A CGE-Model of Parking in Zurich: Implementation and Policy Tests

Anne-Kathrin Bodenbender

Supervision:
Prof. Kay W. Axhausen, ETH Zürich
Prof. Thomas F. Rutherford, UW Madison
Rashid A. Waraich, ETH Zürich

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UNIVERSITY OF WISCONSIN–MADISON

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

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Anne-Kathrin Bodenbender
Birchstrasse 40
8057 Zürich
phone: +41-78-813 22 66
annekathrin.bodenbender@gmail.com

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Abstract

This thesis develops a computable general equilibrium model for parking and applies it to the city center of Zurich to analyze different parking policies. The presented model distinguishes between people driving through the network, looking for on-street parking and looking for garage parking. By considering the probability of not finding a parking spot, the model accounts for spillover from those agents that cannot find parking right away and therefore are cruising for parking. The model framework also considers heterogeneity of agents by accounting for different valuations of time according to their income.

The policy analysis is mainly influenced by the SF*park* project in San Francisco where demand responsive pricing for parking has been introduced. This means that parking fees are adjusted to the demand; parking spots with higher demand have higher parking rates and vice versa. The impacts of demand responsive pricing for on-street parking, garage parking and coordinated for on-street and garage parking are examined. It is found that the coordinated approach used in SF*park* has the best results and reduces overall traffic flow as well as travel times.

Keywords
Computable general equilibrium model; parking; parking policy analysis; SF*park*; Zurich

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Anne-Kathrin Bodenbender
Birchstrasse 40
8057 Zürich
Tel: +41-78-813 22 66
annekathrin.bodenbender@gmail.com

Juli 2013

Zusammenfassung

In der vorliegenden Arbeit wird ein Gleichgewichtsmodell zum ruhenden Verkehr entwickelt bzw. erweitert. Das Modell wird für die Innenstadt Zürichs angewandt um verschiedene Ansätze zur Parkraumbewirtschaftung zu beurteilen. Es wird zwischen Durchgangsverkehr und Suchverkehr sowohl für Parkplätze im Strassenraum als auch für Parkplätze in Parkgaragen unterschieden. Die Berücksichtigung der Wahrscheinlichkeit keinen Parkplatz zu finden erlaubt es, die Auswirkungen von Parkplatz Suchverkehr auf den Durchgangsverkehr mit einzubeziehen. Heterogenität der Agenten wird im Modell ebenfalls berücksichtigt, indem Agenten unterschiedliche Zeitwerte - in Abhängigkeit ihres Einkommens - zugeordnet werden.
Die Analyse der verschiedenen Massnahmen zur Parkraumbewirtschaftung wird u.a. durch das Projekt SF*park* beeinflusst, das seit 2010 in San Francisco in einem Pilotbetrieb getestet wird. In diesem Projekt werden die Gebühren für Parkplätze in Abhängigkeit der Nachfrage gesteuert. Parkplätze mit grosser Nachfrage sind teurer als solche mit niedriger Nachfrage. Die Auswirkungen von nachfragegesteuerten Parkplatzgebühren werden für drei verschiedene Szenarien untersucht: 1. Gebühren für Strassenparkplätze werden durch die Nachfrage gesteuert. 2. Gebühren für Parkgaragenplätze werden durch die Nachfrage gesteuert. 3. Beide Ansätze werden kombiniert. Der Vergleich zeigt, dass der kombinierte Ansatz das beste Resultat ergibt, bei dem sowohl die Verkehrsmengen als auch die Reisezeiten deutlich verkürzt werden.

Schlüsselwörter

Gleichgewichtsmodell; ruhender Verkehr; Parkraumbewirtschaftungsanalyse; SF*park*; Zürich

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1 Introduction

The number of motor vehicles on earth has been increasing dramatically over the last 50 years (Shoup, 2005). This does not only lead to traffic congestion which has become a major issue for many big cities around the world, but it also beckons questions concerning optimal parking policies. According to Shoup (2005) the average car spends about 95% of its life parked, while roughly 30% of cars in congested traffic are cruising for parking. This implies that a more efficient parking policy should be able to reduce traffic congestion. In San Francisco, California, a project called SF*park* is being tested since the end of 2010. The project's developers advertise that new technologies and policies improve the parking situation in San Francisco: "With SF*park*, we can all circle less and live more." (SFpark, 2013)

Developing parking interaction models will help us understand the impacts new parking policies can have on travel behavior before testing them in a real scenario. One possible structure for parking interaction models is a computable general equilibrium (CGE) model. CGE models are widely used in economics to evaluate the impacts of policy reforms in many different fields (Wing, 2004). In this thesis a CGE model is developed to evaluate the impacts of different parking policies.

This thesis builds upon Matthias Oswald's thesis (Oswald, 2012), submitted to ETH Zurich in July 2012, using Oswald's results and the collected data to implement the model for the city of Zurich. The goal was not only to implement the model but also to examine the impacts of different policies. This study examines different ideas of the SF*park* project for the city of Zurich. The model presented here is not a parking interaction model since at this stage only the impacts on parking behavior are examined. Effects on travel behavior such as mode choice or time of trip are not yet implemented.

The thesis is structured as follows: Section 2 presents a literature review of modeling parking, cruising for parking, and recent parking policies in the United States and in Europe. Section 3 describes the applied modeling approach and presents a policy analysis case study in Zurich, Switzerland. Finally, the results and findings of the policy are presented in Section 4. The thesis concludes with considerations for further research in Section 5.

2 Literature Review

This section provides a brief literature review of modeling parking. The first part gives an overview of different parking models, followed by a review of literature on cruising for parking. The last part gives some insights into recent developments in parking policies, including a distinction between the United States and Europe as well as an overview of recently developed parking applications for smartphones. Since this thesis is a continuation and extension of the thesis submitted by Oswald (2012), the overview of parking models is structured the same as his chapter on parking models. The models discussed here add to discussed in his work.

2.1 Modeling Parking

Young (2008) presents an overview of a hierarchy of parking models as well as of model types. He first describes four different hierarchy levels that are used to analyze parking policies. The first level is of microsimulations that describe the movements of vehicles in a parking lot. These models are used to evaluate the performance of a parking facility and give information on travel and search times. The second level focuses on activity centers such as the central business district (CBD) or the downtown area of a city. These types of models, called sub-center or regional models, focus on the relationship between the level of utilization and travel and search time. Public transportation links and pedestrian links are considered in the sub-center models. The next level looks at area-wide or metropolitan modeling. These models concentrate on the interaction between travel demand and supply and level of service of parking. The fourth level of models looks at the impact parking has on urban land use and the location choices of businesses and private households. These models are not targeted at parking policy.

In a second step Young (2008) classifies models according to the type of information they provide. He distinguishes between parking design, parking allocation, parking search, parking choice and parking interaction models. These different model specifications and some examples of such specifications will be discussed in the following paragraphs.

Parking design models seek to optimize performance of parking facilities. They are seen in the first level of the hierarchy. Iranpour and Tung (1989) present a model for the optimal design of a corner parking lot.

The second category, parking allocation models, formulate the parking problem in terms of the allocation of a fixed number of cars arriving at the parking facilities. These models are mostly seen at levels two and three of the hierarchy. Young (2008) describes four different types of allocation models: (1) Optimization models attempt to maximize the efficiency of parking facilities. Such models are used to find the optimal location of parking facilities. (2) Constraint models which relax the condition that drivers only seek an optimal parking spot. (3) Gravity models that are also used in the trip distribution calculation of traffic models. Here the origin-destination matrix is determined by the trip productions and attractions as well as by some simplified assumption about the differentiation between origin and destination. (4) The last category of allocation models assigns the vehicles to the street and parking network of an area using an origin-destination matrix. These models are used to analyze the impacts of changes in transportation management for different modes of travel. In Ellis *et al.* (1972) a parking allocation model is applied to the city of Pittsburgh, Pennsylvania for long-duration work trips. In this model trip costs include walking distance and the capacity of the parking facility. To examine the trade-offs between cost and distance, the concept of minimizing a parker's disutility is used. The allocations estimated in the model are very close to those observed. Similarly, Austin (1973) proposes a model to estimate the usage of parking facilities in a central business district in which every driver wants to minimize his or her disutility associated with parking. Heterogeneity of drivers is recognized by taking into account people's variation in their valuation of walking time and perception of walking time. Disutility is measured as a combination of parking cost and walking time from the parking facility to the final destination.

The third category of models, parking search models, simulate drivers' movements through the road and parking system. These models focus on the process of gathering information about the parking system, taking into consideration drivers' prior knowledge of that system to find an acceptable parking spot. These models help to understand the impact of parking information on route choice; they also provide information on time spent searching and on the choice strategy. In Axhausen and Polak (1996) a model to estimate search time for off-street parking, given total demand for off-street parking, is extended to include the effects of a parking guidance system. The study offers insights into the impact that parking guidance systems can have on parking search behavior and has found that drivers' knowledge of an area plays an important role. Thompson and Richardson (1998) model the search process motorists use, in order to describe parking search behavior. The searching patterns of parkers are represented in terms of their expected gain in utility which measures the attractiveness of a specific car park. They show that experience does not necessarily lead to the selection of a better car park since car parking systems are uncertain by nature. Lam *et al.* (2006) propose a parking search model to evaluate the consequences of different parking policies and infrastructure improvements. In the proposed model drivers simultaneously decide on their time of departure, route, parking location and parking duration in a road network with multiple user classes and multiple parking facilities. The model is formulated as a variational inequality problem, and is solved by a heuristic solution algorithm. The authors present numerical results for two sample networks. Those show that travel demand, walking distance, parking capacity and parking charge have the most significant influence on parking behavior. In Martens and Benenson (2008) an agent-based parking search model is presented and applied to a neighborhood in the city center of Tel Aviv, Israel. The proposed model examines the effects of urban parking policies concerning residential parking. As a test scenario, the construction of a local, residentially used underground parking garage is considered. It is found that the main effect of greater parking supply is the reduction of time drivers spend searching for a parking spot. Dieussaert *et al.* (2009) present an agent-based parking search model to simulate the traffic effects of parking search behavior (SUSTAPARK). A search strategy is used to determine drivers' movements and a cellular automaton translates these into a computer program. It is shown, that the complexity of modeling parking can be reduced by dividing the problem into its basic components such that agents have to follow certain rules.

Another category of parking models that Young (2008) describes are parking choice models. These measure drivers' reactions to changes in supply, pricing and operation strategy of parking facilities. For instance, drivers can change their mode of transportation, trip start time, destination or whether they want to cancel the trip. In Golias *et al.* (2002) a disaggregated binary logit model based on stated preference technique is developed for choosing between on- and off-street parking. The study has been conducted in the city of Piraeus, Greece. The authors find that the most important factor for parking choice is its price. All other variables that have a significant effect on parking choice are time related, such as search time, duration of parking and walking time from the parking location to the final destination. Furthermore they show that parking choice is independent of driver and trip characteristics. Hilvert *et al.* (2012) present a mixed logit model for parking choice that addresses a driver's pretrip decisions such as parking type, parking facility, or on-street search area and route choice. The model is based on stated and revealed preference data from the city center of Tel Aviv, Israel. It is applied to a parking choice scenario to examine the effects of certain parking attributes on respondents' choices. As in Golias *et al.* (2002) it is found that the dominant factor in parking choice is the price, but in-vehicle time and walking time also play an important role. Hilvert *et al.* (2012) also analyze the value drivers place on time and the effect passengers have on this. They find that the value of time is lower for solo drivers than for drivers traveling with passengers.

The last group of parking models described in Young (2008) are parking interaction models. These try to depict the behavior of drivers in response to different parking policies. They are mostly found in levels two and three of the hierarchy. Hess (2001) develops a multinomial logit model to assess the probabilities of commuters choosing to drive alone, use public transit, or carpool, when parking at the work place is free vs. when it is not. They show that when there is a charge for parking, the number of workers who use public transportation can double, and the number of cars used to get to work (driving and carpooling) can be reduced by 30%. These findings indicate that charging commuters the true cost of parking is the best way to influence a driver's mode choice. Shiftan and Burd-Eden (2001) propose a multinomial logit model to predict responses to different parking policies. The model is based on a stated preference study conducted in Haifa, Israel. They show that workers would rather choose a different travel mode or time of travel than change their destination or cancel their trip. These decisions are less transparent among nonworkers as they are just as likely to choose either option. The results of this study suggest that the effects of parking policies very much depend on the people who are affected by them. Albert and Mahalel (2006) present a model that evaluates the differences in attitudes towards congestion tolls and parking fees, and then estimate the impact of these policies on travel demand and behavior. The model is based on a stated preference survey conducted at the Israel Institute of Technology. It is found that the acceptance of the parking fee (percentage of people choosing to pay the fee) is much higher (46%) than that of the congestion toll (28%). It also shows that a large number of people, 54% for the introduction of a parking fee and 72% for the congestion toll, prefer an alternative to paying the toll; this indicates a strong tendency to avoid new tolls.

2.2 Cruising for Parking

According to Shoup (2005) 30% of traffic in downtown areas in the United States is the result of cruising for free on-street parking. Cruising is the individually rational choice if on-street parking is cheaper than off-street parking. Since this is the case in most cities, drivers decide to search for a cheap parking spot and thereby congest traffic, cause accidents, waste fuel, pollute the air and make the environment less attractive for pedestrians and bikers (Shoup, 2006). Shoup (2006) develops a model of the benefits and costs of cruising to help understand how we choose to cruise or to pay. Shoup finds that drivers are more likely to cruise for parking if curb parking and fuel are cheaper, off-street parking is more expensive, they want to park for longer periods of time, their value on saving time is lower, and they are alone in the car. The model predicts that charging the market price for curb parking can eliminate cruising. Shoup concludes that the right price for curb parking will bring benefits for everyone and that, since the pricing for curb parking is in general handled by city governments, every city could find this optimal fee. These ideas have been implemented in the SF*park* project in San Francisco (see Section 2.3.4). Arnott and Inci (2006) look at cruising for parking from an economic perspective. They propose a parking model that accounts for traffic congestion as well as on-street parking. Their model also finds that increasing the on-street parking fee is efficient in eliminating cruising for parking without causing parking to become unsaturated. They show that cruising time is close to zero with perfect information about parking spaces and optimal pricing of parking. Van Ommeren *et al.* (2012) examine cruising for parking in the Netherlands and propose an extremely stylized partial equilibrium static model. Some of their results differ greatly from those found in Shoup's work, though these are likely explained by the very different approaches to parking policy (e.g. the pricing of on-street parking) in Europe and the United States. Van Ommeren *et al.* (2012) report an average cruising time of 36 seconds (compared to an average cruising time of 7.8 minutes in Shoup (2006)) and that drivers cruise for parking in around 30% of trips. They find that decisions about cruising time are based on a trade-off between costs (time loss) and benefits (lower parking price) of cruising. Cruising decreases with income, but increases with trip and parking duration. They also find that cruising is more common with some activities (leisure) than with others (work). To simulate the impact of cruising on traffic congestion in urban areas Gallo *et al.* (2011) propose a multilayer parking choice model consisting of a demand model, a supply model and an assignment model. The proposed model is then tested on a real-scale network of the city of Benevento, Italy. It can be shown that for low demand levels, flow estimates as well as increase in vehicle kilometers are suitable. The model can be used to evaluate the effects of new parking facilities on traffic congestion.

