLUSION

MATSim is a powerful and modular agent-based transport simulation framework, allowing for the simulation of complex interactions of multiple agents competing in both time and space within the transportation network. Despite this, the most basic implementation of MATSim fails to capture one of the most fundamental aspects of car travel: parking. Attempts have been made to include parking within the MATSim framework, one focusing on the choice of parking locations but excluding parking search, the other concentrating on parking search without differentiating between different types of parking and considering their costs. Thus, both approaches are incomplete.

The MATSim scenario for Switzerland is itself based on the eqasim framework, which integrates discrete choice models into MATSim. However, the current mode choice models use only static values for parking-related attributes and are thus incapable of capturing the influence of parking demand and supply on travel behaviour as a whole. Additionally, the synthetic population used as an input to the simulation is rudimentary in its inclusion of parking availability at home and work, and outright lacking in information on publicly available parking. This thesis will therefore attempt to amend these shortcomings.

4

A FIRST CASE STUDY: HOW MUCH PARKING SPACE CAN CARSHARING SAVE?

Chapter 3 briefly described the main building blocks of the multi-agent transport simulation MATSim, previous attempts to incorporate parking choice and search behaviour within MATSim and their limitations, as well as the MATSim scenario for Switzerland and its limitations with regards to simulating parking behaviour. Before attempting to address these issues, this chapter aims at providing an example of the kind of parking-related questions MATSim can help answer through a case study. It is adapted from the following peer-reviewed conference contribution:

Tchervenkov, C., M. Balać, S. Hörl, H. Becker and K. W. Axhausen (2019) How much parking space can carsharing save?, paper presented at the *98th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2019.

4.1 INTRODUCTION

Carsharing is a service that aims to provide an alternative to car ownership. First implementations resembled a traditional rental service, but with some substantial differences: (a) cars were available for short-term rentals (charged per hour or minute) (b) the fleet was distributed among the unstaffed stations in the service area and (c) users needed to pay a membership fee on a monthly or yearly basis or (d) share in the capital costs of the cars.

Technological advances have allowed for new versions of carsharing, namely one-way station-based and free-floating carsharing. Free-floating services have increased the flexibility of carsharing, which in turn has further lead to an increase in their membership levels (Shaheen and Cohen, 2013; Shaheen *et al.*, 2015). However, it is still a niche product that is rarely able to capture a substantial mode share.

Previous research on carsharing has mostly focused on understanding its impacts on the environment, car ownership, user groups and usage patterns (Martin *et al.*, 2010; Martin and Shaheen, 2011; Becker *et al.*, 2018). Cervero and Tsai (2004), Martin *et al.* (2010) and Martin and Shaheen (2011) have shown that carsharing reduces the vehicle kilometres travelled (VKT) and negative emissions. Shaheen and Cohen (2013) have shown that carsharing has a tendency to promote a car-free lifestyle, thus reducing car ownership, which has been one of the leading arguments for the sustainability of carsharing services. Carsharing arguably also reduces the demand for parking and can even be used as a parking management strategy (Millard-Ball *et al.*, 2006) in both the public and private domain. In the process, it would give back valuable space to people currently occupied by cars.

Most of the studies on user groups of carsharing services show that members are young and well educated males (Becker *et al.*, 2017a; Schmöller *et al.*, 2015). Becker *et al.* (2017a) show that in a free-floating carsharing service in Basel, Switzerland, 70% of users are male and 70% hold a university degree compared to 37% in the control group.

Studies on usage patterns can be split into two groups: those based on available empirical data and those based on transport simulation frameworks. Using empirical data, researchers have shown that members of free-floating carsharing services are prone to have larger trip frequencies and more inter-modal travel behaviour than non-members (Kopp *et al.*, 2015). Becker *et al.* (2017b) also find that free-floating carsharing is frequently used when it saves time compared to other modes. Simulation tools were also used to investigate impacts and usage patterns of carsharing (Martínez *et al.*, 2017; Heilig *et al.*, 2018; Balać *et al.*, 2017a). All studies show that there is an untapped potential of free-floating carsharing in the researched cities. Balać *et al.* (2017a) also show that carsharing has a potential to utilize parking space much more efficiently than privately-owned vehicles, not only on a temporal level but also on a spatial level, by increasing the turnaround of parking spaces across the city, thus reducing the potential search times for parking.

In conclusion, policies favouring the allocation of substantial space to parking take away this valuable space from other users in the process and give it to cars which are used for only small portions of the day. Free-floating carsharing is a service that provides fast point-to-point connections with an increased flexibility over more traditional carsharing services, with the promise of positive impacts on the environment, travel behaviour and potential car ownership. However, the impact of free-floating carsharing services on overall parking demand is not yet fully understood.

Using travel behaviour patterns from Zurich as an example, this chapter explores the potential reductions in parking demand with different levels of free-floating carsharing service and different penetration rates.

4.2 METHODOLOGY

The main objective of this case study is to provide an estimate for the maximum number of parking spaces that can be removed from a city due to the availability of a free-floating carsharing service. To achieve this, different adoption rates, where all adopters give up their private vehicle to become customers of the carsharing service, are examined. For each one, a minimum carsharing fleet size is determined to ensure a desired level of service. Then, given this new vehicle fleet composition, the resulting parking demand is computed.

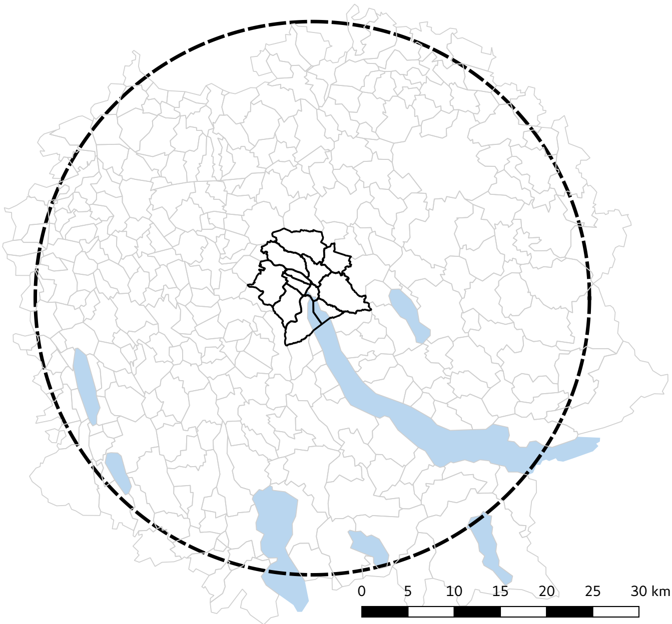
The analysis is conducted using the travel demand patterns and parking supply data within the limits of the city of Zurich. The following sections provide an overview of the steps taken to estimate the potential parking supply reductions given a free-floating carsharing service, meeting the defined service level requirements for different levels of free-floating carsharing adoption.

4.2.1 *Travel demand*

The analysis of parking demand in the presence of free-floating carsharing services inevitably starts with an understanding of where, when and how people travel around a city. This study examines parking demand in the case of Zurich, Switzerland using the simulation output of a 10% sample from the MATSim scenario for Switzerland introduced in Section 3.3. The simulation output events serve as the basic input for further parking demand and supply analysis.

The model, which reproduces current mode shares and trip distributions, consists of the population performing at least one of their activities within the Zurich agglomeration, geographically consisting of an area with a 30km radius centred around the Bellevue tram station situated just outside the Old Town by Lake Zurich. The study area considered is shown in Figure 4.1 with the city of Zurich outlined, which also serves as the free-floating carsharing service area. The procedure for extracting the Zurich model from the Swiss one is further detailed in Hörl (2020, chap. 4.2).

FIGURE 4.1: The city of Zurich as the case study area



This study area contains a 10% sample of a total population of 1,576,860 agents, of which 816,880 drive a car and where 198,400 vehicles park within the Zurich city limits at some point during a typical work day. The scenario only considers passenger transport and therefore excludes freight transportation, service vehicles, business vehicles and tourists. Additionally, only an average weekday is simulated, thereby excluding city residents who own a car, but only use it a few times a month (e. g., weekend excursions). All of these have an additional impact on parking demand within the city.

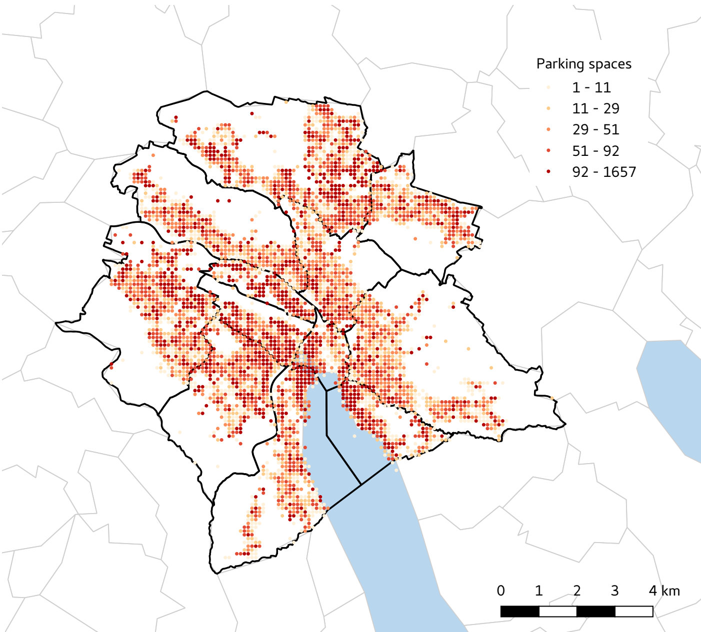
Currently, there is no free-floating carsharing service operating in Zurich. However, there is a nationwide station-based (round-trip) carsharing service, operating around 280 vehicles in Zurich. In addition, Zurich has various one-way and free-floating schemes offering access to a total of around 550 shared electric scooters, 400 electric bikes and 700 conventional bikes. Insights on possible fleet sizes for free-floating carsharing schemes can be derived from the cities of Basel and Geneva, which are about half of

Zurich's population size and operate fleets of 100-150 vehicles[1]. Moreover, earlier research estimates the customer potential of free-floating carsharing at about 11% of the population holding a driver's license (Becker *et al.*, 2017a).

4.2.2 *Parking infrastructure*

The parking infrastructure considered in this study consist of all parking spaces located solely within the limits of the city of Zurich. These include 206,747 private parking spaces, 51,420 public on-street parking spaces and 16,777 public spaces located inside parking garages. These parking spaces are distributed among a total of 47,938 different locations (parking facilities). Figure 4.2 shows the capacity of these parking facilities, aggregated on a hectare level. The black outline marks the 12 districts which make up the city of Zurich.

FIGURE 4.2: Capacity of parking facilities in Zurich aggregated on a hectare level



1 https://www.catch-a-car.ch/

There are fees for using the parking spaces, depending on their types. On-street parking is subdivided into white zones (city centre) and blue zones (other neighbourhoods). The price for parking in a blue zone parking space is 300 Swiss francs (CHF) per year for residents and up to 15 CHF per day for non-residents, while it varies depending on location for white zones. Parking in parking garages is more expensive than on-street parking, usually 1-5 CHF per hour. There are also different time limitations for different parking categories.

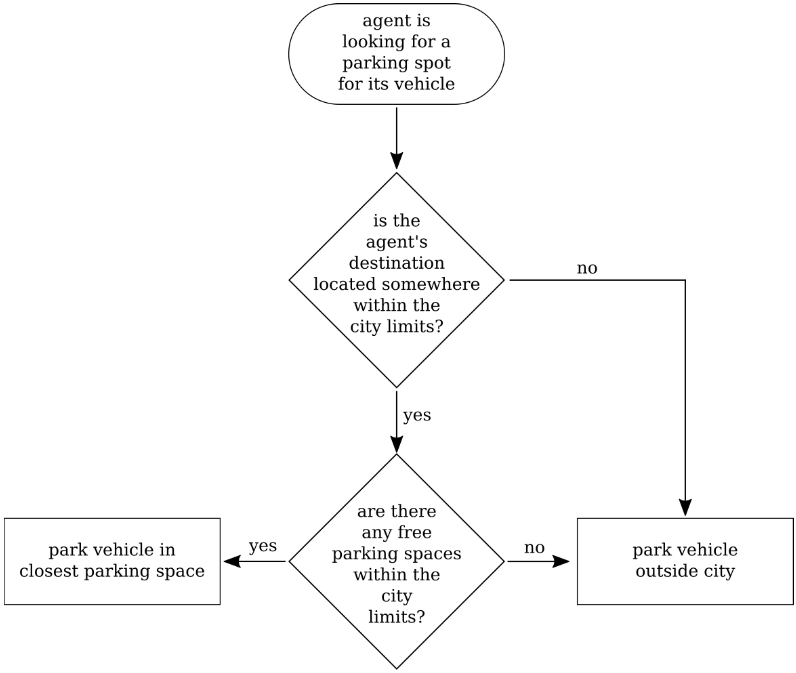
However, these differences are not considered in the scope of this study. This means that agents can simply park at the vacant parking space closest to their destination, irrespective of cost, duration or whether it is private or public. The justification for this is two-fold. First, it allows for a fair comparison, since carsharing vehicles are allowed to park everywhere without any time limit or cost, which is not the case for private vehicles. Second, it allows to push the analysis to the extreme in terms of how much better the parking infrastructure could be used even in the current case. For the simulated agents operating in the study area, a total of 770,510 parking/unparking events occur within the limits of the city of Zurich alone.

4.2.3 *Parking and carsharing simulation*

As highlighted in Section 3.2, the standard MATSim simulation does not take into account the parking infrastructure, meaning that agents park their vehicles directly at the destination facility without considering any parking constraints. Therefore, an additional step is needed in order to obtain the parking locations of vehicles when parking constraints are taken into account. Figure 4.3 shows a flow diagram of the process of how cars are parked, whether they be private or shared, based on the MATSim events associated with the departure from a facility. In the case of unparking a car, an agent is assigned its own vehicle or the nearest available shared vehicle, depending if it drives a private or shared vehicle respectively. As the MATSim simulation contains only 10% of the total population, 10 parking and unparking events are sequentially generated for each agent in the model in order to scale up the parking demand to the 100% case. It should be noted that neither cruising for parking, nor changes in mode choice are considered in this model.

The MATSim equilibrium events are first processed to determine the facilities at which each car-driving agent first uses its vehicle and the

FIGURE 4.3: Vehicle parking algorithm



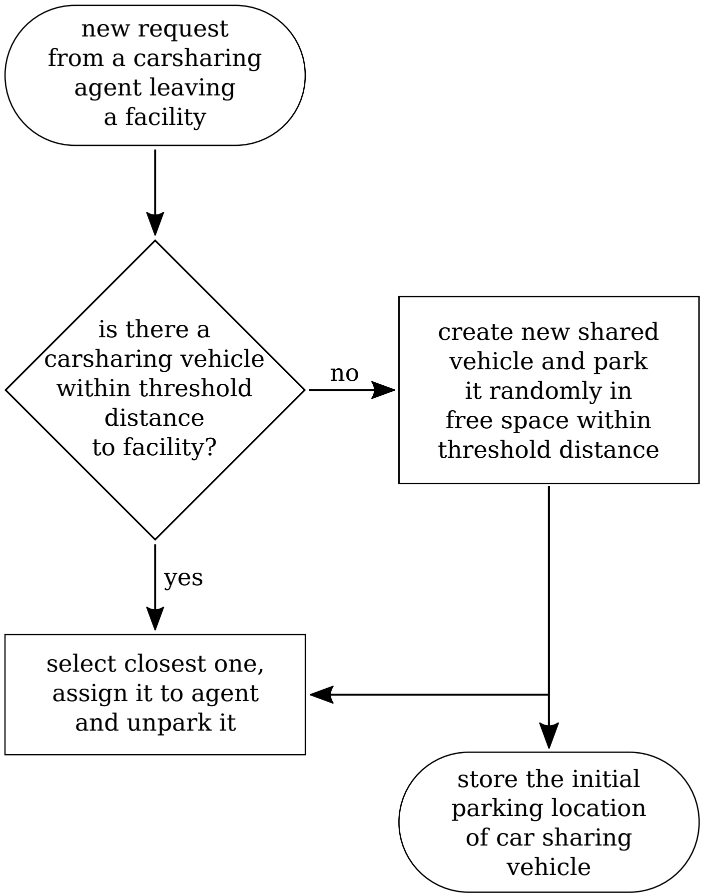
corresponding nearest available parking location to that facility, resulting in a mapping of private vehicles to initial parking locations. While determining the initial parking locations of private vehicles, a list of all agents eligible to become carsharing customers is simultaneously constructed. An agent is considered eligible for carsharing if :

- a car is used by the agent at least once during the day
- all the agent's performed car trips start and end within the carsharing service area

From this set of eligible agents, a random subset corresponding to the fraction of carsharing adopters is selected. Although typically observed adoption rates are of the order of 10%, rates ranging from 10% to 100% of eligible customers are examined in this study. Then, another random sample of these adopters is chosen to give up their private vehicles, which are then removed from the parking infrastructure.

The carsharing service is defined as sufficient to meet the demand if it is always able to provide an available vehicle within a threshold walking distance of the departure facility. Figure 4.4 illustrates the process of generating the minimum required carsharing fleet and initial parking locations based on the requests from carsharing customers in order to provide this desired level of service.

Figure 4.4: Carsharing fleet generation algorithm



Each time a carsharing customer requests a vehicle, the parking infrastructure is queried to check whether a vehicle is available within the threshold walking distance. If such a shared vehicle is available, the agent is assigned the closest one, unparks it, drives it to its destination and parks it at the closest available parking spot. If no such vehicle is available, a new shared vehicle is created and parked at random in one of the available parking spots within the threshold walking distance. Now that there is a vehicle available that meets the minimum service requirements, the agent can unpark it and drive off to its destination. Through this process, a minimum fleet size and initial parking locations of the carsharing vehicles are determined. However, given that these shared vehicles are only first parked when needed and not from the beginning of the day, it is possible that these initial locations would have been occupied earlier and therefore not available. This needs to be corrected for before any estimate on parking demand and supply can be made.

In order to finally estimate the parking demand and potential reductions in parking supply, the MATSim events are processed a final time. The private vehicles are added to the parking infrastructure at their previously determined initial locations, to which the minimum carsharing fleet can now be added. The carsharing vehicles are parked in the free locations closest to the initial guesses provided from the minimum fleet generation process. The MATSim events are then processed and the agents thus move their vehicles from one parking location to another. A log is kept of each parking and unparking event and of all changes in occupancy levels of each parking facility for further analysis.

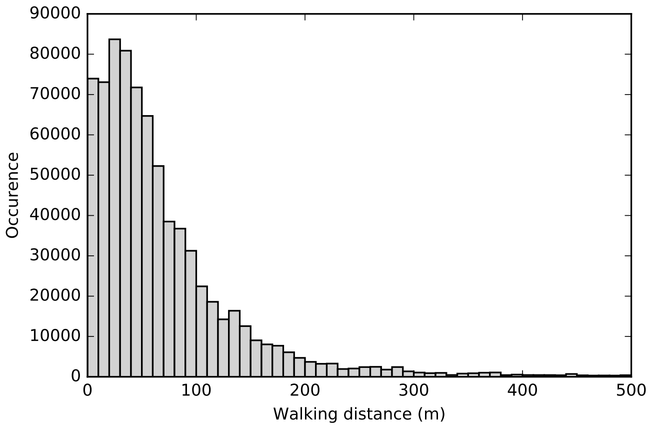
4.3 RESULTS

By examining the current parking demand in Zurich without any carsharing, but where car drivers are nevertheless allowed to park their vehicles at any parking space closest to their destination, baseline values are determined to which further cases including carsharing are then compared.

The distribution of walking distances, taken as the Euclidean distance between parking and facility locations and shown in Figure 4.5, provides a feeling of the baseline level of service enjoyed by these car drivers under these conditions. Indeed, 90% of the total number of walking trips between parking spot and facility locations are less than 153 m.

Next, the time evolution[2] of the overall parking capacity usage in Zurich is plotted in Figure 4.6 to view when most of the vehicles circulating in the city are parked and how much of the overall capacity they use. The solid black line shows the overall parking occupancy levels without carsharing. As one would expect, two different plateau regimes can be observed: one corresponding to the late night/early morning when most vehicles are parked away as the agents are at home, and one corresponding to the midday period when most agents are at work. The latter is higher due to the influx of agents from outside the city limits. Two local minima are observed corresponding to the rush-hour period when most agents are travelling from home to work. It can also be noticed that the usage of the parking capacity never exceeds 50% of the available spaces, suggesting potential reductions in parking supply already today.

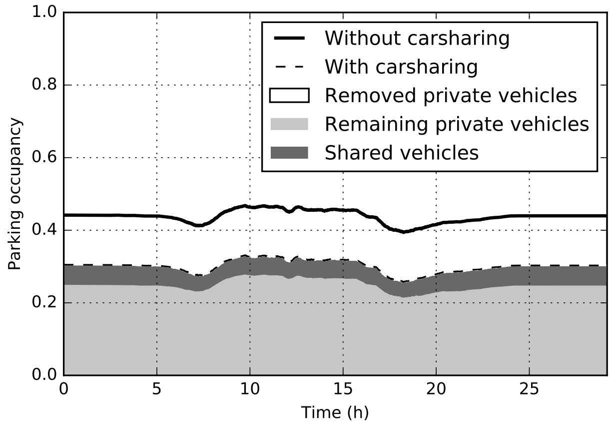
FIGURE 4.5: Distribution of Euclidean walking distances between parking and facility locations for drivers in the base scenario without carsharing



However, to properly compute the number of parking spaces which could potentially be removed, the maximum parking occupancy needs to be analyzed not only temporally, but also spatially. Figure 4.7a shows the maximum registered parking occupancy at a hectare level over the course of a typical day: red indicates high occupancy, whereas blue indicates low occupancy. Based on these maximum hectare occupancy levels, only

2 The simulation considers a 30-hour day, i. e., until 6:00 the following morning.

FIGURE 4.6: Overall parking occupancy over a typical day

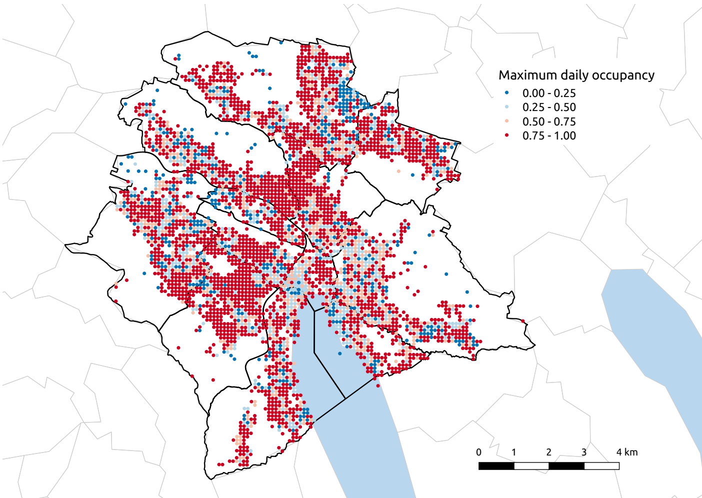


152,623 of the total available 274,944 parking spaces are ever used by car-driving agents when they are allowed to park as close as possible to their destinations without restrictions, representing 55.5% of the total parking spaces in the city. However, since only an average weekday is considered, this does not include car-driving agents who own a car, but only use it a few times a month.

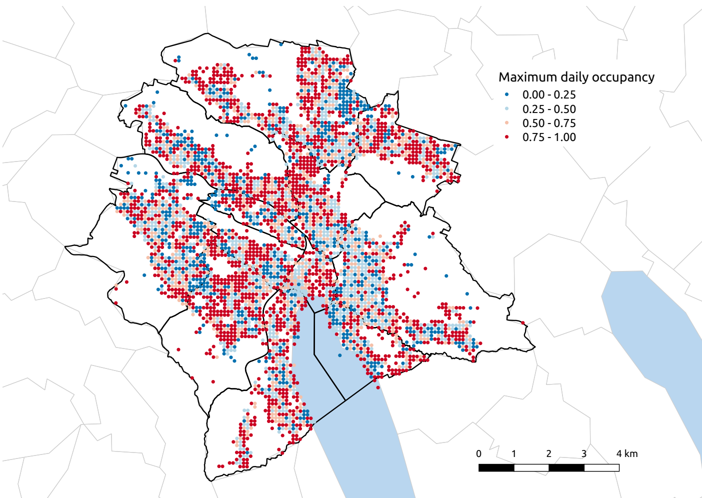
Next, the further reduction of this estimated required parking supply in the presence of free-floating carsharing is explored. Ten different carsharing adoption rates, ranging from 10% to 100% adoption, were tested and in each case, the best-case scenario where the adopting agents gave up their previously-owned private vehicle was used. The agents execute exactly the same plans as in the baseline scenario without carsharing, only the vehicle they use changes. For each adoption rate, the critical fleet necessary to meet the demand was generated such that all carsharing requests are served within a maximum Euclidean distance of 300 m between the parking space and facility. This was repeated each time using 20 different random seeds for selecting the carsharing customers and initial locations of the carsharing vehicles.

The average values over all random seeds for each carsharing adoption rate are analyzed. Table 4.1 shows the number of carsharing users for each adoption rate, the number of carsharing vehicles required to satisfy the

Figure 4.7: Maximum daily hectare-level parking occupancy



(a) Base scenario without carsharing



(b) Best-case carsharing scenario

demand of those users with a reasonable level of service as well as the number of privately-owned vehicles these shared vehicles replace. Only the mean values are reported, as the standard deviations are less than 3% of the mean. The private vehicle replacement rate nearly doubles between the 10% and 100% adoption levels, going from nearly 1.5 up to slightly under 2.7 private vehicles for each shared vehicle for a total required fleet of about 19,370 vehicles.

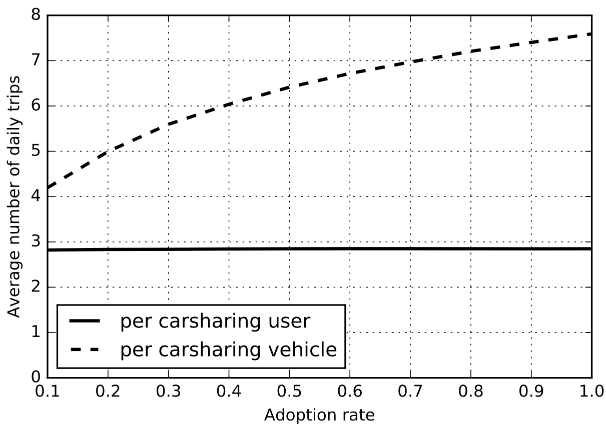
Table 4.1: Vehicle replacement statistics for different rates of carsharing adoption

Adoption rate	Number of users	Fleet size	Vehicles replaced	Replacement rate
0.1	5160	3471	5160	1.49
0.2	10320	5855	10320	1.76
0.3	15480	7848	15480	1.97
0.4	20640	9722	20640	2.12
0.5	25800	11457	25800	2.25
0.6	30950	13134	30950	2.36
0.7	36110	14768	36110	2.45
0.8	41270	16316	41270	2.53
0.9	46430	17858	46430	2.60
1.0	51590	19362	51590	2.66

As there are fewer shared vehicles than there previously were private vehicles for the carsharing users, these vehicles perform more trips. Figure 4.8 shows the number of trips per carsharing user and per carsharing vehicle for each adoption rate. Since each carsharing agent previously owned its own car, the trips per user is synonymous to the trips per previously-owned private vehicle. It is therefore obvious that the carsharing vehicles are more efficient. Carsharing users perform on average just under 3 trips per day, but the carsharing vehicles they use perform over 4 trips per day in the 10% adoption rate case, making them 1.5 times more efficient. In the 100% adoption rate case, each carsharing vehicle performs an average of over 7.5 daily trips, nearly 2.7 times as many trips as their previous privately-owned counterpart.

Carsharing vehicles reduce the total number of vehicles within the city and are more efficient in terms of trips per vehicle. However, their users do need to walk longer to access them, as can clearly be seen in Figure 4.9, which shows the change in the 90th percentile walking distance after adopting the service. In the absence of carsharing, 90% of users walked less than 145 m between facility and parking location. With a 10% adoption rate, this distance increases by 50%. However, this percentage difference decreases with a greater carsharing adoption rate since the number of available vehicles increases, reaching a value of under 25% for a 100% adoption rate.

Figure 4.8: Average number of daily trips per carsharing user and vehicle



Finally, carsharing allows for substantial reductions in the number of parking spaces used by private vehicles with growing adoption rate, as shown in Figure 4.10. Indeed, in the best-case scenario where all eligible users trade in their private cars to become carsharing customers, a total of just under 28,000 parking spaces can be removed from the city, representing over 18% of all previously used parking space. It is clear to see that the efficiency of carsharing vehicles in reducing the required parking supply also increases with adoption, growing from 0.36 removed spaces per shared vehicle for 10% adoption up to over 1.45 for 100% adoption.

By increasing the carsharing threshold Euclidean walking distance to 500 m, an estimated 22% of used parking space could be removed, which is just over 33,500 parking spaces representing nearly 2.4 spaces per shared vehicle. This would require a smaller fleet of just over 14,000 vehicles, each replacing almost 3.7 private cars and performing nearly 10.5 trips.

FIGURE 4.9: Increase in 90^{th} percentile walking distance for carsharing users

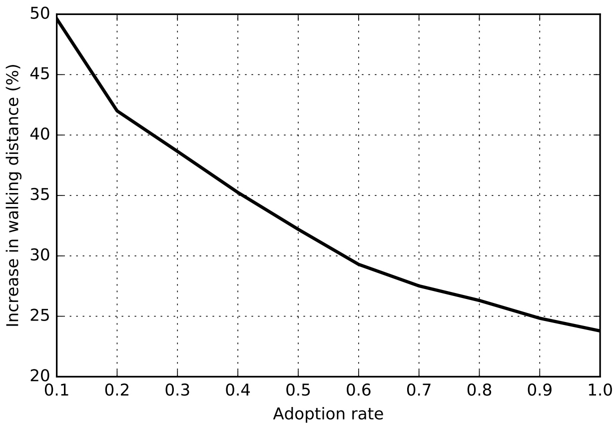
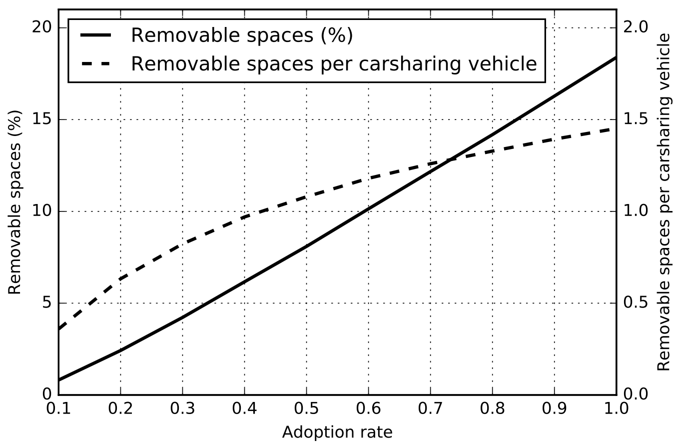
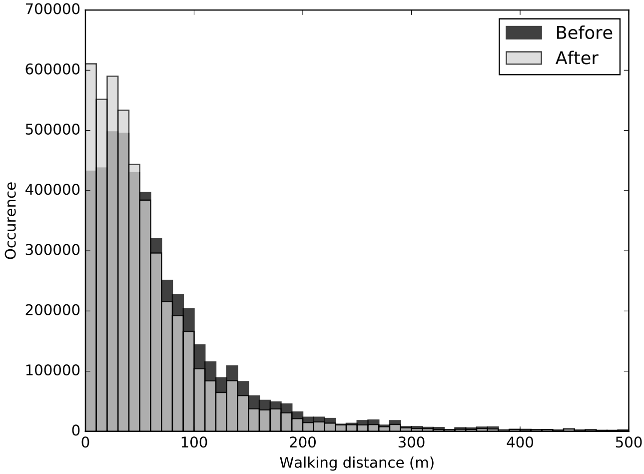


FIGURE 4.10: Parking space reduction due to carsharing

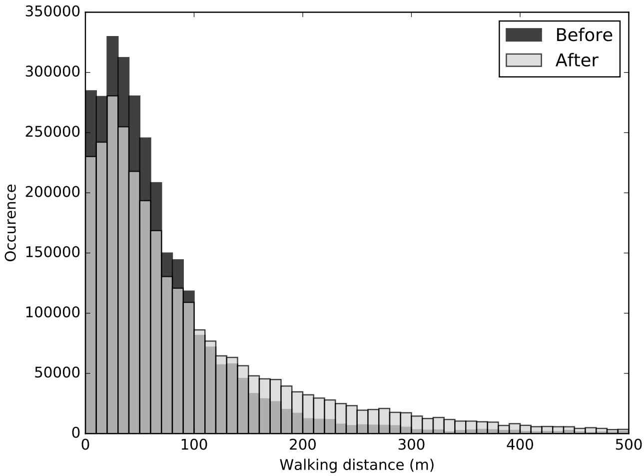


Finally, the best scenario in terms of potential parking supply reduction for the 500 m walking distance threshold with a 100% adoption rate is explored. Figure 4.11 shows the effect on the Euclidean walking distance distribution under these conditions.

