Universidade do Porto
FEUP Faculdade de Engenharia

Programa Doutoral em Sistemas de Transportes
Doctoral Program in Transport Systems

# An integrated approach to urban parking modeling and pricing

## Farzam Salimi

Thesis submitted to the Faculty of Engineering, University of Porto
in partial fulfillment of the requirements for the degree of Doctor
in Transport Systems

**Supervisors**

Professor Jorge Pinho de Sousa
(Faculdade de Engenharia da Universidade do Porto)
Professor António Pais Antunes
(Faculdade de Ciências e Tecnologia da Universidade de Coimbra)

Porto, January 2017

# Abstract

This thesis aims at developing a general framework for supporting decision-making and planning, to deal with parking problems in a systematic way. For this purpose, comprehensive studies were done on the demand and supply dimensions of the parking problem. The problem was fully characterized, with the definition of decision variables, parameters and constraints, and an optimization model was proposed, to maximize the revenue. This model is integrated with a mode choice procedure.

The thesis first analyzes the parking problem, by a comprehensive and critical literature review and by a discussion and classification of the papers in the area.

Then a framework is developed to tackle general parking problems in both the demand and the supply dimensions. This model includes a pre-processing stage and an optimization model with the objective of maximizing revenue. The pre-processing stage includes a binary logit model, and two types of decision variables are used to integrate these stages.

The flexible framework developed in this research for the parking problem is capable of handling two main practical aspects: budget management and environmental concerns. The integrated approach was tested and validated in a small problem instance and in a real case study (developed for the San Francisco county in California).

In summary, the main contribution of this work was the development and implementation of a comprehensive integrated framework, expected to have a significant impact on improving the design of parking policies in urban areas. Accordingly, different, complementary methods and tools were used in estimating optimized parking prices, taking into account both demand and supply, for different zones of metropolitan areas, under various conditions and different perspectives.

# Resumo

Esta tese tem como objetivo principal desenvolver um quadro conceptual geral, para apoiar a tomada de decisão e o planeamento, no tratamento sistemático de problemas de estacionamento. Neste sentido, foram realizados estudos abrangentes nas dimensões da procura e da oferta, no que respeita ao estacionamento. O problema foi caraterizado em pormenor, com a definição de variáveis de decisão, parâmetros e restrições, tendo sido proposto um modelo de otimização, para maximizar as receitas. Este modelo é, no sistema proposto, integrado com o procedimento de escolha de modo.

A tese começa por analisar os problemas de estacionamento, com uma revisão abrangente e crítica da literatura, e com uma discussão e classificação dos artigos na área.

É, depois, desenvolvido um quadro conceptual para tratar os problemas de estacionamento em ambas as dimensões da procura e oferta. Este modelo inclui uma etapa de pré-processamento e um modelo de otimização para maximizar as receitas.

A etapa de pré-processamento inclui um modelo binário *logit*, com dois tipos de variáveis de decisões são utilizados a permitir integrar estas duas etapas.

O quadro conceptual flexível desenvolvido nesta investigação permite tratar dois aspetos principais do problema: a gestão dos orçamentos e as preocupações ambientais. Esta abordagem integrada foi testada e validada numa pequena instância ilustrativa e no contexto de um caso de estudo (desenvolvido a partir de São Francisco, na Califórnia).

Em resumo, a principal contribuição deste trabalho foi o desenvolvimento e implementação de um quadro conceptual integrado e abrangente que se espera possa ter um impacto significativo no desenho e melhoria de politicas de estacionamento em áreas urbanas. Nesse sentido, foram utilizados diversos métodos e ferramentas, para o cálculo dos preços de estacionamento, tendo em atenção tanto a dimensão da procura como a dimensão da oferta, para diferentes zonas de uma área metropolitana e para diferentes perspetivas e condições de operação.

v

**Acknowledgements**

It has been a long journey. I would like to express my thanks of gratitude to my supervisors, professor Jorge Pinho de Sousa and professor Antonio José Pais Antunes.

I specially thank professor Joseph M. Sussman who welcomed me to his research group at the Massachusetts Institute of Technology – MIT, for challenging my assumptions and models. I was one of the luckiest persons who had the opportunity to work under his supervision.

My other thanks belong to Maite Pena-Alcaraz (MIT) and Hamid Reza Asgari (FIU), who discussed with me about my models and their outcomes.

I dedicate this thesis to my family.

# Contents

# 1 Introduction

Mobility of people and goods is a vital need of modern societies. Transport is an important economic driver in the world and it creates millions of direct and indirect jobs. However, there are still some important challenges that need to be addressed. Transportation systems need to be improved especially in the areas of congestion avoidance, sustainability and safety.

Academic research on transportation planning has been of particular interest to engineers, managers and mathematicians for so many years. In this area, benefits and costs (associated, e.g., to mobility, goods movement, productivity and congestion) are, in most cases, explained by mathematical models. These models can be effectively applied to large scale infrastructure projects. However, there is still a knowledge gap in modeling transportation systems for the case of individual travel patterns. These travel patterns and behaviors are affected by many variables, such as the characteristics of individuals and households, opportunities in the destinations, and specific aspects associated with the individuality of the travelers.

In this regard, one interesting aspect of urban mobility is related to the deployment of parks for cars and their role in transportation policies. This doctoral thesis aims at understanding and modeling some issues related to the optimization and the design of parking policies and environmental studies.

## 1.1 Importance of parking pricing and of setting parking policies

In general, there might be three important areas of concern for the future of transportation planning: environmental impacts, space congestion and population growth.

The first area is related to environmental detriments due to transportation systems. Every year tons of CO2 are produced by vehicles, this significantly increasing air pollution. Noise pollution and ground water poisoning through runoffs are two other environmental impacts of transportation systems.

The second area of concern is related to space congestion. Space congestion refers to the concept that every area of a city has a specific physical limit to build the new structures or roads. It means that in a small area with several buildings, there are not so many choices when new structures are considered, and with time passing and with the construction of new buildings and roads in the area, the limitation becomes even more critical.

The third area of concern is the increasing population and economic growth which tends to intensify the congestion. When population and income increase, affordability for the usage of private vehicles

grows. This obviously tends to increase congestion. Currently there are several studies on urban traffic congestion. Some researchers try to find the nature of the traffic congestion such as Taylor (1992); some including Maitra (1999) work on the models and the simulation of the traffic congestion; some concentrate on analyzing the causes of traffic congestion (Huang et al., 2007); and other researchers such as Li (2004) summarize the regular pattern of traffic congestion, or study the relation of land use with traffic congestion (Wang et al., 2011).

The first concern – environmental harms due to transportation systems - can be mollified by technological innovations, but measuring the intensity of damages is a discussable issue. The second – space congestion – and third – increasing population and economic growth – areas of concern must be mitigated with local, state, and federal policies. These aspects will in general be addressed by integrated transportation policies and land use planning (Banister, 2005; Handy, 2008; Straatemeier, 2008).

Regarding space congestion, and in order to evaluate major infra-structure projects, some relevant public policy concerns are in general taken into account. These public policy concerns are different from the private ones. For instance, the private sector will always expect significant financial rewards from the projects. Building a road or a parking will be considered a good thing if the expected tolls are larger than the construction costs. Financial matters are the main focus of these types of analysis. What are the costs and revenues in this project? Am I financially secured in this project?

A broader economic framework, which can answer our questions, includes the short and long term impacts of a project on the local economy. Since any big scale project will need some kind of public acceptance, the nature and magnitude of these economic impacts will be reflected in the level of comfort of public officials to support or grant approvals for the project. However, in general, the main concern of the private sector are the financial returns of the owners and not the broader effects on the economy.

On the other hand, the public sector, which is in general responsible for different kinds of infrastructure systems, has a completely diverse standpoint in identifying needs and evaluating possible projects. The motivation in the public sector is not to get more money, but to fulfill public needs and to help growth in the economy. It does not mean that in the public sector the financial benefits are not important, but they are surely not necessarily dominant.

There are several approaches to support urban growth with higher transit densities. Planning and controlling transit development and parking management are some of the most used methods. However, this growth cannot be predicted in detail. Instead, urban growth is mostly a result of reactions from the population to the application of some incentives. Incentives normally take the form of policies such as regulations, taxes, and economic activities. In this regard, planners and policy makers should concern themselves with the improvement of current systems and the with the way in which individuals react to different policies.

Instruments or tools for handling these problems can be considered to be of one of two types: supply side tools and demand side tools. In the supply side, we have for instance new infra-structures, infra-structure improvement, and new transportation services. On the demand side tools, we have for example the pricing methods such as road pricing and parking pricing.

Road pricing is normally a more expensive solution than parking pricing, and it faces several difficulties. One of the main problems is political opposition to road pricing (politicians consider it as a kind of political poison…), because road pricing entails the price of a service (travel on city streets) that previously was free to use. Moreover, people in general view free traveling in the streets of a city as their own right or, at least, they think that they have earned this right by paying taxes. And people are pessimist about the politicians' motivations, and normally see a proposal on congestion pricing as another tax grab, while the benefits cannot be seen easily. Road pricing would decrease congestion but the reduction might not be obvious. For example, professionals can change their travel schedules to escape paying peak tolls but factory workers and clericals cannot do it easily, this obviously creating some inequity situations. Moreover, congestion pricing requires paying with money rather than time.

A good *parking management system* can be a good global economic solution for these problems. Parking management comprises a wide range of strategies to support a more efficient use of existing parking facilities, to increase the quality of service provided to parking facility users, and to improve parking facility design. Parking management can help address a large number of transportation problems, and achieve a variety of transportation, land use development, economic, and environmental objectives.

Parking management generates several types of benefits. It may for example lead to a decrease of parking requirements, inducing cost savings and consumer affordability. A comprehensive parking management program can often decrease parking requirements by 30% to 50%. Management policies and guidelines can also include un-priced parking, and the assignment of each parking space to an individual driver.

In addition, parking management is an effective way to reduce traffic. It can reduce automobile trips by more than 20%, as a part of a more comprehensive transport demand program. This may also cause a decrease in the road and parking facility costs, air pollution, traffic congestion, and an improvement of the diversity in transport modes. It also allows a higher level of flexibility in terms of facility location, site design, and site building. It helps building managers and building developers by proposing more choices to deal with parking scenarios.

Land use, capacity of higher density, and walkable urban areas become more controllable by this type of management. Parking management can also facilitate the protection of historic buildings and districts and allow designers to flexibly place buildings in specific areas in order to fulfill access, aesthetic and

environmental requirements. This design flexibility is mainly important for infill development and in high land cost areas, allowing the re-growth of CBD (Central Business Districts) and urban communities.

Furthermore, parking pricing and parking limitations can decrease business activities in a given area and make people travel to more suburban locations. However, these impacts depend on how prices are structured and on the quality of travel and location alternatives. If parking revenues are used to improve street conditions and transportation alternatives in a specific zone, they will increase business activities in that zone.