2.3 Parking Policies

Parking policies have an important influence on how a city is perceived and how well it functions. Recently more restrictive parking policies have been discussed as a mean to shift a city's mode share away from car usage towards public transit, biking and walking. The policies undertaken in the United States and in Europe vary significantly due to different starting points. The following section discusses recent developments in parking policy in the United States and in Europe, as well as today's parking policy in Zurich.

2.3.1 United States

Finding a free parking spot in the United States is not a big problem, since parking is free for 99% of trips (Shoup, 2005). Free parking spots can mostly be found in big parking lots of shopping centers, but on-street parking in downtown areas is also often free (though usually limited to a certain time period, e.g. two hours). This leads to a large number of people cruising for parking (see Section 2.2). Some cities in the United States have introduced new parking policies to improve this situation. Weinberger *et al.* (2010) give an overview of parking management strategies in the United States. They outline the following ten key recommendations for government action concerning parking, based on their review of successful innovative parking strategies throughout the country.

1. Eliminate minimum parking requirements and encourage developers to "unbundle" parking

2. Coordinate on- and off-street parking management and charging
3. Charge a price for on-street parking to ensure that performance standards, including occupancy rates, are met
4. Create parking benefit districts where the revenue is returned to the community
5. Use parking technologies that offer customers and policy makers maximum flexibility
6. Reclaim street space from car parking for other needed public uses such as bike sharing, cycling lanes, widened sidewalks or shared spaces
7. Design parking facilities that are well integrated with surrounding buildings and walking environments
8. Incorporate parking policies into metropolitan transportation plans
9. Include innovative parking management in statewide livability initiatives, congestion management, air pollution control strategies, climate action plans and innovative financing programs
10. Promote parking and commuter programs that expand travel choices for employees and customers

Some examples of interesting parking strategies include the following. Boulder, Colorado, Cambridge, Massachusetts and Montgomery County, Maryland have successfully promoted "shared parking", where developers coordinate access to underutilized, nearby parking facilities in other building. In New York City on-street parking spaces are reduced and replaced by exclusive bus lanes, pedestrian zones or bike lanes. In Portland, Oregon, the amount of a building facade that can be dedicated to garage doors is regulated (Weinberger *et al.,* 2010). Nelson and Schrieber (2012) also give interesting examples for implementing innovative parking policies. One of the first cities to implement demand-responsive pricing was Redwood City, California. A goal was set to establish an average vacancy of 15% for every block by adjusting the parking rates. In addition to creating demand-responsive pricing, the city eliminated time limits. The revenue from the new parking policy has been used to fund neighborhood improvements. Another city realizing the benefits of demand-responsive pricing is Washington, DC. A pilot project in the neighborhood of a new baseball stadium introduced demand-responsive pricing along with resident-only restrictions and reinvestment of the meter revenue to the local communities. Additionally, prices were increased during special events as well as for longer stays. Based on the successful results of the pilot project, the city initiated plans for a citywide parking pricing program in 2010 (Nelson and Schrieber, 2012). Another city that has developed an innovative parking policy is San Francisco, California. This project, called SF*park*, is described in more detail below (see Section 2.3.4).

2.3.2 Europe

Many European cities have focused on new parking policies to meet other social goals such as national greenhouse gas targets or EU-wide air quality requirements. Since every car trip begins and ends in a parking space, it seems reasonable to regulate parking in order to regulate car usage. Kodransky and Hermann (2011) give an overview of successful parking policies in Europe. Motivation to change parking policies includes reducing cars cruising for parking and hence reducing traffic congestion, as well as making city centers more lively and pedestrian friendly. Kodransky and Hermann (2011) distinguish four different effective parking management strategies: economic mechanisms, regulatory mechanisms, physical design, and quality of service contracting and technology.

Economic Mechanisms Many European cities set parking fees at varying levels at different locations and times to ensure that the occupancy does not increase past 85% at all times. Some cities like Strasbourg even coordinate on- and off-street parking, pricing and supply. With these measures the more desirable parking spaces, mostly close to the most desired locations, are occupied by people willing to pay the most. Other cities such as Amsterdam and some boroughs in London vary parking prices for residents depending on the CO_2 emission level of the vehicle. Another economic mechanism is the creation of workplace levies. For example, Hamburg allows companies to provide fewer parking spaces than required if they provide transit passes to employers.

Regulatory Mechanisms Parking supply caps have been introduced in Hamburg in 1976 and in Zurich in 1996. In both cities an on-street parking space has to be removed for every newly built off-street parking space. The street space that is gained can in turn be used to widen sidewalks or to build bikeways. Requiring a maximum number of parking spaces instead of a minimum, especially in areas with good public transit access, has been the policy in many Dutch cities. European cities have also regulated the location of parking, to make the use of public transit more attractive. In many cities parking is found in peripheral locations, whereas cyclists and users of public transit have direct access to popular destinations. Often park and ride facilities are located next to peripheral public transit stops (see Figure 1(b)).

Physical Design Bollards function as barriers to prevent cars from parking in public spaces or pedestrian zones and can also be used to restrict access to an area at certain times or for certain vehicles (allowing access for delivery vans). Paris has installed about 350,000 bollards since 2001 and in Madrid bollards are used frequently to prevent cars from parking on sidewalks or blocking building entrances. It is also very common for European cities not to allow on-street parking in historic centers as well as in central shopping areas. By re-purposing space formerly used for parking for bike lanes or pedestrian zones—like in Copenhagen—or even for public transportation hubs, provides an incentive to use other transport modes. In Paris, Copenhagen and Amsterdam parked cars protect bike lanes by acting as a barrier between cyclists and moving traffic (see Figure 1(a)). Copenhagen and Antwerp have play-streets that allow children to play safely on streets where benches, trees and other physical obstructions remind vehicles that they are not the prime user of the street.

Figure 1: Examples of European parking policies

(a) protected bike lane in Amsterdam (b) Park and Ride facility in Strasbourg

Source: Kodransky and Hermann (2011)

Quality of Service Contracting and Technology Some cities have outsourced certain aspects of their parking management to third parties. One example is electronic parking guidance systems that direct drivers to nearby parking facilities via real-time message boards. Those guidance systems are used in every major city in Germany as well as in Barcelona, Antwerp, Paris and many other cities. Another measure that is often outsourced to third parties are pay-by-phone services that allow users to pay a parking fee via their smartphone. Pay-by-phone applications are for example used in London. Smart meters are used in Paris and throughout France to help enforce parking policy. When the meter expires a text message is sent to the driver's mobile phone as well as to the parking enforcement agency.

Many of the above mentioned innovative parking policies have significant impacts, such as reducing the number of private car trips, improving air quality, and revitalizing city centers, and thus have an impact on improving the overall quality of life in urban areas.

2.3.3 Parking Policy in Zurich

The parking policy in Zurich has been very restrictive as a response to air quality issues, limited road capacity and noise pollution (Kodransky and Hermann, 2011). There are 270,000 parking spaces in the city, of which about 220,000 are located on private land and 50,000 are located on public land. 15,000 of those located on private land are accessible for public use (Stadt Zürich, 2013d). Most of these are located in parking garages. Parking fees are highest in parking garages closest to the city center, and then decrease as the distance from the city center increases. Additionally the fees in most garages increase disproportionally with increasing parking duration—each additional hour is more expensive then the preceding hour (Oswald, 2012). Publicly accessible on-street parking spaces are divided into two categories: blue zones and white zones. Blue zones allow free parking for up to 60 minutes, using the European parking disc. Between 6 p.m. and 8 a.m. parking in the blue zone is unlimited, but a parking disc has to be displayed in the car (Stadt Zürich, 2013b). Residents can buy a parking permit for use in a specific blue zone for 300 CHF (312 US$) per year (Stadt Zürich, 2013a), but a parking permit does not guarantee a parking spot. In 2012, 42,000 residential permits were sold even though there are only 34,000 residential parking spots in the city (Stadt Zürich, 2013e). White zones are paid parking zones throughout the city. The fees in the white zone are regulated in the Parkplatzverordnung (PPV, parking ordinance) and differ between zones in the inner city and the rest of the city, with higher prices in the inner city zones. As for garages, the tariffs in the inner city zones increase disproportionally with the parking time (Oswald, 2012).

Figure 2: Changes in on-street parking policy in the city center of Zurich

(a) Rennweg before removal of parking (b) Rennweg after removal of parking

Source: Stadt Zürich (2013c)

Since 1996 a parking supply cap called Historischer Parkplatz Kompromiss (historic parking compromise) has been in place. The idea was to make the city center more pedestrian friendly (see Figure 2). An on-street parking space can be removed by replacing it in a garage to keep the total number of parking spaces provided fixed. Between 1990 and 2010, the number of parking spaces in the city center has been augmented by 1% which corresponds to 76 additional parking spots (Stadt Zürich, 2013c). The new PPV, which was accepted by referendum in November 2010, allows for construction of apartment buildings with no or very few parking spaces, as long as alternative mobility tools are provided. The PPV also gives maximum limits on the amount of parking spaces to be constructed and defines areas which have exceptionally good public transit connections and therefore a reduced demand for parking. In those areas the number of required parking spaces for new developments is reduced (Stadt Zürich, 2013d).

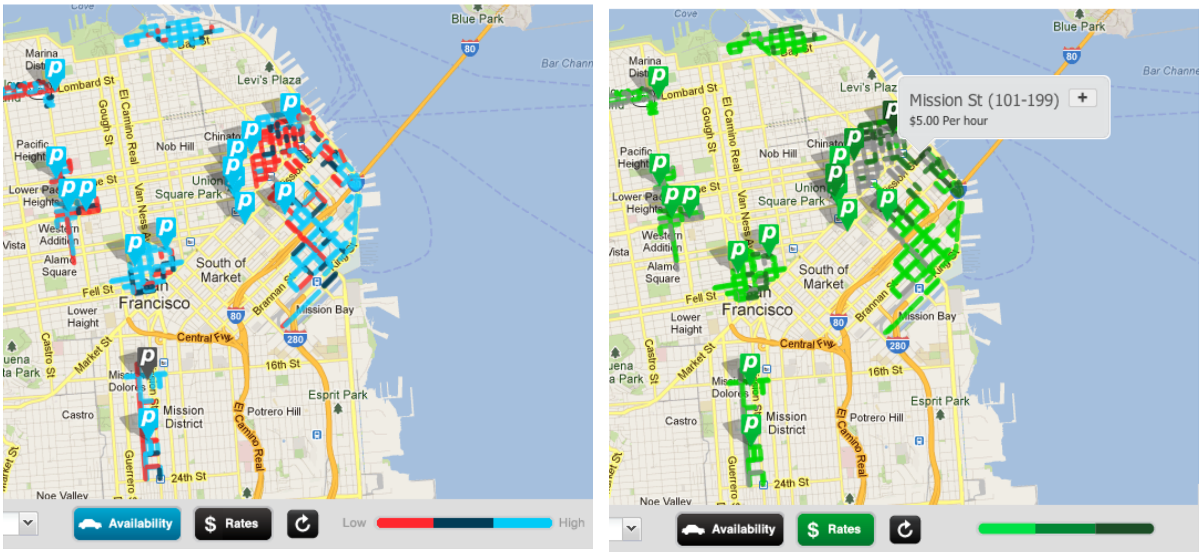
2.3.4 Parking Applications for Smartphones

Smartphones are becoming more important in our every-day life and naturally, applications for parking are being developed. The intentions for developing an application for parking range from providing information on parking availability to offering unused parking spots to drivers. The following paragraphs present three recently developed parking applications that have drawn large interest.

SF*park* As mentioned above, in 2010 San Francisco launched a new parking policy called SF*park*. The goal was to improve the overall parking situation in San Francisco by using new technology and policies with an objective of having 15% on-street parking availability at all times. To achieve this, sensors, smart meters and demand-responsive pricing were introduced. Wireless sensors detect parking availability in real-time and pass this information on to the parking management authorities. With this information, parking managers can adjust prices to reach at most 85% occupancy rates. Parking rates can vary by block, by time of day, and by the day of the week. They are adjusted at most once a month and decrease by no more than 50 cents per hour or increase by no more than 25 cents per hour. The smart meters in San Francisco accept credit cards, coins and parking cards. Information on parking availability and prices is provided through the SF*park* homepage as well as through an iPhone and Android app (see Figure 3). In addition a pay-by-phone system has been developed that allows parkers not only to pay by phone but also to add time to their meters without returning to them and to get a reminder message when the parking time is about to expire. The SF*park* project also includes 14 garages in San Francisco. Rates at these garages vary by time of day and are adjusted in response to demand (SFpark, 2013). Despite strong support for this program there has been some concern and rising criticism. The main concern is that using a smartphone app while driving a car is dangerous. In most countries using a mobile phone while driving a car is against the law (Cellular News, 2009). In many states in the United States such laws have just been passed recently and are not yet enforced (Governors Highway Saftey Association, 2013). Another criticism is that the demand-driven and dynamic pricing seems very excessive and unfair since not everybody can afford to pay 5.00 US$ per hour for a parking spot. Driving a car therefore becomes elitist and only affordable for the wealthy. In addition local businesses are afraid that the high parking prices will reduce the number of people coming into the city and thus reduce their revenue.