FIGURE 4.11: Impact on Euclidean walking distance distributions due to the introduction of carsharing



(a) Trips previously performed using a private car still performed by private car



(b) Trips previously performed using a private car now performed using carsharing

As visualized in Figure 4.11a, walking distances from facilities to parking locations tend to decrease for those agents who previously and still use their private vehicle. This is rather intuitive, since there are fewer vehicles parked in the city and therefore more available space for private vehicle drivers to park closer to their destinations. In contrast, walking distances tend to increase for agents who previously drove a private vehicle and now have switched to carsharing, as can be clearly seen in Figure 4.11b. Due to the constantly changing spatial distribution of the carsharing fleet, carsharing customers will sometimes need to walk further to a parking location to unpark an available vehicle than they initially needed to walk from the location where they parked their previously used vehicle. Indeed, after the introduction of carsharing, 90% of walking trips between parking and facility locations made by those who had not adopted carsharing were less than 136 m as opposed to 160 m before the introduction. On the other hand, this number increased from 145 m to 249 m for those who made the switch.

Figure 4.6 also shows the parking occupancy levels over the course of a typical day after the full adoption of carsharing by all eligible customers in comparison to the baseline scenario. The solid black line shows the overall parking occupancy levels without carsharing, whereas the dashed black line represents the overall parking occupancy levels after 100% of eligible agents for carsharing made the switch. The difference between the solid and dashed line are carsharing customers' previously owned private vehicles that have now been removed from the system, whereas the shaded areas under the dashed line represent the remaining private vehicles and added carsharing vehicles respectively. We can clearly see that the replacement of all eligible trips by carsharing dramatically reduces the overall parking occupancy levels within the city.

Parking occupancy is again further analyzed spatially and the maximum recorded parking occupancy is computed at a hectare level over the course of a typical day. The overall colour in Figure 4.7b shifts toward blue, indicating an overall lowering of the maximum daily parking occupancy levels. Indeed, in this best case where 100% of eligible carsharing agents adopt the service and all car drivers are allowed to park as close as possible to their destinations without restriction, only 119,072 of the previously required 152,623 parking spaces are now necessary to serve the demand, corresponding to a reduction in parking supply of nearly 22%.

4.4 DISCUSSION AND FUTURE WORK

The analyses presented show that the introduction of free-floating carsharing in the city of Zurich can help remove 18% of the parking spaces currently used by private vehicles if all trips that were previously made with a private vehicle are now carsharing trips, while ensuring that a carsharing vehicle is always available within a 300 m Euclidean distance. Furthermore, for the maximum adoption rate and when every adopter gives up its own vehicle, one carsharing vehicle can replace approximately 1.45 parking spaces. By increasing the walking distance to 500 m, the reduction in parking supply increases to 22%, replacing approximately 2.4 parking spaces per carsharing vehicle. At a first glance, these estimates represent a sizeable fraction of the total space in the city, currently only used to store vehicles, that could potentially be converted to other uses. However, there are several limitations to the analysis that now need to be discussed.

First, neither the different types of parking facilities, nor the costs, time limits or any other restrictions associated with parking in a specific location are considered in the analysis, whether it be in the base scenario or any of the scenarios including carsharing. This simplification allows both for a fair comparison of carsharing and private vehicles when both are equally allowed to park on the same spaces without any restrictions as well as an analysis of how much better the parking infrastructure could be potentially utilized. It does however present some limitations. These parking policies, among others, help regulate the number of car users in the city and control congestion. Completely ignoring them could therefore lead to negative impacts such as a higher share of trips performed by car and higher congestion levels, which could completely offset the positive benefits brought on by a reduction in parking demand. It would therefore be important to considering parking types, costs and duration limits in future work.

Next, the estimated potential 44.5% reduction in parking supply in the baseline case without any carsharing should be viewed as an upper limit, since there indeed needs to be some minimal amount of vacant parking available, in part to accommodate the vehicles that are excluded in the MATSim scenario (e. g., delivery and service vehicles, business vehicles, tourists, etc.) but also to make sure no high parking search times or congestion builds up. Nevertheless, it suggests that there do exist some substantial gains that can already be made today in terms of reducing parking supply and free up space for other uses.

In addition, some limitations and improvements can also be mentioned when additionally considering the impact of carsharing on the usage of the parking infrastructure. In order to generate the optimal fleet to meet the demand for carsharing while insuring a minimal level of service, carsharing vehicles are simply added as they are needed until all requests are served. This makes it convenient for modelling purposes, but it creates a lot of idling times that have negative impacts on the system and as a result, would most likely not happen in reality. Thus, the number of required carsharing vehicles is probably overestimated and consequently so is the amount of parking space needed to store them. More efficient techniques for generating a fleet of carsharing vehicles capable of meeting the demand should therefore be investigated. With such large fleet-sizes, the relocation of carsharing vehicles might come into play. This in turn might further optimize the service, removing those vehicles that are not so frequently used and even further reduce the parking needs. However, this would raise maintenance and organizational costs for the service providers.

Finally, the potential destination, departure time or mode choice effects that might be triggered by such a carsharing service are ignored in this model, as the agents' baseline plans are maintained as is and only those eligible for the service switch their modes from car to carsharing. This additional simplification is important to point out as it might affect the impacts on parking. One might suppose that in the presence of a highly performing carsharing service, usage would increase and so would parking demand.

4.5 CONCLUSION

This work provides a best-case estimate for the required parking supply in the city of Zurich following the introduction of a free-floating carsharing service. By only considering passenger traffic and allowing all agents within the simulations to park in any available parking space closest to their destination locations, it can be shown that up to 22% of all currently used parking spaces within the city could be rendered obsolete after the massive adoption of free-floating carsharing. This of course neglects any parking regulations required to insure sufficient space for delivery, service, business or tourist vehicles and does not account for the potentially higher share of trips performed by car and higher congestion levels induced by such a parking policy. Indeed, parking restriction policies could be used to limit inbound private vehicle traffic and thus increase the share of carsharing, further reducing parking demand. Despite these limitations, these estimates highlight the remarkable fraction of the total space in the city, currently only used to store vehicles, that could potentially be converted to others uses. Evidently, there is still room to better utilize existing parking infrastructure and carsharing could help provide further improvements, both today and in the future.

5

DATA SOURCES

In Chapter 3, the MATSim scenario for Switzerland, along with its limitations with respect to parking, was introduced. Chapter 4 went on to present a first case study examining parking demand in the case of a massive uptake in the demand for free-floating carsharing. This chapter introduces and briefly describes the main datasets used in the rest of this thesis containing relevant parking information for Switzerland.

5.1 SWISS MOBILITY AND TRANSPORT MICROCENSUS

The Swiss Mobility and Transport Microcensus (MTMC) is a telephone survey of the travel behaviour of the Swiss population jointly conducted every five years by the Swiss Federal Office for Spatial Development (ARE) and the Swiss Federal Statistical Office (BFS). The most recent dataset was collected in 2015 (BFS and ARE, 2017) and consists of more than 57,000 interviewed individuals, making it the largest national-level survey on travel behaviour. It contains information about the socioeconomic characteristics of households and individuals, their mobility tool ownership, their performed trips on a given reference day, their occasional journeys (day trips and trips with overnight stays) as well as attitudes towards transport policy in Switzerland. Table 5.1 shows the distribution of the main socioeconomic characteristics across the sample.

Additionally, the survey provides relevant information regarding parking at home, work and place of education. In its section relating to household structure and the characteristics of household members, the MTMC asks all respondents the following questions relevant to parking at home:

- How many cars do you have in your household, including company or service cars that are always at your disposal?
- How many parking or garage spaces do you have at your home, either owned or rented?

The MTMC also contains a number of complementary modules which each are asked to only a share of respondents. Module 2, completed by roughly a third of respondents, focuses on active modes and professional situation and asks the following questions relevant to parking at their place of work or education:

- Do you have the possibility to park a car at your place of work / education (company or school parking, excluding public parking lots)?
- How often do you use this parking space?
- How much does this parking space cost in Swiss Francs per month?

This dataset thus provides a basis for analyzing parking availability and usage at home and work as well as which socioeconomic factors influence these.

Additionally, discrete choice models of transportation mode and route choice were estimated (Weis *et al.*, 2017) using both revealed preference (RP) and stated preference (SP) data collected in connection with the MTMC on behalf of the ARE and with the support of the Swiss Federal Offices for Roads (ASTRA), Transport (BAV), Energy (BFE) and Environment (BAFU), the Swiss Federal Railways (SBB) and several cantons. The utility functions used include variables for both parking search times and costs.

5.2 MOBIS STUDY

The Mobility Behaviour in Switzerland (MOBIS) study (Molloy *et al.*, 2022) is a large-scale randomized controlled trial of transport pricing in Switzerland which took place between September 2019 and January 2020, in which individual mobility behaviour was recorded using a smartphone-based tracking app.

Over 90,000 people living in urban agglomerations in both the German- and French-speaking parts of Switzerland, were invited to participate in the study through an invitation letter sent by mail. If interested, they were asked to first complete an introductory online survey designed to collect both socioeconomic information and transport-related opinions from the general population as well as filter the respondents based on certain inclusion criteria. Specifically, participants were required to:

- use a car at least two days a week (including as a passenger or with a taxi/Uber)
- be aged between 18 and 65

- be able to walk without assistance
- own a smartphone
- not drive in a professional capacity – i. e., postal worker or taxi driver.

Around 22,000 people completed this introductory survey and 7,000 qualified for the tracking study. Of those, 5,466 registered to participate in the MOBIS study and were invited to install the smartphone-based GPS tracking app "Catch-my-Day" developed by MOTIONTAG GmbH[1]. The app segments the GPS data into trip stages and activities. The trip stages are labelled with the transport mode by the app and validated by the participants, whereas the trip purposes were imputed using machine learning as described by Gao *et al.* (2021).

The 8-week GPS tracking period consisted of two consecutive 4-week phases, an observation and treatment phase respectively, The participants received weekly reports of their mobility behaviour by e-mail, which during the observation phase only included tracked distance by transport mode, as all study participants were treated equally during this phase. During the intervention phase, the study participants were randomly assigned to one of three treatment groups (pricing group, information group and control group) and thus some of them received supplementary weekly information on estimated external costs by transport mode and by type of externality. In addition, the pricing group were given a monetary incentive based on the external costs (time loss in congestion, health damages and CO_2 emissions) that were estimated for their tracked trips. Over 3,500 participants completed the 8-week study, which was followed by a concluding online survey.

Table 5.1 compares both the MTMC and MOBIS datasets in terms of socioeconomic characteristics. The MOBIS sample is biased towards middle-aged, highly educated and wealthier individuals living in larger households. The employment rate across the MOBIS sample is higher than in the MTMC, and MOBIS participants tend to both live and work in urban centres around Zurich and Lake Geneva. They also have a higher car availability and are less likely to own a national or local public transport travel card. These differences mean that weighting the MOBIS data against the MTMC should be considered in order to ensure representativity. However, this also means that there is a higher likelihood of observing car trips within densely-populated urban cores, which is important for studying parking-related behaviour.

1 https://motion-tag.com/

Table 5.1: Comparison of socioeconomic variables from MTMC and MOBIS datasets

	MTMC	MOBIS
Gender		
Male	49.3 %	48.7 %
Female	50.7 %	51.3 %
Age		
Under 18	12.1 %	–
18 - 29	15.7 %	25.8 %
30 - 39	14.4 %	19.4 %
40 - 49	16.3 %	24.9 %
50 - 59	15.6 %	19.7 %
60 - 69	11.9 %	10.2 %
Over 70	14.0 %	–
Education		
Aged under 15	9.0 %	–
Mandatory	17.4 %	6.9 %
Secondary	44.8 %	48.4 %
Tertiary	28.2 %	44.7 %
Unknown	0.6 %	–
Household monthly income		
Less than 4000 CHF	12.1 %	6.8 %
4001 - 8000 CHF	29.2 %	29.1 %
8001 - 12000 CHF	18.9 %	30.0 %
12001 - 16000 CHF	8.0 %	14.3 %
More than 16000 CHF	5.5 %	9.6 %
Unknown	26.3 %	10.2 %
Household size		
1	18.4 %	11.0 %
2	33.4 %	30.3 %
3	16.5 %	21.7 %
4	20.6 %	27.7 %
5 or more	11.1 %	9.3 %
Household region		
Lake Geneva	19.0 %	32.3 %

Continued on next page

Table 5.1: Comparison of socioeconomics from MTMC and MOBIS datasets

	MTMC	MOBIS
Swiss Plateau	22.2 %	16.7 %
Northwestern Switzerland	13.6 %	14.4 %
Zurich	17.6 %	33.9 %
Eastern Switzerland	13.9 %	0.2 %
Central Switzerland	9.5 %	1.7 %
Ticino	4.2 %	–
Not available	–	0.8 %
Household urbanization		
Urban	26.7 %	58.5 %
Suburban	50.4 %	27.6 %
Rural	22.9 %	13.1 %
Not available	–	0.8 %
Employment status		
Employed	51.7 %	71.4 %
Self-employed	5.2 %	7.7 %
Apprentice	2.6 %	1.9 %
Unemployed	40.5 %	19.0 %
Work region		
Lake Geneva	10.7 %	22.6 %
Swiss Plateau	12.8 %	13.1 %
Northwestern Switzerland	7.5 %	10.3 %
Zurich	12.1 %	24.3 %
Eastern Switzerland	7.7 %	0.9 %
Central Switzerland	6.0 %	2.4 %
Ticino	2.0 %	–
Unemployed	40.6 %	19.0 %
Not available	0.6 %	0.3 %
Work urbanization		
Urban	22.7 %	55.6 %
Suburban	27.3 %	11.6 %
Rural	8.8 %	6.4 %
Unemployed	40.6 %	19.0 %
Not available	0.6 %	0.3 %

Continued on next page

Table 5.1: Comparison of socioeconomics from MTMC and MOBIS datasets

	MTMC	MOBIS
Car availability		
Always available	55.8 %	87.9 %
Available by agreement	13.3 %	10.9 %
Not available	4.5 %	1.2 %
Unknown	26.4 %	–
PT travelcard		
National	9.4 %	7.9 %
Local + Half-fare	10.7 %	9.0 %
Local	14.4 %	8.6 %
Half-fare	22.0 %	39.3 %
None	43.4 %	35.2 %
Unknown	0.1 %	–
Home-Work distance (km)		
mean	13.5	11.8
std	90.9	17.1
10%	0.3	0.0
25%	1.4	3.0
50%	5.1	7.4
75%	14.3	14.8
90%	28.4	25.4

At the end of the original study, participants were invited to participate in the follow-up MOBIS:COVID-19 study (Molloy *et al.*, 2021b), aimed at understanding the impacts of the pandemic on mobility in Switzerland. In November 2020, as the panel size began to decrease, new participants were recruited via the Swiss market research company LINK, after completing an introductory survey similar to the one from the original MOBIS study. To achieve a more representative sample of the Swiss population, no requirements on car usage were imposed on the LINK-recruited participants.

5.3 OPEN DATA ZURICH

Since 2012, the city of Zurich have made public administration datasets without sensitive content available in their open data catalogue[2]. The datasets are delivered in a machine-readable format and are free of charge and without any restrictions on use. Open Data Zurich is responsible for the implementation of Open Government Data in the city of Zurich. In addition to the open data catalogue, the Open Data Zurich website gives users access to instructions on how to use open administrative data, application examples and other information related to open data. With regards to parking, several datasets relating to on-street parking spaces and parking garages within the Zurich city limits are available. These datasets are further introduced in the following sections.

5.3.1 *On-street parking*

The Zurich open data catalogue provides information about on-street parking within the Zurich city limits, contained within two separate datasets.

The first dataset[3] includes the location of all publicly accessible on-street parking spaces in the city of Zurich. These parking spaces are further characterized by type, maximum permitted parking duration and whether they are metered (i. e., whether a fee is required). The data are manually collected and updated every two years, with the most recently published dataset reflecting the status at the end of 2019 and containing information about 48,603 publicly accessible on-street parking spaces. The data do not contain any information about parking occupancy.

The second dataset[4] provides geospatial data on the different tariff zones for parking in metered parking spaces in the city of Zurich.

A further detailed description of on-street parking is provided in Section 6.3.1.

5.3.2 *Parking garages*

This dataset includes all parking garages within the city of Zurich that offer publicly accessible parking spaces to customers and/or visitors. The data

2 https://data.stadt-zuerich.ch/

3 https://data.stadt-zuerich.ch/dataset/geo_oeffentlich_zugaengliche_strassenparkplaetze_ogd

4 https://data.stadt-zuerich.ch/dataset/geo_gebietseinteilung_parkierungsgebuehren

are collected manually every two years and updated in the database, with the most recently published dataset reflecting the status at the end of 2021. The dataset contains the locations of the parking garages and the number of publicly available parking spaces in each garage, including the number of reserved for people with disabilities, for women, for electric vehicles, for small vehicles or for carsharing vehicles. A total of 136 parking garages are included in the dataset.

The data are not updated on a daily basis and as such do not contain any information on parking occupancy, albeit this information may be made available by individual parking garages. Additionally, individual parking spaces within a given garage may also be reallocated on short notice or may be rendered inaccessible, e. g., due to construction work.

However, the Open Data Zurich portal does not include any information regarding the operating times or pricing schemes of the different parking garages. Hence, this information needs to be extracted from additional sources.

The parking guidance system (PLS)[5], in operation in the city of Zurich since 2001, informs car drivers by means of signal boards as to where and how many free garage parking spaces are currently available and how these can be reached in the most direct way. The system is available in the downtown area of Zurich, as well as Zurich-Oerlikon and Zurich-West. The Open Data Zurich provides a link to the PLS webpage for 34 of the 136 listed parking garages, which in turn provide information on opening hours and prices.

Parking garage data not contained in the PLS database were collected from the Parkopedia webpage. A web scraping routine was written based on Selenium Webdriver[6] for this purpose. For each parking garage address not contained in the PLS, the address is queried on the Parkopedia webpage, returning a list of parking garages ordered by distance to the queried address. The names of the first 10 garages in the list are matched against the name provided in the Open Data Zurich data, and the data are stored if the names match at least partially. If no matching name is found, then the data from the nearest parking garage in the list are stored.

5 `https://www.pls-zh.ch/`
6 `https://www.selenium.dev/documentation/webdriver/`

6

PARKING SUPPLY

The availability of parking at a given destination plays an important role in mode choice behaviour (McCahill *et al.*, 2016). Thus, understanding parking supply within a city as well as which factors might influence it is crucial to modelling not only parking-related behaviour, but travel behaviour as a whole. This chapter presents and discusses parking supply in Switzerland, with a particular emphasis on the city of Zurich. Parking availability at home and work, as well as public accessible on-street and garage parking, are explored.

6.1 PARKING AT HOME

The MTMC contains data regarding the household of the interviewed individual, including the number of cars owned and the availability of parking at home. Of the 57,090 households included in the survey, 216 did not provide information on the number of cars or available parking spaces at home.

6.1.1 *Descriptive analysis*

Table 6.1 shows the distribution of the number of cars and parking spaces per household, across Switzerland as well as within the five majors cities of Zurich, Geneva, Basel, Lausanne and Bern. Across Switzerland, 77% of households had at least one parking space available at home in 2015, while 60% of Zurich households did not have parking available to them. This trend of most households not having any parking available is consistent across all the major Swiss cities. The number of available parking spaces is linked to car ownership, as shown in Table 6.2, with the majority of households having the same number of parking spaces as cars (65% across Switzerland and over 70% for all the major Swiss cities). This notable difference in parking availability at home in cities is thus a direct reflection of this latter fact. Indeed, over 50% of Zurich households do not own a car, compared to about 22% at the national level. Nevertheless, there are also households that have more or fewer parking spaces available than the number of cars within the household. In fact, 23% of Swiss households had more parking spaces than cars, whereas 12% had fewer. In the city of Zurich, only 7% of households had more parking spaces than cars, and 15% had fewer. This difference between the city of Zurich and the entire country is also observed in the other major Swiss cities, indicating that parking availability at home is indeed influenced by both spatial as well as socioeconomic variables.

Table 6.1: Share of households by number of cars and parking spots at home, in Switzerland and its 5 major cities

Number of cars at home	0	1	2	3+
City				
Zurich	53.0	39.0	7.0	1.0
Geneva	41.0	48.0	9.0	2.0
Basel	52.0	41.0	6.0	1.0
Lausanne	46.0	42.0	10.0	2.0
Bern	57.0	36.0	6.0	1.0
Switzerland	22.0	49.0	23.0	6.0
Number of parking spots at home	**0**	**1**	**2**	**3+**
City				
Zurich	60.0	32.0	7.0	1.0
Geneva	56.0	37.0	6.0	1.0
Basel	71.0	25.0	4.0	0.0
Lausanne	54.0	36.0	8.0	2.0
Bern	65.0	26.0	7.0	2.0
Switzerland	23.0	39.0	24.0	14.0

Data: MTMC 2015

Table 6.3 shows the mean number of available parking spaces at home for different spatial variables. Parking availability is indeed influenced by geographical region, with the mean number of availability spaces being substantially lower in urban regions of Zurich and Northwestern Switzerland (containing the city of Basel) than anywhere else in the country. The more rural and alpine regions of Eastern Switzerland and Central Switzerland have the highest mean number of available parking spaces at home, whereas the Lake Geneva and Swiss Plateau regions, both containing the highly populated cities of Geneva, Lausanne and Bern as well as the Alps, lie somewhere in between.

TABLE 6.2: Share of households with more or fewer parking spaces than cars, in Switzerland and its 5 major cities

City	Fewer spaces than cars 3+	2	1	0	More spaces than cars 1	2	3+
Zurich	0.0	1.0	14.0	78.0	6.0	1.0	0.0
Geneva	0.0	3.0	20.0	71.0	6.0	0.0	0.0
Basel	0.0	3.0	22.0	70.0	4.0	1.0	0.0
Lausanne	0.0	2.0	15.0	74.0	7.0	1.0	1.0
Bern	0.0	1.0	13.0	77.0	7.0	1.0	1.0
Switzerland	0.0	2.0	10.0	65.0	15.0	4.0	4.0

Data: MTMC 2015

Table 6.3 also shows the correlation between parking availability at home and both population density and public transport service quality. In Switzerland, public transport service quality levels, which depend on public transport type, service frequency and distance to the station, are defined by ARE (2011) as follows:

- Level A: Very good service
- Level B: Good service
- Level C: Average service
- Level D: Poor service
- No level: marginal or no service

According to Table 6.3, households in densely populated areas have less than half the number of available parking spaces at home, on average, than those in low density areas. This can be expected, as densely populated areas typically correspond to urban centres where space is scare and public transport service is of better quality, making it a viable alternative to using a car. Further supporting this latter statement, the mean number of parking spaces available at home increases by nearly fourfold as public transport quality decreases.

TABLE 6.3: Mean number of available parking spaces at home across different spatial variables

	Mean number of available parking spaces at home
Region	
Zurich	1.2
Northwestern Switzerland	1.4
Ticino	1.4
Lake Geneva	1.5
Swiss Plateau	1.5
Central Switzerland	1.6
Eastern Switzerland	1.7
Population density	
High	0.8
Intermediate	1.6
Low	2.0
Public transport quality	
Class A	0.6
Class B	1.0
Class C	1.5
Class D	1.8
None	2.3
Overall	1.5

Data: MTMC 2015

Average parking space availability at home varies not only with respect to geography, but also with the socioeconomic characteristics of the household, as shown in Table 6.4. The mean number of available parking spaces at home correlates with household monthly income, with lower-income households having roughly 3 times fewer parking spaces available than higher-income households, on average. The household structure also influences the availability of parking at home, as the mean number of available parking spaces increases with the increasing size of the household. The presence of children also correlates with an increase in the mean number of parking spaces available at home.

TABLE 6.4: Mean number of available parking spaces at home across different household-level socioeconomic variables

	Mean number of available parking spaces at home
Household monthly income	
Less than 2000 CHF	0.7
2000 to 4000 CHF	0.9
4001 to 6000 CHF	1.2
6001 to 8000 CHF	1.4
8001 to 10000 CHF	1.7
10001 to 12000 CHF	1.8
12001 to 14000 CHF	1.9
14001 to 16000 CHF	1.9
More than 16000 CHF	2.2
Unknown	1.6
Household size	
1	0.9
2	1.6
3	1.8
4	2.0
5 or more	2.3
Household type	
Single-person household	0.9
Single-parent with children	1.3
Non-family	1.5
Couples without children	1.7
Couples with children	2.0
Unknown	1.4
Overall	1.5

Data: MTMC 2015

6.1.2 *Availability model*

The availability of parking at home plays an important role in travel behaviour. A driver who does not have parking available at home will be required to search for parking around their home location, whereas one who does will be able to directly drive and park in their dedicated space. Therefore, an adequate model of parking availability at home is a crucial component when constructing an agent-based transport simulation considering parking behaviour.

Parking availability at work can be modelled using a binary logistic regression formulation. Let Y denote a random variable representing the availability of parking at work. The probability of parking being available at work can be expressed using the logit formulation as

$$P(Y = 1 | \mathbf{X}; \beta) = \frac{\exp(\mathbf{X}\beta)}{1 + \exp(\mathbf{X}\beta)} \tag{6.1}$$

with $\mathbf{X}$ the independent explanatory variables and β the corresponding coefficients. The following spatial and household-level variables, previously described in Section 6.1, are used for the regression analysis:

- Population density at home (discrete)
- Public transport service quality at home (discrete; recoded)
- Household monthly income (discrete; recoded)
- Car availability in household (dummy)
- Household size (discrete)
- Household region (dummy)

Observations with missing values were removed. Additionally, the values for public transport service quality and household monthly income were recoded as shown in Table 6.5. As expected, some of the variables are correlated. For example, population density is correlated with public transport service quality, as shown in Table 6.6: higher population densities are associated with a higher share of households with higher public transport service quality and lower densities with higher shares of lower public transport service quality. In order to account for these correlations, these variables are interacting within the estimated model. A similar correlation exists between household size and the number of cars within the household, with larger households possessing more cars on average, as shown in Table 6.7. In this case, car availability interacted with household size is used as a proxy for other household-level characteristics. The descriptive statistics of the independent variables are summarized in Table 6.8.

TABLE 6.5: Value recoding for logistic regression of parking availability

Variable	Original value	Recoded value
Household monthly income	Less than 2000 CHF	1000
	2000 to 4000 CHF	3000
	4001 to 6000 CHF	5000
	6001 to 8000 CHF	7000
	8001 to 10000 CHF	9000
	10001 to 12000 CHF	11000
	12001 to 14000 CHF	13000
	14001 to 16000 CHF	15000
	More than 16000 CHF	17000
Public transport quality	Class A	4
	Class B	3
	Class C	2
	Class D	1
	None	0

Data: MTMC 2015

TABLE 6.6: Link between population density and public transport service quality at home

Population density	Public transport service quality [%]				
	Class A	Class B	Class C	Class D	None
High	45.0	36.0	13.0	5.0	1.0
Intermediate	8.0	20.0	31.0	29.0	12.0
Low	1.0	2.0	12.0	42.0	43.0

Data: MTMC 2015

TABLE 6.7: Link between household size and number of cars per household

Household size	Mean number of cars per household
1	0.6
2	1.3
3	1.5
4	1.7
5 or more	1.8

Data: MTMC 2015

TABLE 6.8: Parking availability at home, descriptive statistics

	mean	std	10%	25%	50%	75%	90%
Car available [%]	85.8	–	–	–	–	–	–
Household size	2.6	1.3	1.0	2.0	2.0	4.0	4.0
Household income [kCHF/month]	8.2	4.2	3.0	5.0	7.0	11.0	15.0
PT quality at home	1.9	1.3	0.0	1.0	2.0	3.0	4.0
Population density at home [%]							
High	22.0	–	–	–	–	–	–
Intermediate	57.0	–	–	–	–	–	–
Low	21.0	–	–	–	–	–	–
Household region [%]							
Zurich	11.5	–	–	–	–	–	–
Northwestern Switzerland	13.4	–	–	–	–	–	–
Ticino	4.6	–	–	–	–	–	–
Lake Geneva	20.6	–	–	–	–	–	–
Swiss Plateau	22.8	–	–	–	–	–	–
Central Switzerland	11.6	–	–	–	–	–	–
Eastern Switzerland	15.5	–	–	–	–	–	–
Parking available [%]	83.6	–	–	–	–	–	–

Data: MTMC 2015

Table 6.9 shows the results of the logistic regression model. Most coefficients are significant and all have the expected signs. The probability of having parking available at home increases with car availability, household size and household monthly income. On the other hand, the probability decreases with increasing quality of public transport services combined with increasing population density, indicating that it is less likely for a household to have parking within an urban environment with good public transit connections.

TABLE 6.9: Parking availability at home, logistic regression model results

Variable	Coef.	SE
Constant	-0.930^{***}	0.083
Car available	3.662^{***}	0.083
Household size	0.131^{***}	0.031
Household size × Car available	-0.167^{***}	0.035
Household monthly income / 1000	0.076^{***}	0.005
PT quality × High density	-0.573^{***}	0.016
PT quality × Intermediate density	-0.298^{***}	0.019
PT quality × Low density	-0.240^{***}	0.048
Household region (reference = Swiss Plateau)		
Zurich	0.384^{***}	0.067
Northwestern Switzerland	0.213^{***}	0.062
Ticino	0.056	0.093
Lake Geneva	0.138^{*}	0.056
Central Switzerland	0.784^{***}	0.075
Eastern Switzerland	0.435^{***}	0.064
N:		40430
ρ^2:		0.406
$\mathcal{LL}_{null}$		-18067
$\mathcal{LL}_{final}$		-10732

Standard errors: $^{***}: p < 0.005$, $^{**}: p < 0.01$, $^{*}: p < 0.05$

Marginal probability effects (MPE) are computed as the weighted average of the difference in the predicted probability for each observation due to a marginal change in the independent variable and are shown in Table 6.10. Car availability, population density and public transit quality have the largest effects. Having a car available within the household increases the probability of having parking at home by 55.1%, while high population density and public transport quality (class A) result in a decrease of 7.1% and 14.2%, respectively, when comparing to the reference. A 10% increase in household monthly income only contributes an additional 0.4%, and a unit increase in household size an additional 0.3%. The household region contributes between 0.5% and 6.5%, all else being equal, compared to living within the Swiss Plateau.

Table 6.10: Parking availability at home, marginal probability effects

Variable	MPE [%]
Car available	55.1
Household size, 1 unit increase	0.3
Household monthly income, 10% increase	0.4
Population density at home	
Intermediate	-1.2
High	-7.1
PT quality at home	
Class D	-3.3
Class C	-6.7
Class B	-10.3
Class A	-14.2
Household region (reference = Swiss Plateau)	
Zurich	3.3
Northwestern Switzerland	1.9
Ticino	0.5
Lake Geneva	1.2
Central Switzerland	6.5
Eastern Switzerland	3.7

A more sophisticated model would estimate the number of available parking spaces at home given both spatial and socioeconomic variables, either by means of a Poisson or negative binomial regression model. However, given the fact that MATSim is currently unable to simulate household-level decisions in terms of car use, such a model would not be of much use within the context of constructing an agent-based transport simulation considering parking. Therefore, a parking availability model is sufficient for this purpose.

6.2 PARKING AT WORK

In addition to household parking availability, the MTMC provides data on non-public parking availability at work. The following section describes which factors influence this availability.

6.2.1 *Descriptive analysis*

As shown in Table 6.11, 75% of Swiss employees have access to a parking space at their place of work: 54% to a free and 21% to a paid parking space. The share of employees without parking available at work is higher in all 5 major cities than the national average, with Basel topping the list at 53% of employees without parking made available by their employer. Within the city of Zurich, 60% of employees have parking available, which in about half the cases was free to use. Thus, as with parking at home, parking availability at work also depends on the location.

TABLE 6.11: Share of employees with parking available at work, in Switzerland and its 5 major cities

	Parking available at work [%]		
City	Yes, free	Yes, paid	No
Basel	25.0	22.0	53.0
Geneva	30.0	25.0	45.0
Zurich	31.0	29.0	40.0
Bern	30.0	40.0	30.0
Lausanne	40.0	32.0	28.0
Switzerland	54.0	21.0	25.0

Data: MTMC 2015

As with residential parking availability, the availability of non-public parking at work is influenced by the level of urbanization of the workplace municipality, as shown in Table 6.12. Only 62% of Swiss employees working in densely populated urban areas have access to non-public parking, while the share increases with decreasing population density to 87% in low-density municipalities. The share of free parking also decreases with increased urbanization, going from 82% in most rural municipalities to 33% in urban centres. Public transport service quality additionally affects the availability of parking at work, as fewer people have parking available at their work location with increasing public transport quality. The share of employees with parking available decreases from 91% for the lowest public transport quality level to 57% for Class A. The share of free parking similarly decreases with increasing public transport quality. The share of employees with parking available to them also depends on the region, with employees working in Zurich and Ticino having the lowest and those in Eastern and Central Switzerland the highest availability of workplace parking.