In terms of environmental impacts, parking consumes a significant part of urban land. Paving of this land has several environmental impacts such as ground water recharge reduction, difficulty in storm-water control, heat island effects, and green space reduction.

To have a more detailed perspective about environmental impacts, it is necessary to mention that there are complex relationships between what can be considered as the natural world and what can be considered as the manmade world, and any project can change those relationships. For instance, construction activities transform natural spaces into manmade spaces. Every construction needs materials such as wood, concrete and steel, their utilization meaning changes in the environment and changes in the natural world. Some of the key environmental concerns in this regards are ecosystems, pollution, wetlands, aquifers, and drainage, wildlife habitat, renewable versus nonrenewable resources and climate change.

Ecosystems can be damaged in several ways such as with pollution. Pollution – that can be defined as the introduction of foreign elements into the water, air or soil – can provoke the death of some species of insects or of specific plants or animals. Toxic chemicals are another type of pollution poisonous for some types of species, and they can make the water quality unsustainable for some types of fishes. There are several levels of concern in the environmental impacts of projects, that are relevant in the case of our research:

1. usage of different materials in operation and construction;
2. pollution and impacts on air, water and soil quality;
3. loss of habitat, ecosystems damaging, impacts on plants and wild life;
4. effects in local environment such as noise, shade and aesthetics:
5. sustainability.

One of the most important concerns in the environmental impacts of projects (especially in parking studies) is air and noise pollution. The health risks of traffic related noise and air pollution have been widely acknowledged by plentiful epidemiological studies. Increasing risks of heart attacks, the exacerbation of asthma among children, and reduction in life expectancy are some examples of these

risks. These health risks generate huge external costs for society and they are not reflected in the market price of transportation or counted in the distribution of economic resources.

In addition, air pollution and greenhouse gas emissions vary between different means of commuting. Graphs 1.1 and 1.2 show amount of emissions in different modes of transportation (Hybrid Automobile, 2-Person Carpool in Hybrid, Gasoline Automobile, 2-Person Carpool in Gasoline Automobile, Gasoline Light Truck or SUV, Diesel Light Truck or SUV, Diesel Transit Bus with 10 Passengers, Diesel Transit Bus with 40 Passengers) (Song et al. 2014).
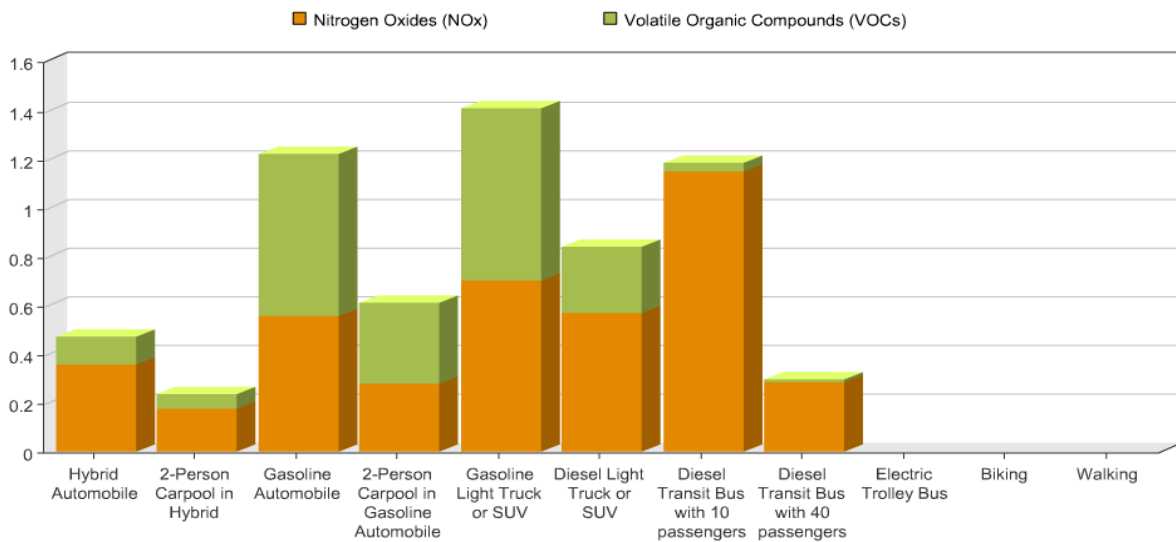


Graph 1.1. Smog-forming Pollution ($NO_x$ and $VOC_s$) from different means of commuting
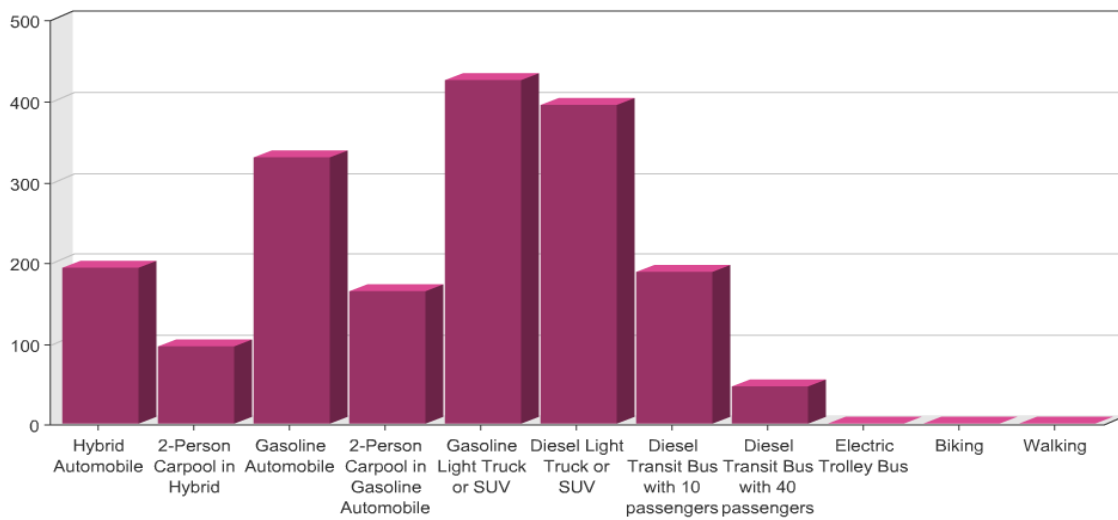


Graph 1.2. Greenhouse Gas Emissions from different means of commuting
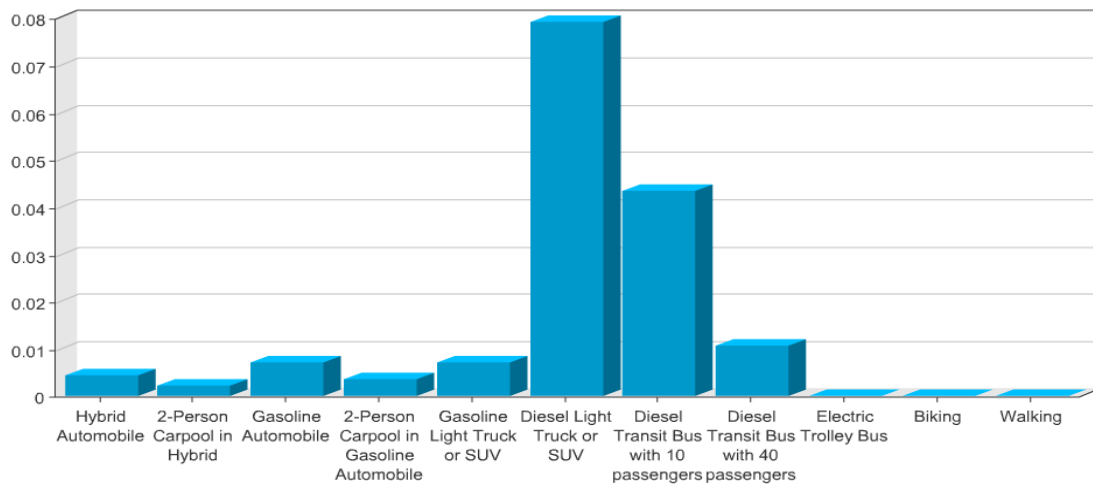
Graph 1.3. Particulate Matter (PM$_{2.5}$) emissions from different means of commuting

In these graphs, the unit of emissions is "grams per passenger kilometer" and we are assuming 100 percent city driving. Moreover, the parking grounds are often located in commercial and high density residential areas; so by proper management, urban sprawl and environmental impacts can be controlled.

On the other hand, parking management involves several types of costs. Parking pricing and their physical limitations normally tend to create congestion in neighboring zones. This congestion leads often to increased management control costs, and to conflicts between neighbors when trying to find an empty space to park. Additional responsibilities for drivers, public officials and facility managers are the other types of costs with which parking management is often faced (Litman, 2006; Kuzmyak et al. 2003; Rye, 2010).

## 1.2   Problem statement

Finding a vacant parking space in rush hours is a significant problem in all major cities. However, very little formal economic analysis has been done about the most obvious issues in this area, and a large amount of questions are not yet fully answered:

- If traffic congestion is correctly characterized and priced, how should parking fees be computed?
- Instead, what are the second best parking fees, when traffic congestion has not been priced?
- Based on the pricing of automobile congestion and public parking, should *on-street* parking fees be taxed or regulated?
- For different pricing patterns, how much land should be allocated to on-street parking?
- People normally use on-street parking for their short-time activities such as shopping. Should there be any difference between *short-time* and *long time* on-street parking pricing?

- On the other hand, if prices for on-street parking increase to the point that traffic flow decreases, what will happen to local businesses?
- Can CBDs (Central Business Districts) be affected by increasing parking pricing and become less popular?

*Off-street parking* is a costly solution to decrease traffic congestion and parking problems. But, if there is no more on-street parking available in a part of a city, and demand for more empty space to park still exists, building off-street parking seems inevitable. So, an *integrated model* of on-street and off-street parking is required:

- What happens to the price of on-street parking when new off-street parking is offered close to it?
- What happens to businesses near a new off-street parking?

Until now, all the studies have been focused on on-street parking separately, and we have not yet found any comprehensive and integrated study on the relationships between on-street and off-street parking.

It should also be noted that there is yet a significant political resistance to pricing road usage in many jurisdictions and consequently, road pricing remains scarcely used in an urban context. In the absence of road pricing, efficient pricing of parking may probably be an effective toll policy for combating congestion on the streets. In practical applications, parking pricing strategies are more commonly used than road pricing, as their deployment needs lower investment costs and can be made without using advanced technologies. The policies that can be used by an integrated system are of different types and grades, implying a changes in the land-use, or increasing the attraction of people to public transport systems, as well as their level of satisfaction.