Figure 3: Availability and price information in SF*park*

(a) Availability (b) Prices



Source: SFpark (2013)

ParkMe This app gathers data from parking meters that are connected to the internet as well as from garage ticket machines to display real-time parking availability. ParkMe has been available as an iPhone or Android app since 2012 and includes 25,000 locations throughout the world. Information on parking availability is provided as a heat map that shows the user where parking is most likely available. The app also offers rate information, route guidance and a parking timer (ParkMe, 2013).

parkU A different type of parking app is parkU. This Zurich-based project offers unused and privately owned parking spots to drivers looking for a parking spot. Residents or companies that own parking spaces that they do not need at certain times (maybe even always) can offer these through parkU's website. A driver looking for parking can book a space for certain times on parkU's website or through a smartphone app (ParkU, 2013). ParkU has been in effect since the beginning of 2013 and is now expanding to other Swiss cities. One problem of this business idea could be that it will be hard to enforce parking offenders, namely people who stay longer in the parking spot than the time they paid for. Since it is not a public parking spot city enforcement is not in charge but the owner of a private parking spot still relies on being able to park in his spot when he needs it. According to parkU so far there have been no problems with unlawful parking (Tagesanzeiger, 2013).

3 Model Description

Computable general equilibrium (CGE) models are widely used in economics to evaluate the impacts of policy reforms in many fields such as fiscal reform and development planning, international trade, or environmental regulation (Wing, 2004). The model developed in this thesis follows an approach developed by Prof. Rutherford, Prof. Axhausen and van Nieuwkoop at ETH Zurich, which formulates the parking model as a joint model of network assignment and parking search (van Nieuwkoop *et al.,* 2012). The parking model is formulated as a mixed complementarity problem (MCP), a problem with complementarity constraints that may be equalities as well as inequalities. A more detailed description on using MCPs to model parking can be found in Rutherford and van Nieuwkoop (2011).

3.1 Methodology

The parking model presented here consists of a simplified street network in which agents search for a parking space. Agents differ with respect to their origin, valuation of time and their destination. There are two different types of parking in the city: on-street parking and garage parking. On-street parking is located along the streets (directed links in the network), and parking garages are located at the intersection (nodes in the network) closest to their location. The network is represented as a directed graph, existing of nodes, denoted as i or j, and arcs, corresponding to pairs of nodes, referenced as a or origin-destination pair (i, j). Agents enter the network at inflow nodes and end at destination nodes.

The model builds upon the static traffic equilibrium formulation by Wardrop (1952), according to which agents make individually rational but collectively irrational route choices. It is assumed that agents are fully informed about all alternatives and their features, have consistent and stable preferences, and optimize their utility over time. According to Wardrop (1952) utility optimization means choosing the fastest available route from origin to destination. To avoid an implicit or explicit enumeration of all paths between origin-destination pairs, a multi-commodity flow formulation is used to solve the Wardropian equilibrium as presented in Ferris *et al.* (1999). The multi-commodity flow formulation has two classes of constraints. The first class includes the primal constraints, including the conservation of flow of agent type h through node j as well as the constraints of garage and on-street parking capacity. In the classic formulation, conservation of flow means that the number of agents (X_h) traveling from all adjacent nodes to node j (X_{hij}) has to be equal to the number of agents leaving node j (X_{hji}). In the parking model the agents have three options at every node:

- Continue to an adjacent node: X_{hji}
- Search for on-street parking on the link between node j and i: Y_{hji}
- Park in a parking garage at node j (if one exists): Z_{hk}

By considering the probability π of not finding a parking spot, the model accounts for spillover of agents that keep on looking for parking, and therefore are cruising for parking. Drivers looking for on-street parking on arc a do not find a parking spot with probability π_a, and those looking for parking in parking garage k do not find a spot with probability of π_k. The conservation of flow can now be written as:

$$\sum_{a(j,i)} X_{hji} + \sum_{a(j,i)} Y_{hji} + \sum_{k}(1-\pi_k)Z_{hk} = \sum_{a(i,j)} X_{hij} + \sum_{a(i,j)} \pi_a Y_{hij} + \mathcal{A}_{hj} \quad \perp \quad T_{hj} \tag{1}$$

where $\mathcal{A}_{hj}$ is the number of agents arriving at node j, if j is an inflow-node.

The other two primal constraints of the model consider the amount of parking. The number of people parking in garage k cannot exceed the capacity of garage k:

$$\mathcal{P}_k^G \geq \sum_{h}(1-\pi_k)Z_{hk} \quad \perp \quad \mathcal{F}_k^G \tag{2}$$

An agent parking at garage k will pay a fee $\mathcal{F}_k^G$ that clears the market for garage parking. The same holds for on-street parking. The number of people parking along arc a has to be smaller or equal to the parking spots provided along that arc:

$$\mathcal{P}_a^S \geq \sum_{h}(1-\pi_a)Y_{ha} \quad \perp \quad \pi_a \tag{3}$$

The second class of constraints ensures that if there is a positive flow of agents h on arc (i, j), the corresponding time to reach the destination using this arc is minimized (Wardrop, 1952). Since drivers have three different choices at each node, there are three arbitrage conditions to reflect this constraint. The first option, driving to an adjacent node without looking for parking, has the following arbitrage condition for every agent of type h:

$$\tau_{ij} + T_{hj} \geq T_{hi} \quad \perp \quad X_{hij} \geq 0 \tag{4}$$

where τ_{ij} is the travel time from node i to node j, T_{hj} the minimum travel time from j to the final destination, and T_{hi} the minimum travel time from i to the final destination. $\perp$ is used to indicate complementarity slackness, which means that exactly one of the inequalities has to be tight and exactly one will have slack. This means that one has to be an equality, while the other is a strict inequality. In equilibrium, if the time to travel to the final destination using a given arc a_{ij} is greater than the minimum travel time to the destination from node i, then the flow of agents X_{hij} on the a_{ij} arc will be zero. If the travel time from node i to node j plus the minimum travel time to get from node j to the final destination is equal to the minimum time to travel from node i directly to the destination T_{hi}, then the flow of agents traveling on arc (i, j) X_{hij} will be positive.

The second option agents have is to search for on-street parking on the link between node i and j. The arbitrage condition for this option is given by:

$$\tau_{ij} + (1 - \pi_a)\left(\mathcal{W}_a^S + \frac{\mathcal{F}_a^S}{v_h}\right) + \pi_a T_{hj} \geq T_{hi} \quad \perp \quad Y_{hij} \geq 0 \tag{5}$$

with τ_{ij} denoting travel time from i to j, π_a representing the probability of not finding an on-street parking spot on arc a, walking time from a to the destination $\mathcal{W}_a^S$, on-street parking fee $\mathcal{F}_a^S$, and valuation of time v_h. Again due to complementarity, one of the inequalities has to be tight, and one will have slack. This means that drivers search for on-street parking on arc a ($Y_{hij} > 0$) if the time cost of going from i to j, plus the walking time from the arc to the destination, plus the parking fee in time units $\left(\frac{\mathcal{F}_a^S}{v_h}\right)$, plus the minimum time from j to the destination (T_{hj}) if they don't find a parking spot (π_a) is equal to the minimum time to go directly from i to the destination (T_{hi}). If it is greater than T_{hi}, the number of agents searching for parking on arc a (Y_{hij}) will be equal to zero.

The third option agents have is to go from i directly to a parking garage k (if it exists). This option is represented by the following arbitrage condition:

$$\tau_z + (1 - \pi_k)\left(\mathcal{W}_k^G + \frac{\mathcal{F}_k^G}{v_h}\right) + \pi_k T_{hi} \geq T_{hi} \quad \perp \quad Z_{hk} \geq 0 \tag{6}$$

with parking search time τ_z, probability of not finding a garage parking spot π_k, walking time from parking garage k to the final destination $\mathcal{W}_k^G$, parking fee $\mathcal{F}_k^G$, value of time v_h and minimum time from i to the destination T_{hi}. The parking search time τ_z is different from the travel time on an arc τ_a. Agents looking for a garage parking spot do not travel along an arc to do that, but are assumed to go straight from an intersection into the parking garage. The time it takes to find a parking spot in the garage is denoted by τ_z. Due to complementarity, one of the inequalities above has to be tight, while the other will have slack. This means that this condition is linked with the number of agents type h, parking at parking garage k (Z_{hk}). Drivers park at parking garage k ($Z_{hk} > 0$) if the time to search for garage parking τ_z, plus the time to walk from k to the final destination ($\mathcal{W}_k^G$) plus the price of parking at garage k in time units $\left(\frac{\mathcal{F}_k^G}{v_h}\right)$ plus the time it takes from node i to the final destination in case they don't find a spot at k ($\pi_k T_{hi}$) is equal to the minimum time from i to the final destination T_{hi}. If it is larger than T_{hi}, the number of agents parking at garage k (Z_{hk}) will be equal to zero.

In addition to these constraints there are two equations defining the flow of agents on a given arc a and the travel time delay due to congestion on arc a. The aggregate flow (F_a) on a given arc a is defined as the number of agents driving through arc a without looking for parking (X_{ha}) plus the number of agents searching for parking on that arc (Y_{ha}):

$$F_a = \sum_h X_{ha} + Y_{ha} \tag{7}$$

The travel time on a used arc is different from the travel time on an unused arc. Traffic models frequently account for this by using the Bureau of Public Roads function (Bureau of Public Roads, 1964). It is also used in the model presented here:

$$\tau_a = \tau_{a_0}\left(1 + \alpha\left(\frac{F_a}{C_a}\right)^\beta\right) \tag{8}$$

where τ_{a_0} is the free flow travel time on the given arc, F_a the flow on arc a, C_a the capacity of arc a and α and β are parameters, usually set to 0.15 and 4 respectively. In this model α is calibrated and β is set to 4.

The search time for finding a garage parking spot τ_z depends on the occupancy of the garage, in the same style as the travel time on a street. To calculate it a BPR-style function is used:

$$\tau_z = \tau_{z0}\left(0.5 + 0.5\left(\frac{Z_k}{C_k}\right)^{\beta}\right) \tag{9}$$

where τ_{z_0} is the search time when the parking garage is fully occupied, Z_k the amount of cars in the garage, C_k the capacity of the parking garage and the parameter β is set to 4. With this formulation the search time for a garage parking spot is reduced by 50% when the parking garage is empty and increases with increasing occupancy of the garage.

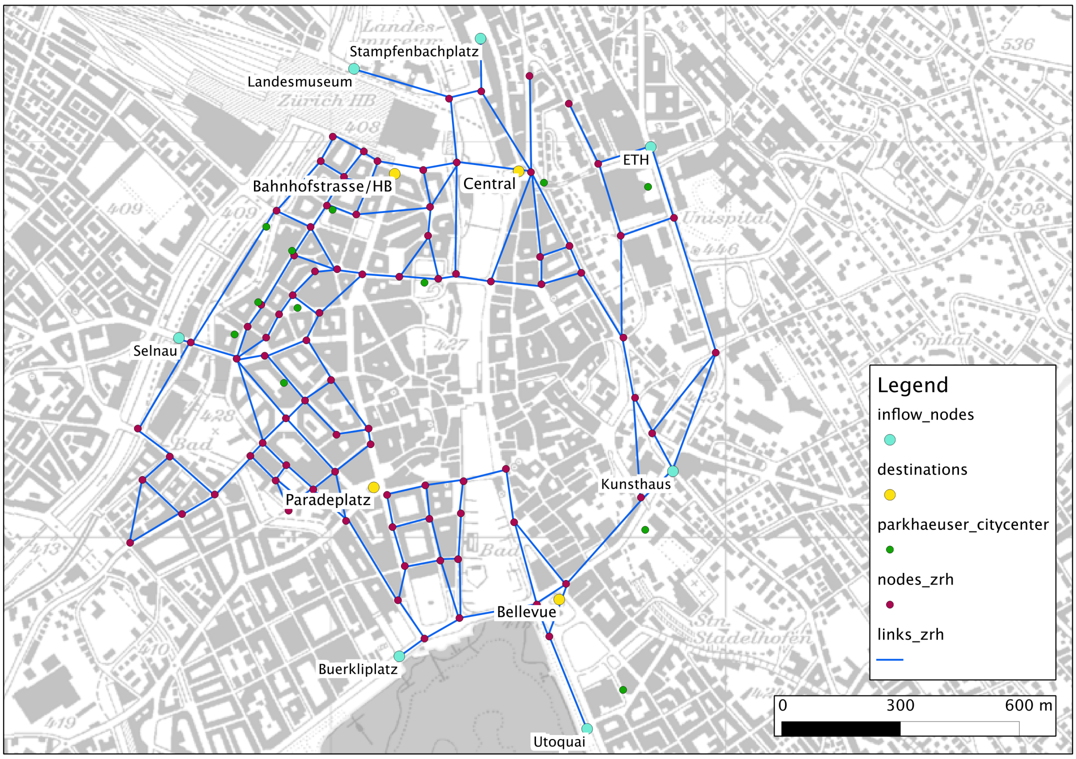
Equations 1 to 9 form a mixed complementarity problem (MCP) and can be used to solve the user equilibrium. In this thesis GAMS (General Algebraic Modeling System) is used to solve the model.

3.2 Case Study: Zurich

The above described model has been tested in a case study for the city of Zurich, Switzerland. For this purpose a simplified street network of the city center has been developed (see Figure 4). The network is described as a directed graph with 94 nodes i and 214 directed arcs a.

For the policy analysis five scenarios are developed. First a benchmark scenario is developed which reflects today's parking policy where people pay a fixed parking fee that is lower for on-street parking than for off-street parking. The prices for on- and off-street parking are taken from Oswald (2012) and reflect the prices when parking for two hours, which is the average parking duration in Zurich (Oswald, 2012). For simplicity, on-street parking fees are 5 CHF per two hours throughout the network. The fees for garage parking are shown in Table 3. It is assumed that 80% of all on- and off-street parking spots are used, resulting in a utilization rate of 80%. The number of people entering the network is determined by this utilization rate. Agents choose between four different destinations in the city center: *Bellevue*, *Central*, *Hauptbahnhof* and *Paradeplatz*. Drivers can enter the network at seven different locations (inflow nodes): *Bürkliplatz*, *ETH*, *Kunsthaus*, *Landesmuseum*, *Selnau*, *Stampfenbachplatz* and *Utoquai*. The

Figure 4: Simplified Street Network of the city center in Zurich



Source: Kanton Zürich (2013)

destinations and inflow nodes are also depicted in Figure 4.