TABLE 6.12: Share of employees with parking available at work, by spatial characteristics of the workplace

	Parking available at work [%]		
	Yes, free	Yes, paid	No
Region			
Lake Geneva	48.0	23.0	29.0
Swiss Plateau	57.0	21.0	22.0
Northwestern Switzerland	54.0	22.0	24.0
Zurich	45.0	25.0	30.0
Eastern Switzerland	67.0	14.0	19.0
Central Switzerland	61.0	18.0	21.0
Ticino	43.0	19.0	38.0
Population density			
High	33.0	29.0	38.0
Intermediate	62.0	19.0	19.0
Low	82.0	5.0	13.0
Public transport quality			
Class A	29.0	28.0	43.0
Class B	48.0	29.0	23.0
Class C	65.0	20.0	15.0
Class D	78.0	9.0	13.0
None	87.0	4.0	9.0
Switzerland	54.0	21.0	25.0

Data: MTMC 2015

One would expect the availability of non-public parking at work to also depend on the spatial characteristics of the home location, as employees living in lower density areas typically poorly connected by transit (i. e., making them dependent on a car) would see to it that their employer facilitate their commute to work by providing parking. The shares of parking availability at work by home spatial characteristics are shown in Table 6.13. Indeed, the observed trends are similar to workplace spatial variables. Access to non-public parking at work increases with decreasing population density in the home municipality, as does the share of free parking. These shares are also affected by public transport service quality at home, with fewer employees have parking available at their work location with increasing public transport quality. The trends with respect to home region are nearly identical to those with respect to the workplace region, likely highlighting the fact that most employees live and work within the same region.

TABLE 6.13: Share of employees with parking available at work, by spatial characteristics of the home location

	Parking available at work [%]		
	Yes, free	Yes, paid	No
Region			
Lake Geneva	49.0	22.0	29.0
Swiss Plateau	57.0	21.0	22.0
Northwestern Switzerland	54.0	22.0	24.0
Zurich	45.0	25.0	30.0
Eastern Switzerland	65.0	16.0	19.0
Central Switzerland	61.0	18.0	21.0
Ticino	44.0	17.0	39.0
Population density			
High	36.0	26.0	38.0
Intermediate	58.0	20.0	22.0
Low	65.0	16.0	19.0
Public transport quality			
Class A	37.0	24.0	39.0
Class B	45.0	25.0	30.0
Class C	55.0	20.0	25.0
Class D	61.0	19.0	20.0
None	68.0	17.0	15.0
Switzerland	54.0	21.0	25.0

Data: MTMC 2015

In addition to spatial variables, an employee's employment characteristics is also expected to influence their access to parking at work. Table 6.14 summarizes how parking availability at work is affected by workload.

TABLE 6.14: Share of employees with parking available at work, by employment characteristics

	Parking available at work [%]		
	Yes, free	Yes, paid	No
Workload			
Full time	57.0	22.0	21.0
Part time	49.0	19.0	32.0
Work sector			
Primary or secondary	80.0	6.0	14.0
Tertiary	45.0	24.0	31.0
Employment status			
Own company	62.0	23.0	15.0
Self-employed	59.0	17.0	24.0
Family company	66.0	10.0	24.0
Other private or public company	53.0	21.0	26.0
Apprentice	56.0	15.0	29.0
Managerial position			
Yes	57.0	23.0	20.0
No	51.0	21.0	28.0
Household monthly income			
Less than 6000 CHF	55.0	16.0	29.0
6001 to 12000 CHF	55.0	21.0	24.0
More than 12000 CHF	50.0	27.0	23.0
Switzerland	54.0	21.0	25.0

Data: MTMC 2015

Across Switzerland, 79% of full-time employees have access to parking (57% for free) as opposed to 68% of part-time employees (49% for free). Particular professional sectors have a higher tendency of providing parking to their employees. People employed in the primary and secondary sectors a more likely to have parking available (more often for free) than those employed in the tertiary sector. The professional position also plays a role in non-public parking availability at work. When considering employees in private or public companies (i. e., excluding the self-employed and employees in family businesses), employees with managerial positions are more likely to have parking available. Indeed, 80% of employees with a managerial role have parking available at work (57% for free), as opposed to 72% of those without a managerial role (51%). Although the MTMC does not include personal income, the share of employees with available non-public parking at work does negatively correlate with household monthly income. In other words, the higher the household monthly income, the higher the share of employees with parking available at work.

6.2.2 *Availability model*

As with parking at home, the availability of parking at work also plays an important role in travel behaviour. Drivers with parking readily available at work are more likely to commute to work by car than those who are required to search for parking. Thus, modelling this availability is crucial to constructing an agent-based transport simulation considering parking behaviour. Since only about a third of MTMC respondents provided information on parking at work, these models can be used to impute parking space availability for the rest of the sample. Parking availability at work is also modelled using a binary logistic regression formulation (see Equation (6.1)) using the following variables:

– Gender (dummy)

– Workload (full or part time) (dummy)

– Household monthly income (discrete; recoded)

– Public transport service quality at home and work (discrete; recoded)

– Population density at work (discrete)

– Workplace in Ticino (dummy)

Observations with missing values were removed and the values for public transport service quality and household monthly income were recoded as in Table 6.5. Table 6.15 summarizes the descriptive statistics of the independent variables. Population density is interacted with public transport service quality at work to account for correlation between these variables. Other variables describing the workplace, such as the work sector, employment status and work position, were excluded from the final model, because they are missing for a sizeable share of the MTMC sample and would hence first need to be imputed when applying these models during population synthesis. Therefore, household monthly income and workload are instead used as proxies.

Table 6.15: Parking availability at work, descriptive statistics

	mean	std	10%	25%	50%	75%	90%
Gender = Male [%]	55.2	–	–	–	–	–	–
Workload = Part time [%]	37.4	–	–	–	–	–	–
Household income [kCHF/month]	9.4	4.1	5.0	7.0	9.0	13.0	17.0
Public transport quality							
at home	1.9	1.3	0.0	1.0	2.0	3.0	4.0
at work	2.5	1.4	0.0	1.0	3.0	4.0	4.0
Population density at work [%]							
High	33.9	–	–	–	–	–	–
Intermediate	51.9	–	–	–	–	–	–
Low	14.2	–	–	–	–	–	–
Workplace in Ticino [%]	3.8	–	–	–	–	–	–
Parking available [%]	76.3	–	–	–	–	–	–

Table 6.16 shows the results of the logistic regression model, where all coefficients are significant and present the expected signs. The probability of having parking available at work increases with income and being a male. On the other hand, the probability decreases with increasing quality of public transport services at work and home combined with increasing population density at work, indicating that employers are less likely to provide parking in urban centres with good public transit connections, as well as to those working part time.

The computed marginal probability effects are shown in Table 6.17. The characteristics of both the home and work locations have a large effect on the probability of having parking at work. High population density and public transport quality (class A) at the workplace result in a decrease of 7.8% and 28.1%, respectively, when comparing to the reference, while high public transport quality at home corresponds to a decrease of 8.6%. A 10% income increase and being a male contribute a 0.6% and 7.1% increase and working part time a 6.3% decrease in probability. Working in Ticino corresponds to a 17.9% decrease in probability, all else being equal.

TABLE 6.16: Parking availability at work, logistic regression model results

Variable	Coef.	SE
Constant	2.28^{***}	0.12
Male	0.44^{***}	0.07
Part-time job	-0.39^{***}	0.07
Household monthly income / 1000	0.04^{***}	0.01
PT quality (work) × High density (work)	-0.51^{***}	0.03
PT quality (work) × Intermediate density (work)	-0.37^{***}	0.03
PT quality (work) × Low density (work)	-0.35^{***}	0.08
PT quality (home) × PT quality (work)	-0.05^{***}	0.01
Workplace in Ticino	-0.98^{***}	0.14
N:	7618	
ρ^2:	0.126	
$\mathcal{LL}_{null}$	-4168.7	
$\mathcal{LL}_{final}$	-3643.8	

Standard errors: *** : $p < 0.005$

TABLE 6.17: Parking availability at work, marginal probability effects

Variable	MPE [%]
Male	7.1
Part-time job	-6.3
Household monthly income, 10% increase	0.6
Population density at work	
Intermediate	-1.0
High	-7.8
PT quality at work	
Class D	-3.9
Class C	-9.8
Class B	-18.0
Class A	-28.1
PT quality at home	
Class D	-2.0
Class C	-4.1
Class B	-6.3
Class A	-8.6
Workplace in Ticino	-17.9

6.3 PUBLIC PARKING

In addition to non-public parking at home and work, drivers can park in public parking spaces. These can be split into two main categories: on-street parking and publicly accessible parking garages.

6.3.1 *On-street parking*

As introduced in Section 5.3.1, Open Data Zurich provides data for on-street parking within the city of Zurich, where there are 48,603 publicly accessible on-street parking spaces divided into 7 types, as detailed in Table 6.18. Since the majority of on-street parking within the city of Zurich is of either the blue or white zone type (67.8% and 30.3% respectively), this section will focus on describing these two in more detail.

TABLE 6.18: Number of on-street parking spaces in Zurich by type

Parking type	Number of spaces	Share (%)
Blue zone	32956	67.8
White zone	14710	30.3
Disabled	434	0.9
Taxi only	307	0.6
Coaches	105	0.2
Taxi / cargo	69	0.1
Electric vehicles	22	0.1
Total	48603	100.0

Data: Open Data Zurich 2019

6.3.1.1 *Blue zone parking*

Blue zone parking spaces are free of charge. However, vehicles can only be parked in blue zone parking spaces for a limited duration and must display their arrival time on a parking disc to be left visible inside the vehicle. Alternatively, it is also possible to purchase a daily or yearly parking card allowing to park within blue zones for an unlimited period of time. For the city of Zurich, these cost 15 CHF and 300 CHF, respectively.

There are a total of 32,956 blue zone parking spaces within the city of Zurich, of which the absolute number and density per hectare for each city district are shown in Table 6.19, while the densities per hectare for each city quarter are mapped in Figure 6.1a. Both the absolute number and density of blue zone parking spaces are low within district 1, corresponding to the historic city centre, while they are at their highest in the more central quarters of districts 2 through 8. The blue zone parking densities further decrease in the peripheral districts.

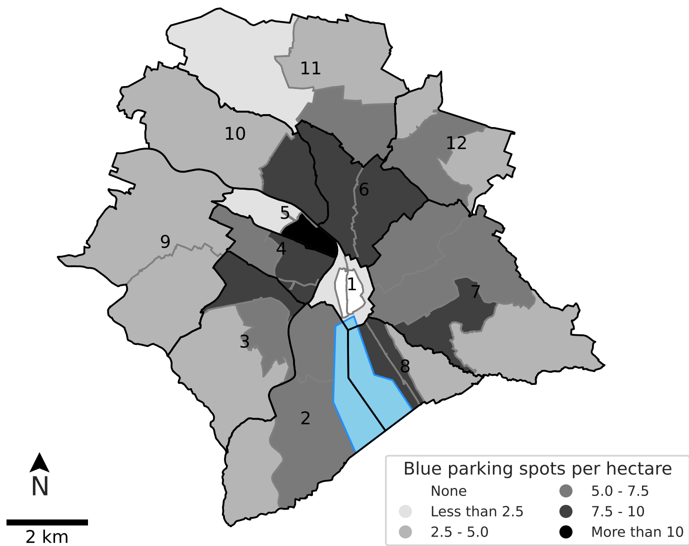
TABLE 6.19: Number and density of on-street parking spaces by Zurich city district

District	Number of spaces			Density [per hectare]		
	Blue	White	Both	Blue	White	Both
1	82	1339	1421	0.53	8.64	9.17
2	3655	1853	5508	5.41	2.74	8.15
3	3641	1450	5091	6.25	2.49	8.74
4	2081	913	2994	7.26	3.19	10.45
5	988	730	1718	5.27	3.90	9.17
6	3423	528	3951	8.52	1.31	9.83
7	4393	2021	6414	5.13	2.36	7.49
8	1718	1358	3076	5.96	4.71	10.67
9	3228	1732	4960	3.85	2.07	5.92
10	3154	922	4076	5.11	1.49	6.61
11	4407	1315	5722	3.72	1.11	4.83
12	2186	549	2735	5.19	1.30	6.49

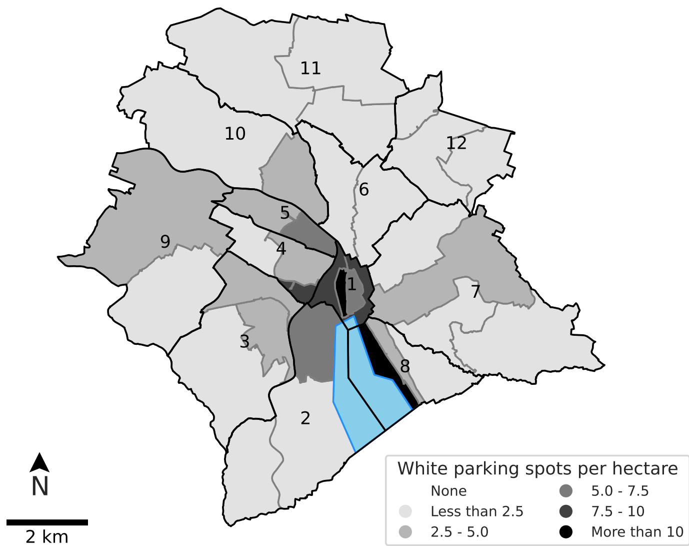
Data: Open Data Zurich 2019

Restricted access to blue zone parking is in effect from Monday to Saturday between 8:00 and 19:00 (see Table 6.20 for a detailed breakdown). During this time window, vehicles arriving between 8:00 and 11:30 and between 13:30 and 18:00 may be parked in the blue zone for one hour, while outside these time windows, parking is unlimited. This means, e. g., that vehicles arriving between 11:30 and 13:30 can remain parked until 14:30. On Sundays and public holidays, parking is restricted only if indicated; otherwise, there are no time restrictions.

FIGURE 6.1: Number of on-street parking spaces per hectare by Zurich city quarter



(a) Blue zone parking



(b) White zone parking

TABLE 6.20: Maximum parking duration in blue zones in Zurich

Day	Arrival time	Maximum duration
Monday – Saturday	8:00 – 11:30	1 hour
	13:30 – 18:00	1 hour
	Otherwise	No limit
Sunday and public holidays	All day	No limit

6.3.1.2 *White zone parking*

White zone parking spaces consist of metered parking which often have specific time restrictions indicated at the meter. There are a total of 14,710 white zone parking spaces within the city of Zurich. The absolute number of white zone parking spaces and parking density per hectare for each city district are shown in Table 6.19, while the parking density per hectare for each city quarter are plotted in Figure 6.1b. Contrary to blue zone parking, both the absolute number and density of white zone parking spaces are at their highest within district 1 and decrease when moving towards the peripheral districts.

The time restriction for each white zone parking space, which vary between 15 minutes and 200 hours, is provided in the Open Data Zurich portal and shown in Table 6.21. The most common parking duration limit is 2 hours at 34%, followed by 4 hours at 16%, 6 hours at 10% and 15 hours at 10%. Over 50% of white zone parking spaces are limited in duration to below 4 hours, while 14% of them do not have a provided parking duration limit.

The city's regulations on parking and parking meter control fees (Stadt Zürich, 2016) define three high-tariff metered parking areas in the city of Zurich, as shown in Figure 6.2: the inner city, the centre of Oerlikon and a part of Zurich West. The base parking meter control fee is 0.50 CHF per 20 minutes within these areas. For parking lasting more than 30 minutes, an additional parking fee of 0.50 CHF for each 10 minutes within the first two hours, and of 0.50 CHF per hour thereafter, is charged. A special regulation also exists for metered parking at the zoo. On Sundays and public holidays, the fees and parking duration limits around the zoo are set as in Table 6.22.

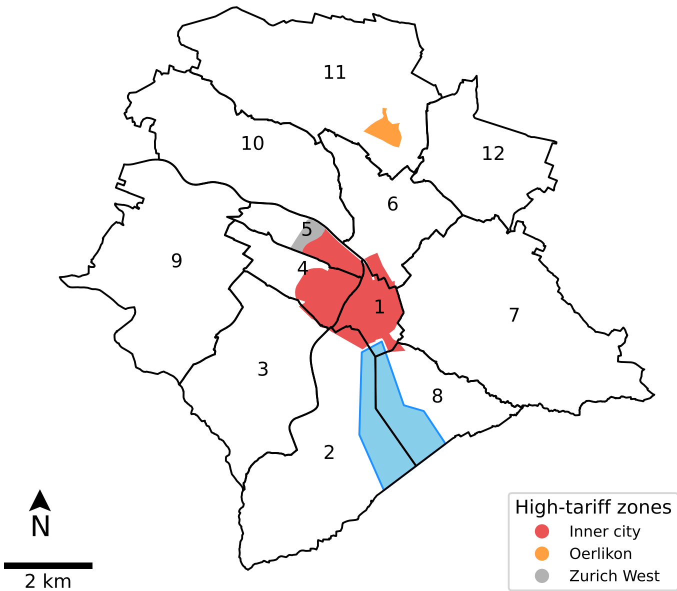
In all other areas of the city of Zurich, and at the zoo outside the special regulation days, a base parking meter control fee of 0.50 CHF per hour is charged.

TABLE 6.21: Share of white zone parking spaces by maximum allowed parking duration in Zurich

Maximum allowed parking duration [h]	Share [%]	Maximum allowed parking duration [h]	Share [%]
1/4	0.3	6	9.9
1/2	3.2	8	0.1
3/4	0.2	12	1.0
1	7.1	15	10.1
2	34.1	24	0.3
3	2.4	48	1.6
4	16.0	200	0.1
5	0.1	Not available	13.5

Data: Open Data Zurich 2019

FIGURE 6.2: High-tariff metered parking areas in the city of Zurich



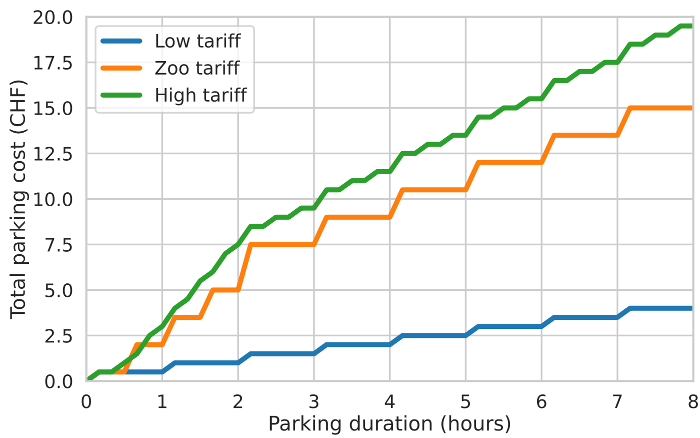
Data: Open Data Zurich 2019

TABLE 6.22: Maximum parking duration and fees in white zones around Zurich Zoo

Parking duration [hours]	Parking meter control fee [CHF]	Additional parking fee [CHF]	Total fee [CHF]
0.5	0.50	—	0.50
1	1.00	1.00	2.00
1.5	1.50	2.00	3.50
2	2.00	3.00	5.00
3	3.00	4.50	7.50
4	4.00	5.00	9.00
5	5.00	5.50	10.50
6	6.00	6.00	12.00
7	7.00	6.50	13.50
8	8.00	7.00	15.00

Figure 6.3 shows a comparison of the cost of parking within these different tariff zones for different parking durations. The high- and Zoo-tariff zones are roughly 4 to 5 times more expensive than the low-tariff zones for a given parking duration.

FIGURE 6.3: Cost of parking in white zones by parking duration for different tariff zones in Zurich



The operation times of the metered parking spaces are shown in Table 6.23. Drivers are required to pay the parking meters in the high- and low-tariff zones from 9:00 to 20:00 Monday through Saturday. In the Zurich West high-tariff zone, the meters are operated from 9:00 to 20:00 Monday through Wednesday and continuously from 9:00 on Thursday to 9:00 on Sunday. Outside these times, parking in white zones is free.

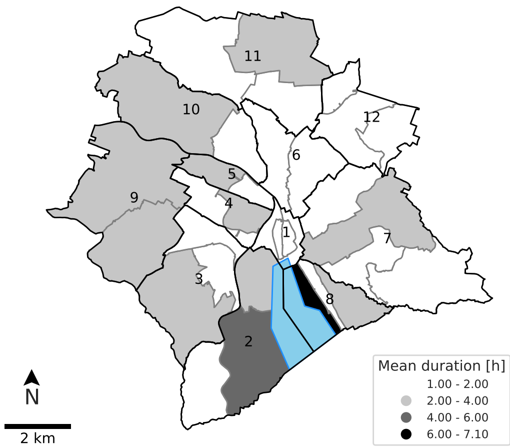
Table 6.23: Operating times of white metered parking in Zurich

Tariff level	Zone	Operation times
High	Inner city	Monday - Saturday, 9:00 - 20:00
	Oerlikon	Monday - Saturday, 9:00 - 20:00
	Zurich West	Monday - Wednesday, 9:00 - 20:00
		Thursday 9:00 - Sunday 9:00
Low	-	Monday - Saturday, 9:00 - 20:00

Considering both blue zone and white zone parking spaces jointly, the relative ease of parking on-street in Zurich can be further explored. Figure 6.4 shows the mean maximum on-street parking duration by Zurich city quarter when considering both blue and white zone parking spaces for which the maximum allowed parking duration is available. On-street parking in most central quarters, as well as those in the north and eastern parts of the city, have an average parking duration limit of under 2 hours, while the average maximum parking duration is higher in the western quarters and is at its highest along the lake.

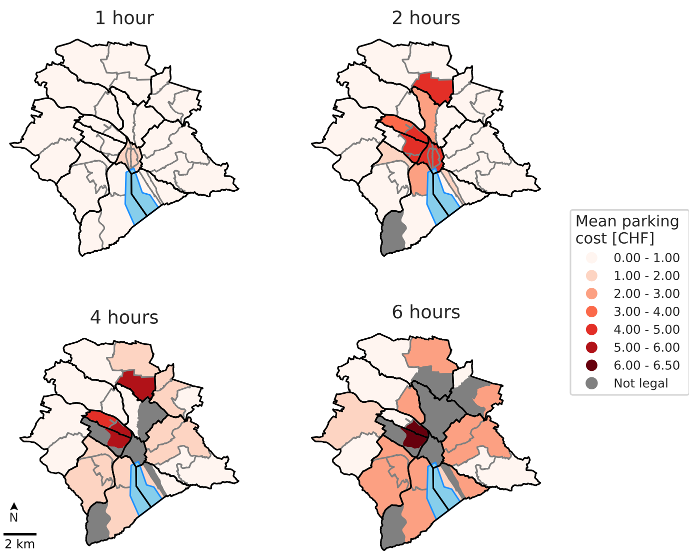
These parking duration limitations also have an effect on the mean cost of on-street parking across the city. Figure 6.5 shows the spatial distribution of the mean cost of parking on-street for different parking durations. Parking for one hour is essentially free throughout the city, except within district 1 where blue zone parking is nearly non-existent. As the parking duration increases, so do the average costs, first within the more central quarters and then further out into the periphery. In addition, the number of quarters where parking is not possible during the day increases with parking duration, a direct reflection of the spatial distribution of the maximum parking duration limits within the city.

FIGURE 6.4: Mean maximum on-street parking duration by Zurich city quarter



Data: Open Data Zurich 2019

FIGURE 6.5: Mean cost of parking on-street by parking duration and city quarter



Data: Open Data Zurich 2019

6.3.2 *Parking garages*

As introduced in Section 5.3.2, the Zurich Open Data portal contains a list of all the publicly accessible garages within the city limits. This list includes the name, address, coordinates and number of parking spaces available at each location, but does not include any information on the operating times or pricing scheme. Therefore, this information was collected from third parties.

Figure 6.6 shows the locations of parking garages within Zurich, where the marker size indicates the number of available parking spaces and the colour the cost of daytime parking for 2 hours on a weekday. Grey-coloured markers indicate parking locations where no weekday price information could be collected. Parking costs tend to be higher in the city centre as well as in the centre of Oerlikon and drop toward the periphery. This is made clearer in Figure 6.7a, which shows the costs of parking for 2 hours in relation to distance to Zurich main station (HB), where there is a clear decreasing trend in the parking cost as a function of distance. Similar decreasing trends are observed for other parking durations. Nevertheless, the costs increase with increasing parking duration, irrespective of the distance to Zurich HB, as shown in Figure 6.7b.

6.3.2.1 *Modelling parking garage prices*

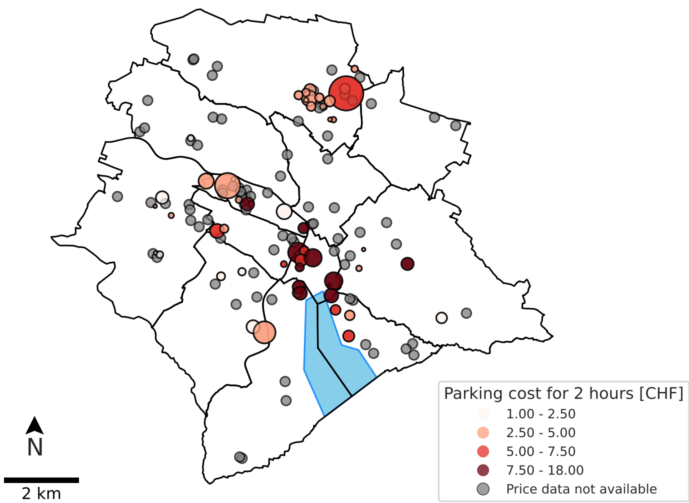
Pricing information could only be collected for 69 out of the 136 parking garages listed in the Open Data Zurich catalogue. In order to be able to impute parking cost values for all parking garages within the city of Zurich, a parking garage pricing model is thus estimated.

Oswald (2012) modelled the cost of parking for 2 hours in a garage as a linear relationship of the distance between the garage and Zurich HB, consistent with what is observed in Figure 6.7a. However, parking costs also increase with increasing parking duration as shown in Figure 6.7b. Therefore, the model proposed by Oswald for garage parking costs c is further generalized to the following functional form:

$$c = (\alpha + \beta x)\, t = \rho t \tag{6.2}$$

where x is the distance to Zurich HB and t the parking duration. Equation (6.2) essentially states that the hourly rate for parking in a parking garage, $\rho = (\alpha + \beta x)$, is linear with the distance to Zurich HB, as proposed

FIGURE 6.6: Location, size and cost of parking garages in the city of Zurich



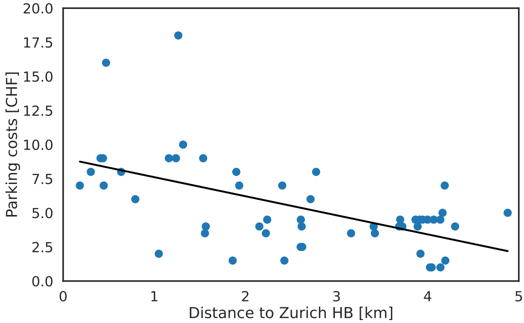
Data: Open Data Zurich 2021, Parkopedia 2022, PLS 2022

by Oswald (2012), and that the total parking costs then scale linearly with parking duration. Equation (6.2) additionally has some desired properties: at any given parking duration, the cost of parking is maximum when the distance to Zurich HB is null, and the parking costs are zero for null values of parking duration, independent of distance.

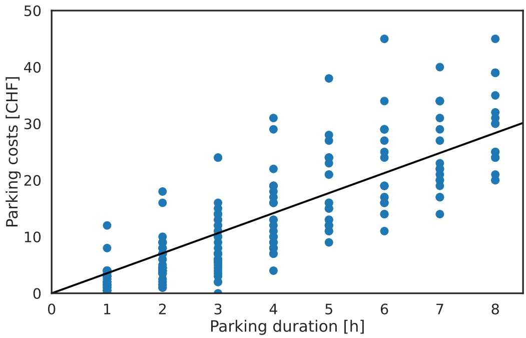
The descriptive statistics of the collected parking garage data are shown in Table 6.24 and the results of the ordinary least squares regression in Table 6.25. All estimated coefficients are significant and present the expected signs. The coefficients can be interpreted as such: The base hourly rate ρ for parking in a garage directly at Zurich HB is 5.28 CHF per hour, and each kilometre one parks further away from Zurich HB reduces this hourly rate by 0.82 CHF. Figure 6.8 shows the distribution of these hourly rates estimated for all 136 parking garages within the city of Zurich, for which the average hourly parking rate for the city of Zurich is 2.91 CHF per hour.

Figure 6.9 compares the cost of parking in a white zone parking space and parking garage within both the low- and high-tariff zones within the city of Zurich, and the results are striking. Within the high-tariff zones, parking in a parking garage is up to twice as expensive as parking on-street in a white zone space, and within the low-tariff zones, it is nearly 5

FIGURE 6.7: Spatial and temporal relationships in the cost of parking in a Zurich city garage



(a) Parking costs for 2 hours in relation to distance to Zurich HB



(b) Parking costs in relation to parking duration

Data: Open Data Zurich 2021, Parkopedia 2022, PLS 2022

times as expensive. Garage parking within low-tariff zones is nearly equally expensive as high-tariff white zone parking. Based on the arguments of Shoup (2006), such a price difference has the potential to trigger high levels of parking search traffic within the city at certain times of day.

TABLE 6.24: Parking garage costs, descriptive statistic

	mean	std	10%	25%	50%	75%	90%
Distance to HB [km]	2.3	1.3	0.4	1.3	2.2	3.4	4.1
Parking duration [h]	3.4	2.2	1.0	2.0	3.0	5.0	7.0
Parking costs [CHF]	11.5	10.3	1.5	3.5	8.0	17.2	27.0

Data: Open Data Zurich 2021, Parkopedia 2022, PLS 2022

TABLE 6.25: Parking garage costs, OLS regression results

	Coef.	Std.Err.
α	5.28***	0.33
β	-0.82***	0.13
N (# garages):	272 (69)	
R^2:	0.937	
$\mathcal{LL}_{final}$	-752.47	

Standard errors: *** : $p < 0.005$

FIGURE 6.8: Distribution of estimated hourly parking garage rates in Zurich

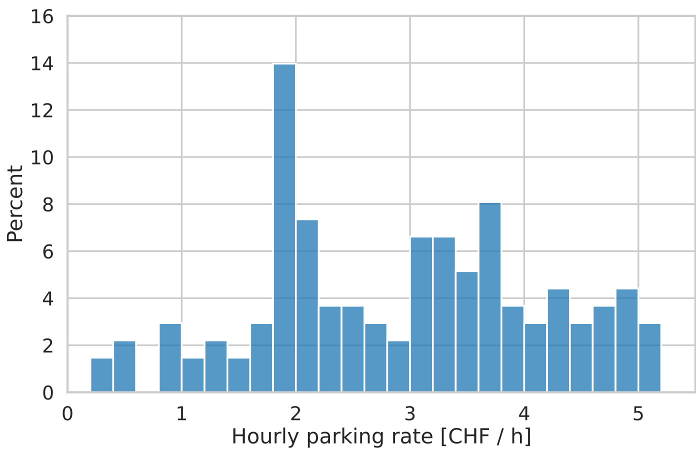
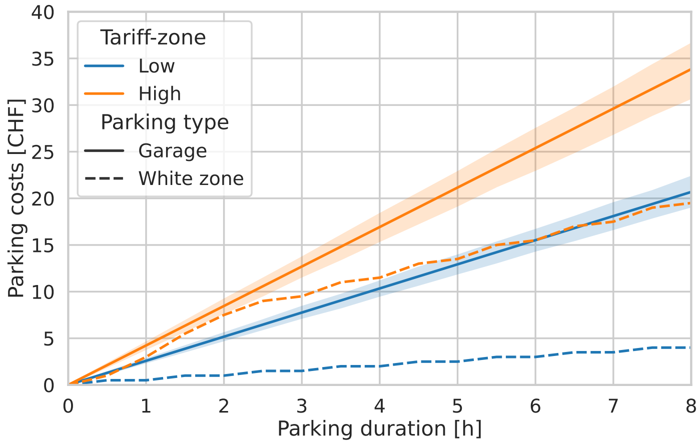


FIGURE 6.9: Comparison of white zone and garage parking costs within low- and high-tariff zones in Zurich for different parking durations



6.4 CONCLUSION

This chapter explored parking supply, initially focusing on available parking at home and at work across Switzerland, and later on the supply of public parking within the city of Zurich. A large majority of Swiss households (77%) have parking available at their place of residence, mainly attributable to car ownership within the household, but additionally influenced by the quality of public transit as well as population density around the home location. Parking is also available to most Swiss employees (75%) in some form, and again this availability is mainly affected by population density at the work location as well as the quality of public transit both at work and at home.