The effects of parking fees go beyond the boundaries of transportation systems and can affect the urban environment, directly or indirectly, and in many aspects. For example, applying parking fees can greatly reduce the accessibility of some zones. Thus, a precise study of parking pricing strategies and their effects on urban mobility is necessary to optimize transport systems performance and to limit undesirable effects on the accessibility of fared zones. Furthermore, effects of an integrated system for parking pricing are unavoidable on other modes of transportation.

### 1.2.1 Stakeholders

Table 1.1 lists the main stakeholders of this complex system and their wishes and needs. This table results from compiling information from several sources (Litman, 2006; Kuzmyak et al. 2003; Rye, 2010) and from a personal reflection on the problem.

Table 1.1. Stakeholders and their wishes and needs

| Level | Stakeholders | Needs and wishes |
|---|---|---|
| Supplier | Private garage owners | They wish to have the maximum revenue from their garages based on the availability of parking spaces and parking fees. In addition, increasing attraction of the zone and the number of businesses helps them to increase their revenue. <br><br> They need minimum revenue to continue their work and compensate their amortization costs. |
| | Local traffic authorities | They wish to maximize revenue from on-street and off-street parking spaces. They should prepare enough parking spaces to control traffic flow. <br><br> They need to minimize construction costs of new off-street parking. |
| Receiver | Shoppers | They wish to find vacant places for short time parking as near as possible to their destinations. <br><br> They expect to be charged an affordable price. |
| | Workers | They wish to find empty spaces for long time parking as near as possible to their work places. <br><br> They need to be charged an affordable price. |
| | Residence | They wish to travel with minimum traffic on the streets close to them. <br><br> They need to park their private vehicles in a safe place with minimum charge. |

This multitude of stakeholders clearly makes the problem more challenging and, in order to take into account their different perspectives, requires the adoption of multi-criteria approaches.

### 1.2.2  Controllable variables

There are of course, several variables that can be controlled by some of the problem stakeholders (these are our decision makers). One of these items is the *price of parking*. By increasing the parking prices, willingness to pay for it decreases, and travelers are persuaded to use public transportation more than

their private vehicles. In addition, it is possible to develop some businesses by decreasing the parking costs in the area. Low parking costs will lead travelers to go to those areas more than the others with the higher parking prices.

The number of *on-street parking facilities* existing on the streets is also controllable. By making restrictions to on-street parking, traffic flow decreases. But, we need to consider that this item also affects the land-use policies and businesses in the specific areas under study.

Another controllable item is the *construction of off-street parking facilities* in specific areas of a city. Construction costs are high and may vary a lot. On the other hand, there could be considerable revenues from charging private vehicles. However, in some areas with serious traffic problems this might be the only available solution.

### 1.2.3  Flexibility issues

Despite the fact that *flexibility* is more and more an important component of the daily life of people and organizations, it is extremely hard to precisely clarify its definition in specific applications, particularly in the area of transportation engineering and management in the construction industry. Generally, a large part of the literature on flexibility concentrates either on strategic management in organizations or flexible manufacturing systems. The main differences between these typical areas and the area of our study are the orientation of the flexibility concept, and the consideration of different objects.

In our context, some definitions of *flexibility* should be presented. Flexibility is defined as a collection of physical possibilities corresponding to technological options (De Groote, 1994). Another definition of flexibility is the capacity to change or respond to changes in time, costs, or results, with a small deterioration of effectiveness (Upton, 1994). Bucki and Pesqueux point the fact that flexibility is the capability to adapt to the current situation in a reversible way (Bucki and Pesqueux, 2000). Wadhwa and Rao mention that the most important aspect of flexibility is the ability to implement many scenarios, which helps making the right decision (Wadhwa and Rao, 2004). Wiltbank highlights the change of accent from improvement of planning to efforts to improve the forecasting ability and the speed in changing environment (Wiltbank et al. 2006). Another definition of flexibility views flexibility as the ability to respond or readapt in a reversible manner to the changing competitive environment, from the point of view of time and methods (Lim et al. 2007).

Current parking systems are rather inflexible and often deployed with little concern to detailed geographic and demographic factors that can affect parking demand at a specific location or time. They are constructed based on studies that are mostly done for new, suburban sites with un-priced parking in situations that are not adequate for urban areas with better public transportation systems. So, it is necessary to study the types and degrees of flexibility for parking systems designed to be integrated

with other modes of transportation, and estimate the reaction of individuals (on the demand side) for all transportation modes.

As it was mentioned before, this suggests a given understanding of flexibility, but there are other possible definitions of flexibility. This definition is associated with parking conditions that can change not only with demand, but also along the time. Specifically, in terms of off-street parking, with very high construction costs, the deployed systems should be flexible in terms of demand and time. In this regard, "flexibility" policies are necessary to minimize costs and maximize traffic flow.

For instance, a flexible design will help the investments in an off-street parking. In this regard, two alternatives can be considered. A first alternative is investing a considerable amount of money in the first year of the planning horizon, assuming that the demand for that parking will not change for many years. A second alternative is investing a part of the money to build a small park, then invest the rest of the budget every five years to expand the current parking capacity, considering that the demand for that park is probably not high now, but it may increase along time. So the flexibility in design has to be considered and there are differences between the typical approaches and a flexible approach to the infrastructure design in this case.

We believe that the first important difference is would be to minimize the negative attitude towards risk. Flexibility decreases the possibility of negative events (losses) and at the same time it increases the possibility of positive events (opportunities). Another important difference is an active attitude, this meaning to be prepared for the possible changes instead of just waiting for them and acting in response to a given situation. This is very important to deal with the long lifecycles of transport infrastructure elements, and with the unavoidable changes in systems of this type, due to internal and external uncertainties. The third difference is related with the two previous differences, and is the possibility of implying the changes. This simple example about parking investment shows the importance of flexibility in terms of managing demand in time.

### 1.2.4   Expected results of the thesis

The first main expected achievement of this doctoral thesis is an integrated framework to model car parking in connection with other transport modes, and covering both on-street and off-street parking. We will start with a first simplified model. Then other characteristics will be added to that model, if they are applicable. This framework should be as much comprehensive as possible, and should be applicable to most parking problems.

The second main result of the thesis is a set of tools (models and algorithm) for optimization. Optimizing construction costs and revenues for off-street parking, and finding an economic way to add these costly

structures to current parking models, is the main purpose of these tools. These tools will put together travel demand models with optimization models, thus leading to a single integrated parking model.

The third important outcome of this document is to include environmental concerns into the parking studies and to understand the importance of environmental impacts and externalities due to changes in parking policies.

The last main result will be the definition and design of a set of concepts or models to assess flexibility of parking systems and to help improve flexibility. This integrated model will cover uncertainty in the demand and in the dynamics of the model.

## 1.3   Main objective of the work and research questions

In spite of the importance of parking policies, just a few studies in this area have been done in recent years. Graph 1.4 shows the number of articles published from 1995 to 2017 (as referenced by the "Web of Science") with the word "parking" in their title. This search was refined in the following four specific areas: engineering, urban studies, transportation, and operations research / management science. Graph 1.5 shows the number of citations of those articles in the same search. These two graphs make it clear that the number of publications and citations is growing in this area of research.
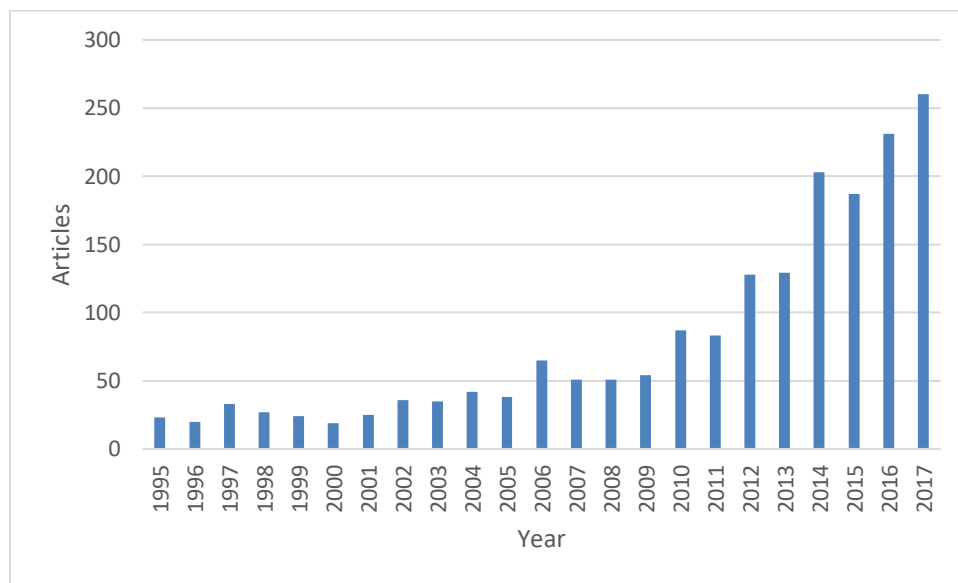


Graph 1.4. Number of published articles on WOS including the word "parking" in the title
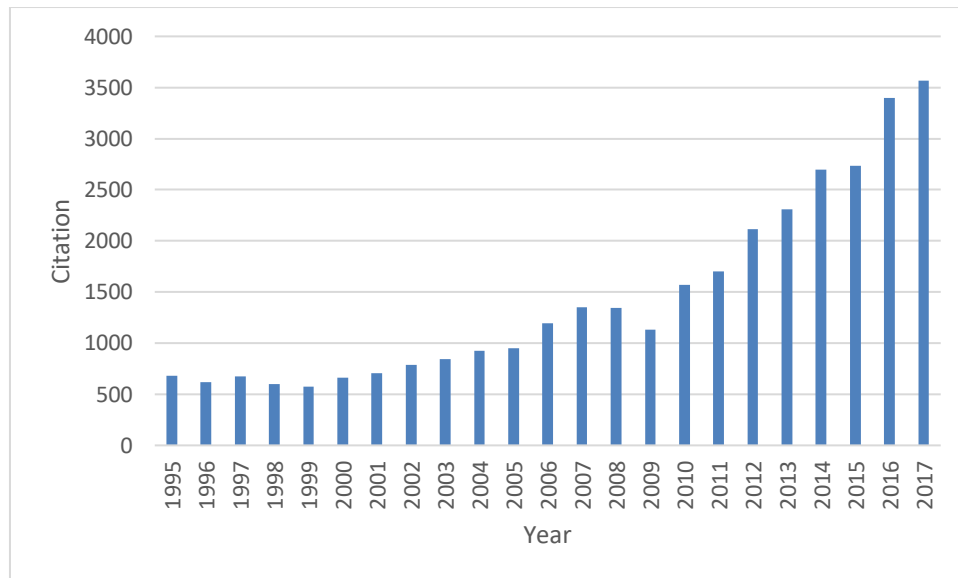
Graph 1.5. Number of citations to articles based on WOS including the word "parking" in title

In recent years, research on parking has increased a lot and became quite broad in scope. The studies in the area of parking done in recent years cover many different aspects, but typically, each study concentrates on a very specific subject, and it is not easily applicable to other cases. There is therefore, among several approaches and tools, a need for a framework to support the design of adequate city parking prices.