Table 1: Traffic shares for inflow nodes

Inflow Node	Traffic Share
Bürkliplatz	19.1%
ETH	19.3%
Kunsthaus	10.6%
Landesmuseum	15.7%
Selnau	10.4%
Stampfenbachplatz	16.2%
Utoquai	8.7%

A rough estimate of traffic shares for the seven inflow nodes is determined from the MATSim scenario for Zurich (Meister *et al.*, 2010) (see Table 1). The percentage of agents to each destination is calibrated, assuming traffic flows consistent with minimum system costs (see

Table 2: Traffic shares to each destination

Destination	Traffic Share
Bellevue	33.8%
Central	14.9%
Hauptbahnhof	25.3%
Paradeplatz	26.0%

Table 2). The resulting OD Matrix can be found in Appendix A. The parking fees and capacities for the parking garages are derived from Oswald (2012). As for on-street parking, it is assumed that agents park for two hours, and prices are adjusted accordingly. In the simplified model twelve parking garages in Table 3 are considered for the city center of Zurich. In addition to the 2,659 garage parking spots, there are 1,652 on-street parking spots along the directed arcs in the network. Information on the location of the on-street parking spaces is taken from Oswald (2012). These parking spots are then assigned to the streets using GIS software. It is assumed that an equal number of parking spots exists on either side of a two-way street for simplicity. Agents differ with respect to their origin, determined by the inflow-node and their value of time. It is assumed that agents originating from *Utoquai* and *Kunsthaus* have the highest value of time and those originating from *Stampfenbachplatz* have the lowest. The idea is that every inflow node is linked to an area of living with higher or lower housing prices and therefore higher or lower income. Given the estimated value of time of 27.7 CHF per hour provided by König *et al.* (2004), Table 4 gives computed values based on household types as defined in the model. These inputs are then used to implement a reference equilibrium describing today's parking policy in Zurich. When implementing the model for the city of Zurich, fixing either the parking fee $\mathcal{F}$ or the probability of not finding a parking spot π lets us determine the other variable endogenously. This means that if the parking fees are fixed to today's prices, then the probabilities of not finding parking are determined endogenously and vice versa.

Table 3: Prices and capacities for parking garages in the city center

Parking Garage	Parking Fee [CHF/h]	Capacity
Central	8	49
Centrum Garage	16	11
ETH Hauptgebäude	4	146
Gessnerallee	8	608
Globus	7	170
Hohe Promenade	8	502
Jelmoli	7	218
Migros City	6	56
Opera	9	299
Sihlporte	9	40
Talgarten	8	110
Urania	9	450

Source: Oswald (2012)

Table 4: Valuation of time by household type

Inflow Node	Valuation of Time [CHF/min]
Bürkliplatz	1.5
ETH	1.5
Kunsthaus	2.5
Landesmuseum	2.0
Selnau	1.0
Stampfenbachplatz	0.5
Utoquai	2.5

4 Policy Analysis and Results

This section describes the framework for the policy analysis and the results when implementing three different parking policies in the city of Zurich.

4.1 Framework

Typically the calibrated equilibrium framework for policy analysis follows four steps. In a first step the model is calibrated to stylized facts describing the world as we know it today. Then elasticities are imposed that characterize how agents change their behavior in response to changes in economic incentives. A third step involves verifying that the model replicates the reference equilibrium. In a last step, a set of counterfactual simulations is defined that explore specific policy proposals. In the policy analysis conducted here the benchmark model represents today's parking policy in Zurich. Since the version of the model presented here does not include changes in mode choice, time of day or what kind of activity is undertaken, there are no imposed elasticities to evaluate these changes in behavior. In the last step—defining counterfactual simulations—three different parking policies are implemented for the Zurich model:

- A policy similar to SF*park*, in which garage and street parking prices are adjusted such that all agents can park at their desired location as long as they are willing to pay for it (SF*park*).
- Demand-responsive pricing for on-street parking, in which garage fees are identical to those in the benchmark, and parking fees for on-street parking are adjusted such that the probability of finding on-street parking is equal to 100% (optimal on-street pricing).
- Demand-responsive pricing for garage parking, in which on-street parking fees are fixed to the fees we have today, and parking fees for garage parking are adjusted such that the probability of finding a garage parking spot at the desired garage is equal to 100% (optimal garage pricing).

The results are compared with today's parking policy in Zurich as well as with the social optimum, in which the overall time cost for all agents is minimized by pricing accordingly.

4.1.1 Status Quo Scenario *(status quo)*

The status quo scenario presents the world as we know it today—with some simplifications. First, the price for on-street parking is set to be equal throughout the network. An on-street parking fee of 5 CHF for two hours is assumed since it is assumed that agents park for two hours, which is the average parking duration in Zurich (Oswald, 2012). In addition, the prices for garage parking are based on actual prices for a parking duration of two hours (see Table 3). How many agents park in a garage or on a certain street is determined through the probabilities of not finding a parking spot on the street π_a or in a garage π_k. To implement this in the model, Equations 5 and 6 are solved with fixed parking fees $\mathcal{F}^S$ of 2.5 CHF per hour and $\mathcal{F}^G$ according to Table 3.

4.1.2 SF*park* Scenario *(SFpark)*

To conduct the policy analysis for SF*park*, variables have to be set such that they represent an implementation of SF*park*. The demand-responsive pricing for parking in SF*park* leads—in the ideal case—to a situation in which every driver looking for parking on the street or in a garage can find that spot at his preferred location. To implement this, the probability of not finding an on-street parking spot π_a as well as the probability of not finding a garage parking spot π_k are both set to zero. This means that every agent can park at his desired parking spot—as long as he is willing to pay the price. The parking fees are determined endogenously so that π can be equal to zero.

4.1.3 Optimal On-Street Pricing Scenario *(optimal on-street)*

For this policy the garage prices are fixed to today's fees and demand-responsive pricing is only introduced for on-street parking. This means that only the probability of not finding an on-street parking spot π_a is set to zero while the probability of finding a garage parking spot is still driven by today's prices. By setting the probability of finding on-street parking to zero, we equate demand for parking spaces with a fixed supply by allowing for fluctuating prices in the final equilibrium. That is, one can always find parking in the nearest location provided one is willing to pay the nominally increased prices.

4.1.4 Optimal Garage Pricing Scenario *(optimal garage)*

This policy assumes fixed prices for on-street parking and demand-driven prices for parking garages. Parking fees $\mathcal{F}^S$ and probabilities π_k are fixed to solve Equations 5 and 6. The on-street parking fees are set to today's prices of 2.5 CHF per hour and probabilities of not finding a garage parking spot are fixed to zero. By this the probability of not finding on-street parking π_a as well as the prices for garage parking $\mathcal{F}^G$ are determined endogenously.

4.1.5 Social Optimum Scenario *(SO)*

In the social optimum scenario it is not the cost of every agent that is minimized, but the overall time cost in the system. Parking fees are not considered here, since from an economic point of view they only represent a monetary transfer from one agent (driver) to another agent (owner of the parking spot). The objective function to be minimized in the social optimum can be written as follows:

$$OBJ^{SO} = \sum_h v_h \left(\sum_a \left(\tau X_{ha} + \tau Y_{ha} + \mathcal{W}_a^S Y_{ha} (1 - \pi_a) \right) + \sum_k (1 - \pi_k) \mathcal{W}_k^G Z_{hk} \right)$$

The social optimum minimizes overall system costs but not the user costs. Assuming that drivers optimize their costs (and not overall system costs), it is hard to achieve behavior that reaches the social optimum. Social optimum is then usually achieved by introducing fees such as road pricing or higher parking fees (Menendez, 2011). Here the social optimum is used to analyze how close the different parking policies come to minimizing overall system costs by introducing optimal on-street pricing, optimal garage pricing or both (the case of SF*park*).

4.2 Results

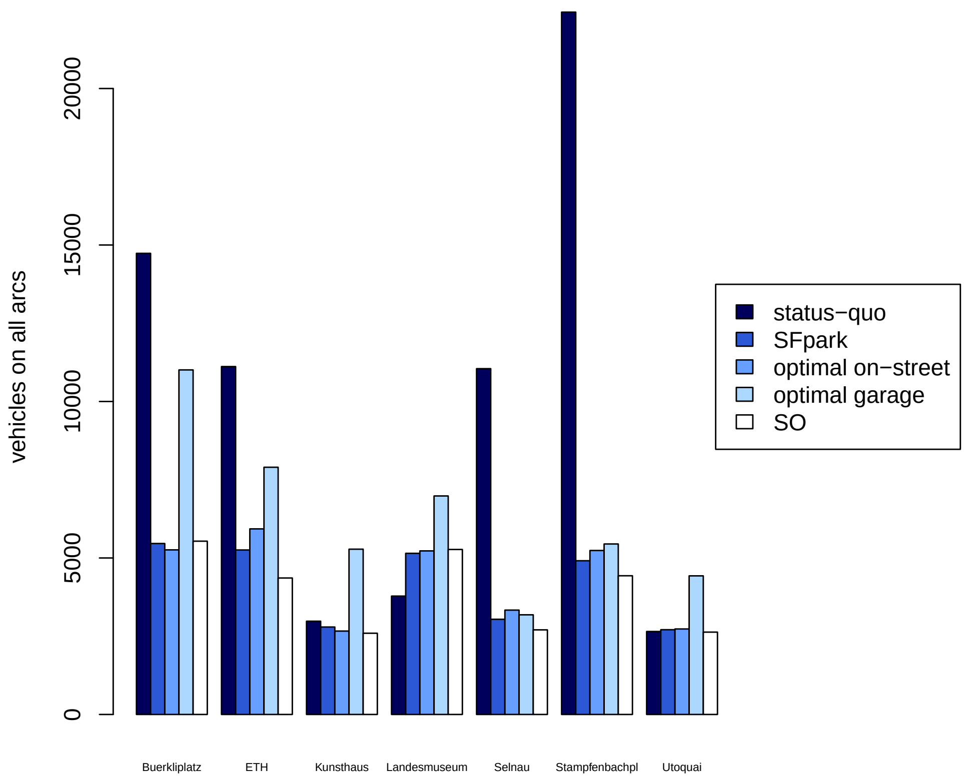
4.2.1 Overview

Tables 5, 6, 7 and 8 give an overview of the different cost parameters for the three different parking policies. For each scenario the time spent walking, driving and driving due to search traffic and searching, the vehicle kilometers for driving and searching, the time cost for walking, driving and driving due to search traffic and searching, as well as the parking fees for on-street and garage parking and the generalized costs are reported. The numbers are reported as an average by household and as an average over all households. When comparing the average numbers for the different scenarios large differences between the vehicle kilometers spent searching and the monetary costs are noticeable. Explanations for this are given in Sections 4.2.5 and 4.2.6.

4.2.2 Traffic Volume

The main goal of the policy analyses examined here, is to reduce the amount of people cruising for parking and thereby reduce congestion on the streets. To evaluate this, the total traffic volume F_a as well search traffic Y_a are compared between the different scenarios within the whole network as well as for the different inflow nodes and destinations. Table 9 shows the changes in traffic volume in the network in absolute values and by percentage, and Figure 5 the total traffic volume by household type/origin for the different scenarios. The overall

Figure 5: Total traffic volume by household (inflow node)



traffic volume is reduced by about 65% for those scenarios in which on-street parking prices are demand-responsive (SF*park* and optimal on-street pricing) and only by 42% for the optimal garage pricing scenario in which on-street parking prices stay fixed and only garage parking prices are regulated through the demand. This can mainly be explained by the reduction in search traffic for the different scenarios. With a reduction of 97% for both the SF*park* and the optimal on-street pricing, search traffic is almost eliminated, while this is not the case for the

Table 5: Time, vehicle kilometers, time costs and fees by household and on average for the status quo

		Bürkliplatz	ETH	Kunsthaus	Landesmuseum	Selnau	Stampfenbachplatz	Utoquai	Average
Total travel time	[min]	13.85	14.26	11.07	12.00	16.62	18.92	12.23	14.31
Driving	[min]	1.61	1.45	0.80	2.26	2.42	3.54	1.50	1.98
Driving due to search traffic	[min]	0.81	0.64	0.05	0.10	5.23	11.53	0.03	2.71
Searching	[min]	8.61	8.61	6.08	5.16	9.87	11.67	6.72	8.26
Walking	[min]	3.64	4.21	4.19	4.57	4.33	3.72	4.01	4.07
VKM	[km]	22.36	16.70	8.15	6.99	30.80	40.17	8.83	19.93
Searching	[km]	17.91	13.37	5.82	3.06	22.71	29.97	6.27	14.86
Driving	[km]	4.46	3.33	2.33	3.92	8.09	10.20	2.57	5.07
Time cost traveling	[CHF]	20.78	21.40	27.67	23.99	16.62	9.46	30.58	20.72
Driving	[CHF]	2.41	2.18	2.01	4.53	2.42	1.77	3.74	2.67
Searching	[CHF]	12.91	12.91	15.19	10.32	9.87	5.84	16.81	11.62
Walking	[CHF]	5.46	6.31	10.47	9.14	4.33	1.86	10.03	6.43
Monetary Costs	[CHF/h]	5.28	4.75	7.00	7.50	3.05	2.50	7.04	5.18
Garage parking	[CHF/h]	4.11	3.75	6.45	7.24	0.94	0.00	6.40	3.93
Street parking	[CHF/h]	1.17	1.01	0.56	0.26	2.11	2.50	0.64	1.20
Generalized Costs	[CHF]	43.25	43.67	59.74	53.29	31.97	19.24	63.10	43.32

Table 6: Time, vehicle kilometers, time costs and fees by household and on average for SF*park*

		Bürkliplatz	ETH	Kunsthaus	Landesmuseum	Selnau	Stampfenbachplatz	Utoquai	Average
Total travel time	[min]	6.09	8.95	4.78	7.71	8.90	9.71	6.28	7.65
Driving	[min]	2.49	2.88	2.38	3.72	2.80	3.25	2.98	2.95
Driving due to search traffic	[min]	0.01	0.01	0.00	0.03	0.00	0.00	0.00	0.01
Searching	[min]	0.56	1.38	0.37	1.22	1.84	2.02	0.94	1.20
Walking	[min]	3.04	4.69	2.03	2.77	4.26	4.44	2.36	3.50
VKM	[km]	8.29	7.89	7.64	9.51	8.48	8.79	9.03	8.50
Searching	[km]	0.76	0.35	0.92	0.47	0.10	0.05	0.72	0.46
Driving	[km]	7.53	7.54	6.72	9.04	8.38	8.74	8.31	8.04
Time cost traveling	[CHF]	9.13	13.42	11.94	15.42	8.90	4.85	15.71	11.10
Driving	[CHF]	3.74	4.32	5.94	7.45	2.80	1.62	7.46	4.55
Searching	[CHF]	0.83	2.07	0.92	2.43	1.84	1.01	2.35	1.60
Walking	[CHF]	4.56	7.03	5.08	5.54	4.26	2.22	5.90	4.95
Monetary Costs	[CHF/h]	2.28	0.69	3.62	1.81	0.29	0.31	2.66	1.55
Garage parking	[CHF/h]	0.39	0.33	0.05	0.52	0.27	0.30	0.03	0.30
Street parking	[CHF/h]	1.90	0.36	3.58	1.28	0.02	0.02	2.63	1.25
Generalized Costs	[CHF]	18.68	22.87	24.73	25.79	14.66	8.20	28.10	19.95