Public parking is provided within the city of Zurich under three main forms: free yet time-limited blue zone parking, metered white zone parking and parking garages. White zone parking space are highly concentrated around the central city districts, whereas blue zone parking is mainly located in central districts outside the city centre. Parking garages can be found throughout the city, and their costs generally decrease with increasing distance to the city centre. Parking garages are also substantially more expensive than metered on-street parking, between 2 to 5 times more depending on the location within the city.

7

PARKING AS A FRINGE BENEFIT

In Chapter 6, the supply of parking in Switzerland at home and work were both described and their availability was modelled using logistic regression. This chapter further addresses the issue of parking provisions at work, and how they specifically influence commuting behaviour as part of an employee's fringe benefits package. Parts of this chapter are based on the following peer-reviewed conference contribution:

Tchervenkov, C., M. Balać and K. W. Axhausen (2022) The impact of employer fringe benefits on commuting to work by car in Switzerland, paper presented at the *101st Annual Meeting of the Transportation Research Board*, Washington, DC, January 2022.

7.1 INTRODUCTION

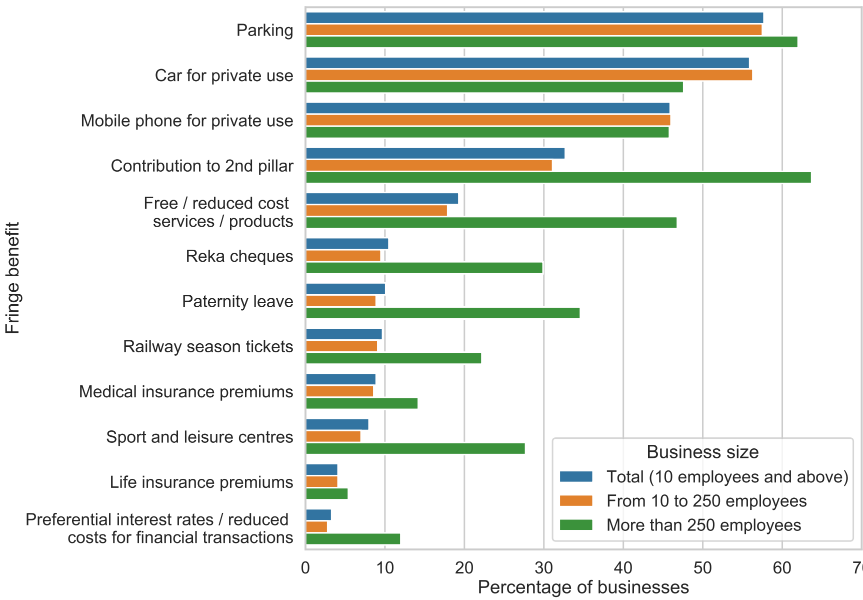
In Switzerland, commuting to work is, after leisure, the second largest generator of travel demand. Based on the data from the Swiss Mobility and Transport Microcensus (MTMC) (BFS and ARE, 2017), the average person in Switzerland travelled 37 km daily, of which 16 km for leisure trips and 9 km for work trips in 2015. Despite Switzerland having one of the densest and most reliable public transportation networks in the world, 62% of the kilometres travelled to work were carried out using individual motorized transport.

Many employers offer their employees fringe benefits as a perk for working for the company to attract and retain qualified workers; the most common fringe benefits in Switzerland in 2010 according to the Swiss Federal Statistical Office (BFS) (BFS, 2010) are shown in Figure 7.1. 58% of companies in Switzerland offered parking and 56% offered a car for private use to at least some of their employees. However, barely 10% of companies offered a railway season ticket subscription. These mobility-related benefits influence the employees' mobility tool ownership and possibly their mode choice behaviour; however, the impacts of mobility-related fringe benefits in Switzerland are still unclear.

In the specific case of Switzerland, a detailed survey of fringe benefits offered by employers was last conducted by the BFS in 2010 (BFS, 2010) in parallel to the Swiss Earnings Structure Survey. Although aggregate results are available, the raw data are not. In addition, the impact of these fringe benefits on Swiss mobility behaviour has not been examined.

This chapter presents the results of the mobility-related fringe benefits survey conducted on the MOBIS study participants and analyzes both who receives these fringe benefits and how these jointly influence the mode share for work commute trips. It is organized as follows: First, the data are briefly described and the cleaning, enrichment and weighting steps are detailed. Next, a descriptive analysis of the data is presented. Afterwards, a logistic regression model is formulated and the estimated parameters and marginal effects are presented. Finally, a discussion and conclusion are provided.

FIGURE 7.1: Most common fringe benefits in Switzerland by business size as a percentage of businesses



Data: BFS 2010

7.2 DATA: CLEANING, ENRICHMENT AND WEIGHTING

An online survey on fringe-benefits was sent to 1,259 participants from the MOBIS study (see Section 5.2) in May 2021. The invited participants were all employed, were either still participating in the MOBIS:COVID-19 study or opted into receiving further survey invitations, and had previously answered a survey about parking at home. 635 participants (50.4%) responded: 444 from the original MOBIS panel and 191 from the new LINK panel.

The respondents were asked more detailed questions pertaining to their employment situation, their work commuting behaviour and the mobility-related fringe benefits they were offered by their employer back in autumn 2019, before the start of Covid-19. More specifically, they were first asked for their workload (as a percentage of a full-time job), their work sector (private or public), the coordinates of their main work location and the number of days a week they physically commuted to work on average. They were then asked to specify the number of days a week, on average, that they commuted to work using the following transport modes: car/motorbike as a driver and as a passenger, public transport (PT), bike and walk.

Next, they were asked whether several mobility-related fringe benefits were offered to them by their employer. These include a company car for their personal use, a company car shared among multiple employees, PT subscriptions, dedicated employee parking, carsharing and bikesharing subscriptions and bike-related infrastructure (parking, locker room, showers, etc.). In addition, they were also asked about other parking options near work as well as their locations. Where relevant, they were asked to provide how much these benefits would cost them after any employer subsidy. Finally, they were asked which benefits they ultimately chose to use and in the case of parking, how often a week on average.

The remainder of this section details the multiple cleaning, enrichment and filtering steps up to the final weighting of the collected fringe benefit data. The collected survey data were first cleaned. Participants who did not provide their workload (9), never commute to work (26), or were self-employed (35) were removed from the sample, yielding 580 participants. The remaining data were then enriched with socioeconomic attributes, such as age, gender, household size and income, as well as mobility tool ownership information obtained from the introductory surveys conducted during the course of the MOBIS study. Private mobility tools (car, motorbike, bike) were not considered available if the participant needed to borrow them from someone else. Participants with a GA travel card (unlimited travel on PT in Switzerland) were assumed to have no other PT subscriptions, as this would be redundant. Participants who

- were not aged between 18 and 65 (1),
- did not report their household monthly income (37), or
- claimed having purchased a discounted PT subscription through their employer but did not indicate owning the subscription in the introductory surveys (23)

were removed from the sample. Additionally, 6 LINK-recruited participants had missing socioeconomic information, yielding 514 participants.

Whereas the coordinates of the work location were provided by the participants during the fringe-benefits survey, their home location coordinates were determined from the GPS data collected during the MOBIS study. These data contain both GPS points for the trips and activities performed by the participants, along with imputed transport modes and purposes (Gao *et al.*, 2021), respectively. The imputed home activities were first clustered using the `Scikit-learn` (Pedregosa *et al.*, 2011) implementation of the DBSCAN clustering algorithm (Schubert *et al.*, 2017). Each participant's home location coordinates were then computed as the weighted centroid (by activity duration) of the main cluster, i. e., the one where the most cumulative time was spent during the tracking study.

The municipality name and classification (urban, suburban or rural), postal code, canton, second-level NUTS (Nomenclature of Territorial Units for Statistics) administrative division and PT service quality level was determined for both the home and work coordinates of each participant.

Since the participants had also previously been asked to provide the postal codes for both the home and work locations in the previous MOBIS surveys, the imputed locations could therefore be validated. Home locations for which the postal code provided in the MOBIS surveys did not match the one corresponding to the imputed coordinates were deemed implausible. In the fringe benefits survey, each participant was shown the coordinates of the work location where they spent the most time according to the GPS data, as an initial guess. The participants were then asked to correct the information if needed. Work locations were deemed implausible if the participant did not make any corrections to the shown work location and if the corresponding postal code did not match to the one provided in the MOBIS surveys. 509 home locations and 512 work locations could be computed, of which 24 and 25 respectively were deemed implausible and removed, yielding 459 participants.

Each remaining participants' work commute trip, from their home to work location coordinates, was routed using the Google Maps Directions API[1]. The median morning departure time and most common departure day of the week for commute trips, extracted from the recorded GPS data, were used as routing input departure times. The routing provided total travel times, including congestion, for the car, PT, bike and walk alternatives, as well as the number of transfers using PT and whether part of the PT trip was carried out by train. A valid PT route could not be identified for 9 participants, which were removed, yielding 450 participants.

As we are interested in the impact of mobility-related fringe benefits on the share of work trips by car, a final sample of 404 participants who either have a car or motorbike available to them is generated and weighted against the MTMC using Iterative Proportional Fitting (Lomax and Norman, 2016) implemented in the Python `ipfn` package (Forthomme, 2021). To match both the MOBIS study participation criteria and the previous filtering steps, the following sub-sample of MTMC individuals are used for the weighting: those who have a car or motorbike available, are employed (excluding those who are self-employed), are aged between 18 and 65, whose income level and work location are known, and who are not living or working in the Canton of Ticino. The following variables were then used for the weighting:

- gender
- age group
- education level
- household monthly income and size
- home and work location NUTS-2 division
- home and work municipality classification
- car, motorbike and bike ownership
- PT subscription

Table 7.1 shows the population distributions of the sample, before and after weighting, compared to that of the MTMC. Prior to weighting, older, more educated and wealthier participants living and working in urban areas in the Greater Zurich region were over-represented in the sample.

1 https://developers.google.com/maps/documentation/directions/overview

Table 7.1: MTMC and sample distribution (%), before and after weighting

Variable	MTMC	Sample Unweighted	Sample Weighted
Male	58.08	54.95	58.08
Age group			
18-24	7.70	3.22	7.70
25-29	9.75	8.42	9.75
30-34	12.21	8.17	12.21
35-39	11.98	11.39	11.98
40-44	13.53	14.60	13.53
45-49	14.08	14.11	14.08
50-54	13.42	16.09	13.42
55-59	10.66	13.61	10.66
60-65	6.67	10.40	6.67
Education level			
Mandatory	9.42	4.21	9.42
Secondary	50.87	46.04	50.87
Higher	39.71	49.75	39.71
Household monthly income			
Less than 4000 CHF	4.45	1.49	4.45
4001 - 8000 CHF	35.64	28.47	35.63
8001 - 12000 CHF	33.39	36.88	33.39
12001 - 16000 CHF	15.86	21.53	15.86
More than 16000 CHF	10.67	11.63	10.67
Household size			
1	16.74	16.58	16.74
2	32.30	33.42	32.30
3	19.11	17.82	19.11
4	22.45	23.27	22.45
5 or more	9.40	8.91	9.40
Household location (NUTS 2)			
Lake Geneva region	18.72	18.32	18.93
Espace Mittelland	24.29	15.35	24.64
Northwestern Switzerland	14.15	19.31	14.36
Zurich	16.51	39.60	16.75

Continued on next page

Table 7.1 – continued from previous page

Variable	MTMC	Sample Unweighted	Sample Weighted
Eastern Switzerland	15.29	2.97	14.13
Central Switzerland	11.04	4.46	11.20
Household location type			
Rural	26.86	14.11	26.86
Suburban	6.98	9.16	6.98
Urban	66.16	76.73	66.16
Work location (NUTS 2)			
Lake Geneva region	18.94	18.07	18.94
Espace Mittelland	23.52	16.09	23.52
Northwestern Switzerland	12.96	20.30	12.96
Zurich	19.37	36.39	19.37
Eastern Switzerland	14.13	4.70	14.13
Central Switzerland	11.08	4.46	11.08
Work location type			
Rural	16.47	6.93	16.47
Suburban	5.07	4.95	5.07
Urban	78.46	88.12	78.46
Mobility tool ownership			
Car	96.50	98.51	96.50
Motorbike	19.75	17.08	19.75
Bike	77.09	77.48	77.09
Carsharing membership	3.08	5.69	3.08
Public transport subscriptions			
GA travel card	7.14	8.66	7.14
Half-fare travel card	35.55	55.94	35.55
Other travel card	16.33	4.21	16.33

7.3 DESCRIPTIVE ANALYSIS

A descriptive and univariate analysis is conducted on the weighted sample. The distributions with respect to company car ownership, parking availability, public transport subscriptions and service quality, as well as other fringe benefits, is analyzed, as well as these benefits' effect on commuting mode shares, computed in terms of the number of trips. Figure 7.2 shows the distribution of the number of days a week commuted to work and Figure 7.3 the modal split for work trips. Over 60% of commuters commute to work 5 days a week and over 70% of work trips are driven by car.

FIGURE 7.2: Distribution of the number of days commuted to work per week

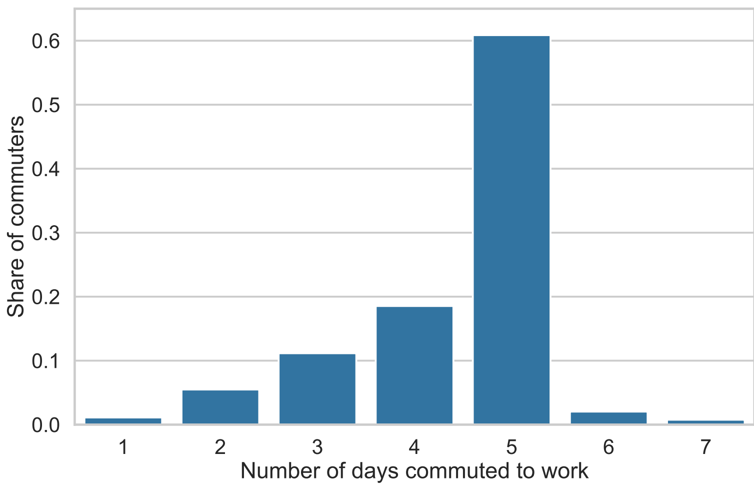
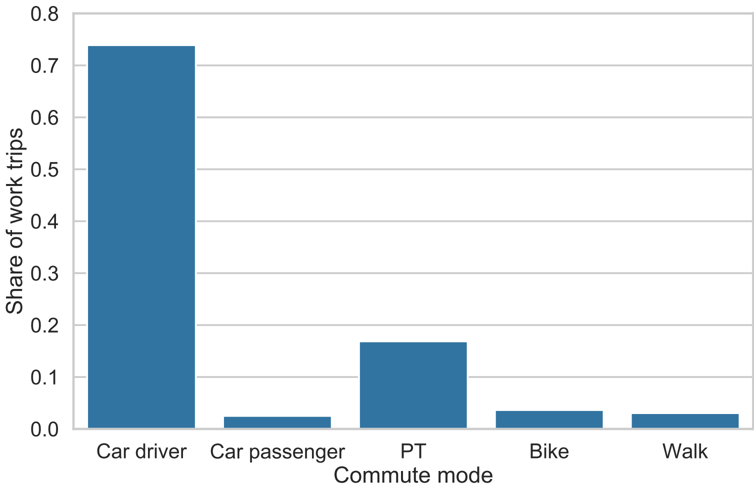


Table 7.2 describes who is offered a company car by their employer. Nearly 10% of commuters are offered a company car, of which 83% make use of the offer. These numbers are in line with those reported by Gutiérrez-i Puigarnau and Van Ommeren (2011). Company cars are primarily offered to wealthier male commuters, in their late 20s or in their 40s, belonging to larger households and for whom public transport service quality at work is lower. The predominance of males with company cars is also reported by Macharis and De Witte (2012). As shown in Figure 7.4, the share of

FIGURE 7.3: Overall modal split for work trips



work trips driven by car is significantly[2] larger by 11% for those having a company car.

Table 7.3 shows the percentage of commuters who have either free or paid parking available at their place of work, differentiated by parking type. Also shown is the percentage for whom the given parking type is unavailable or unknown. The percentage values add up to 100% row-wise, but not column-wise, as a commuter may have multiple types of parking available to them at their place of work. In the case of Park & Ride facilities, these are not available directly at work, but rather on the way to the workplace. Based on our weighted sample, nearly half of commuters have a free dedicated outdoor parking space provided to them by their employer.

Grouping all parking types together and ignoring Park & Ride facilities, 64% of commuters have at least one free parking option available to them at work (83% of the time offered by their employer), 32% have only paid options available and a mere 4% do not have any parking option available at work. Figure 7.5 shows the effect of free parking availability at work on mode share. The share of work trips driven by car is significantly[3] larger by

2 p-value < 0.001 with two-sided t-test
3 p-value < 0.001 with two-sided t-test

TABLE 7.2: Commuters who are offered a company car by their employer

	Company car offered by employer (%)	Offer accepted (rel. %)
Overall	9.98	83.20
Breakdown by...		
Gender		
Female	1.34	46.82
Male	16.21	85.37
Age group		
18-24	0.00	-
25-29	16.12	91.85
30-34	3.16	10.93
35-39	0.44	100.00
40-44	17.12	86.84
45-49	19.96	74.02
50-54	8.94	94.71
55-59	9.67	91.85
60-65	9.15	96.36
Household monthly income		
Less than 4000 CHF	0.00	-
4001 - 8000 CHF	5.21	80.70
8001 - 12000 CHF	11.31	82.33
12001 - 16000 CHF	17.83	78.65
More than 16000 CHF	14.25	96.86
Household size		
1	8.38	89.28
2	8.29	94.49
3	9.16	92.23
4	11.62	52.38
5 or more	16.40	100.00
Public transport service quality at work		
A	7.95	52.51
B	7.65	90.70
C	13.48	99.20
D	3.85	100.00
None	29.49	90.53

FIGURE 7.4: Effect of having a company car on the share of work trips per mode

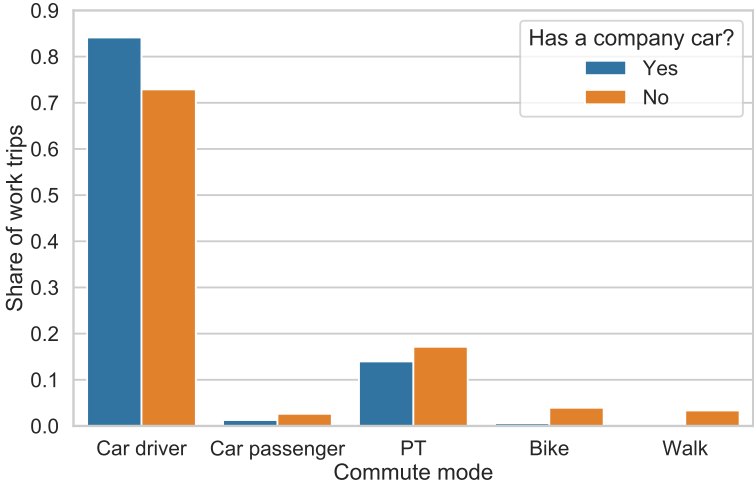


TABLE 7.3: Percentage of available parking by type

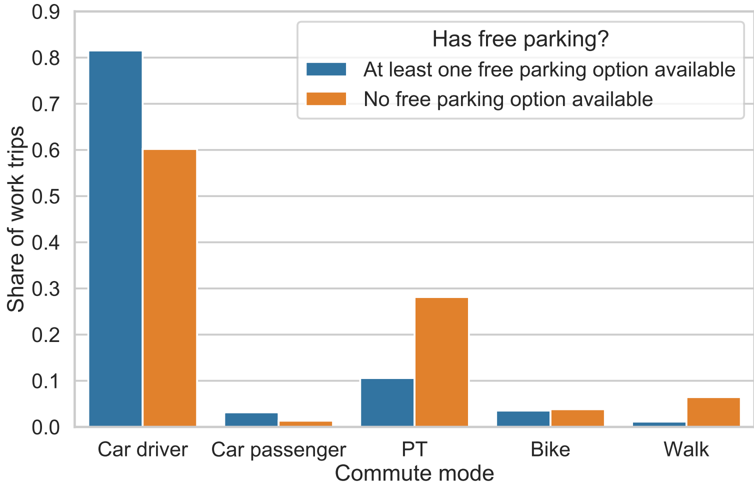
Parking type	Free	Paid	Not available	I don't know
Dedicated parking outdoors	46.57	16.65	35.28	1.49
Dedicated parking garage	13.29	13.55	71.96	1.19
On-street parking	12.75	10.59	70.60	6.06
Parking lot	24.49	20.10	51.25	4.16
Parking garage	2.95	16.39	75.20	5.46
Park & Ride facility	1.02	8.41	83.42	7.14

21% for those who have at least one free option available, indicating that free parking has a significant impact on commuter mode choice.

Table 7.4 shows the percentage of commuters who were offered a discounted public transport travel card by their employer. In each case, the relative share of those who bought the travel card using the employer discount or on their own as well as those who did not buy the travel card is also shown.

Employers seem to play a large role in the choice of purchasing a travel card. The share of employees who did not purchase a travel card is systematically lower when a discount was offered by the employer. Indeed, 67%

FIGURE 7.5: Effect of free parking availability on the share of work trips per mode



of those who were offered a discounted GA travel card by their employer purchased one, whereas less than 3% of those who did not receive an offer purchased the travel card on their own. The trend is similar for the half-fare travel card, where 65% purchased a travel card when offered by the employer, whereas only 31% did so without an offer. Given its relative low cost, this travel card quickly becomes worthwhile if one travels even occasionally by public transport in Switzerland, which explains the higher purchase percentage for those who did not receive a discount from their employer. In the case of other travel cards (e. g., local, regional and point-to-point season tickets), 13% accepted the offer, whereas 22% of those who were offered a discounted travel card decided to buy one on their own instead. This could be explained by the fact that the offered travel card does not always correspond to the employee's specific needs, who then opts for a different option. The share of employees opting to buy their own travel card is about the same as for those who did not receive a discount from their employer (23%); thus, the employer's discount still results in an increased likelihood of purchasing the travel card. Overall, 19% of commuters are offered a discounted PT travel card, with 68% making use of the offer. Of the remaining 81% who do not receive a discount, 49% still purchase some form of PT travel card.

TABLE 7.4: Commuters offered a discounted PT travel card by their employer

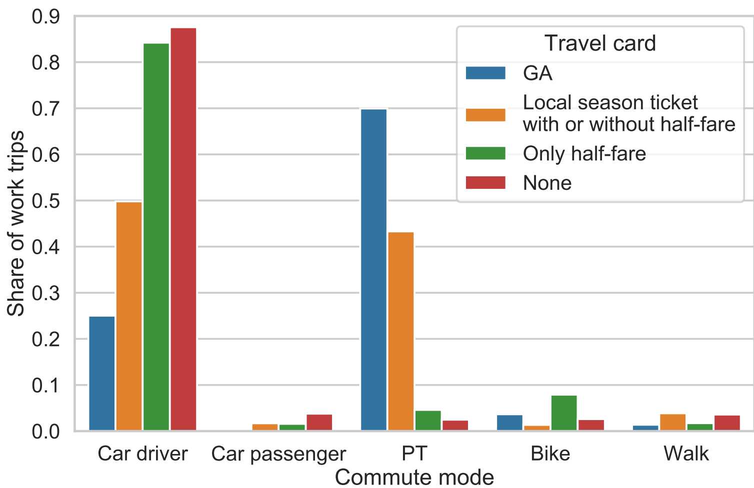
Travel card	Discount offered by employer [%]		Travel card purchased [rel. %]		PT quality Home	PT quality Work	Household income [k CHF]
GA	Yes	7	–	–	0.40	0.68	9.2
			via employer	67	0.48	0.70	9.2
			did not buy	33	0.25	0.62	9.4
	No	93	–	–	0.45	0.63	7.9
			on their own	3	0.33	0.90	9.6
			did not buy	97	0.45	0.63	7.9
Half-fare	Yes	12	–	–	0.43	0.69	6.3
			via employer	65	0.42	0.65	5.4
			did not buy	35	0.45	0.75	7.8
	No	88	–	–	0.44	0.63	8.2
			on their own	31	0.45	0.64	8.9
			did not buy	69	0.44	0.62	7.9
Other	Yes	6	–	–	0.56	0.82	7.0
			via employer	13	0.50	0.84	9.3
			on their own	22	0.65	0.85	11.2
			did not buy	65	0.54	0.80	5.2
	No	94	–	–	0.44	0.63	8.1
			on their own	23	0.52	0.80	9.1
			did not buy	77	0.41	0.57	7.8
Sample average					0.44	0.64	8.0

Also shown in Table 7.4 are the average public transport service quality at home and work, which have been recoded as specified in Table 6.5, and household monthly income. GA travel cards tend to be offered to higher income commuters, whereas half-fare and other travel cards to lower income commuters. The average PT service quality at work is substantially higher for those who were offered a local season ticket discount compared to those who were not, whereas the difference is less pronounced in the case of GA or half-fare travel cards. Those who purchase a local season ticket also tend to be wealthier and have a higher PT quality level at home and work than average, whereas no clear trend is apparent in the case of the half-fare card.

The employer discount seems to have the greatest effect on purchasing a GA travel card. When looking at those who were offered a discount, PT quality at home is substantially higher for those who purchased the travel card, whereas average incomes are similar. However, when looking at those who did not receive a discount, it is income rather than PT quality that seems to be the determining factor, although a more detailed analysis is needed to confirm this.

Figure 7.6 shows the effect of owning a public transport travel card on commuting mode shares. The share of work trips driven by car is significantly[4] lower by 62% for those who own a GA travel card compared to those who do not own any public transport subscription. The share of car trips is also significantly[5] lower by 38% for those who own a local season ticket, with or without a half-fare card. Only owning a half-fare card has very little influence on mode share, the share of car trips only being 3% lower, yet still significant[6]. These results indicate that the possession of public transport subscriptions, which is heavily influenced by the employer, has a significant impact on commuting mode choice.

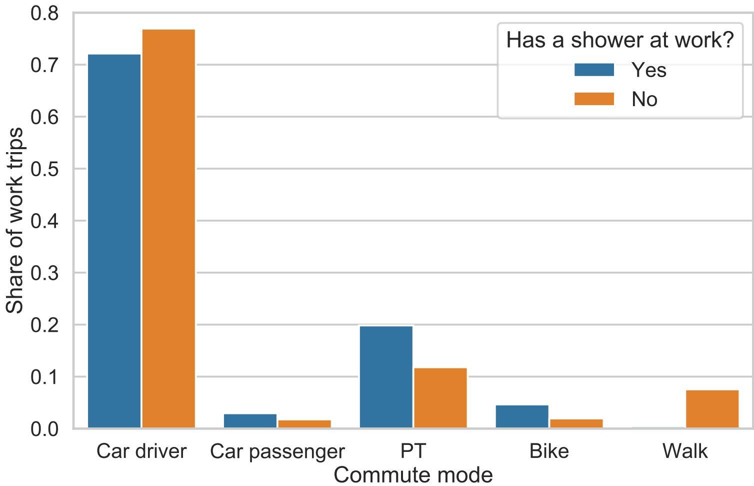
FIGURE 7.6: Effect of PT travel card on the share of work trips per mode



4 p-value < 0.001 with two-sided t-test
5 p-value < 0.001 with two-sided t-test
6 p-value < 0.1 with two-sided t-test

Finally, some employers have showers available for their employees, which might be particularly appreciated by those who bike to work. Based on the collected data, 63% of commuters have a shower available at their place of work. Figure 7.7 shows the effect of provided showers on commuting mode shares. The share of work trips by car are slightly yet significantly[7] lower by 5% when showers are made available at the workplace. As expected, the share of bike trips are also slightly higher.

Figure 7.7: Effect of shower availability at work on the share of work trips per mode



7.4 Regression Analysis

From the descriptive analysis in Section 7.3, it is clear that the majority of participants commute to work 5 days a week and by car, and that having a company car, free parking, a public transport subscription, and a place to shower at work all significantly influence the choice of commuting to work by car. In the following section, a multivariate logistic regression model is estimated in order to quantify which of these fringe benefits plays the greatest role in choosing to commute by car when considered together.

7 p-value < 0.05 with two-sided t-test

The proportion p of days the participants commute to work by car, that is the average number of days per week that the participant commutes to work by car divided by the average number of days per week they commute to work in general, is modelled using a logistic regression formulation as in Equation (6.1). The following variables are used for the regression analysis:

– Male (dummy)
– Age (continuous)
– Household monthly income (discrete; recoded)
– Car travel time (continuous)
– Next-best travel time using other alternatives (continuous)
– Public transport service quality at home (discrete; recoded)
– Public transport service quality at work (discrete; recoded)
– Company car (dummy)
– Free parking available (dummy)
– GA or local season-ticket (dummy)
– Bike available (dummy)
– Shower available at work (dummy)

The values for public transport service quality and household monthly income are recoded as in Table 7.5. Additionally, the household size category *5 or more* is set to 5. Descriptive statistics of the unweighted data are summarized in Table 7.6.

Table 7.5: Value recoding for logistic regression

Variable	Original value	Recoded value
Household monthly income	Less than 4000 CHF	3000
	4001 to 8000 CHF	6000
	8001 to 12000 CHF	10000
	12001 to 16000 CHF	14000
	More than 16000 CHF	17000
Public transport quality	Class A	4
	Class B	3
	Class C	2
	Class D	1
	None	0

Table 7.6: Commuting to work by car, descriptive statistics (unweighted)

	mean	std	10%	25%	50%	75%	90%
Male [%]	55.0	–	–	–	–	–	–
Age	45.2	11.2	29.0	37.8	46.0	54.0	60.0
Household income [kCHF/month]	8.7	3.9	1.7	6.0	10.0	10.0	14.0
Car travel time [min]	21.7	16.6	7.0	11.5	18.4	27.3	38.7
Next-best travel time [min]	42.0	28.6	10.3	21.0	37.1	56.2	78.9
Public transport quality							
at home	1.9	1.2	0.0	1.0	2.0	3.0	4.0
at work	2.8	1.3	1.0	2.0	3.0	4.0	4.0
Company car [%]	9.4	–	–	–	–	–	–
Free parking available [%]	59.2	–	–	–	–	–	–
GA or local season-ticket [%]	24.5	–	–	–	–	–	–
Bike available [%]	77.5	–	–	–	–	–	–
Shower available at work [%]	61.6	–	–	–	–	–	–
Share of commuting by car	0.7	0.4	0.0	0.0	1.0	1.0	1.0

The model is estimated using Python's `statsmodels` package (Seabold and Perktold, 2010) and the results are presented in Table 7.7. The majority of the coefficients present the expected signs. The share of car trips to work decreases when the ratio between the next-best travel time and car travel time increases and decreases with increasing quality of public transport services at home and work. Having a company car and a free parking option increase the proportion of car trips, whereas having a GA or local season ticket as well as a shower available at work decrease the proportion of car trips. The coefficients for the travel time ratio, free parking availability and public transport subscriptions are significant at the 0.1% level, whereas household monthly income is significant at the 5% level and having a company car at the 10% level.

TABLE 7.7: Commuting to work by car, logistic regression model results

Variable	Coef.	SE
Constant	−0.001	1.028
Male	−0.271	0.275
Age / 10	0.016	0.121
Household monthly income / 1000	−0.090**	0.035
Next-best travel time / Car travel time	1.144***	0.288
PT quality home × PT quality work	−0.044	0.033
Free parking available	1.065***	0.276
GA or local season-ticket	−2.227***	0.312
Company car	2.584*	1.502
× Free parking available	−2.114	1.558
× GA or local season-ticket	0.217	1.442
Bike available	−0.438	0.383
× Shower available at work	−0.193	0.324
N:		404
ρ^2:		0.348
$\mathcal{LL}_{null}$		-256.12
$\mathcal{LL}_{final}$		-167.04

Standard errors: *** : $p < 0.001$, ** : $p < 0.05$, * : $p < 0.1$

Marginal probability effects (MPE) are then calculated, first by computing the difference in the predicted probability of commuting by car for each observation given a marginal change in the independent variable, and then by computing the weighted average of these probabilities across all observations in the sample using the weights from Section 7.2. The results are shown in Table 7.8.

Mobility tool ownership, mediated by the fringe benefits offered by an employer, have a large effect on the probability of commuting to work by car. Having a company car and a free parking option available at work increases this probability by 16.1% and 14.2% respectively, while having a GA or local season-ticket and a shower available at work decreases it by 40.9% and 2.2% respectively. The overall ease of commuting between the home and work location with alternatives to the car also highly influence the probability of commuting by car. A 10% decrease in travel time for the next-best alternative to the car results in a 3.2% decrease in probability of commuting by car, while improving public transit quality at home and work result in a decrease of up to 6.8% and 4.8% respectively.