In addition, another reason why these studies have not been applied properly yet is the lack of integration with travel demand models. Travel demand and parking policies are two major areas of study which should be integrated with each other, as this integration seems to have a big potential.

Furthermore, in previous years the "flexibility" concept in parking studies was simply viewed as the integration between transportation policies and land-use planning. But flexibility is a very wide concept, with many diverse interpretations and a considerable potential. Applying some ideas on flexibility to the development of parking policies and to parking pricing is another main objective of this dissertation.

This research project was defined to adequately address the relevant gaps which have been identified in the literature. There are three main goals to have been achieved by the end of the dissertation:

- to develop an integrated and comprehensive framework for addressing the parking problem and applying it to a real case study – this framework integrates public transportation, to evaluate the effects of different parking strategies and help decision making and the definition of policies;

- to integrate the "off-street parking" problem into the proposed basic framework and optimize construction costs and revenues, as a way to provide authorities with economic solutions to solve these problems in specific geographical areas;
- to introduce flexibility issues into the current models, by addressing both the demand and time dimensions.

The results or deliverables of this dissertation will be an *integrated framework* to support problem structuring and decision-making, a *decision support tool* for that framework, and a *methodology to increase the flexibility* of policies for car parking.

Based on these objectives and on the gaps identified in previous works, we have formulated two main research questions, as presented below.

### 1.3.1   Research Question 1 [RQ 1]

The first research question is about the importance of parking policies and how much helpful can be a framework to support decision making in this domain. Previous works obviously lack this type of comprehensive framework. Therefore, the main question here is:

*Can an integrated framework significantly impact on improving design of parking policies in urban areas?*

To answer this question, we obviously need to develop the referred framework and test it in a set of representative situations.

### 1.3.2   Research Question 2 [RQ 2]

The second research question is related to the huge costs of building off-street parks. Normally building an off-street park has considerable investment costs, but these costs and the net cost revenues can be optimized. The question is:

*Can a flexible design substantially optimize off-street parking costs in an urban area?*

To answer this question, a set of new concepts will be designed, and a simulation approach is going to be used.

## 1.4   Methodological approach

A set of general concepts, principles and techniques, such as a demand-supply based approach and mathematical programming models, are used as the methodology. Different techniques are put together

and two innovative models are proposed to tackle the parking problem. The main model is an *optimization model,* with an objective function designed to maximize the revenue. A *demand-supply based approach* is used as an input for this optimization model. The demand-supply approach will allow the control of the demand side by controlling the supply side.

In general, we consider that drivers need to park their car in their destination zones. If they find an empty place, they will park there, and if they cannot find an empty place (because of some restrictions), they will park their vehicle in other zones, or they will not travel by car, using another transportation mode.

In the demand-supply approach, we try to cover the demand with some facilities (we call them supplies) and try to find the proper solutions related to the parking problem. The demand for parking happens when a traveler finds something attractive to do in a destination and he chooses to travel by his private vehicle. We assume a rational traveler selects the private vehicle over the public transportation based on the cost of the trip, which includes monetary cost and time cost. We have chosen the *logit* models for the problem of selecting between public transportation and private vehicles.

One important component of the travel cost by private vehicle is the parking cost. In general parking is a complementary part of a trip and the parking tariffs have an important role in the decision of traveling by car. We assign a separate role for parking price in the trip cost and we will study the effects of this cost in the mode choice by *logit* models.

The next step of this methodology is related to the parking spaces. The parking spaces are divided into two main categories of *on-street* parking (curbside parking) and *off-street* parking (garages). These two types are normally being managed by government (or some public, municipal authority) and private companies, respectively. In the perspective of this dissertation, we believe there should be a uniform supervision on both of these parking types, in terms of facilities and pricing – we therefore analyze these two types of parking together.

The pricing strategy that we use in this thesis is based on the maximization of the total revenue, in order to find a solution for the expensive structure of off-street parking. This means we enter the choice of building or expanding an off-street parking into account, to answer the overload of demand, while we are also using other tools such as increasing the parking price. So, in this methodology we use both mechanisms (changes in parking prices and new off-street parks) to prevent excessive demand and decrease cruising for parking.

In this work, parking price has two opposite effects. First, in the demand side: by increasing the parking price, the number of travelers who uses their private vehicle decreases. This drop in number of travelers tends to reduce the total profit that we will get from the parking spots (this profit includes all parking revenues minus costs). On the other hand, increasing parking prices has a direct positive effect in the

revenues. So, we face a direct positive and an indirect negative effect of parking prices in total revenue. The optimization model is designed to find the optimum price for parking spaces, with respect to the expensive cost of the off-street parking structure.

In addition, underpriced parking spaces can create several externalities such as congestion of cruising for parking and harmful environmental impacts. After designing a flexible *base model* for the parking problem, we will try to cope with these externalities by considering them into different parts of the analysis process. The methodology will be comprehensively described in chapter 3.

## 1.5   Structure of the dissertation

This dissertation includes five main chapters.

After a comprehensive introduction of the problem and the research scope and objectives in chapter 1, we continue with the literature review in chapter 2. Thirty-nine articles in the area of parking studies will be briefly presented and a summary of them will be presented in a table. These papers are mostly gathered based on the way they relate to parking problems and studies. In addition, we categorized parking related research activities into demand and optimization approaches. This literature review hopefully shows the diversity of perspectives related to parking problems (from 1965 to 2015).

In chapter 3 we describe the adopted methodology and define the supply-demand relationship in the parking problem. In this chapter a comprehensive method related to the estimation of the demand is presented. This method starts from the concept of utility and generalized cost for a trip, and uses *logit* models to perform the mode choice.  In addition to the demand component, the optimization model and its objectives and variables will be described in chapter 3, and the developed integrated framework will be presented in detail. The objective of this optimization model is to maximize the revenue, by considering changes in the parking tariffs and in the construction costs of the new parking garages.

Chapter 4 contains the optimization approach and it will fully describe the developed mathematical models. In this chapter we will present this mathematical formulation in detail, and we will define all the variables and parameters. Another part of this chapter is devoted to the formulation of the additional parking externalities (that complemented the base model) such as *cruising time* and *environmental issues*. At the end of the chapter, a numerical example is presented to show the capabilities of  of the models and to assess the results.

Finally, in chapter 5, we apply the models to a real size case study (San Francisco county) and fully test, validate and assess the whole developed approach.. In this chapter we used the accessible online travel survey related to this area, and gathered other geographical information to calibrate and run our models.

This dissertation is completed with the literature references, and with annexes that present all the details and figures used in this dissertation.

# 2 Related works

Theoretical works on parking policies and on the design of parking facilities are scarce. But, as it was shown in the previous section, the interest on this subject has increased in recent years. In particular, no comprehensive study has been done related to *off-street parking*. In general parking studies till now have mostly concentrated on the *cruising time* for parking, normally trying to study and decrease the cruising time for parking, aiming at avoiding congestion.

Among the main research projects in this topic, we would highlight the work by Donald Shoup and Richard Arnott (Arnott, 2005; Shoup, 2005), who have achieved outstanding results in the economy and in the externalities of the parking problem. In his studies Shoup (Shoup, 2005) is mostly concentrated on cruising for parking, while Arnott (Arnott, 2005) has an economic approach to this problem. They have looked at the problem in different perspectives, and have proposed practical models to address it (in this chapter, we also review some of their important works).

The parking problem itself includes a variety of subjects and, to have a comprehensive knowledge about this problem, it is necessary to investigate different types of approaches. The diversity in the research subjects is vast, covering different topics such as economic issues, demand and supply perspectives, optimization methods, cruising times, etc.

In this chapter, the reviewed papers are classified based on their specific approach, focusing on optimization, demand modeling, flexibility and environment. However, these works often have some overlaps, this meaning it is possible that we categorize an article, for instance in the *demand* section, and there are some contributions for other sections, such as *flexibility* or *optimization*. However, the majority of works is based on demand and supply studies. This categorization on topics such as demand, optimization, etc. allows a better understanding of the parking problem, and is used to highlight the importance of its different variables.

Finally, we will close the chapter with a comprehensive table, summarizing the findings and learnings from the reviewed works.

## 2.1 Optimization

The articles related to *optimization* are numerous. Especially in recent years researchers became more interested in using these techniques in parking studies. These works have different focus such as parking space management as it is the case of the work by Mackowski (Mackowski et al., 2015) who formulate

a dynamic non-cooperative bi-level model to fix parking prices in real time, for effective parking access and space utilization. Qian (Qian and Rajgopal, 2014) showed that any ideal flow pattern can be attained by charging parking prices in each area that only depend on the time or occupancy, regardless of origin and destination of users of this area. Another recent example is the paper by Inci (Inci and Lindsey, 2015) that study the downtown parking markets in which the spatial competition among the garage and curbside parking, nonlinear pricing and curbside parking search congestion are concurrently at play. Caicedo (Caicedo et al. 2012) propose a methodology for predicting real-time parking space availability, by allocating simulated parking requests and estimation of future departures. It should be mentioned that in some cases, the reviewed papers include both the demand and the optimization sides, but they may be considered in only one of these categories, because the emphasis is on one of these aspects in that specific paper.

### *Roth, G.J. (1965). 'Paying for parking'. London institute of economic affairs, series of Hobart paper, 0073-2818.*

Maybe "*Paying for parking*" by Roth (Roth, 1965) is one of the earliest attempts to present parking pricing as a problem, in a comprehensive way. Basic principles, willingness to pay for a parking space and methods for allocating the available space are just a glimpse of numerous aspects that Roth discussed in his book.

To deal with the parking problem, he mentions two fundamental principles. First, the current parking space in towns should be made available to people who needs it more. Second, since the space in town is scarce, the demand for it must compete with the demand for other land uses. These two basic principles directly or indirectly have been used in most of the parking related articles till now.

In terms of willingness to pay, two methods have been presented by Roth to allocate limited resources when the demand is unlimited. The first method is to allocate resources to people who are considered by a public authority to be in greatest need, and the second strategy is to put services and goods for rent or on sale, and allocate them to those willing to pay more.

Another important issue discussed in this work is the adverse effects of parking subsidies in public transportation. Parking subsidies encourage long term parkers, such as people who want to go to work. With regard to congestion, it is not desirable to encourage them, because they are the people who normally travel during the peak hours, and at the same time they have the alternative of using public transportation for all or part of their journeys. Moreover, cars that park on the road with no payment increase traffic congestion and, thereby, increase the cost of public transport, by decreasing the regularity of its service. Also parking spaces with artificially low prices hide the true cost of drivers' journeys and feed the natural resistance to paying the economic public transportation fares. So, even if

increasing the parking fares would not alter the number of spaces in use, it would lead people to perceive public transportation fares in a better way.