Table 7: Time, vehicle kilometers, time costs and fees by household and on average for optimal on-street

		Bürkliplatz	ETH	Kunsthaus	Landesmuseum	Selnau	Stampfenbachplatz	Utoquai	Average
Total time traveling	[min]	6.93	11.44	5.01	8.62	10.84	13.69	6.24	9.30
Driving	[min]	2.42	3.42	2.38	3.79	2.66	3.88	3.04	3.14
Driving due to search traffic	[min]	0.02	0.03	0.00	0.02	0.22	0.00	0.00	0.04
Searching	[min]	0.76	3.74	0.40	1.69	3.70	6.07	0.93	2.62
Walking	[min]	3.75	4.28	2.23	3.14	4.47	3.74	2.27	3.54
VKM	[km]	7.98	8.91	7.29	9.65	9.30	9.38	9.10	8.81
Searching	[km]	0.81	0.26	0.94	0.57	0.21	0.00	0.72	0.48
Driving	[km]	7.17	8.65	6.35	9.08	9.09	9.38	8.38	8.33
Time cost traveling	[CHF]	10.39	17.15	12.52	17.23	10.84	6.85	15.60	12.92
Driving	[CHF]	3.63	5.13	5.95	7.58	2.66	1.94	7.60	4.76
Searching	[CHF]	1.13	5.61	0.99	3.38	3.70	3.03	2.34	3.01
Walking	[CHF]	5.63	6.42	5.58	6.27	4.47	1.87	5.67	5.15
Monetary Costs	[CHF/h]	10.77	8.00	12.79	10.27	7.80	7.07	11.87	9.56
Garage parking	[CHF/h]	1.60	5.39	0.55	3.68	6.15	7.08	2.47	3.98
Street parking	[CHF/h]	9.18	2.37	12.25	7.60	1.65	0.00	9.40	5.58
Generalized Costs	[CHF]	38.13	42.38	44.18	45.74	32.77	24.38	46.17	38.70

Table 8: Time, vehicle kilometers, time costs and fees by household and on average for optimal garage

		Bürkliplatz	ETH	Kunsthaus	Landesmuseum	Selnau	Stampfenbachplatz	Utoquai	Average
Total time traveling	[min]	7.41	9.35	6.96	8.69	9.20	10.84	7.56	8.69
Driving	[min]	2.49	3.44	2.48	3.55	3.06	3.85	2.79	3.14
Driving due to search traffic	[min]	0.05	0.05	0.01	0.27	0.00	0.00	0.00	0.06
Searching	[min]	2.13	2.00	2.06	2.19	2.12	2.57	2.29	2.19
Walking	[min]	2.80	3.91	2.43	2.96	4.02	4.43	2.47	3.36
VKM	[km]	16.71	11.87	14.45	12.89	8.88	9.75	14.76	12.82
Searching	[km]	9.40	3.96	8.51	4.97	0.47	0.27	8.20	5.05
Driving	[km]	7.31	7.91	5.94	7.92	8.40	9.48	6.55	7.78
Time cost traveling	[CHF]	11.11	14.03	17.41	17.38	9.20	5.42	18.90	12.88
Driving	[CHF]	3.73	5.16	6.19	7.09	3.06	1.92	6.99	4.72
Searching	[CHF]	3.19	2.99	5.15	4.38	2.12	1.28	5.73	3.35
Walking	[CHF]	4.19	5.87	6.07	5.91	4.02	2.21	6.17	4.82
Monetary Costs	[CHF/h]	2.04	1.48	2.38	1.78	0.98	0.58	2.07	1.58
Garage parking	[CHF/h]	0.56	0.89	0.71	0.55	0.84	0.48	0.76	0.66
Street parking	[CHF/h]	1.54	0.60	1.68	1.23	0.14	0.10	1.31	0.92
Generalized Costs	[CHF]	20.99	24.35	30.82	29.04	16.24	9.43	32.08	22.54

optimal garage pricing where search traffic is only reduced by 66%. In the case of optimal garage pricing, the search traffic of people looking for on-street parking is not affected as much, since the probability of finding on-street parking is not set to 100% but is driven by the fixed prices for on-street parking. This leads to a smaller reduction in search traffic. For households with a low valuation of time, total traffic volume is reduced in all scenarios. The traffic volume increases for households entering the network at *Landesmuseum* and *Utoquai* with all parking policies. The changes in traffic volume by origin are highest for households with the lowest valuation of time. This seems puzzling at first sight but can be explained by the fact that households with a higher valuation of time were more likely to pay for parking in the status quo scenario and therefore did not search for on-street parking, while households with a lower valuation of time spent more time cruising for an on-street parking spot. This time is now reduced dramatically. In addition to the results presented here, a comparison of search traffic volumes by origin and of total traffic volumes as well as search traffic volumes by destination can be found in Appendix B.

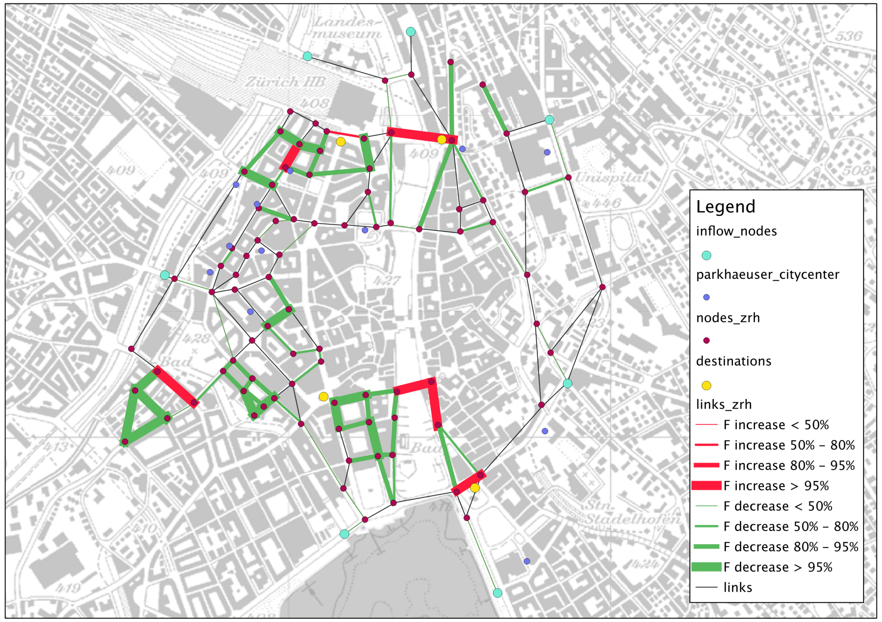
Table 9: Changes in traffic volume between status quo, SFpark, optimal on-street, optimal garage and SO

	status quo	SFpark	optimal on-street	optimal garage lot	SO
Total traffic [veh. in network]	79,500	29,000	31,200	46,400	27,500
Change	-	-64%	-61%	-42%	-65%
Search traffic [veh. in network]	59,800	1,600	1,700	20,400	1,600
Change	-	-97%	-97%	-66%	-98%

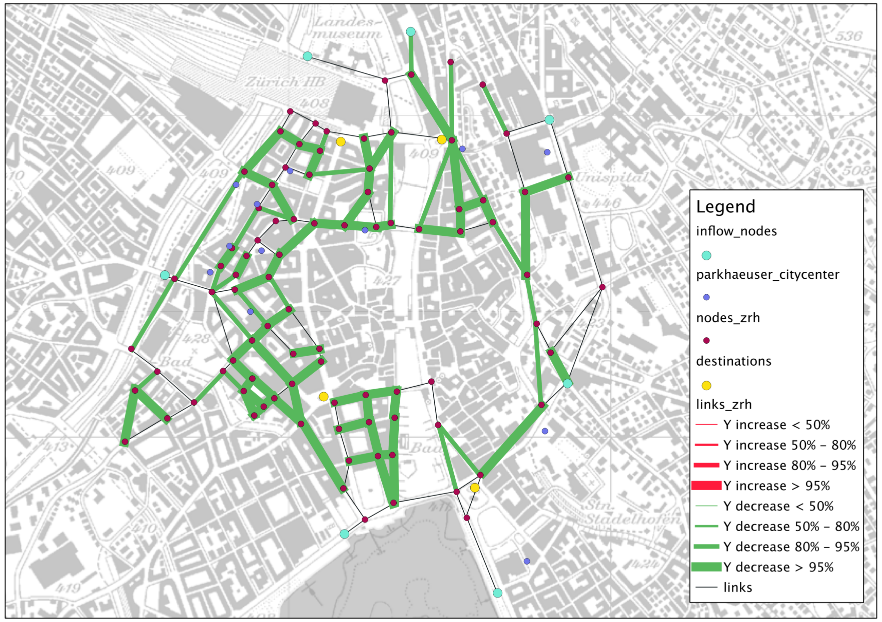
SF*park* Figure 6 shows the changes in overall traffic volume (Figure 6(a)) and search traffic volume (Figure 6(b)) on the arcs, when implementing SF*park*. Not only are the reductions in the overall network largest when implementing SF*park*, moreover, the effects on the streets are the highest. That is, the number of streets experiencing an increase in traffic volume is the smallest between all three policies. This seems plausible since the probability of finding an on-street parking spot as well as the probability of finding a garage parking spot is 100%. This means that drivers can directly drive to their desired parking location and find a spot there. Search traffic in the network is almost eliminated. It can be seen that SF*park* reduces not only search traffic and overall traffic in the network but that it also comes very close to the reduction achieved with the social optimum where the reduction in overall traffic is 65% (compared to 64% for SF*park*) and 97% for search traffic (which is the same as for SF*park*).

Figure 6: Changes in total traffic volume (F_a) and search traffic volume(Y_a) with SF*park*

(a) Changes in total traffic (F_a)



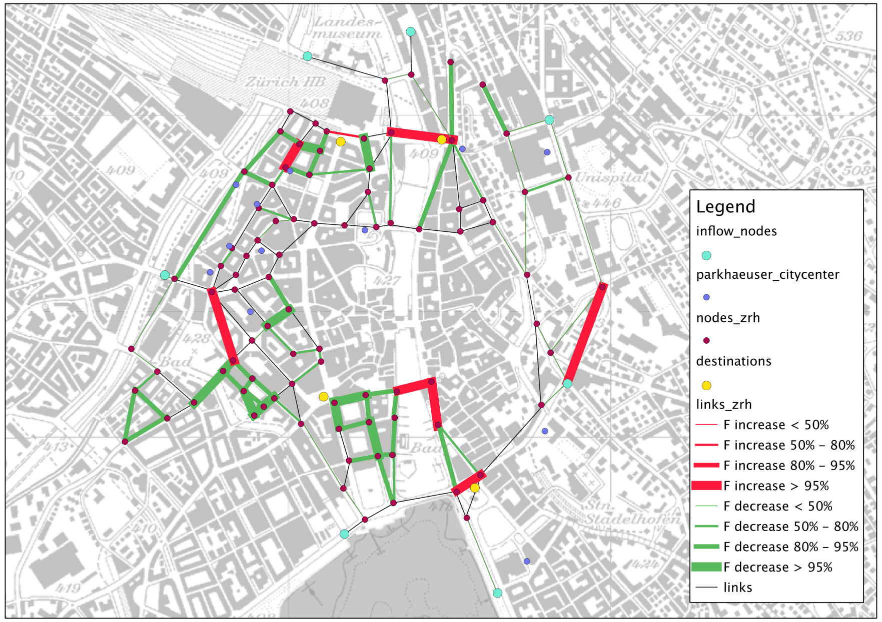
(b) Changes in search traffic(Y_a)



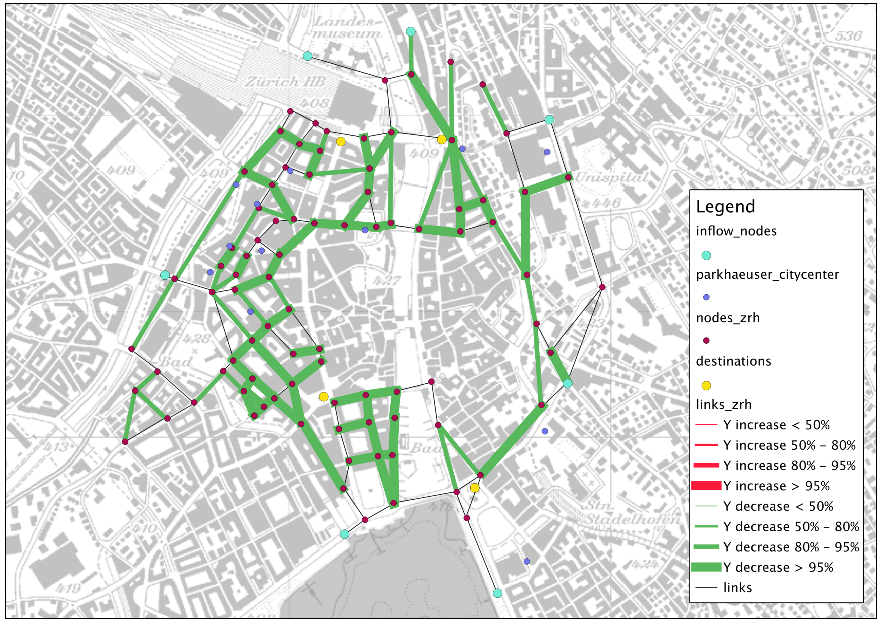
Source: Kanton Zürich (2013)

Figure 7: Changes in total traffic volume (F_a) and search traffic volume (Y_a) with demand-responsive pricing for optimal on-street pricing

(a) Changes in total traffic (F_a)