TABLE 7.8: Commuting to work by car, marginal probability effects

Variable	MPE [%]
Male	-3.7
Age, 10-year increase	0.2
Household monthly income, 10% increase	-1.0
Car travel time, 10% decrease	3.3
Next-best travel time, 10% decrease	-3.2
PT quality at home	
class D	-1.7
class C	-3.3
class B	-5.1
class A	-6.8
PT quality at work	
class D	-1.2
class C	-2.4
class B	-3.6
class A	-4.8
Company car	16.1
Free parking available	14.2
GA or local season-ticket	-40.9
Bike available	-7.7
Shower available at work	-2.2

7.5 DISCUSSION

The regression analysis performed in Section 7.4 confirms that company cars, free parking and public transport subscriptions all play a significant role in an employee's choice to commute to work by car, the latter resulting in a decreased probability of commuting by car by 40.9% and the former two in an increase of 16.1% respectively 14.2%. Time-efficient alternatives to the car also have a significant impact on commuting behaviour, with a 10% decrease in travel time for the next-best alternative to the car resulting in a 3.2% decrease in the probability of commuting by car. Improving public transit quality at home and work also contribute to reducing the likelihood of commuting by car. This likelihood also seems to decrease with income, which might be linked to the ability to purchase a GA subscription or to living in a location better connected by public transit.

By extension, the results also show the employer's role in mobility tool ownership and thus in commuting mode choice. Public transit subscriptions influence commuting to work by car the most, with discounted subscriptions favouring commuting to work by public transit. Given that the choice of purchasing a public transit subscription not only depends on public transit quality at home and work, but also on income, providing discounts could further encourage more people to purchase such subscriptions, in turn increasing the likelihood of opting for alternatives to the car when commuting to work.

Free parking also strongly influences commuting to work by car. Given that 83% of those who have at least one free parking option available to them at work receive it from their employer, this employer fringe benefit has a strong impact on the choice of commuting by car. Thus, policies discouraging the offer of free parking, such as cashing out employer-paid parking (Shoup, 1997), could prove beneficial.

The current analysis is conducted on the sub-sample of MOBIS participants who have a car or motorbike available to them. However, since the LINK panel also contains participants without a car, it would be possible to estimate a model for all commuters, and have car availability as one of the variables. The model could also be extended using a fractional multinomial logit formulation (Mullahy, 2015) to estimate the share of trips by all different alternatives. In addition, logistic regression models could also be developed to understand the trade-offs made when choosing between a bundle of fringe benefits offered by employers (Nijland and Dijst, 2015), thus quantifying to what extent the employer can effectively shape mobility tool ownership in Switzerland.

7.6 conclusion

The impacts of mobility-related fringe benefits on mobility tool ownership and commuting behaviour in Switzerland were analyzed using the responses of a large-scale online survey. The results show that 10% of commuters are offered a company car, 64% of commuters have at least one free parking option available at work, 83% of the time offered by their employer, and 19% of commuters are offered some form of discounted public transit subscription. The effect of each fringe benefit on the overall share of work trips by car is statistically significant.

A multivariate logistic regression analysis was conducted to quantify which of these fringe benefits plays the greatest role in choosing to commute by car when considered jointly. Public transport subscriptions, company cars and free parking all play a significant role in an employee's choice to commute to work by car. Thus, policies encouraging more Swiss employers to offer public transport discounts instead of company cars and free parking could prove beneficial in reducing the share of car trips to work.

8

PARKING BEHAVIOUR FROM GPS DATA

This chapter extends the work from the following conference contributions:

Tchervenkov, C. and K. W. Axhausen (2022) Measuring parking search behaviour using GPS data, paper presented at the *22nd Swiss Transport Research Conference*, Ascona, May 2022.

Tchervenkov, C. and K. W. Axhausen (2022) Searching for parking: The case of Zurich, paper presented at the *10th Symposium of the European Association for Research in Transportation*, Leuven, June 2022.

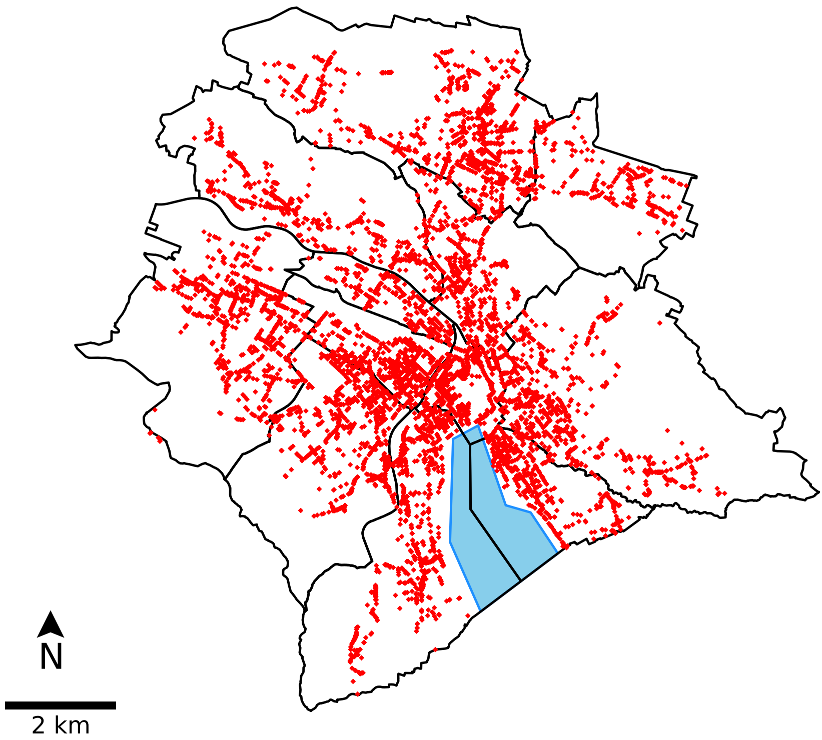
8.1 INTRODUCTION

This chapter presents an analysis of parking behaviour in Zurich, Switzerland using already segmented and labelled GPS data collected within the context of the MOBIS study, as introduced in Section 5.2. The analysis focuses on 11,461 car trips which end within the city of Zurich, representing 1,151 participants, the parking locations of which are shown in Figure 8.1. These car trips are those:

- which contain a single car stage, eventually preceded or followed by walk stages
- where the mean car speed is between 1 and 150 km/h
- where the car travel distance is over 500 m
- where the car travel time is over 5 minutes
- where the total travel time is under 5 hours
- where the origin activity is further than 500 m from the destination activity, such as to exclude round trips

An additional survey was sent to participants after the MOBIS tracking study asking them questions related to their parking situation both at

Figure 8.1: Observed parking locations within the city of Zurich based on filtered GPS data from the MOBIS study



home and work. Respondents were asked if they had parking available at home or whether they parked on-street, and whether they most often parked on-street, in a parking lot or in a parking garage when driving to work. 448 of the 1,151 participants in the sample completed this additional survey, corresponding to 830 home trips and 1,580 work trips. Thus, the data include both trip purpose, socioeconomic and mobility tool ownership information, allowing for the analysis of parking search as a function of both trip purpose and parking availability at the destination. Finally, parking facility location data for both on-street parking and parking garages (see Sections 5.3 and 6.3 for more details) are collected for the city of Zurich and used to estimate both parking garage costs and parking type choice.

8.2 PARKING SEARCH BEHAVIOUR

This section focuses on quantifying parking search within the city of Zurich and understanding which factors influence it. It starts by describing the methodology used for quantifying search behaviour, before presenting and discussing the computed results.

8.2.1 *Methodology*

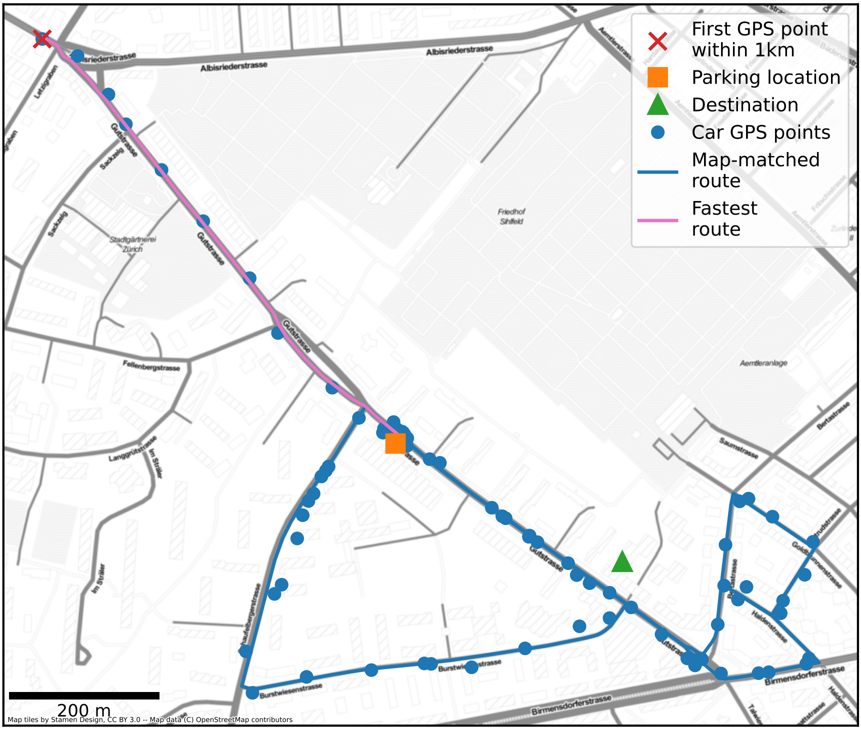
This section briefly presents the methodology used for measuring parking search behaviour from GPS data. The approach requires GPS data segmented into trip stages and activities labelled with the transport mode used and purpose respectively.

Figure 8.2 illustrates the methodology applied to an example trip within the city of Zurich, where the car GPS data points are shown as blue circles on the map. Only the car GPS data within a 1-km radius[1] around the destination activity, marked here with a green triangle, are considered for further parking search analysis, as this is assumed to be the area where parking search actually occurs. The red X indicates the first car GPS point within this radius and is considered the parking search start coordinate, while the orange square indicates the last point and is considered to be the observed parking location. First, the car GPS data are map-matched (blue solid line) to the underlying OpenStreetMap (OSM) road network using the pgMapMatch algorithm proposed by Millard-Ball *et al.* (2019). This algorithm has some notable advantages when it comes to measuring parking search behaviour. First, unlike the map-matching algorithm developed by Schüssler and Axhausen (2009) and used by Montini *et al.* (2012), it allows for repeating links within the map-matched trajectory as well as U-turns, which are indeed likely to occur when searching for parking. Second, it also provides each map-matched path with a likelihood measure of the match being correct. In this analysis, only matches with a likelihood above 90% are kept. Next, the least-cost path in terms of travel time (pink solid line) is computed between the parking search start coordinate and parking location using the pgRouting Turn Restriction Shortest Path algorithm[2]. Finally, based on these map-matched and least-cost paths, several metrics have then been developed in order to quantify parking search.

1 Previous work by Montini *et al.* (2012) focusing on Zurich used an 800-m radius, but also stressed the need to expand this radius to fully observe parking search.

2 `https://docs.pgrouting.org/3.1/en/pgr_trsp.html`

FIGURE 8.2: Example of map-matching car GPS points to OSM road network



OBSERVED TRAVEL DISTANCE AND TRAVEL TIME The first simple metric which can be used to quantify the amount of parking search for trip i is the observed travel distance $d_{mm,i}$ and travel time $t_{mm,i}$ for the map-matched path within the 1 km radius around the destination.

EXCESS TRAVEL DISTANCE In an ideal world, a driver would drive up to their destination along the least-cost path and park directly in front of the door. However, in reality drivers are expected to sometimes have to deviate from this ideal case when searching for a place to park, resulting in excess travel distance which can be attributed to parking search. For each trip i, the excess travel distance $d_{excess,i}$ is defined as the difference in length between the map-matched and least-cost paths between the parking search start and end coordinates:

$$d_{excess,i} = \max\left(d_{mm,i} - d_{lc,i}\ ,\ 0\right) \tag{8.1}$$

Given that the least-cost path is computed in terms of travel time and not distance, there is no guarantee that $d_{mm,i} \geq d_{lc,i}$. Indeed, it is possible that a driver is observed to have chosen a route that is shorter in terms of distance, but longer in terms of travel time, thus yielding a negative excess distance value. To avoid this, such negative values are simply set to zero as an upper bound.

SEARCH TIME In a similar fashion to the excess travel distance, the parking search time for trip i is defined as:

$$t_{search,i} = \max\left(t_{mm,i} - t_{lc,i}\ ,\ 0\right) \tag{8.2}$$

The least-cost path travel time $t_{lc,i}$ should always be shorter than the observed travel time along the map-matched path; however, this is not always the case in practice, as drivers do not always respect speed limits. Thus, negative search time values are also set to zero as an upper bound.

DUPLICATE TRAVEL DISTANCE In addition to deviating from the least-cost path, drivers can drive along the same links in the network several times, thus duplicating parts of their route. The duplicate travel distance $d_{duplicate}$ is computed as the sum of all paths segments that have been visited more than once along the map-matched path.

DISTANCE BETWEEN PARKING LOCATION AND DESTINATION Another indicator of the difficulty of finding parking in an area, and thus of parking search, is the Euclidean distance between the parking location and the destination d_{park}, with the parking search end coordinate taken as a proxy for the parking location.

OVERALL SHARE OF CRUISING TRAFFIC The overall share of traffic cruising for parking η can be defined as a function of excess travel distance

$$\eta = \frac{\sum_{i=1}^{N} d_{excess,i}}{\sum_{j=1}^{M} d_{mm,j}} \tag{8.3}$$

where N is the number of trips that end within the Zurich city limits and $M \geq N$ is the number of trips that enter the city limits, independently of whether they end there.

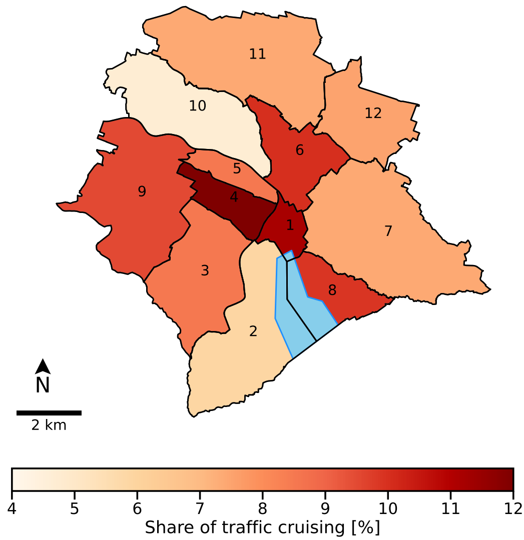
8.2.2 *Results*

The following section presents and discusses the computed parking search metrics as a function of different trip attributes. To get an overall picture of the level of parking search within the city of Zurich, mean values for each metric as well as the overall share of cruising traffic are computed for each city district. Figure 8.3 shows the share of traffic cruising and average search times in Zurich for each city district, whereas Table 8.1 shows all average metric values as well as the share of traffic cruising for each district compared to the entire city. The share of cruising traffic and average search times are mainly greater in the central districts than in the periphery.

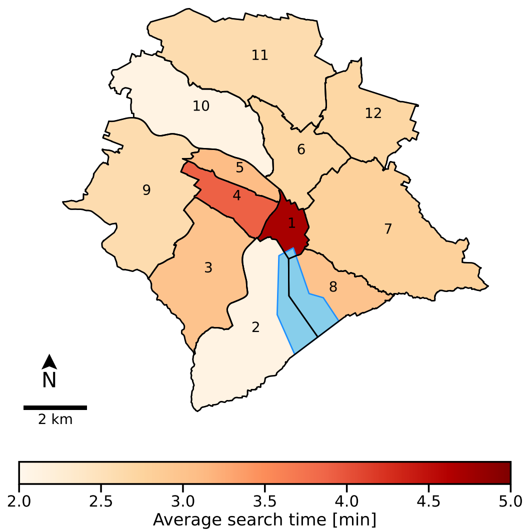
TABLE 8.1: Parking search metrics by Zurich city district

District	Mean value				Share of traffic
	d_{excess} [m]	t_{search} [min]	$d_{duplicate}$ [m]	d_{park} [m]	cruising η_d [%]
1	162.9	4.7	20.4	164.4	11.2
2	80.1	2.1	13.0	98.1	5.9
3	118.1	3.0	19.4	114.4	8.5
4	170.3	3.9	25.7	108.1	12.0
5	123.1	3.1	15.8	124.0	8.5
6	134.3	2.7	17.2	119.2	10.0
7	100.1	2.8	15.8	114.4	7.4
8	136.6	3.0	21.3	110.4	9.9
9	135.9	2.6	26.4	105.0	9.5
10	64.6	2.1	14.1	91.0	4.7
11	101.0	2.6	16.1	105.2	7.4
12	105.4	2.7	25.5	97.2	7.5
All	117.9	2.9	19.0	112.1	8.5

FIGURE 8.3: Parking search in Zurich by city district



(a) Share of traffic cruising [%]



(b) Average search time [min]

The values presented in Table 8.1 can be considered as an upper bound for both the share of cruising traffic within the city of Zurich. In Equation (8.3), the denominator should consider all trips that travel within the study area. However, since only the parking search path within a 1 km radius around the destination is considered, the true total distance travelled in the denominator will be strictly greater than the value used in all the estimates in Table 8.1. In the case of parking search time, the reference travel time used is also a lower bound as it is based on the free-flow travel speeds, and thus the true search time will be necessarily less than the one estimated here. Nevertheless, these upper bounds on the overall share of cruising traffic (8.5%) and average search time (2.9 minutes) are both substantially less than the mean values estimated by Shoup (2006), which are 30% and 8.1 minutes respectively.

Figure 8.4 shows the overall share of cruising traffic and average search time over the entire day, obtained with a rolling computation using an hourly window. The share of cruising traffic is relatively stable throughout the day, with both a standard deviation and an interquartile range of roughly 2%. The average search time varies between 1 and 4 minutes, with higher search times during the day and lower search times at night. Figure 8.5 further shows the average search time by Zurich city district over a typical weekday, using an hourly rolling window. Average search times are highest in the central district, i. e., district 1 highlighted in red, and vary between 3 and 7 minutes with peaks in the late afternoon and early evening corresponding both to both evening rush hour and shopping times.

Table 8.2 shows the average value of the different computed parking search metrics, while Table 8.3 shows the share of trips which exhibit cruising for parking, for different socioeconomic characteristics of the individuals and different trip attributes. The share of cruising trips are computed as the share of trips where the considered parking search metric is above a given threshold: 200 m for excess travel distance, 5 min for parking search time and 0 m for duplicated distance.

In general, all parking search metrics seem to be affected by the socioeconomic characteristics of the individual: excess travel, search time and duplicated distance generally decrease with increasing age, education level and household monthly income, while older and wealthier individuals tend to park further away from their destination, albeit by only a few meters. The share of cruising trips also generally decreases with age, education level and household monthly income.

FIGURE 8.4: Share of traffic cruising and average search time in the city of Zurich over the day

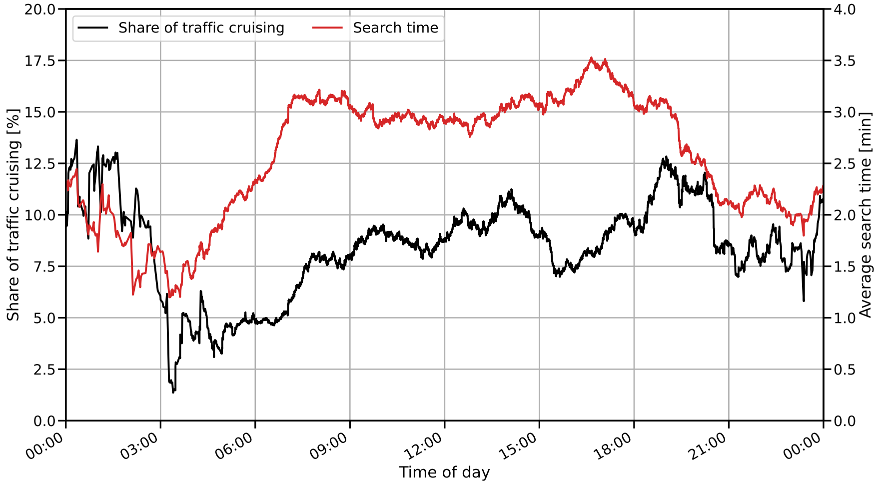
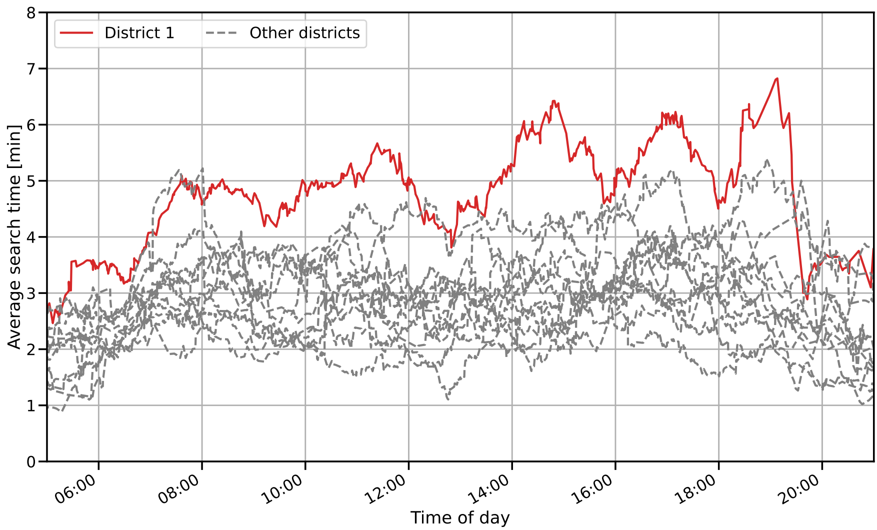


FIGURE 8.5: Average search time over a typical weekday by Zurich city district



Indeed, the characteristics of parking supply around the final destination also impact parking search. The more on-street parking spaces exist within 1 km of the destination, the more individuals tend to have to search for parking, both based on the mean parking search metric values as well as the share of cruising trips. Large numbers of on-street parking within an area could also indicate high demand in general, leading to a scarcity in cheap available parking thus causing more search behaviour. Additional indications supporting this hypothesis are that the average parking search metric values and the share of cruising trips are smaller when the share of blue-zone parking is higher, and they are larger as the hourly parking garage rate increases around the destination. Parking duration also impacts parking search behaviour; the mean metric values and share of cruising trips are both lower for very short or very long parking durations. Indeed, it is not worthwhile for individuals parking for only a short duration to search for parking extensively.

Parking search depends on the availability of parking at the destination, which in turn can depend on the nature of the destination activity itself. Indeed, one might expect parking search to be less pronounced in areas with higher parking availability (e. g., at work where dedicated parking is more common, or at home) and more pronounced in areas where the competition for parking is higher (e. g., at shopping or leisure activities in the city centre). Trips performed to home and work exhibit the lowest, whereas shopping and leisure trips the largest values across all metrics, which is consistent with expectations. The overall share of cruising trips also varies when considering the purpose of the trip. Shopping and leisure trips show the highest share of cruising trips, whereas trips performed to home and work fall on the lower end of the spectrum for each metric. Finally, weekends and evenings exhibit the lowest share of cruising trips.

TABLE 8.2: Average parking search metrics by socioeconomic and trip attributes

Variable	Average parking search metric value			
	d_{excess} [m]	t_{search} [min]	$d_{duplicate}$ [m]	d_{park} [m]
Gender				
Female	115.6	2.9	18.9	110.8
Male	119.7	2.9	19.2	113.2
Age				
18 - 29	142.9	3.0	24.4	114.4
30 - 39	110.9	2.8	17.4	104.3
40 - 49	112.7	2.9	18.3	113.7
50 - 59	118.7	3.1	17.9	112.5
Over 60	93.7	2.7	15.0	118.1
Education				
Mandatory	141.5	3.0	19.4	123.0
Secondary	126.0	2.9	20.5	108.1
Tertiary	108.3	2.9	17.5	115.6
Household monthly income				
Less than 4000 CHF	116.3	3.0	21.0	105.7
4001 - 8000 CHF	115.5	2.8	19.0	103.9
8001 - 12000 CHF	117.4	2.9	19.7	114.1
12001 - 16000 CHF	125.9	3.0	14.5	120.2
More than 16000 CHF	101.1	2.9	17.8	122.8
Unknown	144.2	3.1	24.7	109.4
Trip purpose				
Home	101.2	2.5	18.0	98.2
Work	94.1	2.8	13.0	110.2
Shopping	135.0	3.1	24.0	117.4
Leisure	161.7	3.3	27.0	123.9
Other	110.7	2.9	16.8	115.1
Parking duration				
Under 1h	117.1	2.8	18.5	99.7
1h - 2h	157.8	3.4	25.1	113.0
2h - 4h	150.5	3.3	25.2	126.3
4h - 8h	102.3	2.9	16.6	120.1
Over 8h	93.3	2.6	15.1	113.9

Continued on next page

Table 8.2 – continued from previous page

Variable	Average parking search metric value			
	d_{excess} [m]	t_{search} [min]	$d_{duplicate}$ [m]	d_{park} [m]
Number of on-street parking spaces within 1km of destination				
Less than 1k	63.1	2.1	16.1	102.3
1k - 2k	83.7	2.2	18.7	107.5
2k - 3k	123.7	2.9	16.5	111.7
More than 3k	151.2	3.6	22.0	118.1
Share of blue-zone parking				
Less than 50%	152.7	4.3	19.7	150.6
More than 50%	112.9	2.7	18.9	106.7
Hourly parking garage rate				
Less than 2 CHF	86.6	2.1	18.7	95.2
2 - 4 CHF	101.4	2.5	17.9	110.7
More than 4 CHF	145.1	3.6	20.5	118.0
Familiar with destination				
Yes	105.9	2.8	15.9	106.9
No	157.2	3.3	29.5	129.2
Day of week				
Weekday	113.4	2.9	18.2	110.6
Saturday	141.8	2.9	22.2	118.5
Sunday	121.1	2.5	21.2	116.0
Time of day				
6:00 - 18:00	119.7	3.1	19.4	111.7
18:00 - 6:00	112.0	2.4	17.9	113.5
Overall	117.9	2.9	19.0	112.1

TABLE 8.3: Share of cruising trips by socioeconomic and trip attributes

Variable	Share of cruising trips [%]		
	$d_{excess} > 200$ m	$t_{search} > 5$ min	$d_{duplicate} > 0$ m
Gender			
Female	15.6	13.9	12.6
Male	16.2	14.0	13.8
Age			
18 - 29	18.4	15.0	15.1
30 - 39	15.1	12.6	12.4
40 - 49	15.8	14.0	13.0
50 - 59	15.9	15.9	12.8
Over 60	13.2	11.6	12.4
Education			
Mandatory	21.9	13.2	14.2
Secondary	17.6	13.9	13.3
Tertiary	14.0	14.0	13.1
Household monthly income			
Less than 4000 CHF	15.7	14.2	13.5
4001 - 8000 CHF	16.2	11.6	12.2
8001 - 12000 CHF	16.1	14.1	13.5
12001 - 16000 CHF	16.5	15.6	13.1
More than 16000 CHF	13.1	14.9	13.7
Unknown	19.0	17.1	15.3
Trip purpose			
Home	14.0	10.3	13.2
Work	13.4	12.9	11.7
Shopping	18.9	16.2	14.2
Leisure	20.8	17.3	16.0
Other	14.1	15.3	11.0
Parking duration			
Under 1h	16.6	13.5	11.8
1h - 2h	21.3	18.4	16.1
2h - 4h	19.4	17.9	15.8
4h - 8h	13.7	14.3	13.3
Over 8h	12.5	10.7	12.2

Continued on next page

Table 8.3 – continued from previous page

Variable	Share of cruising trips [%]		
	$d_{excess} > 200$ m	$t_{search} > 5$ min	$d_{duplicate} > 0$ m
Number of on-street parking spaces within 1km of destination			
Less than 1k	8.5	7.5	12.6
1k - 2k	12.2	7.8	12.2
2k - 3k	16.2	13.4	12.7
More than 3k	20.1	20.7	14.7
Share of blue-zone parking			
Less than 50%	21.0	30.3	14.2
More than 50%	15.2	11.6	13.1
Hourly parking garage rate			
Less than 2 CHF	12.4	6.6	13.3
2 - 4 CHF	13.7	9.6	12.3
More than 4 CHF	19.5	21.0	14.3
Familiar with destination			
Yes	14.7	12.4	12.2
No	20.2	19.0	16.7
Day of week			
Weekday	15.4	14.4	12.9
Saturday	19.3	14.3	14.8
Sunday	15.4	9.5	14.0
Time of day			
6:00 - 18:00	16.5	15.7	13.3
18:00 - 6:00	14.1	8.4	13.0
Overall	15.9	14.0	13.2

The data are next analyzed in terms of parking availability at home based on the responses of a complementary survey on parking availability at home and work. The computed parking search metrics for trips to home dependent on parking availability are presented in Table 8.4, whereas the corresponding shares of cruising home trips are shown in Table 8.5. Participants who claim to either own or rent a parking space at or near their place of residence are considered to have parking available at home, whereas the others are assumed to rely on on-street parking. The average excess travel distance and duplicate distance are roughly 2 respectively 4 times larger for participants without parking available to them at home, and the share of trips exhibiting parking search is roughly double that of those with parking available.

TABLE 8.4: Average parking search metrics for home trips given parking availability at home

Parking available at home	Mean value d_{excess} [m]	t_{search} [min]	$d_{duplicate}$ [m]	d_{park} [m]
Yes	61.1	2.2	9.8	90.9
No	140.8	3.1	41.0	83.7
All	73.3	2.3	14.6	89.8

TABLE 8.5: Share of cruising home trips given parking availability at home

Parking available at home	Share of cruising trips [%] $d_{excess} > 200$ m	$t_{search} > 5$ min	$d_{duplicate} > 0$ m
Yes	9.3	7.4	10.4
No	19.8	16.8	16.0
All	10.9	8.8	11.3

The data are further analyzed in terms of the type of parking used at work. Table 8.6 shows the computed parking search metrics for work trips differentiated by the most-used type of parking as specified in the survey, while Table 8.7 shows the corresponding shares of cruising work trips. Participants who claim to most often park in a parking garage have the lowest share of trips exhibiting parking search at around 8% (based on duplicated distance), whereas the share climbs to just over 16% for those parking on-street (based on excess distance). The excess travel and duplicate distances attributed to parking search are more than twice as long for those parking on-street than for those parking in a garage, and parking search times are also higher. However, the distance between the parking location and the destination is about 15% larger for those parking in a garage.

Table 8.6: Average parking search metrics for work trips by parking type

Parking type	Mean value			
most used	d_{excess} (m)	t_{search} (min)	$d_{duplicate}$ (m)	d_{park} (m)
Garage	63.2	2.7	8.4	118.1
Parking lot	84.6	2.8	12.0	104.8
On-street	129.1	3.2	18.0	102.8
All	90.8	2.9	12.7	107.8

Table 8.7: Share of cruising work trips by parking type

Parking type	Share of cruising trips (%)		
most used	$d_{excess} > 200$ m	$t_{search} > 5$ min	$d_{duplicate} > 0$ m
Garage	9.0	13.3	8.1
Parking lot	14.8	12.4	12.7
On-street	16.5	15.8	14.6
All	13.7	13.5	12.0

8.2.3 *Discussion*

The upper bound of the overall share of cruising traffic and the average parking search time for Zurich (8.5% and 2.9 minutes respectively) were found to both be less than the mean values estimated by Shoup (2006) (30% and 8.1 minutes respectively). However, since the share of cruising traffic estimates are based only on GPS data within the last kilometre of the trip, they are still probably overestimating reality. In order to obtain even more accurate estimates, the total distance travelled should consider the entire trip through the city of Zurich. The average parking search times estimated for the central Zurich district are also about half those estimated by previous studies conducted in Zurich (Cao *et al.*, 2019).

The estimated share of trips exhibiting parking search behaviour ($\sim$15%) is higher than previous estimates (5-6%) making use of GPS data (Weinberger *et al.*, 2020). This could be due to the larger area (1 km radius) considered for parking search, and the effects of this search radius should be further analyzed.

Several parking search strategies (e. g., searching en-route to the parking location, first driving directly to the destination before starting the search, etc.) were observed during this analysis. While it is difficult to distinguish specific patterns within these strategies using the current methodology, and future work should focus on better classifying these different strategies, some insights can nevertheless be drawn using the current approach. Of the 11,461 car trips analyzed, a substantial 62% present no excess travel distance, which is similar to the share reported by Montini *et al.* (2012). Thus, as a first insight, drivers more often than not simply travel along the least-cost path, parking en route as they approach their final destination. But what is to be said about the remaining 38% of trips, and what influences their observed routes? Part of the answer can again be found when looking at the supply of on-street parking along the routes. Indeed, when comparing the density of on-street parking spaces along the map-matched and least-cost routes, it can be observed that the chosen routes possess a slightly higher yet significant[3] number of on-street parking spaces per kilometre, 6.4 additional parking spaces per kilometre on average. Hence, in 38% of cases, the supply of on-street parking dictates, at least in part, the routes individuals select when travelling towards their destination.