Three methods are proposed for decision making for available on-street parking spaces: first come first served; time limitation; and pricing. In the "first come first served" scenario the available parking spaces go to the drivers who get them earliest. This approach is in the favor of people who travel earlier in the morning and discriminates individuals, such as shoppers, who have later arrivals.

The "time limitation" method is used to guarantee a high turnover of cars in the available parking spaces. One of the benefits of this method is fairness. "It is better for eight vehicles to be able to use a street parking space in a day, than for one to occupy it all day" (Roth, 1963). Another benefit of this approach is that it gives priority to short term parking. Normally short term parks are meant for social and business activities, that are considered to be more appropriate for private cars.

In the "pricing" method, high prices tend to decrease the demand and low prices to stimulate it. The pattern of prices suggested by this method should lead to the following situation: if the total number of parking spaces in an area is fixed, a small portion of spaces in every area should be vacant at most of the times, so that parkers could find those spots easily.

The book also presents several different charging methods for parking spaces, such as parking meters, ticket-issuing machines, personal parking meters in the vehicle, and road pricing meters. According to the author, the road pricing meter used as a personal parking meter was (at least at that time) the most interesting, with the payment for parking then being performed together with the payment for the use of road space for moving.

The following general stages to deal with the parking problem are proposed:

1. introduction of a parking system for street parking, such as parking meters, ticket issuing machines or road pricing;
2. estimation of the cost of off-street parking, given in the different zones of the area;
3. assessment of the demand for parking spaces in different zones of the area.
4. building the car parks where the demand for space is high enough to cover the costs, taking into account the effects of car parks in terms of amenity, traffic flows and other considerations.

Introduce Parking System → Estimating off-street Parking Costs → Evaluating the demand → Building Car parks
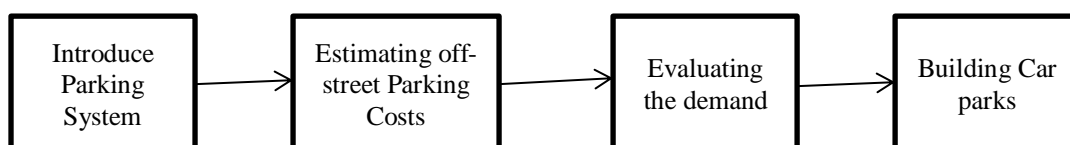
Figure 2.1. Stages to deal with parking problem

In terms of the system suppliers, three possibilities exist: a private enterprise; local authorities; and the central government. For private suppliers, this business is normally unfavorable, as they mostly provide the goods in which there is the demand at prices that cover the costs. Even when charges can cover costs, hostile opinions against the payment for free parking is a big preventing point for private parties. This hostility and the existence of low parking alternatives such as on-street parking often tend to make private enterprises reluctant to invest money and effort in providing car parks.

*In conclusion, "Paying for Parking" is one of the first comprehensive theoretical works on the parking problem, and the proposed framework still provides (after all these years) quite good guidelines for the design of practical, implementable solutions. However, works based on this framework have mostly concentrated on micro-simulation approaches, not adequately considering the critical role of demand.*

**Arnott, R., Palma, A.D., Lindsey, R. (1990). 'A temporal and spatial equilibrium analysis of commuter parking'. Journal of Public Economics, vol. 45, pp. 301-335.**

Another important theoretical work is a discussion paper (Arnott et al., 1990), examining the effects of parking spaces on the congestion of morning rush hours, and measuring the advantages of road tolls and parking fees, as tools for decreasing that congestion. In this paper, three pricing methods are considered: an optimal time varying road toll; competitively set parking fees; and optimal location dependent parking fees.

The "congestion" model that the author used in this paper was basically structured by Vickery (1969) and developed by Hendrickson and Kocur (1981), Fargier (1983), Arnott (1985) and Cohen (1987). Previous theoretical work on the dynamics of rush hour traffic congestion disregarded parking as an important aspect of urban transportation. In this paper the authors take a first step to correct this view, by testing the effects of time and costs of parking on morning travelers' departure time and parking location decisions.

In fact he shows that when parking and road use are mostly free, travelers occupy parking spaces in order of reduced accessibility. This reaction increases the period of individuals' arrivals at work and consequently the aggregate schedule delay costs grow. On the other hand, competitive pricing of parking tends to decrease the schedule delay costs, but cannot decrease congestion.

This work also considers time-varying road tolls and location dependent parking fees, for optimal pricing schemes. The road toll can be planned to remove congestion but it does not change the order in which parking spaces are occupied. On the contrary, the optimal location dependent parking fee considers queueing, and motivates travelers to park at the most distant spots first, so the schedule delay costs decrease significantly. It is also shown that for most practical parameter values the parking fee is

more effective than the road toll. Gathering tolls and road pricing has some logistical drawbacks and political oppositions – the paper therefore recommends that parking fees deserve more attention than they have had received until then.

In this paper, several features of real world parking have not been considered. First of all the authors assume that it is not necessary to search for parking spots, and that all of those spots are positioned along radial commuting routes. However, both the drivers who park the whole day or those using parking residential and commercial areas for shorter periods, are not "organized" systematically to use space by accessibility. They need to search to find an empty space to park. Search adds a random element to traveler's arrival time, and some of the travelers do not know that they will arrive early or late for work.

Second, some differences between on-street and off-street parking may be quite important for drivers. These differences include entry and exit delays, inappropriate ramp geometry and poor visibility for some vacant spaces (Hunt. J. D. 1988). In fact, both of these parking types have their specific kinds of delays. On-street parkers interrupt traffic when they are entering or exiting a spot or by double parking. Users of off-street parking make congestion when queues grow outside parking garages. Also both of these parkers increase congestion while they are cruising for parking spaces.

"Time-of-day" or "length-of-stay" parking fees are two other important strategies that can be applied to encourage shoppers or businessmen to travel during off-pick hours. It should also be noted that some travelers use employer provided or subsidized parking – according to Shoup (1982) this will normally increase congestion.

In addition, these authors consider that the total number of travelers is fixed, but it is always possible that some of the travelers have access to carpooling or public transportation. Moreover, road tolls and parking fees can reduce congestion, by affecting the parking location decisions and the travel time, possibly decreasing the total amount of traffic.

*Finally, the most important limitation of this work is possibly that the CBD is considered as a point, not as a zone. It would be more realistic and useful to model the CBD as a zone inside which employment and parking are geographically distributed. It should also be noted that drivers travel different distances on downtown roads, based on where they live. Road tolls could possibly count the traveled distances, and charge travelers based on those distances, but parking fees cannot.*

*Glazer, A. and Niskanen, E. (1992). 'Parking fees and congestion'. Regional science and urban economics, vol. 22, pp. 123-132.*

This paper tries to show that if the road usage is priced lower than optimal, the sum of the parking fees along time can induce welfare, but a parking fee per time unit cannot. In fact, increasing the parking price motivates travelers to park for a shorter time, and normally leads more drivers to park in the same spot during each day, therefore increasing traffic. Indeed the authors try to investigate the relationship between parking and congestion, proposing a model with three main characteristics.

The first characteristic is taking into account both parkers and through drivers. Travelers can park in downtown or pass by downtown while their destination is somewhere else. An optimization model is designed to maximize the social welfare per time unit, by using socially optimal parking fees, road usage fees, and a number of parking spaces. The authors conclude that when the elasticity of demand for the drivers who pass downtown is finite, an optimal sum of parking fees is positive.

In a second step they test the effect of a parking fee on the consumer welfare when profits are not returned to consumers. Basically by increasing road prices, the consumers' welfare decreases. However, increasing the parking fees reduces the length of time each driver parks in a place, and it allows more consumers to park. This can increase the overall consumers' welfare. So, an increase in the parking fee per time unit inevitably reduces the consumer surplus of the original parkers. But then more persons can park as each of the original drivers parks for a shorter time, and the new parkers, by some assumptions, have positive consumer surplus. If the marginal utility of each parker is a diminishing function of the length of time he/she parks, then the losses of the original parkers can be covered by the gain of new parkers.

In a third model search costs are included. The model considers the cruising time of a driver varies with the number of other drivers who are searching for parking space, and with their cruising time. In this model all travel costs except the cruising cost are assumed to be zero. Multiple parking places are considered in the model.

*In conclusion, policy makers normally view parking pricing as a substitute for road pricing, as a way to reduce congestion. But, according to this paper, the desired effects may not occur. Counting on assumptions such as "an increase in the cost of parking is equal to the increase in the travel costs" may just hold for the travelers who park for a fixed amount of time. But this assumption fails for through drivers or for the drivers who can vary their parking time. So, when a large amount of traffic is due to these types of drivers, an increase in parking fees may have no or even negative effect on congestion.*

*Shoup, D. (2006). 'Cruising for Parking'. Transport policy, vol. 13, pp. 479-486.*

This paper is one of the most comprehensive sources about *cruising for parking*. It presents a model of drivers' behavior about the decisions related to cruising for parking or paying for it, and it suggests it is more likely to cruise for parking when on-street parking and fuel are cheap, the driver is alone, off-street parking is expensive, the driver is willing to park for a longer time, and the driver estimates a low value for saving time. Also this model shows that changing the on-street parking prices to at least the price of nearby off-street parking can eliminate cruising. Somehow the decision of the drivers for cruising and parking is mostly in the hands of authorities who set the on-street parking prices. Their wrong decisions may lead to traffic congestion, air pollution, accidents and waste of fuel.

There are different factors that affect the drivers' decision about cruising or paying for the parking, with several variables explaining theses decisions: hourly price of on-street parking (p); hourly price of off-street parking (m); parking duration (t); time spent for searching on-street parking (c); fuel cost of cruising (f); number of people in the car (n); and value of time spent on cruising (v). The saved money by parking at the curb and the cruising cost for on-street parking can be computed as follow.

t(m-p)   - amount of money that is saved by parking at the curb;

fc       - money cost of cruising for on-street parking;

nvc      - monetary cost of time spent on cruising for on-street parking;

fc+nvc   - monetary and time cost of cruising for on-street parking.

The search time for which drivers become indifferent between cruising and paying is given by $c^*$ – at $c^*$ drivers understand that after that time, there is no net saving for them when compared to the off-street parking.

$$c^* = \frac{t(m-p)}{f+nv} \qquad (1)$$

Analyzing the elasticity for the cruising time, five main results can be derived. First, the elasticity of cruising time with respect to the on-street parking price depends only on the on-street and off-street parking price. When the on-street parking is low, the elasticity of cruising time is also low, this meaning that an increase in the parking price has a small effect on the amount of on-street parking spaces. The on-street parking price is inelastic, and by increasing the on-street parking price there will not be more empty spaces. But, if the price of on-street parking is close to the off-street parking price, then by any small changes in the price, big changes will happen to congestion, i.e. the demand for on-street parking can be considered totally inelastic till the point that its price surpasses the off street parking price (it is in this point that the demand for on-street parking becomes very elastic).