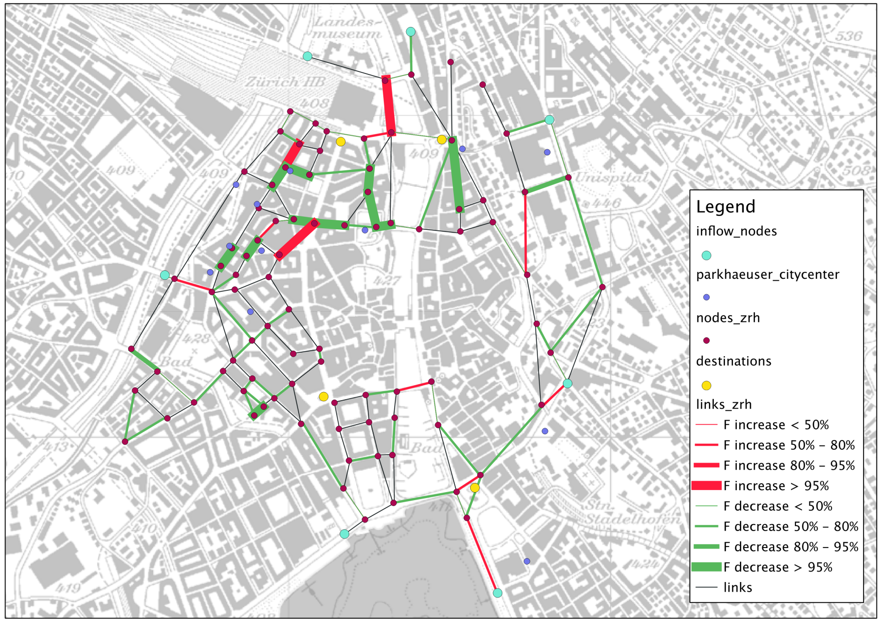
(b) Changes in search traffic (Y_a)



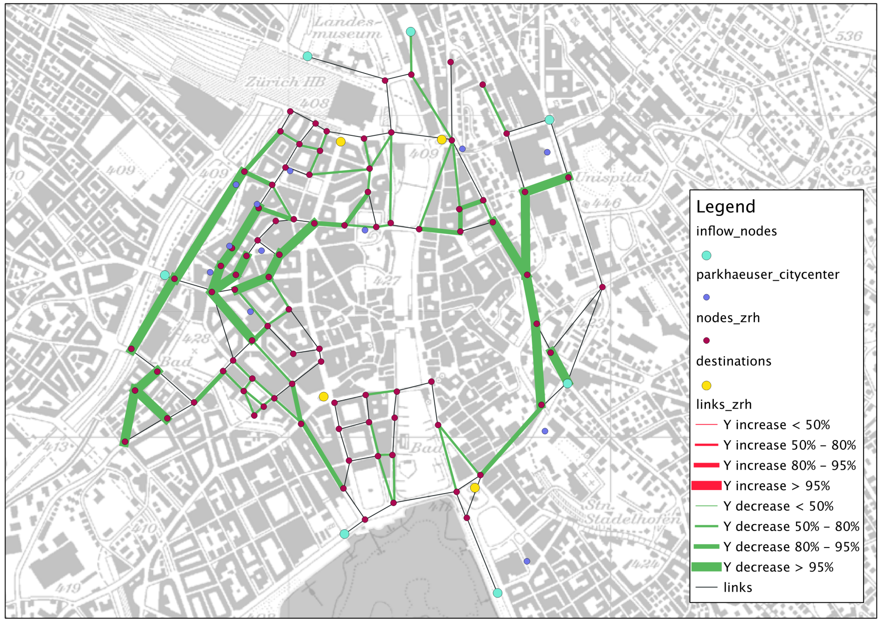
Source: Kanton Zürich (2013)

Figure 8: Changes in total traffic volume (F_a) and search traffic volume (Y_a) with demand-responsive pricing for optimal garage pricing

(a) Changes in total traffic (F_a)



(b) Changes in search traffic (Y_a)



Source: Kanton Zürich (2013)

Optimal on-street pricing Figure 7 depicts the changes in total traffic (Figure 7(a)) and search traffic (Figure 7(b)) on the arcs when implementing demand-responsive pricing for on-street parking (optimal on-street pricing). It seems plausible that search traffic is either being reduced or not affected since the probability of finding an on-street parking spot is 100%. In addition to the search traffic on the arcs, total traffic on the arcs is reduced for the majority of arcs as well. Some arcs also experience an increase in total traffic by as much as 95%.

Optimal garage pricing Figure 8 shows the changes in total traffic (Figure 8(a)) and search traffic (Figure 8(b)) on the arcs when implementing demand-responsive pricing for garage parking (optimal garage pricing). The reduction of search traffic on the arcs is smaller than when with optimal on-street pricing. The same holds for the total traffic in the network even though fewer streets experience an increase in total traffic. When looking at the effects on the whole network, the results of optimal garage pricing are inferior to those of optimal on-street pricing. One reason for this is that agents searching for a garage parking spot are only considered to be search traffic while in the parking garage and not while they drive from one intersection to the next. This is justified because it is assumed that if a driver does not find a garage parking spot he either shifts to searching for on-street parking or he keeps on driving through the network until he gets to the next parking garage.

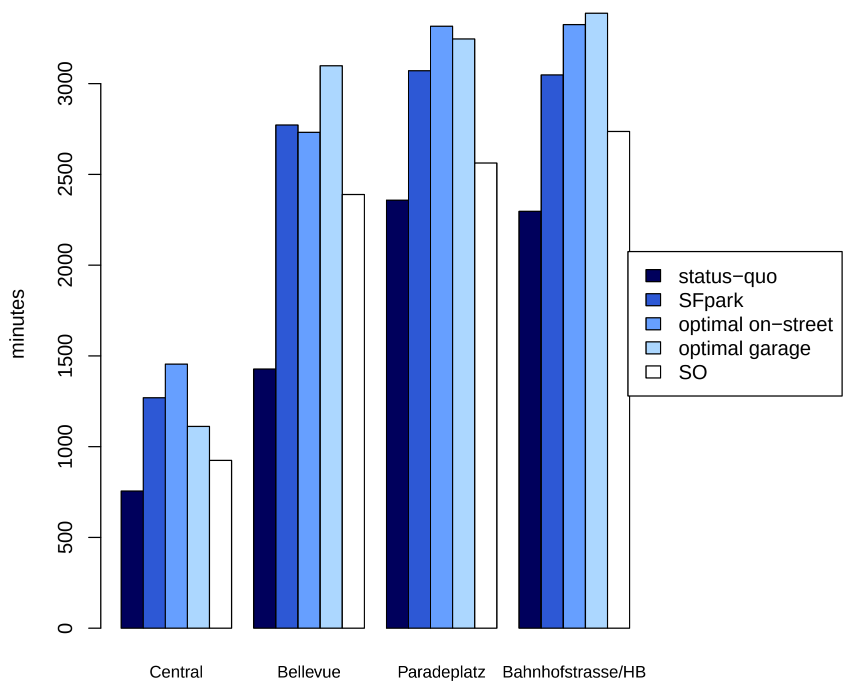
4.2.3 Changes in Time

When exploring the impact of a new parking policy, there are numerous variables of interest in addition to changes in traffic volume. For instance, other important aspects are differences in driving time, search time and walking time. Driving time is the time agents spend driving without searching for parking: $X_a \tau_a$. Search time is the time agents spend looking for a parking spot. This can either be an on-street parking spot ($Y_a \tau_a$) or a garage parking spot ($Z_k \tau_z$). The time costs give information on how much time agents spend in the network and whether and how it changes with different parking policies. Table 10 compares the overall time costs for all agents in the network for the different scenarios. It shows that overall time costs are reduced by 53% when SF*park* is implemented. Walking time and search time decrease while travel time increases. This is the case for all scenarios. With the introduction of demand-responsive pricing, search time for street parking decreases while search time for garage parking increases. The introduction of optimal garage pricing leads to a reduction in search time for garage parking as well as for on-street parking. The explanation for this is similar as for the changes in traffic volume. By providing on-street parking at a price that lets the probability of finding an on-street parking spot be equal to one, agents spend more time just traveling and less time searching. While the reduction in traffic volume is greater with the introduction of optimal on-street pricing

Table 10: Changes in time between status quo, SFpark, optimal on-street, optimal garage and SO

		status quo	SFpark	optimal on-street	optimal garage	SO
Driving time	[min]	6,800	10,200	10,800	10,800	8,600
Search time street	[min]	28,500	4,100	9,000	7,500	4,500
Search time garage	[min]	8,300	3,700	8,600	4,700	4,200
Walk time	[min]	17,700	12,100	15,600	11,600	12,600
Total Time	[min]	61,300	30,100	44,100	34,700	29,900

Figure 9: Total driving time by destination



compared to optimal garage pricing, the opposite is true when looking at reduction in travel times. The reduction in overall travel time achieved with SF*park* is similar to that achieved in the social optimum. With optimal on-street pricing a reduction in travel time can be achieved but only by 17% compared to 48% with SF*park*. Figures 9, 10 and 11 depict overall travel time, search time and walking time by destination. Travel time, search time and walking time by household can be found in Appendix C. Overall it can be observed that the changes in walking time and travel time are rather small, whereas the changes in search time are much higher. For agents with destination *Bellevue* walking times increase when implementing optimal garage pricing as well as in the social optimum. A reason for this could be that agents use parking garages further from the destination that are now cheaper. Comparing the time changes for all

Figure 10: Total search time by destination

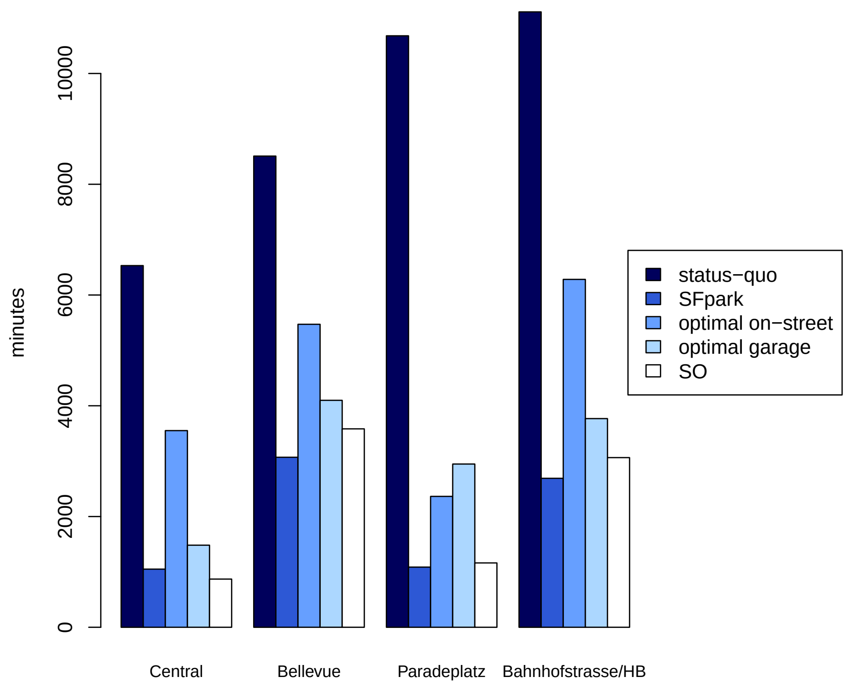
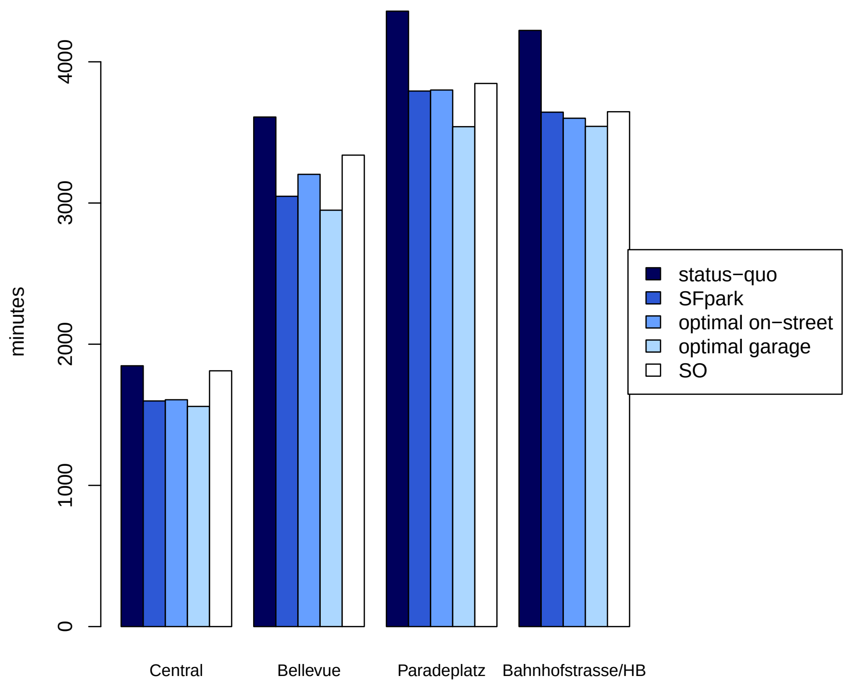


Figure 11: Total walking time by destination



three policies, SF*park* leads to the highest reduction (53%) in all time categories, while optimal garage pricing also reduces time costs by 44%.