8.3 PARKING TYPE CHOICE

Section 8.2 attempted to characterize and quantify parking search behaviour using the GPS data collected during the MOBIS study. However, the understanding of where people park is even more crucial to modelling parking search behaviour. Do people bother to search for on-street parking or do they rather go directly to a parking garage? Which factors, including parking search, egress walking and parking costs, play a role in this decision? This section explores these questions.

3 p-value < 0.001 with two-sided t-test

8.3.1 *Dataset*

The publicly accessible parking facility data for the city of Zurich (see Sections 5.3 and 6.3) contain both the locations of on-street (blue and white) and garage parking facilities within the city of Zurich. Thus, each trip in the MOBIS sample can be classified as having parked on-street or in a garage based on the parking facility nearest to the trip end coordinate. However, given that it is not permitted to park longer than the posted time limit in some publicly accessible on-street parking spaces, the total parking duration for each trip must be considered when making the assignment.

Parking duration is computed as the time elapsed between the car trip end coordinate and the start of the next car trip. The distributions of the computed parking duration by trip purpose are shown in Table 8.8. As expected, parking duration is longest at home (mean and median values of 19.8 h and 13.6 h) and at work (mean and median values of 6.1 h and 3.9 h), while it is shortest for shopping trips (mean and median values of 3.5 h and 0.6 h). Overall, vehicles are parked on average for 8.6 hours after a given trip. Trips where vehicles are parked for more than 24 hours are removed from subsequent analysis, yielding a remaining 10,602 trips representing 1,125 participants, i. e., 92.5% of the original sample in terms of trips and 97.7% in terms of participants.

Table 8.8: Parking duration by trip purpose, sorted by mean duration

Trip purpose	Parking duration [h]						
	mean	std	10%	25%	50%	75%	90%
Home	19.8	28.6	1.0	6.0	13.6	20.5	42.8
Work	6.1	11.8	0.3	1.1	3.9	9.0	10.8
Other	5.5	12.3	0.1	0.2	1.0	4.5	15.0
Leisure	5.4	15.2	0.2	0.8	1.9	4.0	12.2
Shopping	3.5	9.1	0.1	0.2	0.6	1.9	9.7
All	8.6	18.5	0.2	0.8	2.9	10.2	19.2

The nearest legal parking facility of each type, considering parking duration, is matched to the parking search end coordinate of each trip, the distributions of which are shown in Table 8.9. Most trips end closer to on-street parking (mean distance of 206 m) than to garage parking facilities (mean distance of 325 m). Further subdividing on-street parking into blue and white zones, the average distance from the nearest legal blue-zone space is 80 m and 255 m from the nearest legal white zone space. When considering all parking facility types combined, the average trip ends within 115 m of a legal public parking facility, while 49% of trips end within 50 m, 64% within 100 m and 79% within 200 m of a legal public parking facility.

TABLE 8.9: Distance to the nearest parking facility by type

Parking facility type	Distance to the nearest parking facility [m]						
	mean	std	10%	25%	50%	75%	90%
On-street parking	206.0	277.7	3.8	13.7	67.3	317.4	611.2
Blue zone	80.2	108.5	3.3	10.9	46.0	100.8	202.5
White zone	254.8	269.4	10.1	45.5	165.3	378.8	626.6
Parking garage	324.9	242.5	66.5	142.6	269.5	439.8	674.7
All	115.0	144.8	3.8	13.0	51.7	170.4	324.7

The high share of trips ending far away from publicly accessible parking might be due to a few reasons. First, 72% of trips which end more than 100 m from a public parking space are either home (45%) or work (27%) trips. Thus, private parking may simply be the only available option for these trips. Although data on the number of available private parking spaces on both the plot and building levels exist in Zurich, they were collected in 2007 and are thus largely outdated. Next, the parking facility classification is based on the end coordinate of the car trip stage, and thus relies on the correct segmentation by the GPS tracking app used for the MOBIS study. Given that we expect to observe low travel speeds when participants park, it is plausible that these trip segments are incorrectly identified as walking and that the car trip stage ends prematurely, thus increasing the distance to the nearest parking facility. Finally, the mean parking duration for trips ending within 100 m of a public parking space is about 3 hours, while it is 8.6 hours for those ending further than 100 m away. Additionally, over 95% of these far-away trips are parked more than 1 hour and over 88% are parked more than 2 hours, thus excluding all blue-zone parking and a large share of white-zone parking as a legal parking option. These high parking duration values can be due to either errors in the mode labelling performed by the tracking app, or simply to missing GPS data, which in both cases would increase the duration between subsequent car trips. In fact, when ignoring parking duration during assignment, the average trip ends within 32 m of a public parking space and 90% of trips end within less than 80 m of a public parking facility. However, parking duration does indeed limit on-street parking options and needs to be considered. We therefore choose a more conservative stance by considering parking duration during assignment and exclude all trips ending more than 100 m from any publicly accessible parking spaces from further analysis, yielding a remaining 6,766 trips representing 1,031 participants, i. e., 59% of the original sample in terms of trips and 89.6% in terms of participants.

The remaining trips are then classified based on the type of parking facility nearest to the trip's end coordinate: on-street parking or parking garage. The results of this classification are shown in Table 8.10, for all trips and by trip purpose. Based on this classification, 84.6% of trips end nearest to a legal on-street parking space, while 15.4% end nearest to a parking garage[4]. The share of trips ending nearest to a parking garage is lowest for home and leisure trips at 12.5% and 12.2% respectively, while it is highest for shopping and work trips at 17% and 20% respectively.

TABLE 8.10: Share of trips by assigned parking facility type

Trip purpose	Assigned parking facility [%]	
	Parking garage	On-street parking
Leisure	12.2	87.8
Home	12.5	87.5
Other	14.1	85.9
Shopping	17.0	83.0
Work	20.0	80.0
All	15.4	84.6

However, the ultimate goal is to model the decision of parking on-street or within a parking garage given the expected parking search and egress walk distances as well as parking costs. Given that parking is often readily available at both home and work in the form of private parking, these trips were removed from the data. Additionally, all trips with either only a parking garage or a legal on-street parking option within a 1 km radius from the destination were removed, as there is no real choice in these cases. Finally, all trips in the dataset consist of the last portion of the trip within 1 km radius around the destination. For some trips, the start coordinate

4 Montini *et al.* (2012) report shares between 5% and 15% depending on the city district.

already lies within this radius, and the trip thus never crosses the boundary. To ensure consistency, all trips which started within this 1 km radius were removed. For the remaining trips, non-chosen alternatives are constructed for the unobserved parking option:

PARKING GARAGE The parking garage nearest to the destination was selected for trips that were observed to have parked on-street, and the travel distance was obtained by routing this trip using the Google Maps Directions API[5]. Egress walk distances were taken as the Euclidean distance between the parking garage and destination, multiplied by a 1.4 detour factor, and the parking costs were calculated for the observed parking duration using the results of the parking garage cost regression model presented in Table 6.25.

ON-STREET For trips that were observed to have parked in a parking garage, search and egress distances are estimated using average values for trips ending near the destination from the rest of the dataset. First, for a given trip for which the unobserved on-street parking attributes need to be estimated, we consider the set of all trips which were observed to have parked on-street, or in cases where it would not have been legal to park in a blue-zone space, the set of all white-zones observations. Then, we select the subset of trips for which the destination lies within 100 m of the destination of the trip to be estimated, and we increase this distance until we have selected at least 20 trips. From this subset of trips, the mean search and egress distance (Euclidean distance multiplied by a 1.4 detour factor) are used as estimates for the expected values of the unobserved on-street parking option attributes, while the cost of the white-zone parking space nearest to the trip's final destination are used as a worst-case estimate of the expected on-street parking cost.

8.3.2 *Regression analysis*

The choice of parking in a parking garage is modelled using a binary logistic regression formulation (see Equation (6.1)), where the utility of parking in parking option $i \in \{\text{garage, on-street}\}$ is expressed as:

5 https://developers.google.com/maps/documentation/directions/overview

$$
\begin{aligned}
U_i = & \beta_{ASC,i} \\
& + \beta_{travelDistance} \cdot x_{travelDistance,i} \\
& + \beta_{egressWalk} \cdot x_{egressWalk,i} \\
& + \beta_{parkingCost} \cdot x_{parkingCost,i}
\end{aligned}
\tag{8.4}
$$

Table 8.11 summarizes the descriptive statistics of the independent variables, as well as of the difference between the garage and on-street values, as this is what ultimately matters for the binary model in Equation (8.4).

Table 8.11: Parking type choice, descriptive statistics

Selected option	Variable	Statistics mean	std	10%	25%	50%	75%	90%
Garage	Travel distance [km]							
(n=217)	parking garage	1.43	0.51	0.99	1.10	1.31	1.57	2.10
	on-street parking	1.40	0.15	1.23	1.30	1.38	1.47	1.61
	difference	0.03	0.48	-0.42	-0.26	-0.08	0.19	0.64
	Egress walk [km]							
	parking garage	0.17	0.16	0.03	0.06	0.12	0.20	0.43
	on-street parking	0.19	0.07	0.10	0.14	0.17	0.22	0.28
	difference	-0.02	0.18	-0.18	-0.11	-0.05	0.04	0.20
	Parking cost [CHF]							
	parking garage	4.51	5.63	0.42	0.96	2.30	5.40	12.83
	on-street parking	3.32	4.70	0.0	0.5	1.0	4.5	9.0
	difference	1.19	6.02	-2.31	-0.17	0.53	2.53	9.22
On-street	Travel distance [km]							
(n=2536)	parking garage	1.49	0.56	0.97	1.17	1.41	1.68	2.04
	on-street parking	1.40	0.51	0.97	1.09	1.28	1.54	1.95
	difference	0.09	0.71	-0.62	-0.22	0.08	0.41	0.78
	Egress walk [km]							
	parking garage	0.43	0.30	0.10	0.20	0.36	0.56	0.90
	on-street parking	0.16	0.15	0.04	0.07	0.12	0.20	0.33
	difference	0.27	0.35	-0.10	0.04	0.23	0.45	0.78
	Parking cost [CHF]							
	parking garage	5.33	8.97	0.44	0.77	2.13	5.76	13.04
	on-street parking	0.97	2.55	0.0	0.0	0.0	0.5	3.0
	difference	4.36	9.21	0.01	0.48	1.33	4.83	11.85

The median values in Table 8.11 are already insightful as they hint at some of the trade-offs people make when selecting between a garage and on-street parking. The median travel distance to a parking garage is shorter than to on-street parking for those who were observed to park in a garage, while it is longer for those who used on-street parking. The same trend is observed when considering egress walking distance: parking garages are closer to the destination in cases where respondents were observed to park in a garage, and are longer in cases where on-street parking was used. On average, parking garage costs are higher than the costs for on-street parking. However, the difference in average costs is lower in cases where respondents were observed to park in a garage than in cases where on-street parking was used.

The logistic regression model is then estimated using the Apollo R-package version 0.2.8 (Hess and Palma, 2019), accounting for the panel structure in the data, i. e., that there are multiple trips per respondent. The estimated coefficients and robust standard errors are shown in Table 8.12, where all coefficients are significant and have the expected signs. The respondents have a general preference for parking on-street, indicated by the negative constant, and the probability of parking in a parking garage additionally decreases as the travel and egress distances as well as costs increase with respect to the on-street option. A similar model considering travel and egress times was also estimated; however, the coefficient for travel time was positive. The difficulty in estimating such a time-based model stems from the fact that observed travel times not only include parking search behaviour, but also traffic conditions such as congestion, and thus might not be a stable indicator of the expected amount of parking search for a given parking option. Nevertheless, the estimated distance-based model can be readily converted to a time-based model by assuming average car travel and walking speeds. E. g., assuming an average car travel speed during parking search of 15 km/h and a walking speed of 5 km/h yields coefficients for travel time and egress time of -3.42 h^{-1} and -16.95 h^{-1} respectively.

Marginal probability effects (MPE) are computed as the difference in the predicted probability for each observation due to a 10% increase in the independent variable and are shown in Table 8.13. Increasing the travel time to find a parking garage by 10% decreases the probability of parking there by 0.2%, whereas increasing the expected travel time to find on-street parking by 10% increases the probability of going to a garage by 0.2%. Egress walk has a more substantial effect, whereby a 10% increase in egress

TABLE 8.12: Parking type choice, logistic regression model results

Variable	Coef.	SE
Constant (reference: on-street)	-1.778^{***}	0.105
Travel distance [km]	-0.228^{*}	0.117
Egress walk [km]	-3.390^{***}	0.301
Parking cost [CHF]	-0.101^{***}	0.019
# individuals:	743	
# observations:	2470	
ρ^2:	0.6537	
$\mathcal{LL}_{null}$	−1712.07	
$\mathcal{LL}_{final}$	−588.90	

Standard errors: $^{***}: p < 0.005$, $^{**}: p < 0.01$, $^{*}: p < 0.05$

walk distance from a parking garage decreases the probability of parking there by 0.5%, whereas a 10% increase in the expected egress walk distance from on-street parking increases the probability of going to a garage by 0.5%. Finally, increasing the average cost of parking in a parking garage by 10% decreases the probability of parking there by 0.2%, whereas a 10% increase in on-street parking costs increases the probability of going to a garage by 0.1%.

TABLE 8.13: Parking type choice, marginal probability effects

Variable	MPE [%]
Travel distance, 10% increase	
to parking garage	-0.2
to on-street parking	0.2
Egress walk, 10% increase	
from parking garage	-0.5
from on-street parking	0.5
Parking cost, 10% increase	
parking garage	-0.2
on-street parking	0.1

Willingness to pay (WTP) indicators are additionally derived by dividing each coefficient by the parking cost coefficient and are shown in Table 8.14. Respondents are willing to pay an additional 2.27 CHF to reduce parking search distance by 1 km, or using more realistic search distances, to pay 0.23 CHF to travel 100 m less to find parking. Assuming a mean parking search travel speed of 15 km/h, this would translate into a WTP to reduce parking search time of about 34 CHF per hour, which is consistent with previous parking location choice studies in Switzerland using stated-preference data. Indeed, Weis *et al.* (2012) report a WTP to reduce parking search time between 33.70 and 36 CHF per hour, depending on the regression model used. Respondents are also willing to pay 3.37 CHF more to have to walk 100 m less from their parking location to their final destination. Reducing walking distance is thus valued more than in-vehicle travel distance.

TABLE 8.14: Parking type choice, willingness to pay

Variable	WTP	Unit
Travel distance	2.27	[CHF/km]
Egress walk	33.69	[CHF/km]

8.4 CONCLUSIONS

Using segmented and labelled GPS data collected from a smartphone-based GPS tracking app, this chapter first analyzes the extent of parking search behaviour in Zurich, Switzerland, as well as how this depends on both socioeconomic characteristics of the participants as well as trip attributes, e. g., location, time of day, purpose and the availability of parking at the destination. GPS data corresponding to over 10,000 car trips ending within the city of Zurich are map-matched to the underlying OSM road network, and the least-cost path between the trip start and end point is then routed on the same network.

Different parking search metrics are computed, as well as the share of trips where these metrics are above certain thresholds. In addition to varying across both socioeconomic attributes as well as by location and time of day, these metrics are found to vary depending on the trip purpose, with leisure and shopping trips resulting in higher values for all metrics and home and work trips in lower values. The availability of parking at home and type of parking at work also play a strong role, with on-street parking leading to longer excess and duplicate travel and higher shares of trips exhibiting parking search. Overall, the share of trips exhibiting parking search varies between 10.3% and 20.8% depending on the trip purpose, and between 13.2% and 15.9% overall. These estimates are higher than previous estimates by Weinberger *et al.* (2020) making use of GPS data, but still less than the 30% suggested by Shoup (2006). The overall share of cruising traffic and average parking search time for Zurich are estimated at around 8.5% and 2.9 minutes, both substantially less than the mean values of 30% and 8.1 minutes estimated by Shoup. The average parking search times estimated for the central Zurich district are also about half those estimated by previous studies conducted in Zurich (Cao *et al.*, 2019).

In a second step, this chapter also explores the choice between searching for on-street parking or parking in a parking garage. Trips are classified as having parked on-street or in a parking garage based on the publicly accessible parking facility nearest to the car trip stage end coordinate, while considering only the parking spaces that can be legally used given the observed parking duration. Based on this classification, on-street parking is observed to be overwhelmingly preferred to parking garages (about 85% of trips); however, parking garages are slightly more commonly used for both shopping and work trips (17% and 20% of trips respectively). The travel and egress walk distances and parking costs of the observed parking location are used for the selected parking option, and are estimated for the non-chosen alternative: by routing to the parking garage closest to the destination for the unobserved garage option or by computing average attribute values from on-street trips ending nearby the final destination for the unobserved on-street option. The choice of searching for on-street parking or parking in a parking garage is modelled using a logistic regression formulation, excluding home and work trips, and all estimated coefficients are significant and present the expected signs. Egress walk distance has the most substantial, albeit small, effect on the probability of parking in a garage, whereby a 10% increase in egress walk distance from a parking garage decreases the probability of parking there by 0.5%. Willingness to pay indicators are also derived, indicating that respondents are willing to pay 0.23 CHF to travel 100 m less to find parking, similar to previous estimates for Switzerland (Weis *et al.*, 2012), and to pay 3.37 CHF to have to walk 100 m less from their parking location to their final destination. Reducing walking distance is thus valued more than in-vehicle travel distance.

9

INTEGRATION INTO AN AGENT-BASED TRANSPORT SIMULATION

This chapter discusses first steps on better integrating parking search behaviour within the MATSim agent-based transport simulation framework for Switzerland. An agent-based transport simulation which includes parking should at least consider the following aspects:

- The simulation should contain detailed information on parking supply (e. g., the availability of private parking at home and work, characteristics of on-street parking and parking garages, etc.).
- Agents should choose between different parking strategies (e. g., parking in a private parking space, driving to a parking garage, searching for on-street parking, etc.) based on their preferences and depending on the availability and characteristics of each option.
- The characteristics of parking at the destination (i. e., expected search times, egress walk times and parking costs) should influence an agent's choice to travel by car.
- The simulation should simulate the entire trip, including the access walk to the parked vehicle, the entire drive to the next parking location (including parking search) and the subsequent egress walk to the final destination.
- The availability of parking should impact car travel times, both by the agent having to search for parking as well as the congestion imposed on others.

With these considerations in mind, and based on the findings from the previous chapters in this thesis, this chapter proposes a methodology for simulating parking within the MATSim agent-based simulation framework. It first discusses the integration of detailed information on parking supply within the synthetic population for Switzerland, before presenting the necessary improvements to be made to the existing framework in order to meet the different considerations listed above. Finally, it concludes by presenting some initial simulation results and discussing limitations and future work.

9.1 SYNTHETIC POPULATION GENERATION

A central step in generating a synthetic population for Switzerland is matching sampled census individuals, which form the basis of the synthetic population, to observations from the MTMC. It is in this way that synthetic agents are assigned activity chains which will eventually become their daily plans within the context of MATSim. More precisely, observations from both datasets are matched using the statistical matching procedure described in detail by Hörl and Balać (2021b). The basic idea behind this procedure is to define a list of attributes on which to match, find all MTMC observations that correspond to these attributes and use their respective observation weights to sample one of them to attach to the target census observation. The attributes thereby act as a restriction on which observations can be sampled and are therefore added sequentially while ensuring a minimum number of observations to sample from; once this threshold has been reached, no more restrictive attributes are added.

The matching procedure is applied in two stages. First, each household head in the sample of census individuals is matched to a MTMC household and then enriched with the following household-level attributes: household monthly income, number of cars and number of bikes. The attributes used for the matching are, in order of application: age, gender, marital status, household size and municipality type. The MTMC household weights are used for the sampling and a minimum of 20 MTMC observations are required to sample from. Persons within households that could not be matched to any MTMC observation are removed from the synthetic population.

Once the household-level attributes have been assigned to the synthetic population households, a second person-level matching is carried out on the entire synthetic population using the following attributes: age, gender, marital status, household size, municipality type, household monthly income, number of cars and number of bikes. The MTMC person weights are used here for the sampling, again with a required minimum of 20 MTMC observations. Unmatched persons, other than those below the age of 6 for which no MTMC observations exists, are removed from the synthetic population.

Imputation of parking availability

Although information on parking availability at home is available in the MTMC, it is basically certain that the matched census individual lives in a different municipality, let alone a different canton entirely, than the MTMC individual. Even the municipality type may well be different, as it only appears later in the list of matching attributes and might therefore never be considered in some instances. In addition, given that the information on household car ownership comes from the first household head matching stage, the newly synthesized household's car ownership will likely differ from that of each individual MTMC observations. Finally, simply carrying over the information on parking availability at home from the original MTMC observation cannot ensure that this information is consistent among synthesized household members. All these factors make it necessary to impute parking availability at home for the synthesized household. This is done using the parking availability model presented in Table 6.9 and the following attributes of the synthesized household: car availability, household size, household monthly income, public transit service quality, population density and region of the home municipality.

Once household parking availability has been imputed and assigned to each household, we can move on to determining the availability of parking at work for each employed agent. Work locations are assigned to each employed agent by drawing candidate work municipalities from mode-specific origin-destination matrices obtained from the Swiss Structural Survey, for which precise locations obtained from the Swiss enterprise registry are subsequently sampled from a multinomial distribution using the number of employees as a weight. As was the case for parking availability at home, parking availability at work cannot be simply carried over from the MTMC observation, as both the home and work locations of the synthesized agent differ from the original observation. As a result, parking availability at work is imputed using the availability model presented in Table 6.16 with the following attributes for the synthesized agent: gender, workload, household monthly income, public transit service quality for both the home and work municipalities and population density of the work municipality.

Now that parking availability at the home and work locations of each agent has been determined, this information is added to the plan files required by the MATSim simulation framework, both as a person-level as well as an activity-level attribute.

Validation of imputation

Table 9.1 compares the synthetic population with the MTMC in terms of overall population shares as well as the share of individuals with parking available at home across different socioeconomic and spatial characteristics of the households. Both the original imputation method consisting of directly copying information on parking availability at home from the MTMC data during statistical matching as well as the imputation using the model presented in Table 6.9 are compared.

In order to quantify the quality of the imputation, the weighted root mean square error (wRMSE) between the MTMC and imputed parking availability shares, using the sample shares for each variable as weights, is computed as

$$wRMSE_{i,s} = \sqrt{\frac{\sum_{k=1}^{N} w_{s,k} \left(x_{m,k} - x_{i,k}\right)^2}{\sum_{k=1}^{N} w_{s,k}}} \tag{9.1}$$

where $x_{m,k}$ is the share of MTMC individuals with parking available for variable k, $x_{i,k}$ is the share of synthetic population individuals with parking available for variable k using imputation method $i \in \{copy,\ model\}$ and $w_{s,k}$ is the associated weight taken as the share of individuals corresponding to variable k within the sample $s \in \{\text{MTMC, Synpop}\}$.

The wRMSE values for the parking availability at home imputation are shown in Table 9.2. The parking availability imputation using the estimated availability model performs substantially better than directly copying across all spatial variables, as indicated by the lower wRMSE values for both types of sample weights. Concerning socioeconomic variables, the model is better at capturing the changes in parking availability at home for different household sizes than the imputation by directly copying, whereas directly copying performs better when considering the number of cars in the household and the household monthly income. Nevertheless, the model performs better on average across all considered variables than the original copying procedure.

TABLE 9.1: Comparison of imputed parking availability at home between MTMC and synthetic population

Variable	Share of sample [%]		Share with parking available at home [%]		
	MTMC	Synpop	MTMC	Synpop	
				Copy[1]	Model[2]
Household size					
1	34.0	35.8	60.8	58.7	60.9
2	35.5	33.0	83.6	84.0	83.9
3	12.9	11.4	84.7	79.9	89.7
4	12.5	12.2	89.2	90.6	88.7
5 or more	5.0	7.6	89.0	90.0	89.0
Number of cars					
0	21.7	22.4	22.3	19.9	28.1
1	48.9	47.5	89.9	89.6	90.0
2	23.3	22.7	95.6	95.6	94.4
3 or more	6.1	7.4	96.5	94.3	92.2
Household monthly income					
Less than 4000 CHF	17.7	21.3	56.8	57.0	59.4
4001 - 8000 CHF	32.9	41.9	76.7	75.7	76.3
8001 - 12000 CHF	17.5	22.8	85.5	86.1	87.2
12001 - 16000 CHF	6.8	7.1	87.2	86.1	89.8
More than 16000 CHF	4.5	6.8	89.8	88.9	93.1
Unknown	20.6	–	81.3	–	–
Region					
Swiss Plateau	22.4	21.6	78.3	73.7	75.7
Northwestern Switzerland	13.7	13.2	75.2	74.6	77.4
Eastern Switzerland	13.6	13.8	83.6	77.9	82.8
Lake Geneva	18.4	18.8	73.7	77.9	74.2
Ticino	4.5	4.7	79.0	74.2	76.4
Central Switzerland	9.2	9.1	84.6	80.0	84.9
Zurich	18.3	18.7	70.6	73.2	74.6

Continued on next page

Table 9.1 – continued from previous page

Variable	Share of sample [%]		Share with parking available at home [%]		
	MTMC	Synpop	MTMC	Synpop	
				Copy[1]	Model[2]
Population density					
High	28.7	32.1	55.8	70.2	63.8
Intermediate	49.5	50.5	84.4	75.8	81.6
Low	21.8	17.4	88.0	85.5	89.7
Public transport quality					
A	17.0	18.8	47.9	68.3	59.6
B	20.6	20.8	68.7	71.3	69.5
C	22.0	22.5	83.7	74.7	81.7
D	24.9	23.6	89.4	82.2	86.8
None	15.6	14.3	90.3	82.7	89.3
Overall	–	–	77.0	75.7	77.3

[1]Copied directly from MTMC observation

[2]Imputed using model in Table 6.9

TABLE 9.2: Comparison of wRMSE for parking availability at home using both imputation methods

Variable	wRMSE weighted by			
	MTMC sample		Synpop sample	
	Copy[1]	Model[2]	Copy[1]	Model[2]
Household size	2.20	1.82	2.14	1.71
Number of cars	1.26	2.96	1.30	3.04
Household monthly income	0.81	1.85	0.81	1.84
Region	4.08	2.35	4.09	2.36
Population density	9.87	4.78	10.25	5.00
Public transport quality	10.57	5.11	10.88	5.34
Average	4.80	3.14	4.91	3.22

[1]Copied directly from MTMC observation

[2]Imputed using model in Table 6.9

Table 9.3 similarly compares the synthetic population with the MTMC in terms of the share of individuals with parking available at work, across different socioeconomic attributes and spatial characteristics of both the home and work locations. Here, the original imputation method consisting of directly copying information on parking availability at work from the MTMC data during statistical matching is compared to the imputation using the model presented in Table 6.16. It is important to note that all computed shares only consider individuals (both MTMC and synthetic population) with at least one work trip within their daily travel plan. In addition, only MTMC observations with known parking availability at work are considered in the comparison.

Table 9.2 shows the wRMSE values for the parking availability at work imputation, again computed according to Equation (9.1). The imputation of parking availability at work using the estimated availability model performs substantially better than directly copying across nearly all considered variables for both types of sample weights; only in the case of gender does the copying procedure perform better. As was the case with parking at home, the main advantage of using the availability model is that it is substantially better at capturing the changes in parking availability across different spatial attributes. Given that spatial characteristics such as population density and public transport quality also influence accessibility and travel times for different travel modes, it is therefore important to adequately impute parking availability across these same spatial variables to be able to capture its influence on mode choice behaviour.

TABLE 9.3: Comparison of imputed parking availability at work between MTMC and synthetic population

Variable	Share of sample^{+} [%]		Share with parking available at work^{+} [%]		
	MTMC*	Synpop	MTMC*	Synpop	
				Copy^{*1}	Model^{2}
Gender					
Female	41.2	42.1	68.9	68.2	70.3
Male	58.8	57.9	81.5	80.9	79.3

Continued on next page

Table 9.3 – continued from previous page

Variable	Share of sample+ [%]		Share with parking available at work+ [%]		
	MTMC*	Synpop	MTMC*	Synpop	
				Copy*1	Model2
Age					
18 - 24	8.2	7.9	73.9	65.0	78.0
25 - 30	11.6	11.6	73.8	77.8	77.9
31 - 45	34.0	34.8	76.1	74.0	72.9
46 - 65	43.9	42.8	77.6	79.1	76.0
Over 65	2.4	2.9	77.1	62.9	82.7
Workload					
Full time	69.7	67.0	78.8	79.4	78.4
Part time	30.3	33.0	70.6	68.3	69.6
Household monthly income					
Less than 4000 CHF	5.3	7.9	66.0	71.4	70.3
4001 - 8000 CHF	33.1	37.7	76.2	74.9	72.8
8001 - 12000 CHF	27.3	31.6	76.9	78.5	77.2
12001 - 16000 CHF	13.3	11.3	78.9	79.4	78.6
More than 16000 CHF	8.8	11.4	80.5	69.0	80.0
Unknown	12.2	–	74.0	–	–
Home region					
Swiss Plateau	22.0	21.8	80.5	76.6	78.0
Northwestern Switzerland	13.7	13.2	77.9	72.4	73.1
Eastern Switzerland	13.7	13.7	81.1	72.4	84.2
Lake Geneva	17.7	19.7	72.3	73.8	73.8
Ticino	3.5	4.2	61.6	76.1	66.0
Central Switzerland	10.0	9.5	80.5	82.1	77.8
Zurich	19.4	17.9	71.3	77.8	70.4
Home population density					
High	27.0	30.8	64.4	72.0	65.5
Intermediate	50.1	49.5	79.1	75.2	78.4
Low	23.0	19.7	84.2	81.5	83.8

Continued on next page

Table 9.3 – continued from previous page

Variable	Share of sample+ [%]		Share with parking available at work+ [%]		
	MTMC*	Synpop	MTMC*	Synpop	
				Copy*1	Model2
Home public transport quality					
A	15.9	18.2	62.4	75.4	61.8
B	18.1	19.1	70.4	71.7	71.0
C	22.4	22.5	76.1	73.9	78.9
D	27.1	24.9	82.9	78.6	80.4
None	16.5	15.3	85.7	78.1	84.4
Work region					
Swiss Plateau	21.4	21.2	81.3	76.2	77.6
Northwestern Switzerland	12.3	12.4	76.8	71.0	74.9
Eastern Switzerland	12.9	12.8	80.5	73.1	84.2
Lake Geneva	18.1	20.0	72.8	74.4	74.2
Ticino	3.6	4.0	62.4	77.3	66.7
Central Switzerland	10.0	9.5	81.7	86.5	78.7
Zurich	21.8	20.1	71.5	75.1	69.7
Work population density					
High	42.0	41.4	65.5	72.4	62.6
Intermediate	46.1	46.6	83.0	76.2	83.4
Low	11.8	11.9	88.9	84.6	89.3
Work public transport quality					
A	33.1	33.7	58.0	74.6	57.4
B	20.5	19.7	77.9	76.0	74.1
C	19.4	18.8	87.4	73.5	86.9
D	17.2	16.6	88.3	75.7	89.8
None	9.9	11.1	91.6	81.3	92.2
Overall	–	–	76.3	75.6	75.5

*Only considering MTMC observations with known parking availability at work

+Only considering persons with a work trip in daily plan

1Copied directly from MTMC observation

2Imputed using model in Table 6.16

Table 9.4: Comparison of wRMSE for parking availability at work using both imputation methods

Variable	wRMSE weighted by			
	MTMC sample		Synpop sample	
	Copy[1]	Model[2]	Copy[1]	Model[2]
Gender	0.64	1.91	0.64	1.90
Age	3.96	2.95	4.06	2.97
Workload	1.36	0.64	1.41	0.66
Household monthly income	4.06	2.35	4.34	2.43
Home region	5.84	2.79	5.90	2.80
Home population density	4.99	0.78	5.17	0.80
Home public transport quality	6.54	1.96	6.75	1.93
Work region	5.51	2.79	5.56	2.78
Work population density	6.60	1.90	6.60	1.89
Work public transport quality	12.93	1.88	12.97	1.85
Average	5.24	2.00	5.34	2.00

[1]Copied directly from MTMC observation

[2]Imputed using model in Table 6.16

Publicly accessible parking facilities

In addition to enriching the synthetic population with imputed information on parking availability at both the home and work locations, the supply of publicly accessible parking facilities, including both on-street parking and parking garages as described in Section 6.3, are stored as MATSim facilities. These facilities are recorded each with their precise coordinates and maximum capacity value, corresponding to the number of parking spaces at the parking facility, along with the parking facility type (i. e. blue zone, low- or high-tariff white zone and parking garage) and maximum permitted parking duration. Each facility is then assigned to the nearest link in the road network, with identical on-street parking facilities in terms of both type and maximum parking duration being aggregated into a single corresponding facility with adjusted capacity on the same link. With this, a synthetic population containing information on parking supply is generated and supplied to the simulation framework.