Second, when the on-street parking is free, the elasticity of cruising time with respect to the off-street parking price is always equal to one. So, reducing a specific percentage of the off-street parking price will result in decreasing the same percentage in the willingness to spend time cruising.

23

Third, the elasticity of cruising time with respect to the parking time is also equal to one. This means that increasing the parking duration tends to correspondingly increase the cruising time. For instance, if a driver is planning to park twice longer than another driver, he/she will be willing to cruise twice longer than to find an empty on-street parking space. On-street parking is the best choice for the drivers who want to park for a short time, but the drivers who are planning to park for longer time, have higher desire to search and find an empty on-street parking space.

Fourth, the elasticity of cruising time with respect to the fuel cost depends on the number of people in the car, on the value of their time, and on the value of fuel. If the value of time of people in the car is much higher than the fuel price, then increasing in the fuel value will not have a considerable effect on cruising time. Fifth, the elasticity of cruising time with respect to the number of people in the car and their value of time is the same. This means that if there are more people in the car, or if their value of time is higher, there will be the same effect on the willingness to cruise.

Figure 2.2 describes the underpriced on-street parking case. As shown, the entire empty spaces are occupied and cars are searching along the block, to find an empty space to park. The data used in this example is from a commercial district in Los Angeles – there are 8 on-street parking spaces in each side of an average size block, with the average cruising time of 3.3 minutes before finding an empty parking space, and two drivers who are searching for a space.



**Underpriced curb parking**

All curb spaces are occupied

Cruising for parking

Average search time = 3.3 minutes
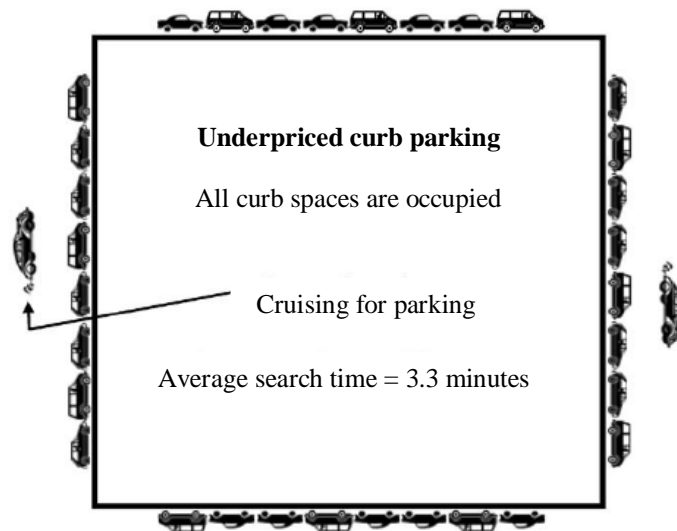
Figure 2.2. Under-priced on-street parking case

Figure 2.3 shows that situation in which the on-street parking price is set high enough, and that in each side of the block we can find an empty space between those eight spaces. It is obvious that there is no need to cruise for the drivers because they can find an empty space in each side or, if they prefer, they can park in an off-street park. So, if the parking price changes during the day in such a way that we can

see the empty spaces during the day, there will be no cruising time. The figure suggests the effects of parking prices in demand, and how correctly priced parking can help to avoid cruising.



**Right-priced curb parking**

1 of 8 curb spaces vacant

No cruising

Average search time = 0
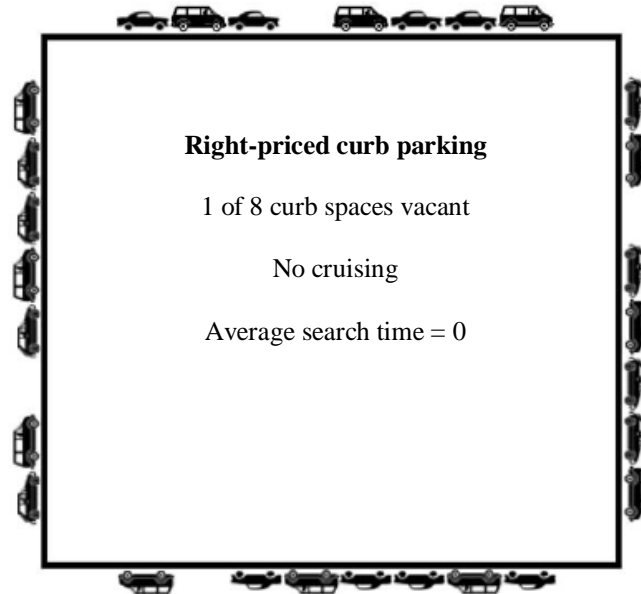
Figure 2.3. Right-priced curb parking

However, Shoup's paper identifies six main complications related to cruising for on-street parking. First, the value of saving time is not the same for all drivers. They may have quite different values of time for different trips, at different hours, or on different days. Even the value of time for each driver is not constant for a given trip, because as they cruise more, the possibility of arriving late to the destination increases, and after not finding a vacant space for a while, the drivers prefer to pay for off-street parking.

The second complication is that the drivers do not know how long it takes to find an empty space to park. In a regular queue, they can see how many people is in front of them, and consequently they can estimate how long it will take to pass the queue, but cruising for parking is like to be in a queue with unknown length and unknown service time. It is possible that they find a vacant space in a minute or in half an hour. The third issue is that on-street parking and off-street parking are not perfect substitutes for each other, and considering their differences just in terms of price is not sufficient. There are other important considerations such as walking time to the destination or the way back to the car. Off-street parking is less convenient in this case, because normally aboveground garages are time consuming to walk and underground garages maybe seem unsafe.

Fourth, the cost of parking spaces is not known to the drivers at the beginning of their trip, as they do not know how long they should cruise and how far they should park. Fifth, in some areas of the city, the time you can stay in an on-street parking is limited, and so the drivers who plan to stay for long may

ignore cruising and go straightly to off-street parking. However, surveys such as Shoup (2005) show that more than half of the drivers who park on-street in a city such as Seattle violate the time limit, or park illegally. Sixth, there are always other options available, no matter how perfectly a system is designed, such as parking in an illegal space and accepting the risk of receiving a ticket, or parking in an off-street parking in a cheaper neighbor area.

*In conclusion, this paper is surely one of the most complete sources for the "cruising time" issues. Cruising for parking happens in downtown crowded areas, and it can be controlled by correctly pricing the parking spaces. The government of a city mostly decides about the on-street parking prices, and has therefore an important role on managing the cruising for parking, with the right pricing of on-street parking possibly leading to significant benefits for everybody.*

**Feng, S., Chen, Y., Li, H., Deng, L. (2009). 'Class of comprehensive optimization of congested road-use pricing and parking pricing'. Journal of transportation systems engineering and information technology, vol. 9, pp. 74-79.**

In this paper, the ideas of congestion road pricing and parking pricing have been combined. Parking pricing is here defined in a different, specific way. The authors assume there is a boundary around the central business district of a city, and that some private vehicles enter that area by paying for roads, with others parking outside the boundary and using public transportation. After designing this network, they developed a *logit* trip mode choice model, and designed a bi-level planning procedure that maximizes total user benefits at the first level, and that uses user equilibrium model with elastic demand at the second level.

Figure 2.4 presents a simple combined trip network. Node *u* is a vehicle passage way, on the boundary of the central business district. At this node, a toll-gate for charging the congestion fee and park and ride system are built. Link 1 is for private cars, and link 2 for public transport. The travelers who are interested to go with their private car, pay the toll at node *u* and go to the destination *v* by link 1. The other travelers park at node *u* and take the public transport there, by link 2.
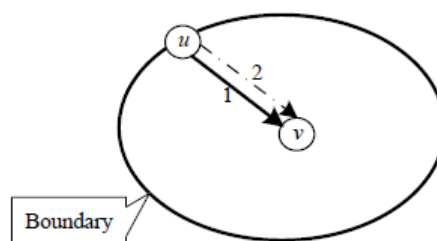


Figure 2.4. A simple combined trip network

*The authors developed a mathematical model for this network, and proposed a heuristic solution algorithm to this bi-level planning problem. They suggest that, in order to attract more travelers for park-and-ride, monetary benefits of congestion pricing should be used for improving parking and public transportation facilities on the boundary of central areas. In addition, these congestion pricing benefits should help decrease the parking prices and public transportation tickets.*

### Arnott, R. (2014). 'On the optimal target curbside parking occupancy rate'. CESifo working paper series, no. 4416.

This paper tries to determine the optimal target curbside parking occupancy rate. It provides a conceptual basis not only for estimating this rate, but also for undertaking a welfare analysis of other policies related to curbside parking. The author assumes that space is isotropic and that the economy is in stochastic steady state, so the ideal rate does not change over time and space.

The approach taken in this work has three parts. The first part studies the results of different search strategies, taking as given the probability distribution of different patterns of parking occupancy over space. The second part computes the probability distribution of different patterns of occupancy over space viewed as stochastic processes for trip generation and termination, under alternative search strategies. The third part derives a maximum target rate.

*The paper mentions that the parking planner controls the curbside occupancy rate only indirectly through the curbside meter rate. He believes that by adding a demand function to the expected full price of a trip, then equilibrium, social surpluses and optimal curbside meter rate can be determined.*

### Larson, R.C. and Sasanuma, K. (2007). 'Congestion pricing: A parking queue model'. ESD working papers, Massachusetts institute of technology.

This work proposes two methods for congestion pricing: Road Pricing (RP), and Parking Pricing (PP). RP poses two main challenges. First, in RP, at least theoretically, *congestion pricing* must apply to each road separately, and what normally has been done is *cordon pricing* (in cordon pricing some cordons were drawn around the CBD (Central Business Districts), and each cordon has its price to enter). Second, RP solutions are costly and require the application of various technological devices.

On the other hand, PP increases the parking price average in a specific area, and with this strategy it charges congestion. This means that instead of charging each vehicle for using each road, vehicles are charged at destination. Furthermore, this approach improves traffic flow by pricing congestion and increasing parking fees in crowded areas.

There are four types of congestion costs. The first type is *waste of time*, which is one of the results of congestion. An upper bound on the waste of time can be calculated by multiplying hours lost in congested roads, in wage per hour; and a lower bound can be estimated by calculating the net gains from reducing congestion. The second type is *waste of resources* and the associated costs. Two examples are wasting gasoline and damaging pavements. The third type is the loss of *environmental quality* and associated costs. Air pollution and noise pollution, impacting people's health, and global warming, are examples of this category. However, their impact can in general be considered smaller than the time and resources loss mentioned above. Finally, we have *loss of business* – congestion tends to decrease the city attractiveness and, therefore, it has a clear negative impact on business.