4.2.4 Generalized Costs

Another cost factor that is of interest in the policy analysis are the generalized trip costs. The generalized costs are calculated as follows:

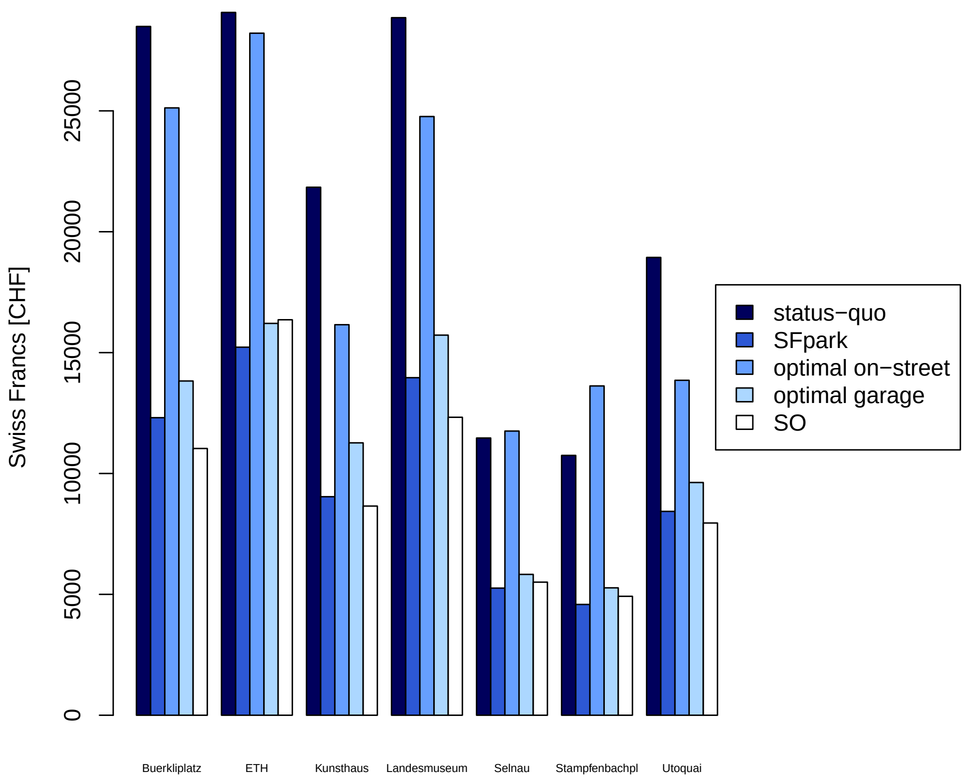
$$\mathcal{K}_h[CHF] = v_h \left[\tau_a X_h + \tau_a Y_h + \tau_z Z_h + \mathcal{W}^G Z_h(1-\pi_k) + \mathcal{W}^S Y_h(1-\pi_a)\right] \\ +\mathcal{F}^S(1-\pi_a)Y_h + \mathcal{F}^G(1-\pi_k)Z_h$$

They consist of the travel time weighted by the valuation of time v_h for all agents X_h, the search time weighted by valuation of time Y_h, the garage search time weighted by the valuation of time v_h, the walking time from the parking garage weighted by the valuation of time for all agents parking in a garage $Z_h(1-\pi_k)$, the walking time from an on-street parking spot weighted by the valuation of time for all agents parking on the street $Y_h(1-\pi_a)$, the parking fee for garage parking for agents parking in a garage $Z_h(1-\pi_k)$ and the parking fee for on-street parking for agents parking on the street $Y_h(1-\pi)$. For simplicity it is assumed that agents value the time for walking, searching and driving at the ratio 2:1.5:1. The generalized costs are highest in the optimal on-street pricing scenario and lowest in the social optimum (see Table 11). This is mostly due to the high differences in search time between the different scenarios, combined with the higher valuation of search time compared to travel time. In the optimal on-street pricing, garage parking fees are still fixed to the observed values, which explains the high generalized costs. Also the high walking times (as mentioned before) lead to higher generalized costs for this scenario. The differences by household and therefore by valuation of time are shown in Figure 12. For households with lower valuation of time (*Selnau and Stampfenbachplatz*) the generalized costs are highest when implementing optimal on-street pricing. The other households experience the highest generalized costs in the status quo scenario. Overall the generalized costs in the SF*park* scenario are very close to those in the social optimum (a reduction of 57% compared to 59%).

Table 11: Generalized cost comparison for status quo, SFpark, optimal on-street, optimal garage and SO

		status quo	SFpark	optimal on-street	optimal garage	SO
Generalized costs	[CHF]	149,400	68,800	133,500	77,700	66,700
Change		-	-54%	-11%	-48%	-55%

Figure 12: Generalized costs by household (inflow node)



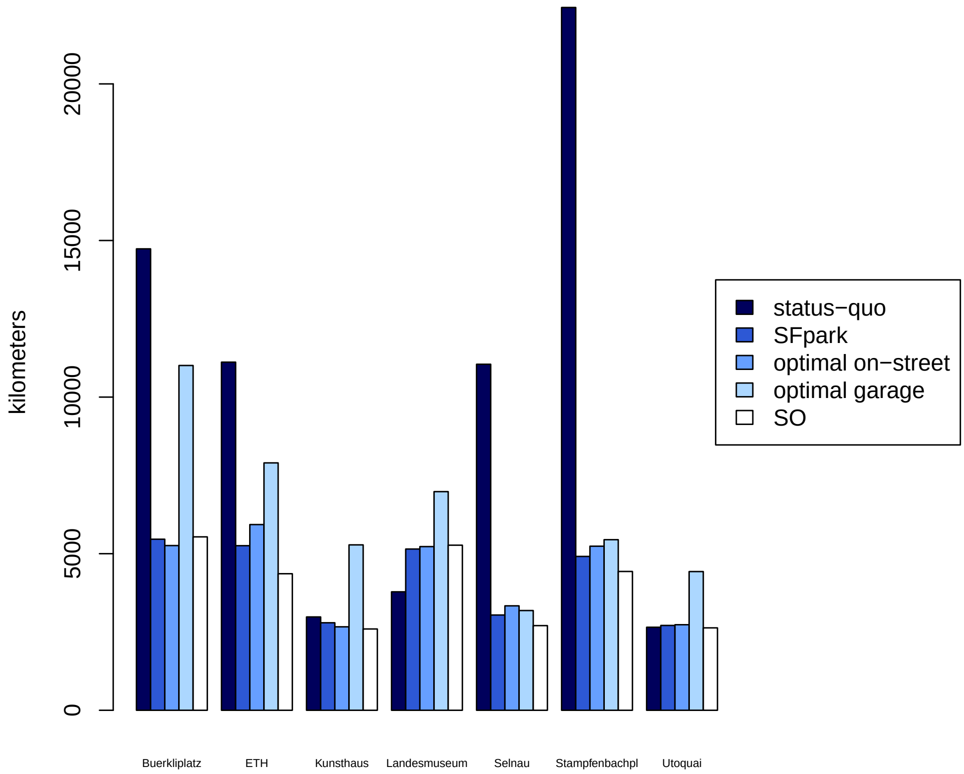
4.2.5 Vehicle Kilometers

Another important aspect of parking policies is the impact traffic has on air as well as on noise pollution. Those impacts are commonly evaluated by considering the vehicle kilometers driven. Table 12 compares the total vehicle kilometers and those for driving and searching, for the three different policies, as well as for the status quo and the social optimum. With SF*park* the total vehicle kilometers can be reduced by 57%. For the other policies the reduction of vehicle kilometers is also very large, with 56% for optimal on-street pricing and 36% for optimal garage pricing. The lower reduction for optimal garage pricing can be explained by the fact that in this scenario the vehicle kilometers spent searching are not reduced as much, since on-street parking is still regulated by the probability of not finding a parking spot. Therefore drivers still cruise in order to find on-street parking. Figure 13 shows the changes in vehicle kilometers for the different scenarios by household.

Table 12: Vehicle kilometers for all different scenarios

		status quo	SFpark	optimal on-street	optimal garage	SO
VKM searching	[km]	51,300	1,600	1,700	17,400	1,500
VKM driving	[km]	17,500	27,700	28,700	26,800	26,100
VKM total	[km]	68,800	29,300	30,400	44,200	27,500

Figure 13: Total vehicle kilometers by household (inflow node)



4.2.6 Monetary Costs

Also interesting, especially for political reasons, are the changes in parking fees. The street parking fees are set to 2.5 CHF/h in the benchmark scenario and range between 0.1 CHF/h and 5.5 CHF/h in the SF*park* scenario and between 2.5 CHF/h and 14.6 CHF/h in the optimal on-street pricing scenario. The prices for all scenarios as well as the probabilities of not finding a parking spot can be found in Table 13. The changes in garage parking fees are shown in Table 14. Those garages with fees equal to zero in the social optimum and the SFpark scenario are not being used by the agents. The changes in parking costs by household can be found in Appendix D. Since on-street parking is cheap and fixed in the status quo as well as in the optimal garage pricing, and garage prices are fixed to observed costs in the optimal on-street pricing scenario, the parking costs increase dramatically for the optimal on-street pricing scenario. Parking costs in the optimal garage pricing scenario are very low because garage parking fees are demand-driven and on-street parking fees are fixed to today's low prices which do not reflect the demand. Table 15 shows the probabilities of finding a garage parking spot for the status quo and the optimal on-street pricing scenario. For the other three scenarios, optimal garage pricing, SF*park* and the social optimum these probabilities are equal to 100%.

Table 13: Parking fees and probabilities of finding on-street parking for status quo, SFpark, optimal on-street, optimal garage and SO

		status quo	SFpark	optimal on-street	optimal garage	SO
Parking Fee	*avg*	2.5	2.5	6.6	2.5	1.6
in CHF/h	*max*	2.5	5.5	14.6	2.5	5.0
	min	2.5	0.1	2.5	2.5	0.0
Probability of	*avg*	4.8%	100%	100%	15.8%	100%
finding a spot	*max*	18.7%	100%	100%	78.7%	100%
	min	0.4%	100%	100%	2.1%	100%

Table 14: Hourly prices for parking garages

		status quo	SFpark	optimal on-street	optimal garage	SO
Central	[CHF/h]	8.00	3.25	8.00	5.24	4.11
Globus	[CHF/h]	7.00	1.60	7.00	2.21	1.21
Hohe Promenade	[CHF/h]	8.00	0.40	8.00	0.90	0.33
Talgarten	[CHF/h]	8.00	0.25	8.00	1.59	0.05
Gessnerallee	[CHF/h]	8.00	0.00	8.00	0.00	0.00
Sihlporte	[CHF/h]	9.00	0.00	9.00	0.27	0.00
Centrum Garage	[CHF/h]	16.00	0.00	16.00	0.20	0.55
Migros City	[CHF/h]	6.00	0.41	6.00	1.22	0.17
ETH HG	[CHF/h]	4.00	0.59	4.00	1.57	5.27
Jelmoli	[CHF/h]	7.00	0.00	7.00	0.69	0.17
Urania	[CHF/h]	8.8	0.62	8.8	1.26	0.86
Opera	[CHF/h]	9.00	0.00	9.00	0.00	0.00

Figure 14: Parking costs by household (inflow node)

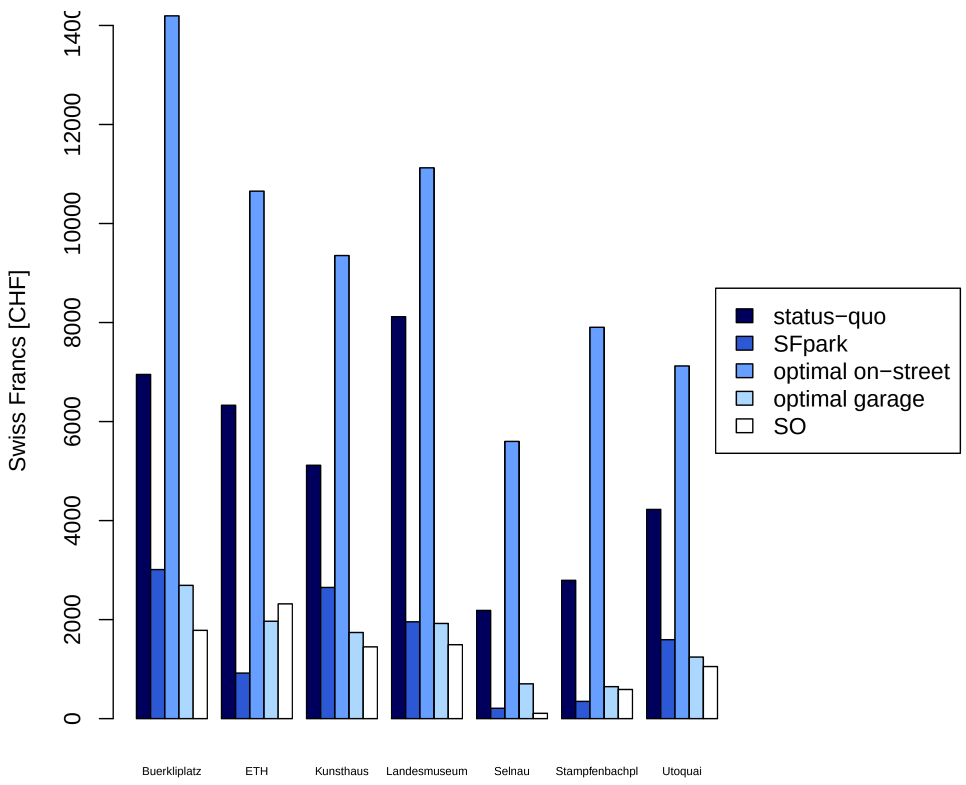


Table 15: Probability of finding a garage parking spot

	status quo	optimal on-street
Central	32%	36%
Globus	48%	46%
Hohe Promenade	86%	77%
Talgarten	62%	74%
Migros City	49%	43%
ETH HG	36%	35%
Jelmoli	75%	71%
Urania	74%	87%

5 Conclusion and Recommendations

This section discusses the results presented in Section 4 and offers some suggestions of future research trajectories.

5.1 Conclusion

This thesis proposes a parking model to evaluate the impact of different parking policies. The model has been applied to the city center of Zurich, to assess three different parking policies. The policy analysis shows that the introduction of demand-responsive pricing for parking can reduce the overall flow in the network dramatically—up to 64% in the SF*park* scenario. In addition the time reduction achieved with all three scenarios is impressive and leads one to conclude that demand-responsive pricing for parking can improve the overall parking situation.

The generalized costs are reduced when demand-responsive pricing is introduced for garage parking, either alone as in the optimal garage pricing scenario or in combination with street parking in the SF*park* scenario. Overall it can be said that demand-responsive pricing has the best results when it is implemented as a coordinated policy between on-street parking and garage parking. In many cities this is not easy to achieve, since parking garages are mostly privately owned and therefore fees cannot be regulated through a citywide parking policy. In this case it is worthwhile implementing demand-responsive pricing for on-street parking (optimal on-street pricing) since the results from the model are very promising for flow and time reduction in the network.

5.2 Recommendations

As a simplification in the model presented here, the valuation of time differs by agents to consider heterogeneity, but does not differ by purpose. For future work it would be interesting to extend the model formulation to include different valuation of time for different purposes. The valuation of walking time should be highest and that for driving lowest: $v_{driving} < v_{searching} < v_{walking}$. In the case study this is considered when calculating the generalized costs but not in the model itself. This would not only influence the generalized costs but would also lead to agents trying to park closer to their destination since the time spent walking has a higher impact than the time spent driving in the car.

Another interesting parking policy mentioned in this thesis is parkU, an application that allows drivers to book a private parking spot to use while they are in the city. For future work it would be interesting to incorporate private parking into the model and analyze the effects an application like parkU would have on parking behavior.

In a next step the model developed here should be extended into a dynamic model in which agents can choose their time of departure depending on the availability of parking and/or how congested the network is. Agents should also be able to choose between different modes of transportation to analyze how a very restrictive parking policy can influence the mode choice of agents.