9.2 MATSIM: SIMULATION AND REPLANNING

This section describes how parking is integrated within the current MATSim scenario for Switzerland, both within the simulation and replanning steps.

Simulation

By default, MATSim simulates all trips as planned, that is from origin directly to destination. The MATSim parking search implementation proposed by Bischoff and Nagel (2017) and schematized in Figure 9.1 subdivides all cars trips into 3 distinct stages (access walk, car, egress walk) separated by 2 car interaction activities (i. e. unparking and parking the vehicle) and dynamically routes the car stage during the simulation in search for a vacant parking space. Non-car trips, on the other hand, are simulated as usual. However, this implementation does not differentiate between different types of parking nor does it consider maximum parking durations; all parking options are identical.

FIGURE 9.1: Flow diagram of car trips including parking

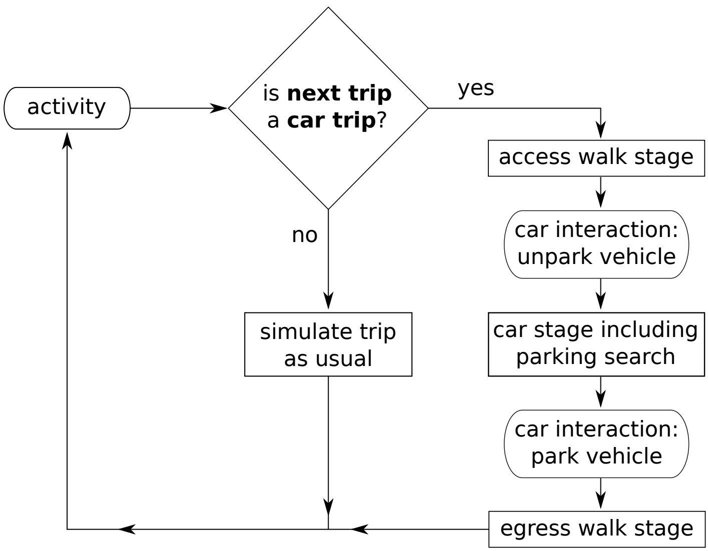
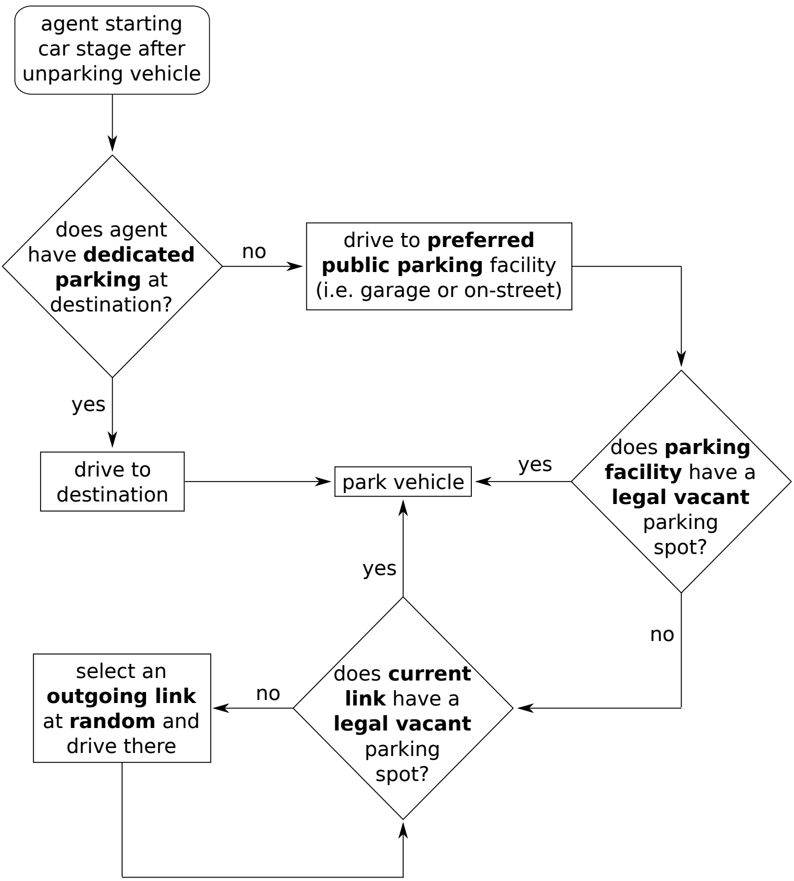


Figure 9.2 shows the flow diagram of the improved parking search algorithm implemented in the course of this thesis, which extends the random search algorithm presented in Section 3.2.2. The algorithm starts at the point where the agent begins the car stage within the car trip after having unparked their vehicle and thus describes the entire second car-trip stage between both car interaction activities in Figure 9.1.

FIGURE 9.2: Flow diagram of parking search algorithm



During population synthesis (see Section 9.1), parking availability at home and work is imputed for each agent, and the parking strategy for the corresponding home and work activities is recorded as *driving to dedicated parking*. In all other cases, this is recorded as requiring to *search for parking*.

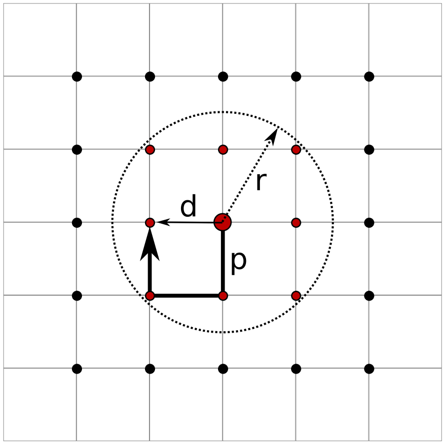
Car trips which end at home or work locations where dedicated parking is available are routed directly there. The agent is then simulated along this route and parks directly at their destination. Otherwise, the car trip is routed to the agent's preferred parking option (i. e. a nearby parking garage or on-street parking facility). The mechanism for selecting this preferred option during the replanning stage is described later in this section. If the preferred option has a legal (with respect to the agent's intended parking duration) vacant parking spot available, the agent parks there. Otherwise, they look for any other legal vacant parking spot on the same link. It is at this point that the search for parking officially starts. If all parking spots on the link are occupied, the agent randomly selects an outgoing link, drives there and searches again for a legal vacant parking spot. This last step is repeated until the agent finds a legal vacant spot to park their vehicle. Note that for home-bound trips, agents without dedicated parking are assumed to have a parking permit and blue-zone parking is thus considered a legal option.

The attentive reader will remark that it is possible for this parking search to drag on indefinitely, notably in the case where all parking options are occupied. To avoid this, a user-defined parking search time limit is introduced, after which the agent is parked illegally on their current link.

During the simulation, average parking search and egress walk distances and times are computed for on-street parking, as schematized in Figure 9.3. As the agent randomly drives from link to link in search of a legal vacant parking spot (path p), the elapsed time and accumulated distance are summed. When the agent finds a legal vacant spot, the egress walk distance (distance d) and corresponding egress walk time are additionally computed. These attributes are then assigned to all network nodes within the extent of nodes visited during the search (radius r), with a minimum radius of 500 m. The attributes are further aggregated based on the 30-minute time bin corresponding to the start of the search, and are averaged across all searching agents. These estimated average parking search attributes, distributed both temporally and spatially, are then available to query in the replanning step prior to the next simulation iteration.

Due the computational cost of simulating such complex transport systems, it is common to simulate only a fraction of the synthetic population, with

FIGURE 9.3: Schema of computation of average on-street parking attributes



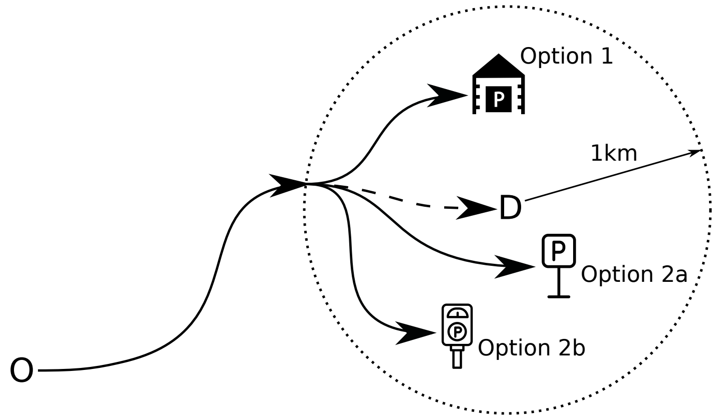
the network storage and flow capacities reduced to the same fraction. On the other hand, parking behaviour is upsampled in a manner similar to what was briefly described in Section 4.2.3, whereby multiple artificial vehicles are generated and stored in nearby vacant parking spots around the location where the agent parked. These vehicles are assigned to the agent and are later all unparked when the agent begins its next car trip. In this way, the effect of the reduced population on parking is accounted for.

Replanning

As introduced in Section 3.3.2, the eqasim framework for MATSim replaces the traditional scoring with a discrete mode choice approach, thus modifying the replanning process (Hörl *et al.*, 2019b). For each replanning agent, feasible tours for their daily plan are constructed while considering both mode availability as well as other constraints. Once these tours have been constructed, attributes relevant to mode choice are estimated for each mode for each trip. Until now, parking-related attributes for the car alternative have not been estimated from previous iterations and have instead been specified as constants within the car utility function (see Equation (3.4)). This section describes the adjustments made to the estimation of the attributes for the utility of the car alternative in order to consider parking.

Figure 9.4 shows the different parking options considered by the car utility estimator. The estimators starts by routing the car trip from its origin activity O to its destination activity D considering the mean observed link travel times from the previous iteration, thus providing a first estimate for the travel time and distance for the car alternative. If the trip is a home or work trip and the agent has dedicated parking available there, they are assumed to prefer this option; the travel times and distances remain unchanged, and the parking search times, access and egress walk times and parking costs for the trip are set to zero.

Figure 9.4: Schema of different parking options considered in car utility estimator



Icons: Parking street by iconpacks from Noun Project,
Parking meter by Graphixs_Art from Noun Project,
Parking garage by SBTS from Noun Project

If the agents do not have dedicated parking available at their destination, they must choose between driving to a parking garage (Option 1) or opting for on-street parking (Option 2a or 2b). Attributes for both options have therefore to be estimated in order to make this choice. The parking type choice model estimated in Section 8.3.2 assumes that agents make the choice of where to park when arriving within a 1-km radius of their destination. Thus, the car path routed directly between O and D needs to be cut back to just outside this search radius, providing a new parking search starting point for which to generate these estimates.

For the parking garage option (Option 1), the least-cost path between the parking search starting point and the parking garage closest to the destination are computed, as is the egress walk distance and parking cost given the planned activity duration. For the on-street parking option, the least-cost path between the parking search starting point and the blue-zone (Option 2a), if legal given the intended parking duration, or white-zone parking spot closest to the destination are computed. As with the simulation, blue-zone parking is always assumed to be legal for home-bound trips. Average parking search and egress walk distances for trips ending in the vicinity of these locations at similar times of day are estimated from the previous iteration (see description of *Simulation* earlier in Section 9.2), while the cost of parking on-street is computed based on parking in that type of on-street parking facility for the intended duration.

Table 9.5 summarizes the values of the different attributes used in the choice of where to park for the different parking options. The choice of parking option is then made based on the model presented in Table 8.12.

Table 9.5: Attributes of parking options considered by parking option selector

Attribute	Parking option	
	On-street parking	Parking garage
Travel distance	to on-street parking facility + estimated search distance	to parking garage
Egress distance	estimated egress distance	distance from garage to destination
Parking cost	based on parking duration	based on parking duration

The characteristics of the selected parking option are then passed on to the utility function for the car alternative within the discrete mode choice model, which has been adapted accordingly. The different attributes for the car utility function, which now depend on the selected parking option, are summarized in Table 9.6. If the agent has dedicated parking, the car attributes are as before: travel time of the routed trip and Euclidean distance both from origin to destination. However, if the agent opts for on-street parking, travel time is taken from the routed trip from origin to the selected on-street parking facility, and the parking search and access and egress walk times are estimated by querying trips at similar times and locations from the previous iteration. Finally, if the agent decides to drive to a parking garage, the travel time is taken from the routed trip from origin to the selected parking garage and the access and egress walk time are based on the distance between the garage and destination, while the parking search time is zero. In both cases, Euclidean distance is computed between the origin and destination activities and the costs are based on parking at the selected parking facility for the intended parking duration. Note that access and egress walk time are computed as twice the estimated value of egress time, since the previous location of the parked vehicle is not stored during the utility computation. However, since car utility is computed on a tour-level, the egress walk time of a previous trip is equal to the access walk of the next trip, and all walk legs will thus be accounted for across the entire tour.

Table 9.6: Car utility attributes for different parking options

Attribute	Parking option		
	Dedicated parking	On-street parking	Parking garage
Travel time	from origin to destination	from origin to on-street facility	from origin to parking garage
Parking search time	–	value estimated from previous iteration	–
Access/egress walk time	–	2 × egress time estimated from previous iteration	2 × walk time from garage to destination
Euclidean distance	from origin to destination	from origin to destination	from origin to destination
Parking cost	–	based on parking duration	based on parking duration

The corresponding car utility function in Equation (3.4) becomes

$$
\begin{aligned}
u_{car} = \ & \beta_{ASC,car} \\
& + \beta_{travelTime,car} \cdot x_{travelTime,car} \\
& + \beta_{searchTime} \cdot x_{parkingSearchTime} \\
& + \beta_{travelTime,walk} \cdot x_{accessEgressWalkTime} \\
& + \beta_{cost} \cdot \left(\frac{x_{euclideanDistance}}{\theta_{averageDistance}} \right)^{\lambda} \cdot x_{cost,car} \\
& + \beta_{parkingCost} \cdot x_{costParking}
\end{aligned}
\tag{9.2}
$$

where the variables for parking search time, access and egress walk time are no longer predefined constants, but rather also directly estimated from previous simulation iterations. Additionally, the coefficient for parking search time is separate from travel time, as previously suggested by Axhausen and Polak (1991), and an extra term also now appears considering the costs of parking. A mode combination for a given tour is then probabilistically selected using a multinomial logit formulation with the updated utility functions.

9.3 RESULTS AND DISCUSSION

This section presents initial simulation results for Zurich using the proposed MATSim simulation including parking within the eqasim discrete mode choice framework. It then continues to briefly discuss some limitations and future work.

The simulation considers a 0.1% sample of all of Switzerland and simulates travel behaviour across the entire country. However, all trips which end outside Zurich are marked as having dedicated parking, and thereby do not have to search for parking, whereas trips ending within the city limits are marked as such only if the agent indeed has parking available (at home or at work). All other trips are thus subject to parking search, effectively limiting the simulation of parking search to within the city of Zurich.

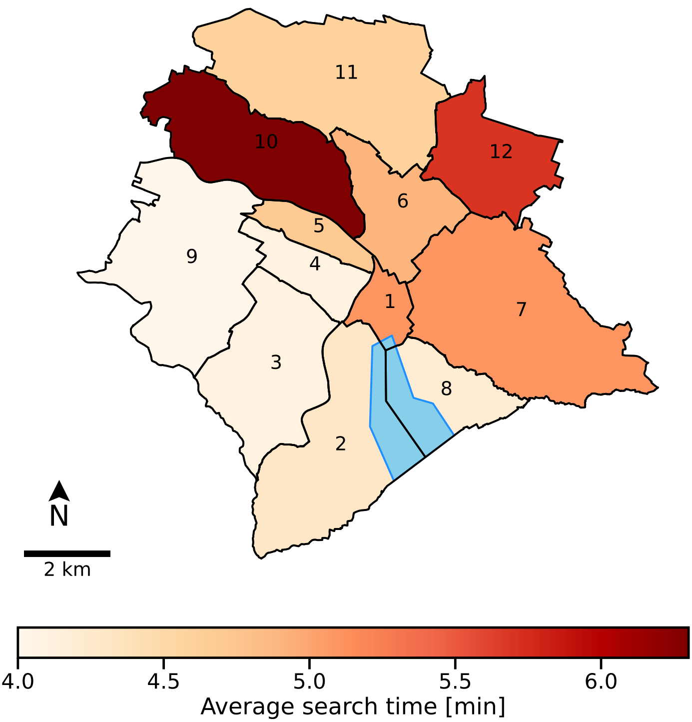
The coefficient values set within the utility functions used for the simulation are based on those previously calibrated by Hörl (2020) and shown in Table 9.7. Although the new utility formulation makes it possible to specify different values for the parking search time and parking cost coefficients within the utility function of the car alternative in Equation (9.2), these have been set to match the parameter values for car travel time and cost, respectively. In addition, a 30-minute parking search time limit is used during simulation.

Figure 9.5 shows the simulated average search times in Zurich for each city district. The values shown here have been capped to 15-minutes to exclude cases of vehicles stuck in traffic. The resulting average search times are comparable to those observed from the MOBIS study GPS data and shown in Figure 8.3b. Search times are generally greater in the central districts than in the periphery; however, there are notable outliers in districts 10 and 12.

TABLE 9.7: Parameters for the mode choice model used in the parking simulation

Transport mode	Parameter	Value	
Car	$\beta_{ASC,car}$	0.827	
	$\beta_{travelTime,car}$	-0.067	[min^{-1}]
	$\beta_{searchTime,car}$	-0.067	[min^{-1}]
	$\beta_{parkingCost,car}$	-0.126	[CHF^{-1}]
Public transport	$\beta_{ASC,pt}$	0.0	
	$\beta_{numberOfTransfers,pt}$	-0.17	
	$\beta_{inVehicleTime,pt}$	-0.019	[min^{-1}]
	$\beta_{transferTime,pt}$	-0.038	[min^{-1}]
	$\beta_{accessEgressTime,pt}$	-0.08	[min^{-1}]
Bicycle	$\beta_{ASC,bicycle}$	-0.1	
	$\beta_{travelTime,bicycle}$	-0.081	[min^{-1}]
	$\beta_{age,bicycle}$	-0.049	
Walk	$\beta_{ASC,walk}$	0.63	
	$\beta_{travelTime,walk}$	-0.141	[min^{-1}]
Other	β_{cost}	-0.126	[CHF^{-1}]
	λ	-0.4	
	$\theta_{averageDistance}$	40.0	[km]

Figure 9.5: Simulated average parking search time in minutes, by Zurich city district



The differences between the simulated and empirically observed parking search times may be attributable to several factors. For one, parking search is dependent on the availability of parking at the destination, which for the simulation ultimately depends on the imputation of parking availability at home and work. Although the imputed shares of parking available at home and work both match the MTMC shares at a national and regional level (see Tables 9.1 and 9.3), this is not the case at the city district level, as can be seen in Table 9.8. The imputed share of Zurich households with parking available at home is substantially larger overall (61.8% versus 39.6%) than what is observed in the MTMC, as well as for nearly every city district. The overall imputed share of persons with parking available at work within the city of Zurich is also larger than what is observed in the MTMC; however, the imputed shares are also substantially lower for some city districts (e.g. districts 9 through 12).

Furthermore, the simulated parking search times are highly dependent on congestion levels within the city. Increased parking availability at home and work typically corresponds to higher shares of car travel, as the generalized cost for the car alternative is lower when dedicated parking is available, which in turn leads to higher congestion levels within the city. Alternatively, lower levels of parking availability at work mean that more individuals need to search for parking, further increasing congestion levels. These two contributing factors, along with the low sampling rate and correspondingly low storage and flow capacities within the network, are likely to have a strong effect on the distribution of congestion within the city, and thus on parking search times.

TABLE 9.8: Comparison of parking availability at home and work in MTMC and synthetic population by Zurich city district

District	Share of households with parking available at home in Zurich [%]			Share of persons with parking available at work in Zurich [%]		
	MTMC	Synpop	Difference	MTMC	Synpop	Difference
1	10.7	50.0	39.3	27.2	48.7	21.5
2	41.4	57.1	15.7	80.8	81.2	0.4
3	28.6	60.0	31.4	69.7	68.0	-1.7
4	19.9	46.7	26.8	47.6	51.4	3.8
5	32.1	70.0	37.9	61.4	60.0	-1.4
6	26.1	47.4	21.3	39.6	56.2	16.6
7	41.9	68.8	26.9	38.0	59.1	21.1
8	25.5	87.5	62.0	52.1	71.4	19.3
9	51.1	59.4	8.3	78.0	66.7	-11.3
10	32.5	70.0	37.5	88.8	60.0	-28.8
11	57.9	80.8	22.9	72.4	56.7	-15.7
12	53.1	46.7	-6.4	81.0	33.3	-47.7
Total	39.6	61.8	22.2	56.4	62.2	5.8

Additionally, the current implementation does not fully consider time constraints, both at the simulation and replanning stages. During the replanning stage, two public parking options are provided to the agent in the computation of the utility of the car alternative if they do not have dedicated parking at the destination: on-street parking or a parking garage.

For the on-street parking option, the estimated attributes are based on the blue-zone parking spot closest to the destination (if the agent can legally park in such a parking spot) or the nearest white-zone parking spot. In the latter case, the intended parking duration is not considered, and thus it is possible that an agent is initially directed to a parking spot where they in fact cannot legally park. This can result in high parking search times if there are no other legal vacant options in the vicinity of the selected parking option.

On the simulation side, the upscaling procedure used to correct for the reduced simulated sample size also does not take time constraints into account. While the simulated vehicle is required to find a legal vacant parking spot, the additional vehicles are stored in parking spots around the simulated vehicle without considering whether they can legally park there. In doing so, it is possible for one simulated vehicle to illegally occupy parking spots that could later have been legally occupied by another vehicle, thus resulting in increased parking search times.

The supply of publicly accessible parking included in the MATSim scenario only considers on-street blue-zone and white-zone parking as well as parking garages, thus excluding other types of parking, e. g., parking provided to customers at a store. These private parking options can prove valuable in situations where no other publicly accessible parking options exist in the vicinity of the destination, and their exclusion is a potential source of increased parking search times. However, the most recent survey to include all publicly accessible and private parking spaces within the city of Zurich was conducted in 2007 (Stadt Zürich, 2007), and given its age, was not used in this thesis. More recent data on such parking would therefore be valuable in providing a full detailed description of available parking at the destination.

Finally, the methodology used to aggregate and estimate parking search metrics for the next iteration could be a further source of error. The current approach focuses on measuring parking search for a given trip, distributing the measured values spatially around the location where the search was recorded, aggregating these values temporally and averaging them out across all observations. However, unlike congestion, parking search can occur even when no observations have been made. Indeed, several vehicles might arrive and park around a given location, after which all nearby parking options are occupied until later when the vehicles are unparked. In the meantime, it would be impossible to find vacant parking in the area, whereas the estimated parking search metrics would be zero since no parking search was recorded in the interim period.

Future work should therefore focus on the following aspects. First, the models for imputing parking availability at home and work, which currently focus on reproducing shares at a national and regional level, should be further refined to match MTMC data at a higher spatial resolution. Second, larger samples should be simulated in order to limit congestion induced by the scaling of network capacity. In an attempt to mitigate the increased computational cost inherent with larger samples, one could consider only simulating traffic within a specific radius around Zurich, as opposed to the entire country. Of course, it would be necessary to verify how many agents actually travel to Zurich from further outside this radius in order to quantify the effect such a simplification might have on the simulation. Next, both the simulation and replanning stages need to fully consider the time constraints of the different parking options. This would avoid agents considering the option of parking on-street in areas where they legally cannot do so. Furthermore, more recent data on private parking options provided at certain destinations need to be gathered and included within the scenario. In addition, the estimation of average parking search metrics to be used in subsequent iterations needs to be adapted to consider time periods when no search has been observed, but all parking spots are nevertheless occupied. An estimation procedure based on average parking occupancy rather than observed search and egress times might prove to be a solution. Finally, as discussed previously, the utility function for the car alternative in Equation (9.2) is designed to allow for parking search time and parking cost coefficient which are separate from the coefficients for travel time and travel costs, respectively. However, in the current implementation, these coefficients have not been differentiated. In order to make full use of this added flexibility, the utility function coefficients should be further calibrated, not only against travel time, distance, speed and mode share distributions, but also against parking occupancy counts. Despite these potential improvements, the current implementation nevertheless provides a starting point for simulating travel behaviour including parking within the MATSim discrete mode choice framework for Switzerland.

10

CONCLUSION AND OUTLOOK

As stated at the very beginning of this thesis, parking is arguably the most crucial element of car travel; every car trip starts by interacting with a parked vehicle and ends with having to find a place to store the vehicle once again. Parking thus has profound implications for travel behaviour, which can only truly be understood by studying it at an individual level.

Although one of the objectives of this thesis is to provide data-driven foundations to simulating parking within an agent-based framework, it also aims at answering several research questions related to parking and travel behaviour in Zurich and Switzerland independent of these simulations. This chapter discusses these contributions as well as their policy implications, before providing an outlook to the future.

10.1 SUMMARY

Chapters 1 to 3 introduce and motivate why parking is important and expose some of the current limitations that exist when simulating parking in an agent-based setting, setting the stage for the chapters that follow. As a simulation case study, Chapter 4 explores the potential reductions in parking demand in Zurich following the introduction and massive adoption of free-floating carsharing and helps highlight the fact that there is still room to better utilize existing parking infrastructure.

Chapter 6 first focuses on the current supply of parking in Switzerland, exploring which factors influence the availability of parking at home and work across the country. A large majority of Swiss households have parking available at their place of residence, mainly attributable to car ownership within the household, but additionally influenced by the quality of public transit as well as population density around the home location. Parking is also available to most Swiss employees in some form, and again this availability is mainly affected by population density at the work location as well as the quality of public transit both at work and at home. The chapter continues by narrowing in on publicly accessible parking within the city of Zurich, which is provided under three main forms: free yet time-limited blue zone parking, metered white zone parking and parking garages. White zone parking space are highly concentrated around the central city districts, whereas blue zone parking is mainly located in central districts outside the city centre. Parking garages can be found throughout the city, and their costs generally decrease with increasing distance to the city centre, although precise pricing schemes are lacking for a substantial share of parking garages. Models were thus developed to be able to impute parking garage prices dependent on their location within the city. Parking garages are further shown to be substantially more expensive than metered on-street parking, with the price difference depending on the exact location within the city.

Parking availability can have substantial impacts on mode choice behaviour, favouring extensive car use in situations where parking is facilitated. Chapter 7 examines the effects of employer-provided fringe benefits, including parking at work, on Swiss commuting behaviour. The analysis confirms that company cars, free parking and public transport subscriptions all play a significant role in an employee's choice to commute to work by car. Time-efficient alternatives to the car can have a significant impact in reducing car-based commuting, as can improving the quality of public transit both at home and work. These results help emphasize just how important an employer can be in shaping a person's mobility tool ownership, and thus their commuting behaviour.

Parking search traffic is often considered an important externality caused by the abundance of inadequately priced on-street parking within a city. Chapter 8 thus starts by measuring the extent of parking search present in the city of Zurich using GPS data collected from a smartphone-based tracking app. The results show that although parking search does exist, the overall share of search traffic and the average parking search time in Zurich are substantially less than previous estimates both for Switzerland and abroad. The observed extent of parking search is influenced by the availability of on-street parking as well as the cost of garage parking near the destination, as well as by the familiarity of the driver with the area. Several parking search patterns are also observed, including searching en-route to the parking location, first driving directly to the destination before starting the search, and driving directly to a parking garage. Trip purpose also plays a strong role, with leisure and shopping trips exhibiting higher levels of parking search. The availability of dedicated parking at home and the type of parking used at work also play a strong role in reducing parking search. Most observed trajectories do not exhibit any parking search; drivers simply drive directly towards their destination, parking en route as they approach. For those who do search for parking, the observed trajectories are dictated, at least in part, by the supply of on-street parking along the routes.

Chapter 8 continues by examining which factors influence the choice of searching for on-street parking or driving to a parking garage in the city of Zurich. On-street parking is observed to be overwhelmingly preferred to parking garages independent of trip purpose, although parking garages are slightly more commonly used for both shopping and work trips. Egress walking distance has the most substantial effect on the choice of parking in a garage, followed by parking search distance and parking costs. Reducing walking distance is also shown to be valued more than reducing in-vehicle travel distance when choosing where to park.

In Chapter 9, some of the key results from the previous chapters are then integrated within an agent-based transport simulation of the city of Zurich; the results from Chapter 6 inform the parking availability at home and work for the generated synthetic population as well as public parking supply within the city, whereas the parking type choice model estimated in Chapter 8 is integrated within the discrete mode choice models used within the agent-based simulation framework. Both these elements provide a first step towards a more accurate representation of travel behaviour by explicitly considering parking behaviour and its influence on mode choice within an agent-based simulation.

10.2 LIMITATIONS AND FUTURE WORK

As summarized above, the empirical and simulation work described throughout this thesis provide answers to the different research questions introduced in Chapter 1. This section lists some of the limitations of this work along with proposed improvements.

Chapter 4 provides a best-case estimate for the required parking supply in the city of Zurich following the introduction and massive adoption of free-floating carsharing, but neglects both parking regulations and prices. These parking policies help regulate car travel into the city and control congestion, and removing them could lead to negative impacts such as induced car travel. Instead, such policies could be used to limit inbound private vehicle traffic and thus increase the share of carsharing, further reducing parking demand. Future work on the topic should thus focus on considering parking types, costs and duration limits, and the improved simulation framework presented in Chapter 9 provides a basis for doing so.

The analysis of the impacts of fringe benefits on commuting behaviour, presented in Chapter 7, focused on car-owners recruited within the context of the MOBIS study. Although the sample was weighted to correct for this bias, more recent additions to the study panel now include people without cars. This would allow for the future estimation of mode choice models for all commuters, thereby providing an even more representative picture of the impacts of fringe benefits on commuting behaviour. Finally, the analysis focused on the impacts of claimed employee benefits. However, employees are often given a choice between a package of several benefits and can choose which ones best suit their needs and preferences. Future work should thus focus on understanding the trade-offs made when choosing between a bundle of fringe benefits offered by employers, in line with previous work conducted by Nijland and Dijst (2015), thereby helping to quantify to what extent employers can effectively shape mobility tool ownership in Switzerland. Such models could further be included within the synthetic population generation, providing a means for investigating the impacts of policies aimed at influencing which fringe benefits are offered to employees on both mobility tool ownership and resulting travel behaviour.

The parking search behaviour and parking type choice analysis in Chapter 8 focused solely on Zurich, mainly due to the availability of open public parking data at the time of the study. Given that similar data are also available for other Swiss cities such as Geneva, the GPS data collected there could also be examined with respect to parking behaviour to generalize the results. Similar work could be applied to all Swiss cities within the MOBIS data as detailed parking data become available. The work conducted in Chapter 8 also brings to light some of the difficulties of working with GPS data. Although they provide a rich source of spatio-temporal information, ensuring consistency within the data requires substantial effort. While the current work relies on trip segmentation and labelling directly provided from the GPS tracking app, further improvements could be made in this regard by considering both trip speed profiles and available parking during segmentation to better determine the trip's exact end coordinate and thus the parking location. Initial work in this direction has begun and should be further pursued. In addition, follow-up work in the direction of spatial pattern recognition, parking strategy pattern clustering and parking strategy variability should be explored, as this would provide further insights into parking search behaviour.

10.3 POLICY IMPLICATIONS

In addition to contributing towards an improved agent-based transport simulation framework, and despite some limitations, this thesis does already provide useful parking-related insights with transport policy implications.

Company cars, free parking and public transport subscriptions all play a significant role in an employee's choice to commute to work by car. The results in Chapter 7 underline the fact that a majority of Swiss workers still have free parking options at their place of work, and that the overwhelming majority of those with free parking available to them at work receive it from their employer. On the other hand, a very small share of employees are offered discounted public transit subscriptions, although these are shown to reduce commuting to work by car the most. Given that the choice of purchasing a public transit subscription not only depends on public transit quality at home and work, but also on income, providing discounts could further encourage the purchase of such subscriptions, in turn increasing the likelihood of opting for alternatives to the car. Thus, policies encouraging more Swiss employers to offer discounts on public transit subscriptions instead of company cars and free parking could prove beneficial in reducing the share of car trips to work.

High garage prices and an over-abundance of on-street parking favour higher levels of parking search within the city. Increasing on-street parking prices, or alternatively reducing the price of parking garages, would help steer drivers directly to parking garages and avoid on-street search traffic, although the latter policy might have also have the effect of increasing overall car travel. Similarly, given that increased egress walk distances for on-street parking favours the choice of parking in a parking garage, policies aimed at further reducing the amount of on-street parking in areas where parking garages are present would favour a shift towards parking garages and thus further reduce on-street search traffic. This could further alleviate overall car travel and help reduce congestion within the city.