The reasons for congestion are both in demand and in supply. From the demand side, it should be mentioned that private vehicles are still the favorite type of transport for individuals. People persist to use private vehicles and PP is easier than RP to solve this problem. Besides, insufficient parking capacity and inappropriate parking pricing are clear problems from the supply side. On-street parking prices must not be much lower than off-street prices, as this would become an incentive to search for on-street parking, leading to more congestion.

Moreover, this paper identifies the stakeholders for PP and RP as follows.

*Government:* federal and local government is less interested in PP because for them extra revenue from RP is higher than from PP. Furthermore, public transport companies prefer RP, because they can use the revenues of RP in the area to improve the public transport on that area.

*Residents:* residents of an area prefer RP and *cordoning* instead of PP, because they would be forced to pay for every parking in their zone if PP applies.

*Business:* the perspective may vary according to the specific businesses and cities. There may be quite different impacts on business from adopting PP or RP.

*Shopping:* retail shops normally do not like to see empty parks near them. So, RP is more interesting than PP for this type of stakeholders.

*Equity issues:* economic measures try to exclude less productive people, to use the limited resources in order to maximize the social surplus. Here the major equity issues are as follows: a) applying PP deprives poor people to use their private car (instead they can use public transportation); b) RP distributes suburban commuter's money to urban ones (this inequity can be corrected by using PP).

*The paper also gives useful insights for an optimization model for the problem (such as objective functions or constraints related, for example, with environmental impacts).*

***Marsden, G.R. (2006). 'The evidence base for parking policies'. Transport policy, 13(6), pp. 447-457.***

Marsden (2006) believes that well designed parking policies, in various ways, contribute to the promotion of a more efficient use of the transport network, lower emissions, higher densities, and better and more inclusive design. A parking policy should not be developed in isolation, but as a part of local and regional spatial and transport planning processes. Its objectives should therefore come from the overall objectives of urban policies, promoting a strong economy supported by an efficient transport system, better accessibility, clean and high quality of urban environment, safe and secure environment, and a more equitable society. Regenerating an area, traffic control, and revenues are other relevant objectives of such policies. In this context, some problematic issues in parking arise:

a) inconsistent definition of demand variability (what is the total car use or parking at a specific site?);

b) possible substitution of some elements in parking demand (short or long stays);

c) the consideration of non-monetary costs of parking;

d) the money and time costs for competing travel options;

e) possible supply effects where different alternatives are available.

*There are several other important points in this study. Possibly costs incurred outside the vehicle (in terms of money or time) are substantially more important than other elements, in mode choice by individuals. Walking time to the destination is valued more highly than search time for a space which in turn is valued more highly than in-car time. Moreover, the modal response to increasing parking charges is different from case to case: in the US, normally, carpooling is a first alternative option. Impact of parking pricing strategies in businesses is low when we have a good public transit system. And the really important action seems to be to improve the accessibility of the workforce to the site of employment.*

***Anderson, S.P. and Palma, A.D. (2002). 'The economics of pricing parking'. Journal of urban economics, vol. 55, pp. 1-20.***

These authors are interested in how parking is allocated away from common desirable locations (normally the CBD). They are concerned about parking places that are unassigned, such as parking for shoppers or tourists. They found that the private ownership of parking lots systematically works, if private owners are diverse and monopolistically competitive. This means each owner must insure that potential parkers find their place at least as attractive as other places in equilibrium (trade-off between the charged price and the number of vehicles that are willing to park at that price level).

In their model, they first propose a basic parking model without externalities of *cruising* (the cruising time is the time that drivers spend to search for vacant parking space). This model considers some

assumptions for the shape of the city, in particular that the expected cost of a parking location is equal to the summation of search costs and walking costs. Later they consider an equilibrium with un-priced parking, and assume that all places have the same cost. They then determine the optimum price for parking based on the distance from the city. In terms of the parking operator, the model considers a monopolistic competition and a function to compute the benefits for the operator, depending on the location. This analysis does not consider aspects such as dynamic pricing, multiple destinations, driver heterogeneity in terms of time value, parking duration, and desired arrival time. They then propose a model that relates the total delay induced by *cruising,* to the number of drivers that are cruising in a given interval. The model relates these factors linearly for simplicity. In a monopolistic context, the price of parking is too low, as the externalities and their effects on traffic flow are not taken into account.

*In fact, this paper lacks a clear strategy about the externalities of cruising for parking. The ideas presented on these issues are quite general, without any real, comprehensive formulation or calculations, or even the application to an actual case study. However, an interesting idea, worth being explored, is that pricing for on-street parking can affect the use of off-street parking, and also that for the cars who are tempted to use off-street parking, the externalities of cruising are meaningless because drivers go to the parking building that they know, without cruising. It is true that the construction costs of off-street parking are too high, but it is possible to somehow compensate these costs by benefits such as decreasing cruising for parking.*

**Brown, S.A. and Lambe, T.A. (1971). 'Parking prices in the central business district'. Pergamon press, pp. 133-144.**

This paper describes an economic model that connects the parking price to the supply and demand distribution of the parking space. The walking distance from the parking lot to an office or a store is the basic mechanism of connecting the price to the distribution of the demand and supply. At the borders of a city, there are always some cheap spaces available that have a few alternative uses and are mostly abandoned. On the other hand, demand for the city center is the highest, so the maximum willingness to pay for parking in the city center for a driver can be established by the effective cost of walking from an area with excess supply to a region of high demand. The duration of his/her visit influences his/her willingness to pay per hour.

The assignment of drivers to the parking spaces can be viewed from two different perspectives. One is the minimization of walking time, and the other is maximizing the leisure and income of the individuals. These aspects are convergent, the first being approached by linear programing, and the second one by non-linear. In general it is easier to model the walking version first, and then check if the results also maximize the individual objectives.

The idea of assigning the parking space to minimize the walking distance was first proposed by Trowbridge (1968), who suggests that the specific number of drivers, $X_{ijpq}$, that are driving to the facility type (q) in a zone (j) depends on their destination (i) and on the parking duration of (p). The total number of drivers must be equal to the demand, $D_{ip}$.

The criterion for assigning travelers to the parking facilities is the total cost for society. This cost includes the number of trips per day, the walking distance, the collection of fees, and the maintenance of parking spaces. The daily cost including all these factors is $C_{ijpq}$ defined as above. The walking distance is calculated by $W_{ij} = |X_i - X_j| + |Y_i - Y_j|$, where $X_i$ and $Y_i$ are the east-west and north-south coordination. The supply side is given by $S_{jq}$ and the ratio values of 0.9 and 0.8 were chosen for curbside and commercial parking spaces. The following optimization model was used for minimizing this total daily cost.

$$\min \sum_{ijpq} X_{ijpq} \, C_{ijpq} \qquad (2)$$

subject to:

$$\sum_{jq} X_{ijpq} = D_{ip} \qquad \text{for p=1,2,3; i=1, …, M} \qquad (3)$$

$$\sum_{i} X_{ij11} \leq 0.9 \, S_{j1} \qquad \text{for j=1, …, N} \qquad (4)$$

$$\sum_{ip} X_{ijp2} \leq 0.8 \, S_{j2} \qquad \text{for j=1, …, N} \qquad (5)$$

$$X_{ijpq} \geq 0 \qquad \text{for all i, j, p, q} \qquad (6)$$

In conclusion, in planning urban developments, figures for demand and supply can be computed by checking whether the resulting price structure is compatible with the estimated mode choices and investment. If the prices or walking distances increase, drivers will tend to use public transportation. To achieve the higher profit from parking is in contradiction with the availability of capacity. An adequate plan should keep the behavior of travelers and investors constant, with parking prices being the connection point between these two groups.

The city government and public parties are obviously in a strong position for the parking business. With tax rules they are able to provide a parking supply in conditions that are costly for private parties to enter. Cheap parking motivates people to go to the CBD and shop there, and decrease the travel costs of employees to go to work, and in a long term perspective, the city may profit from significant increases in the value of land.

*Parking prices are important links between most of the individuals that are somehow involved in the transportation system. These prices directly encourage the landowners, the parking garage managers, the travelers and the urban planners. They also have indirect effects on the other business activities in the CBD and the residence of the surrounding communities. A clear perception of effects of the demand,*

*supply, and walking distance in the parking price can assist all parties to make better decisions for the future of the city.*

**Arnott, R. and Inci, E. (2005). 'An integrated model of downtown parking and traffic congestion'. Journal of urban economics, Elsevier, vol. 60(3), pp. 418-442.**

In this work, a simple economic based model is proposed for the interaction of cars in traffic flows and the cars that are cruising for parking. This article considers a special shape for the city structure, with blocks and roads. The formulation used here considers that the traffic flow is the sum of total traffic and the cars that exit from parking, minus the cars that are parking in vacant places. Some policies are then derived from the model. The case study used in this work is Manhattan in New York City. The main conclusion of this paper is that it is necessary to increase the parking fees to the point that cruising will be eliminated and parking becomes saturated.

*A point that is not mentioned in this article is that in the real world there is no elimination point for cruising. In fact, even if total demand becomes equal to total supply, the last car will need to search the last empty space and it will spend time for cruising. It is therefore better to be more realistic, and consider at least 2 or 3 minutes for cruising. The model is too simple to provide a good policy prescription for car parking, and on-street parking prices should dominate off-street private parking.*

**D'Acierno, L., Gallo, M., Montella, B. (2005). 'Optimization models for the urban parking pricing problem'. Transport policy, Elsevier, vol. 13, pp. 34-48.**

This paper discusses parking pricing strategies. These strategies are more widely used than road pricing, because they do not require the definition of previous policies. The adoption of spatial parking policies based on origin-destination pairs is proposed (here the OD pairs that have a better public transport system, in the origin and in the destination zones, should be priced higher, in terms of parking prices, than zones with poor public transport).

The objective function is the sum of operational net costs of the transit system, local administration revenues from parking, user (monetary and temporal) costs, and external costs. The external costs reduction equals the value of a transit user multiplied by the total transit demand.

*The model is applied to a simple predefined network and not to a real one, and it will be difficult to apply to a real case. No specific framework is proposed for the analysis, and the model is based on too many assumptions. In addition, in the objective function only operational costs are considered, and there is no evidence of huge costs such as the construction cost to build an off-street parking or*

*expanding current public transportation. Moreover, no reference is made to the possible effects of such changes on the demand side.*

**Jun, C. and Wei, W. (2003). 'The planning model for locating urban parking facilities and the design of genetic algorithms'. Proceedings of the Eastern Asia society for transportation studies, vol.4.**

This work has basically concentrated on a planning method for the location of urban parking facilities, using genetic algorithms (GA). A constrained and a non-constrained multi-objective planning model was designed under different conditions of land use, and solved by GA. In the constrained model, people in each zone are concentrated in one point, and in the non-constrained model people are assumed to be distributed by different points in each zone.