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A Resulting OD Matrix for the Case Study

Table 16: OD matrix used in the case study for Zurich

	Bellevue	Central	Hauptbahnhof	Paradeplatz	Total Origin
Bürkliplatz	222.7	98.2	166.7	171.3	658.8
ETH	225.0	99.2	168.4	173.1	665.7
Kunsthaus	123.6	54.5	92.5	95.1	365.6
Landesmuseum	183.0	80.7	137.0	140.8	541.5
Selnau	121.2	53.4	90.8	93.3	358.7
Stampfenbachplatz	188.9	83.3	141.4	145.3	558.7
Utoquai	101.4	44.7	75.9	78.0	300.1
Total Destination	1165.8	513.9	872.6	896.7	**3,449.0**

B Comparison of Traffic Volumes

Figure 15: Search traffic volume (Y_a) in the network by origin for the different scenarios

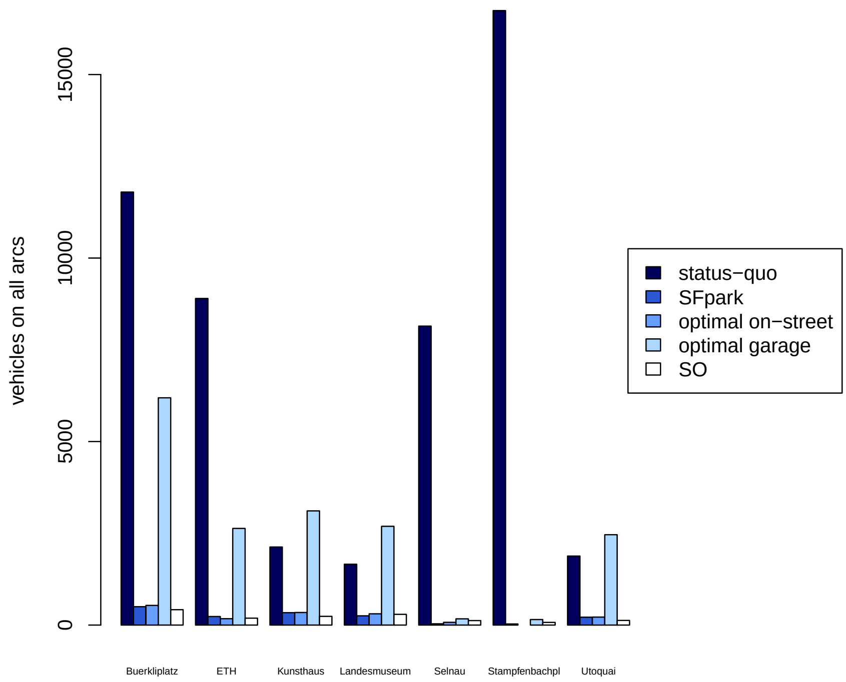


Figure 16: Total traffic volume (F_a) in the network by destination for the different scenarios

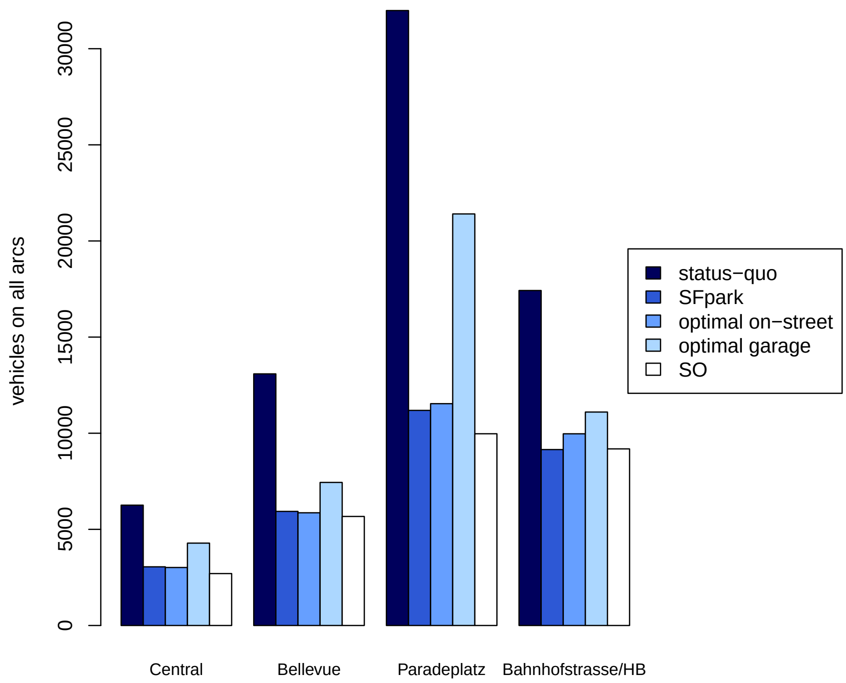
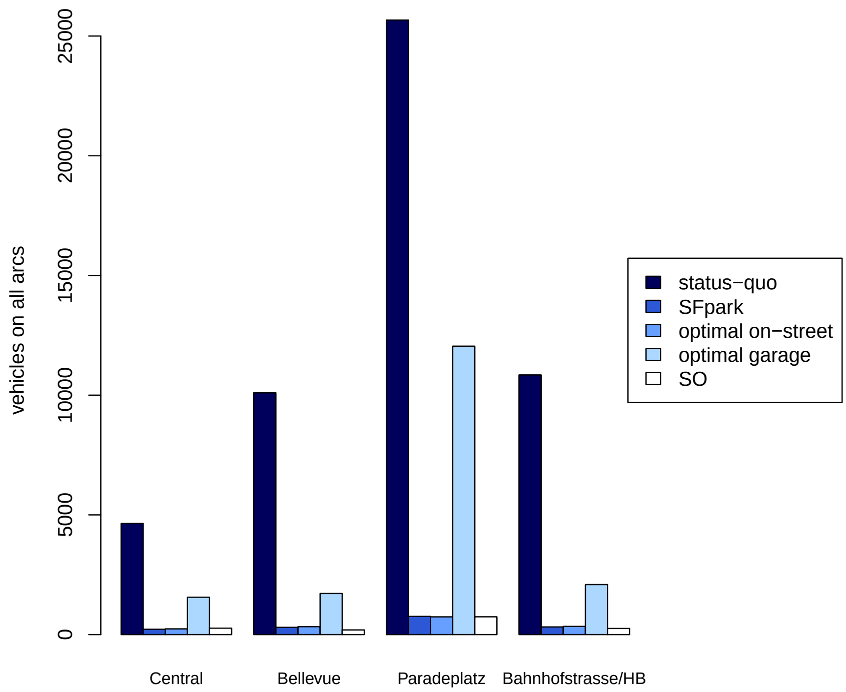


Figure 17: Search traffic volume (Y_a) in the network by destination for the different scenarios



C Time Comparison

Figure 18: Total search time in the network by origin

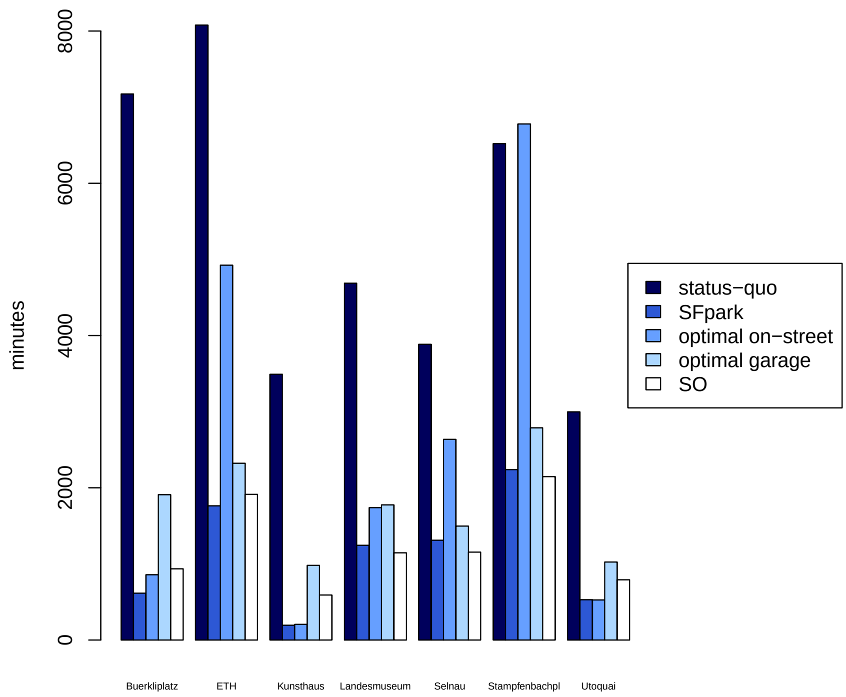


Figure 19: Total drive time in the network by origin

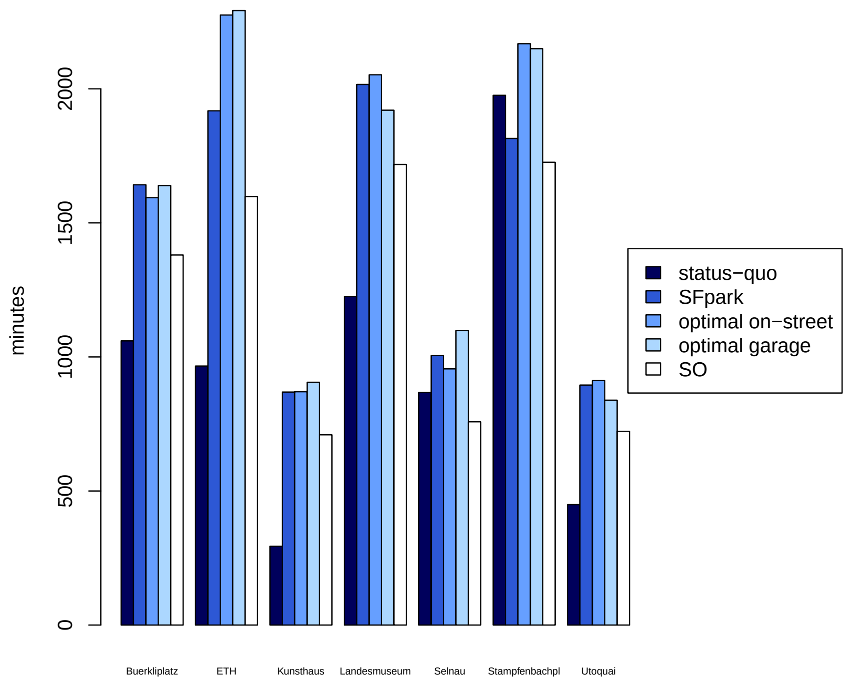
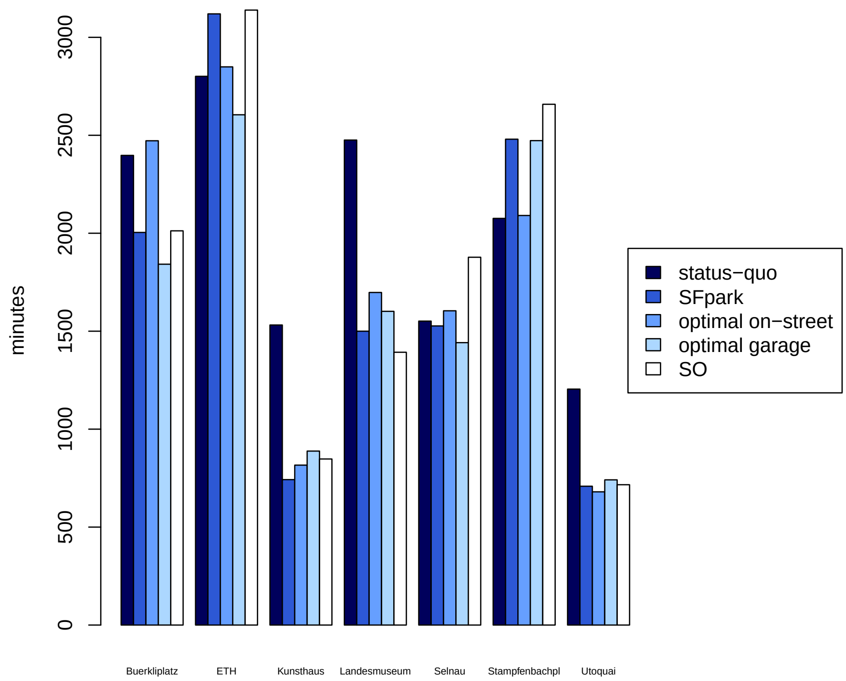


Figure 20: Total walking time in the network by origin



D Comparison of Parking Costs

Figure 21: Parking costs by origin

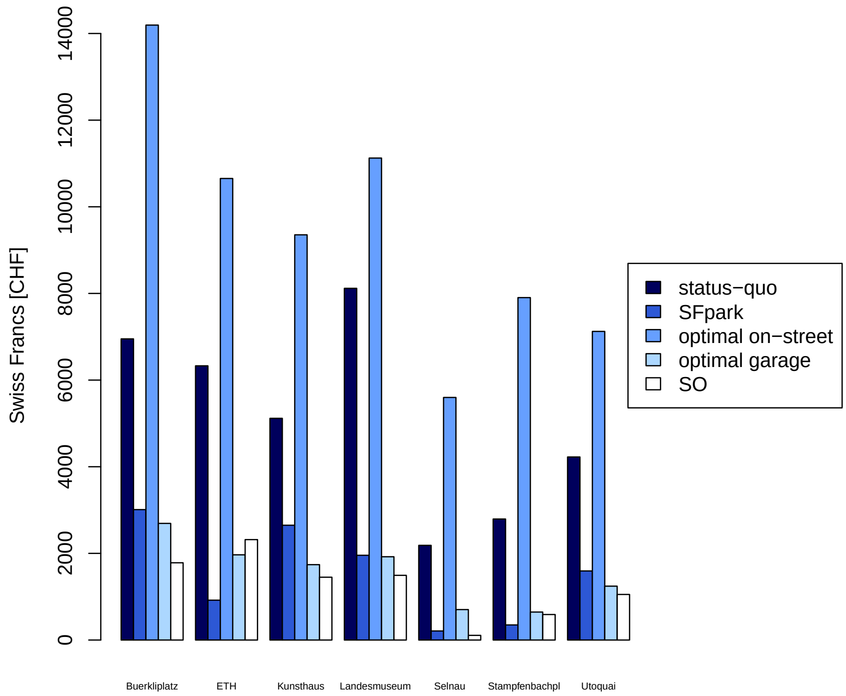


Figure 22: Parking costs by destination