10.4 OUTLOOK

Besides the aforementioned policy implications of the different empirical studies carried out over the course of this thesis, the improved integration of parking within the MATSim agent-based transport simulation for Switzerland provides a valuable tool for parking policy analysis and as such has the potential to fuel future research on parking policy, both in

Switzerland and elsewhere. Indeed, having a transport simulation that is sensitive to the precise location, availability and price of different parking options allows one to study how these all impact travel behaviour.

In a first application, such a framework could be used to investigate parking pricing policy and derive new optimal pricing structures as a measure to shift travel demand away from privates cars. Such policies could be utilized as an alternative to mobility pricing, which was the original focus of the MOBIS study. Given the stiff political opposition to more general mobility pricing schemes, optimized parking pricing might be a more feasible alternative towards a common objective. The proposed simulation framework could constitute a starting point for such work, and could be used to analyze the potential impacts of such policies in reducing both congestion and other transport externalities.

The framework is also transferable to other study areas contingent on the availability of information on publicly accessible parking. In the context of Switzerland, the methodology developed in this thesis could readily be extended to the second-largest city of Geneva. Open data for on-street parking and parking garages similar to Zurich are also readily available there, as are GPS data containing parking search behaviour from the MOBIS study. It would thus be possible to construct similar garage pricing and parking type choice models and compare them to those developed for Zurich. The effectiveness of parking policies could then be studied and compared for both cities.

Increased advocacy for improved cycling infrastructure will likely come at the cost of on-street parking. Ongoing research is already focusing on the idea of a massive reallocation of road space in Zurich away from cars in favour of cycling. This reconfiguration will also impact the number of on-street parking spaces available within the city. Being able to simulate the effects of such indirect parking reduction policies, in conjunction with improved cycling infrastructure, should provide a more complete assessment of the true impacts of such a policy on future urban travel behaviour.

Parking is key to car travel. The more we grasp the full implications of this, the more we can devise more efficient transport policies towards a more sustainable future.

BIBLIOGRAPHY

Adnan, M., F. C. Pereira, C. Miguel, L. Azevedo, K. Basak, M. Lovric, S. R. Feliu, Y. Zhu, J. Ferreira, C. Zegras and M. E. Ben-Akiva (2015) SimMobility: A multi-scale integrated agent-based simulation platform, paper presented at the *95th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2015.

ARE (2011) ÖV-Güteklassen–Berechnungsmethodik, *Grundlagen*, Bundesamt für Raumentwicklung, Bern.

ARE (2022) Externe Kosten und Nutzen des Verkehrs in der Schweiz. Strassen-, Schienen-, Luft- und Schiffsverkehr 2019, *Grundlagen*, Bundesamt für Raumentwicklung, Bern.

Auld, J., M. Hope, H. Ley, V. Sokolov, B. Xu and K. Zhang (2016) POLARIS: Agent-based modeling framework development and implementation for integrated travel demand and network and operations simulations, *Transportation Research Part C: Emerging Technologies*, **64**, 101–116.

Axhausen, K. W. (1989) Eine ereignisorientierte Simulation von Aktivitätenketten zur Parkstandswahl, Doctoral thesis, Universität Karlsruhe, Karlsruhe.

Axhausen, K. W. and J. W. Polak (1991) Choice of parking: Stated preference approach, *Transportation*, **18** (1) 59–81.

Balać, M., H. Becker, F. Ciari and K. W. Axhausen (2019a) Modeling competing free-floating carsharing operators – A case study for Zurich, Switzerland, *Transportation Research Part C: Emerging Technologies*, **98**, 101–117.

Balać, M., F. Ciari and K. W. Axhausen (2017a) Modeling the impact of parking price policy on free-floating carsharing: case study for Zurich, Switzerland, *Transportation Research Part C: Emerging Technologies*, **77**, 207–225.

Balać, M., F. Ciari and K. W. Axhausen (2017b) Modeling the impact of parking price policy on free-floating carsharing: Case study for Zurich, Switzerland, *Transportation Research Part C: Emerging Technologies*, **77**, 207–225.

Balać, M., A. R. Vetrella, R. Rothfeld and B. Schmid (2019b) Demand estimation for aerial vehicles in urban settings, *IEEE Intelligent Transportation Systems Magazine*, **11** (3) 105–116.

Becker, H., M. Balać, F. Ciari and K. W. Axhausen (2020) Assessing the welfare impacts of Shared Mobility and Mobility as a Service (MaaS), *Transportation Research Part A: Policy and Practice*, **131**, 228–243.

Becker, H., F. Ciari and K. W. Axhausen (2017a) Comparing car-sharing schemes in Switzerland: User groups and usage patterns, *Transportation Research Part A: Policy and Practice*, **97**, 17–29.

Becker, H., F. Ciari and K. W. Axhausen (2017b) Modeling free-floating car-sharing use in Switzerland: A spatial regression and conditional logit approach, *Transportation Research Part C: Emerging Technologies*, **81**, 286–299.

Becker, H., F. Ciari and K. W. Axhausen (2018) Measuring the car ownership impact of free-floating car-sharing – A case study in Basel, Switzerland, *Transportation Research Part D: Transport and Environment*, **65**, 51–62.

Benenson, I., K. Martens and S. Birfir (2008) PARKAGENT: An agent-based model of parking in the city, *Computers, Environment and Urban Systems*, **32** (6) 431–439.

BFS (2010) Fringe benefits survey, *Technical Report*, Bundesamt für Statistik, Neuchâtel.

BFS and ARE (2017) Verkehrsverhalten der Bevölkerung: Ergebnisse des Mikrozensus Mobilität und Verkehr 2015, *Statistik der Schweiz*, Bundesamt für Statistik and Bundesamt für Raumentwicklung, Neuchâtel and Bern.

Bhat, C. R., J. Y. Guo, S. Srinivasan and A. Sivakumar (2004) Comprehensive econometric microsimulator for daily activity-travel patterns, *Transportation Research Record*, **1894** (1) 57–66.

Bischoff, J. and K. Nagel (2017) Integrating explicit parking search into a transport simulation, *Procedia Computer Science*, **109**, 881–886.

Brooke, S., S. BrookeIson and M. Quddus (2014) On-street parking search: Review and future research direction, *Transportation Research Record*, **2469**, 65–75.

Brueckner, J. K. and S. F. Franco (2018) Employer-paid parking, mode choice, and suburbanization, *Journal of Urban Economics*, **104**, 35–46.

Bueno, P. C., J. Gomez, J. R. Peters and J. M. Vassallo (2017) Understanding the effects of transit benefits on employees' travel behavior: Evidence from the New York-New Jersey region, *Transportation Research Part A: Policy and Practice*, **99**, 1–13.

Burchard, P. (2021) Including parking availability and prices in the mode choice modelling, *Master Thesis*, IVT, ETH Zurich, Zurich.

Busch-Geertsema, A., M. Lanzendorf and N. Klinner (2021) Making public transport irresistible? The introduction of a free public transport ticket for state employees and its effects on mode use, *Transport Policy*, **106**, 249–261.

Bösch, P. M., F. Ciari and K. W. Axhausen (2016) The IVT 2015 baseline scenario, paper presented at the *16th Swiss Transport Research Conference*, Ascona, May 2016.

Cairns, S., C. Newson and A. Davis (2010) Understanding successful workplace travel initiatives in the UK, *Transportation Research Part A: Policy and Practice*, **44** (7) 473–494.

Cao, J., M. Menendez and R. Waraich (2019) Impacts of the urban parking system on cruising traffic and policy development: The case of Zurich downtown area, Switzerland, *Transportation*, **46** (3) 883–908.

Cervero, R. and Y. Tsai (2004) City CarShare in San Francisco, California: Second-year travel demand and car ownership impacts, *Transportation Research Record*, **1887**, 117–127.

Chaniotakis, E. and A. J. Pel (2015) Drivers' parking location choice under uncertain parking availability and search times: A stated preference experiment, *Transportation Research Part A: Policy and Practice*, **82**, 228–239.

Christiansen, P., Ø. Engebretsen, N. Fearnley and J. Usterud Hanssen (2017) Parking facilities and the built environment: Impacts on travel behaviour, *Transportation Research Part A: Policy and Practice*, **95**, 198–206.

Cornelis, E., A. Malchair, T. Asperges and K. Ramaekers (2007) COCA (COmpany Cars Analysis): rapport final, *Final report*, FUNDP, Faculté des Sciences. Département de Mathématique, Université de Namur, Namur.

Dalla Chiara, G. and A. Goodchild (2020) Do commercial vehicles cruise for parking? Empirical evidence from Seattle, *Transport Policy*, **97**, 26–36.

Fagnant, D. J. and K. M. Kockelman (2018) Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas, *Transportation*, **45** (1) 143–158.

Feeney, B. P. (1986) A review of the impact of parking policy measures on travel demand, *Technical Report*, **308A**, Swedish Road and Traffic Research Institute (VTI), Linköping.

Forthomme, D. (2021) ipfn: Iterative proportional fitting for Python with N dimensions. Code accessible at `https://github.com/Dirguis/ipfn`.

Gao, Q., J. Molloy and K. W. Axhausen (2021) Trip purpose imputation using GPS trajectories with machine learning, *ISPRS International Journal of Geo-Information*, **10**, 775.

Ghimire, R. and C. Lancelin (2019) The relationship between financial incentives provided by employers and commuters' decision to use transit: Results from the Atlanta Regional Household Travel Survey, *Transport Policy*, **74**, 103–113.

Gutiérrez-i Puigarnau, E. and J. N. Van Ommeren (2011) Welfare effects of distortionary fringe benefits taxation: The case of employer-provided cars, *International Economic Review*, **52** (4) 1105–1122.

Hampshire, R. and D. Shoup (2018) What share of traffic is cruising for parking?, *Journal of Transport Economics and Policy*, **52**, 184–201.

Hamre, A. and R. Buehler (2014) Commuter mode choice and free car parking, public transportation benefits, showers/lockers, and bike parking at work: Evidence from the Washington, DC region, *Journal of Public Transportation*, **17** (2) 67–91.

Heilig, M., N. Mallig, O. Schröder, M. Kagerbauer and P. Vortisch (2018) Implementation of free-floating and station-based carsharing in an agent-based travel demand model, *Travel Behaviour and Society*, **12**, 151–158.

Hensher, D. A. and J. King (2001) Parking demand and responsiveness to supply, pricing and location in the Sydney central business district, *Transportation Research Part A: Policy and Practice*, **35** (3) 177–196.

Hess, D. B. (2001) Effect of free parking on commuter mode choice: Evidence from travel diary data, *Transportation Research Record*, **1753**, 35–42.

Hess, S. and D. Palma (2019) Apollo: A flexible, powerful and customisable freeware package for choice model estimation and application, *Journal of Choice Modelling*, **32**, 100170.

Hess, S. and J. W. Polak (2004) An analysis of parking behaviour using discrete choice models calibrated on SP datasets, paper presented at the *44th Congress of the European Regional Science Association: "Regions and Fiscal Federalism"*, Porto, August 2004.

Horni, A., K. Nagel and K. W. Axhausen (2016) *The Multi-Agent Transport Simulation MATSim*, Ubiquity Press, London.

Hörl, S. (2020) Dynamic Demand Simulation for Automated Mobility on Demand, Doctoral thesis, ETH Zurich, Zurich.

Hörl, S. and K. W. Axhausen (2021) Relaxation–discretization algorithm for spatially constrained secondary location assignment, *Transportmetrica A: Transport Science*, 1–20.

Hörl, S. and M. Balać (2021a) Introducing the eqasim pipeline: From raw data to agent-based transport simulation, *Procedia Computer Science*, **184**, 712–719, January 2021.

Hörl, S. and M. Balać (2021b) Synthetic population and travel demand for Paris and Île-de-France based on open and publicly available data, *Transportation Research Part C: Emerging Technologies*, **130**, 103291.

Hörl, S., M. Balać and K. W. Axhausen (2019a) Dynamic demand estimation for an AMoD system in Paris, paper presented at the *30th IEEE Intelligent Vehicles Symposium*, Paris, June 2019.

Hörl, S., M. Balać and K. W. Axhausen (2019b) Pairing discrete mode choice models and agent-based transport simulation with MATSim, paper presented at the *98th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2019.

Hörl, S., C. Ruch, F. Becker, E. Frazzoli and K. W. Axhausen (2019c) Fleet operational policies for automated mobility: A simulation assessment for Zurich, *Transportation Research Part C: Emerging Technologies*, **102**, 20–31.

Kaplan, S. and S. Bekhor (2011) Exploring en-route parking type and parking-search route choice: Decision making framework and survey design, paper presented at the *2nd International Choice Modelling Conference*, Leeds, July 2011.

Kenworthy, J. R., F. B. Laube, P. Newman, P. Barter, T. Raad, C. Poboon and B. Guia Jr (1999) *An International Sourcebook of Automobile Dependence in Cities, 1960-1990*, University Press of Colorado, Boulder.

Kolomatskiy, A., D. Baranov, V. Korchagin and T. Volotskiy (2020) Assessing the effect of different parking pricing policies on DRT demand using multiagent traffic simulation, case study of St. Petersburg, *Procedia Computer Science*, **170**, 799–806.

Kopp, J., R. Gerike and K. W. Axhausen (2015) Do sharing people behave differently? An empirical evaluation of the distinctive mobility patterns of free-floating car-sharing members, *Transportation*, **42** (3) 449–469.

Lee, J. B., D. Agdas and D. Baker (2017) Cruising for parking: New empirical evidence and influential factors on cruising time, *Journal of Transport and Land Use*, **10** (1) 931–943.

Lomax, N. and P. Norman (2016) Estimating population attribute values in a table: "Get me started in" iterative proportional fitting, *The Professional Geographer*, **68** (3) 451–461.

Lopez, P. A., M. Behrisch, L. Bieker-Walz, J. Erdmann, Y. P. Flotterod, R. Hilbrich, L. Lucken, J. Rummel, P. Wagner and E. Wiebner (2018) Microscopic traffic simulation using SUMO, paper presented at the *21st IEEE International Conference on Intelligent Transportation Systems*, Maui, November 2018.

Macharis, C. and A. De Witte (2012) The typical company car user does not exist: The case of Flemish company car drivers, *Transport Policy*, **24**, 91–98.

Maciejewski, M. and J. Bischoff (2018) Congestion effects of autonomous taxi fleets, *Transport*, **33** (4) 971–980.

Mantouka, E. G., P. Fafoutellis and E. I. Vlahogianni (2021) Deep survival analysis of searching for on-street parking in urban areas, *Transportation Research Part C: Emerging Technologies*, **128**, 103173.

Manville, M. (2017) Bundled parking and vehicle ownership: Evidence from the American Housing Survey, *Journal of Transport and Land Use*, **10** (1) 27–55.

Manville, M. and D. C. Shoup (2005) Parking, people, and cities, *Journal of Urban Planning and Development*, **131** (4) 233–245.

Martin, E. and S. Shaheen (2011) The impact of carsharing on public transit and non-motorized travel: An exploration of North American carsharing survey data, *Energies*, **4** (11) 2094–2114.

Martin, E., S. A. Shaheen and J. Lidicker (2010) Impact of carsharing on household vehicle holdings: Results from North American shared-use vehicle survey, *Transportation Research Record*, **2143**, 150–158.

Martínez, L. M., G. H. de Almeida Correia, F. Moura and M. M. Lopes (2017) Insights into carsharing demand dynamics: Outputs of an agent-based model application to Lisbon, Portugal, *International Journal of Sustainable Transportation*, **11** (2) 148–159.

McCahill, C. T., N. Garrick, C. Atkinson-Palombo and A. Polinski (2016) Effects of parking provision on automobile use in cities: inferring causality, *Transportation Research Record*, **2543**, 159–165.

McCahill, C. T. and N. W. Garrick (2010) Influence of parking policy on built environment and travel behavior in two New England cities, 1960 to 2007, *Transportation Research Record*, **2187**, 123–130.

Metzler, D., A. Humpe and S. Gössling (2019) Is it time to abolish company car benefits? An analysis of transport behaviour in Germany and implications for climate change, *Climate Policy*, **19** (5) 542–555.

Millard-Ball, A., R. C. Hampshire and R. Weinberger (2020) Parking behaviour: The curious lack of cruising for parking in San Francisco, *Land Use Policy*, **91**, 103918.

Millard-Ball, A., R. C. Hampshire and R. R. Weinberger (2019) Map-matching poor-quality GPS data in urban environments: The pgMapMatch package, *Transportation Planning and Technology*, **42** (6) 539–553.

Millard-Ball, A., G. Murray and J. ter Schure (2006) Carsharing as parking management strategy, paper presented at the *85th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2006.

Millard-Ball, A., J. West, N. Rezaei and G. Desai (2022) What do residential lotteries show us about transportation choices?, *Urban Studies*, **59** (2) 434–452.

Molloy, J., A. Castro, T. Götschi, B. Schoeman, C. Tchervenkov, U. Tomic, B. Hintermann and K. W. Axhausen (2022) The MOBIS dataset: A large GPS dataset of mobility behaviour in Switzerland, *Transportation*, **7**, 8667–8674.

Molloy, J., A. Castro Fernández, T. Götschi, B. Schoeman, C. Tchervenkov, U. Tomic, B. Hintermann and K. W. Axhausen (2021a) A national-scale mobility pricing experiment using GPS tracking and online surveys in Switzerland: Response rates and survey method results, paper presented at the *100th Annual Meeting of the Transportation Research Board*, Online, January 2021.

Molloy, J., T. Schatzmann, B. Schoeman, C. Tchervenkov, B. Hintermann and K. W. Axhausen (2021b) Observed impacts of the Covid-19 first wave on travel behaviour in Switzerland based on a large GPS panel, *Transport Policy*, **104**, 43–51.

Montini, L., A. Horni, N. Rieser-Schüssler and K. W. Axhausen (2012) Searching for parking in GPS data, paper presented at the *13th International Conference on Travel Behaviour Research*, Toronto, July 2012.

Mullahy, J. (2015) Multivariate fractional regression estimation of econometric share models, *Journal of Econometric Methods*, **4** (1) 71–100.

Naess-Schmidt, S. and M. Winiarczyk (2010) Company car taxation: Subsidies, welfare and environment, *European Commission Taxud Taxation Papers*, **22**, Copenhagen Economics, Copenhagen.

Nagel, K., B. Kickhöfer, A. Horni and D. Charypar (2016) A closer look at scoring, in A. Horni, K. Nagel and K. W. Axhausen (eds.) *The Multi-Agent Transport Simulation MATSim*, 23–34, Ubiquity Press, London.

Nijland, L. and M. Dijst (2015) Commuting-related fringe benefits in the Netherlands: Interrelationships and company, employee and location characteristics, *Transportation Research Part A: Policy and Practice*, **77**, 358–371.

Oswald, M. (2012) Ein Modell des ruhenden Verkehrs in Zürich: Validation und Massnahmenbewertung, *Master Thesis*, IVT, ETH Zurich, Zurich.

Pedregosa, F., G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Passos, D. Cournapeau, M. Brucher, M. Perrot and E. Duchesnay (2011) Scikit-learn: Machine learning in Python, *Journal of Machine Learning Research*, **12**, 2825–2830.

Polak, J. and K. W. Axhausen (1990) Parking search behaviour: A review of current research and future prospects, *Working Paper*, **540**, University of Oxford, Transport Studies Unit, Oxford.

Ramaekers, K., G. Wets, A. De Witte, C. Macharis, E. Cornelis, M. Castaigne and X. Pauly (2010) The impact of company cars on travel behaviour, paper presented at the *12th World Conference on Transport Research*, Lisbon, July 2010.

Scherr, W., P. Manser and P. Bützberger (2020) SIMBA MOBI: Microscopic mobility mobility simulation for corporate planning, *Transportation Research Procedia*, **49**, 30–43.

Schmöller, S., S. Weikl, J. Müller and K. Bogenberger (2015) Empirical analysis of free-floating carsharing usage: The Munich and Berlin case, *Transportation Research Part C: Emerging Technologies*, **56**, 34–51.

Schubert, E., J. Sander, M. Ester, H. P. Kriegel and X. Xu (2017) DBSCAN revisited, revisited: Why and how you should (still) use DBSCAN, *ACM Transactions on Database Systems*, **42** (3) 19.

Schüssler, N. and K. W. Axhausen (2009) Map-matching of GPS traces on high-resolution navigation networks using the Multiple Hypothesis Technique (MHT), *Arbeitsberichte Verkehrs- und Raumplanung*, **568**, IVT, ETH Zurich, Zurich.

Seabold, S. and J. Perktold (2010) statsmodels: Econometric and statistical modeling with Python, paper presented at the *9th Python in Science Conference*, Austin, June 2010.

Shaheen, S. A., N. D. Chan and H. Micheaux (2015) One-way carsharing's evolution and operator perspectives from the Americas, *Transportation*, **42** (3) 519–536.

Shaheen, S. A. and A. P. Cohen (2013) Carsharing and personal vehicle services: Worldwide market developments and emerging trends, *International Journal of Sustainable Transportation*, **7** (1) 5–34.

Shiftan, Y., G. Albert and T. Keinan (2012) The impact of company-car taxation policy on travel behavior, *Transport Policy*, **19** (1) 139–146.

Shin, E. J. (2020) Commuter benefits programs: Impacts on mode choice, VMT, and spillover effects, *Transport Policy*, **94**, 11–22.

Shoup, D. C. (1997) Evaluating the effects of cashing out employer-paid parking: Eight case studies, *Transport Policy*, **4** (4) 201–216.

Shoup, D. C. (2006) Cruising for parking, *Transport Policy*, **13** (6) 479–486.

Simma, A. and K. W. Axhausen (2001) Structures of commitment in mode use: A comparison of Switzerland, Germany and Great Britain, *Transport Policy*, **8** (4) 279–288.

Society for Human Resource Management (2014) 2014 employee benefits: An overview of employee benefit offerings in the US, *Report*, Society for Human Resource Management, Alexandria.

Spieser, K., K. Treleaven, R. Zhang, E. Frazzoli, D. Morton and M. Pavone (2014) Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in Singapore, in G. Meyer and S. Beiker (eds.) *Road Vehicle Automation*, 229–245, Springer International Publishing, Cham.

Spitaels, K., S. Maerivoet, G. De Ceuster, G. Nijs, V. Clette, P. Lannoy, K. Dieussaert, K. Aerts and T. Steenberghen (2009) Optimising price and location of parking in cities under a sustainability constraint "SUSTAPARK", *Final Report*, Belgian Science Policy, Brussels.

Stadt Zürich (2007) Strassenparkierung, *Datendokumentation*, Tiefbauamt, Stadt Zürich, Zurich.

Stadt Zürich (2016) Vorschriften über die Parkierungs- und Parkuhrkontrollgebühren, *Vorschriften*, **551.330**, Stadt Zürich, Zurich.

Steenberghen, T., K. Dieussaert, S. Maerivoet and K. Spitaels (2012) SUSTAPARK: An agent-based model for simulating parking search, *URISA Journal*, **24** (1) 63–76.

Tchervenkov, C., M. Balać, S. Hörl, H. Becker and K. W. Axhausen (2019) How much parking space can carsharing save?, paper presented at the *98th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2019.

Tchervenkov, C., G. Kagho, A. Sallard, S. Hörl, M. Balać and K. W. Axhausen (2022) The Switzerland agent-based scenario, *Arbeitsberichte Verkehrs- und Raumplanung*, **1802**, IVT, ETH Zurich, Zurich.

Thalmann, P. and M. Vielle (2019) Lowering CO_2 emissions in the Swiss transport sector, *Swiss Journal of Economics and Statistics*, **155**, 10.

van der Waerden, P., H. Timmermans and L. Van Hove (2015) GPS data and car drivers' parking search behavior in the city of Turnhout, Belgium, in I. Ivan, I. Benenson, B. Jiang, J. Horák, J. Haworth and T. Inspektor (eds.) *Geoinformatics for Intelligent Transportation*, Lecture Notes in Geoinformation and Cartography, 247–256, Springer International Publishing, Cham.

van Ommeren, J. N., D. Wentink and P. Rietveld (2012) Empirical evidence on cruising for parking, *Transportation Research Part A: Policy and Practice*, **46** (1) 123–130.

Vanoutrive, T. (2019) Commuting, spatial mismatch, and transport demand management: The case of gateways, *Case Studies on Transport Policy*, **7** (2) 489–496.

Voith, R. (1998) Parking, transit, and employment in a central business district, *Journal of Urban Economics*, **44** (1) 43–58.

Waraich, R. A. and K. W. Axhausen (2012) Agent-based parking choice model, *Transportation Research Record*, **2319**, 39–46.

Waraich, R. A., C. Dobler, C. Weis and K. W. Axhausen (2013) Optimizing parking prices using an agent based approach, paper presented at the *92nd Annual Meeting of the Transportation Research Board*, Washington, DC, January 2013.

Weinberger, R. R., A. Millard-Ball and R. C. Hampshire (2020) Parking search caused congestion: Where's all the fuss?, *Transportation Research Part C: Emerging Technologies*, **120**, 102781.

Weis, C., M. Kowald, A. Danalet, B. Schmid, M. Vrtic, K. W. Axhausen and N. Mathys (2021) Surveying and analysing mode and route choices in Switzerland 2010–2015, *Travel Behaviour and Society*, **22**, 10–21.

Weis, C., M. Vrtic, B. Schmid and K. W. Axhausen (2017) Analyse der SP-Befragung 2015 zur Verkehrsmodus- und Routenwahl, *Grundlagen*, Bundesamt für Raumentwicklung, Bern.

Weis, C., M. Vrtic, P. Widmer and K. W. Axhausen (2012) Influence of parking on location and mode choice: A stated choice survey, paper presented at the *91th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2012.

Willson, R. W. and D. C. Shoup (1990) Parking subsidies and travel choices: Assessing the evidence, *Transportation*, **17** (2) 141–157.

Young, W., R. G. Thompson and M. A. Taylor (1991) A review of urban car parking models: Foreign summaries, *Transport Reviews*, **11** (1) 63–84.

CURRICULUM VITAE

PERSONAL DATA

Name	Christopher Tchervenkov
Date of Birth	January 14, 1990
Place of Birth	Cincinnati, United States
Citizenship	Canada, Bulgaria, United States

EDUCATION

2017– 2022	ETH Zurich, Zurich, Switzerland
2014 – 2017	École polytechnique fédérale de Lausanne, Lausanne, Switzerland *Final degree:* M.Sc. in Microengineering
2009 – 2013	École Polytechnique de Montréal Montréal, Canada *Final degree:* B.Eng. in Engineering physics *Exchange Year:* KTH, Stockholm, Sweden

EMPLOYMENT

Oct 2017 – Dec 2022	Research Assistant *Institute for Transport Planning and Systems*, Zurich, Switzerland
Feb 2016 – Jul 2016	System Engineering Intern *IRsweep AG*, Zurich, Switzerland
Jan 2014 – Jul 2014	Optical Engineering Intern *FlatFrog Laboratories AB*, Lund, Sweden

May 2011 – Aug 2011	Physics Research Intern *Institut national de la recherche scientifique*, Varennes, Canada
May 2010 – Aug 2010	Physics Research Intern *École Polytechnique de Montréal*, Montréal, Canada

PUBLICATIONS

ARTICLES IN PEER-REVIEWED JOURNALS

Molloy, J., A. Castro, T. Götschi, B. Schoeman, **C. Tchervenkov**, U. Tomic, B. Hintermann and K. W. Axhausen (2022) The MOBIS dataset: a large GPS dataset of mobility behaviour in Switzerland, *Transportation*, **7** (4) 8667–8674.

Molloy, J., T. Schatzmann, B. Schoeman, **C. Tchervenkov**, B. Hintermann and K. W. Axhausen (2021) Observed impacts of the Covid-19 first wave on travel behaviour in Switzerland based on a large GPS panel, *Transport Policy*, **104**, 43–51.

Molloy, J., **C. Tchervenkov** and K. W. Axhausen (2021) Estimating the external costs of travel on GPS tracks, *Transportation Research Part D: Transport and Environment*, **95**, 102842.

Molloy, J., **C. Tchervenkov**, B. Hintermann and K. W. Axhausen (2020) Tracing the Sars-CoV-2 impact: The first month in Switzerland, *Transport Findings*, **104**, 43–51.

Tchervenkov, C., S. Hörl, M. Balać, T. Dubernet and K. W. Axhausen (2020) An improved replanning strategy for congested traffic conditions in MATSim, *Procedia Computer Science*, **170**, 779–784.

CONFERENCE CONTRIBUTIONS

Hörl, S., **C. Tchervenkov** and M. Balać (2020) A generalizable pipeline for agent-based transport models in France, paper presented at the *9th Symposium of the European Association for Research in Transportation*, Lyon, September 2020.

Molloy, J., A. Castro, T. Götschi, B. Schoeman, **C. Tchervenkov**, U. Tomic, B. Hintermann and K. W. Axhausen (2021) A national-scale mobility pricing experiment using GPS tracking and online surveys in Switzerland:

Response rates and survey method results, paper presented at the *100th Annual Meeting of the Transportation Research Board*, Online, January 2021.

Tchervenkov, C. and K. W. Axhausen (2022) Searching for parking: The case of Zurich, paper presented at the *10th Symposium of the European Association for Research in Transportation*, Leuven, June 2022.

Tchervenkov, C. and K. W. Axhausen (2022) Measuring parking search behaviour using GPS data, paper presented at the *22nd Swiss Transport Research Conference*, Ascona, May 2022.

Tchervenkov, C., M. Balać and K. W. Axhausen (2022) The impact of employer fringe benefits on commuting to work by car in Switzerland, paper presented at the *101st Annual Meeting of the Transportation Research Board*, Washington, DC, January 2022.

Tchervenkov, C., M. Balać, S. Hörl, H. Becker and K. W. Axhausen (2019) How much parking space can carsharing save?, paper presented at the *98th Annual Meeting of the Transportation Research Board*, Washington, DC, January 2019.

Tchervenkov, C., J. Molloy and K. W. Axhausen (2018) Estimating externalities from GPS traces using MATSim, paper presented at the *18th Swiss Transport Research Conference*, Ascona, May 2018.

Tchervenkov, C., J. Molloy, A. Castro and K. W. Axhausen (2020) MOBIS study: A review of common reported issues, paper presented at the *20th Swiss Transport Research Conference*, Online, May 2020.

WORKING PAPERS, RESEARCH REPORTS AND OTHER CONTRIBUTIONS

Axhausen, K. W., J. Molloy, **C. Tchervenkov**, F. Becker, B. Hintermann, B. Schoeman, T. Götschi, A. Castro Fernández and U. Tomic (2021) Empirical analysis of mobility behavior in the presence of Pigovian transport pricing, *Research Report, ASTRA 2017/006*, **1704**, ASTRA, UVEK, ETH Zurich, Bern, Zurich.

Listemann, F., C. Pilloud, F. Rischatsch, A. Schlageter, L. Sieger, **C. Tchervenkov** and K. W. Axhausen (2022) Parkplatzverfügbarkeit und Parkgebühren: Eine Fallstudie in Zürich, *Strasse und Verkehr*, **12**, 36–41.

Tchervenkov, C., G. Kagho, A. Sallard, S. Hörl, M. Balać, K. W. Axhausen (2022) The Switzerland agent-based scenario, *Arbeitsberichte Verkehrs- und Raumplanung*, **1802**, IVT, ETH Zurich, Zurich.

SUPERVISED THESIS AND PROJECT WORK

Burchard, P. (2021) Including parking availability and prices in the mode choice modelling, *Master Thesis*, IVT, ETH Zurich, Zurich.

Garaicoechea, I. (2020) Potential of autonomous-mobility-on-demand across Switzerland, *Master Thesis*, IVT, ETH Zurich, Zurich.

Glauser, T. (2018) Internalisierung der externen Kosten, *Bachelor Thesis*, IVT, ETH Zurich, Zurich.

Klaus, R. (2021) Did we measure the COVID-19 impact correctly?, *Master Project Report*, IVT, ETH Zurich, Zurich.

Mathys, F. (2018) Auslegung der Ladeinfrastruktur für automatisierte elektrische Fahrzeuge am Beispiel Zürichs, *Bachelor Thesis*, IVT, ETH Zurich, Zurich.

Muggli, M. (2020) MaaS bundling: A first approach towards a bundling strategy based on revealed preference data, *Master Project Report*, IVT, ETH Zurich, Zurich.

Sarris, A. (2022) Trips with overnight stays during Covid-19, *Bachelor Thesis*, IVT, ETH Zurich, Zurich.

Scherer, A. (2018) Agenten-basierte Modellierung des Strassengüterverkehrs in der Schweiz, *Master Project Report*, IVT, ETH Zurich, Zurich.

Schmid, P. (2018) Impact of autonomous vehicles on urban accessibilities and travel time, *Bachelor Thesis*, IVT, ETH Zurich, Zurich.

Uhlmann, M. (2021) Activity spaces and behavioural innovation during COVID-19, *Master Project Report*, IVT, ETH Zurich, Zurich.