First the planning area was subdivided in some traffic zones based on attraction, land use, and walking distances to parking area. Then two points in every zone were defined: one representing most of the demand of that zone (demand point); and another point representing the parking supply. The objective function considered in this work (to be minimized) is based on the distance between demand zones and supply zones.

*Minimizing this distance seems to be an interesting idea, but this paper has no references to the pricing of parking. It is possible to add this distance to other formulations and associate a cost to it. However, the main weakness of this method is parking demand points. Specifically, in big cities parking demand is distributed in a zone and it is not just one point. In addition, priority to using either on-street or off-street parking is not clear in this study.*

**Abidi, S., Krichen, S., Alba, E., Molina, J.M. (2015). 'A new heuristic for solving the parking assignment problem'. Procedia computer science, Elsevier, vol. 60, pp.312-321.**

This paper describes a problem on parking spaces assignment for a given group of drivers, and is based on a real case study. To solve the problem a hybrid genetic algorithm is proposed, and this approach is then compared it with three other algorithms. The paper shows that the parking guidance systems usually do not reduce the cruising time for a free parking space. There would therefore be a need for a system to consider all the relevant information and find vacant parking spaces.

Within this framework, the idea is to free the drivers from taking the parking decisions, by automatically preparing the best path from the current position to the parking space. To enhance the overall performance of parking assignment, a demand assignment method is provided. I.e., instead of sending parking information to the drivers and letting them choose their empty space to park, this method tries

to assign the drivers to the parking spaces by considering the distance to parking space, expected parking cost, and time limitations.

The objective here is to minimize the sum of the vehicle costs and the sum of the distance, considering some specific constraints. Moreover, to solve the problem, a new hybrid heuristic is proposed which is a combination of a GA and a GRASP meta-heuristic procedure.

A case study was defined for the city of Tunis, considering traffic congestion and limited areas for parking. Data was gathered, and 17 parking facilities selected in the city center, with GPS data and geographical information used to improve the simulation model.

*Unfortunately, this work does not consider all relevant practical aspects, particularly in what concerns changes in the demand side, and in modeling the cruising time.*

**Arnott, R. (2006). 'Spatial competition between parking garages and downtown parking policy'. Transport policy, Elsevier, vol. 13, pp. 458-469.**

In the perspective of the economic theory, the spatial competition between parking garages is a key feature for a parking policy. This work studies the optimization of a parking policy in the center of a business downtown district, structured in four different parts. The first part is related to the parking garage operator's problem. In the second part, the authors assume there is no on-street parking and they try to derive an equilibrium in the parking garage market. Then, they compare the social parking policy to the equilibrium solution. As the market power is in the parking garage operator's side, the equilibrium of spatial competition is not efficient, and a parking policy can be used to tackle this weakness. In the third part, on-street parking in considered, analyzing its underpricing effects in the parking policy. The fourth part brings the public transportation into account and checks the interactions of public transportation with minimum and maximum off-street parking standards.

In the parking garage operator's problem, one specific garage, based on a symmetric location and neighbors' garage parking fees, selects the parking price to maximize its profits. For simplicity all the drivers are assumed to park for the same amount of time. Another assumption of the model is that there is a grid road network with garage market areas, and a diamond shape. The profit function of the parking garage operator is as follows:

$$\Pi = S_0 k - C(k, h; r) \qquad (7)$$

subject to:

$$k = T \int_M D(x, S_0; S, d) 4x dx \qquad (8)$$

with: parking duration T; parking garage 0's profit per time unit, $\Pi$; capacity of garage 0, k; number of floors of parking garage 0, h; land rent, r; cost of parking garage 0, $C(k, h; r)$; distance from parking garage 0, x; parking fee per unit time charged by other parking garages, S; parking fee per unit time charged by parking garages 0, $S_0$; grid distance to the boundary of garage 0's market area, b; grid distance between parking garages, d; garage 0's demand per unit area at x, $D(x, S_0; S, d)$.

This work studies different parking policies and scenarios. Ignoring the on-street parking, in the first scenario, leads to have a discretely spaced parking garage, with a transfer of the market power to the private parking garage operators. The spatial competition between parking garages is determining the equilibrium in the parking garage market. Moreover, in this policy, the parking prices are inefficient because they are defined by the different parking garages, and it is highly possible that there is space between them. So, the effects of a parking policy in decreasing efficiency should be considered by the parking policy makers.

The model assumes that the full parking price is being set by the competition between garages, with three types of benefits, namely decreasing cruising time for parking, reducing overall traffic congestion, and helping the distortionary taxation. Moreover, public transportation affects the provided parking policies and can significantly decrease the parking costs.

*In conclusion, this paper tries to provide an economic and broader view on the parking problem in a downtown area. But it ignores some important details such as the value of time, the travel distance, the parking duration, construction costs of the parking garages, the interaction with public transportation, and parking prices.*

### Gallo, M., Montella, B., D'Acierno, L. (2011). 'A multilayer model to simulate cruising for parking in urban areas'. Transport policy, Elsevier, vol.18, pp. 735-744.

This paper proposes a simulation model for park selection in urban networks, to study the effects of cruising for parking on traffic congestion, and parking choices, including the effects of search time and walking time. This model is a multi-layer supply model and each layer simulates a trip segment. There are three segments described in this paper: trip by car from the origin to the destination; cruising for parking space in the destination zone; and walking from the park space to the destination. The impacts of cruising in congestion were studied when the average parking occupancy becomes more than 70%.

The authors assumed that the demand and origin-destination matrix is fixed and in steady state. Other considered assumptions are that the total capacity of all parking facilities is known, and that in one hour interval the cars do not leave their spaces. Moreover, every driver chooses his/her path in the way that his/her perceived cost of travel becomes minimized.

The following figure presents the layers of the model and the studied network. Trips start at origin centroids, $O_i$, and the walking route between the origin centroid and the real node of the road network is shown by connector links. Then the travelers drive to the destination centroids, $CD_i$. These destination centroids are linked and connected to the cruising layers by an inter-layer link between the destination centroids and support node (used only for connection purposes). At the cruising level, these nodes are connected to the parking nodes, $pn_x$, by parking links. Then there is another inter-layer link that connects these parking nodes to the walking layers, and only at the walking level is it possible to reach to the destination centroids, $D_i$.
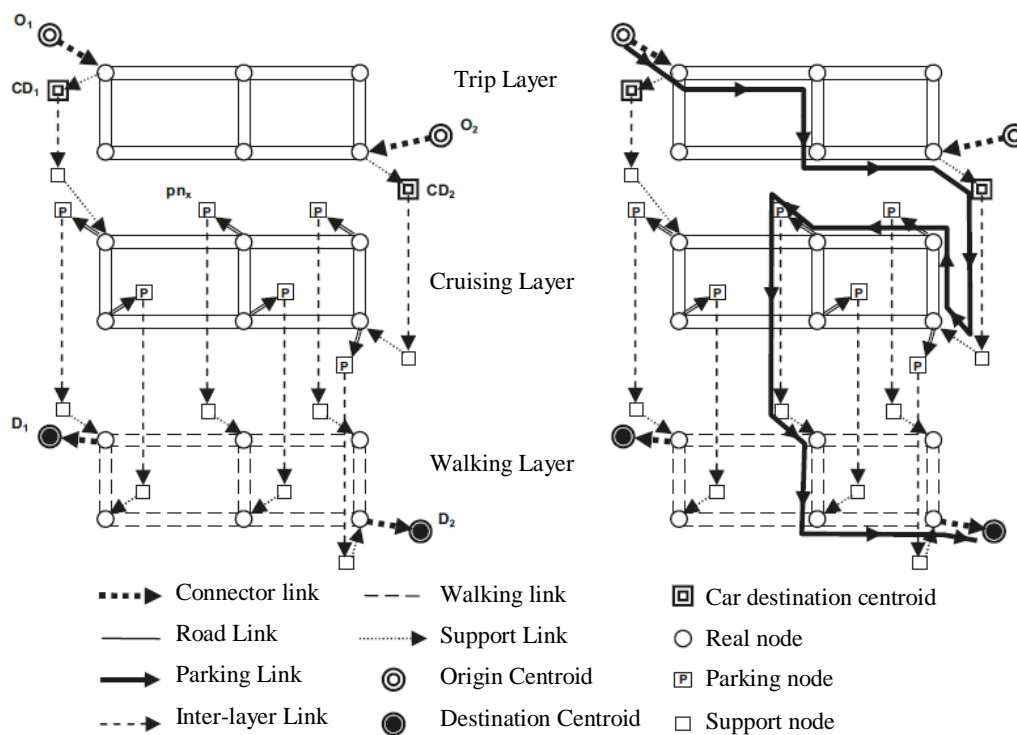


Figure 2.5. Layers of the model (Gallo, et al. 2011)

*This model mainly tries to tackle the problem of cruising for parking in a congested area. A numerical example shows the model is useful when the occupancy rate is going to be higher than 70%. The model seems to have some problems such as zoning, information about the parking capacities, and location of centroids. These problems basically show that this methodology (and, in general, these network-based models) is only useful for small cases with few small zones. However, when we are analyzing big cities with numerous zones and several origin-destination points, we clearly need other types of approaches.*

*Caicedo, F., Blazquez, C., Miranda, P. (2012). 'Prediction of parking space availability in real time'.*
*Journal of expert systems with applications: an international journal, vol. 39, pp. 7281-7290.*

Intelligent parking reservation (IPR) systems provide the ability of selecting a parking facility based on the costumers' preferences. I.e., costumers can rapidly park their vehicles, with no need to search for an empty space, they pay in advance, and thus they avoid queues. Some of these systems collaborate with in-vehicle navigation systems and give some real time information to the users, about parking fees, capacity, and current parking utilization.

In particular, this paper proposes a methodology to forecast real time parking space availability in the form of an IPR system. This methodology includes three sub-levels to: simulate and assign parking requests; estimate future departures; and predict parking availabilities. The requests for parking are assigned iteratively by using an aggregated approach. In fact, this approach is being used as a function of simulated drivers' preferences and parking availability, and is based on a calibrated discrete choice model for choosing parking alternatives.

The proposed methodology assigns several requests in a probabilistic approach, yielding a simple and less time consuming algorithm. For predicting parking spaces availability in real time, by using the current and historical information, a real-time availability forecast algorithm is proposed. To incorporate the effect of receiving availability information to predict and characterize user choices or assign parking requests, a discrete choice model was developed. This model is first calibrated with the data from a study of parking preferences, considering arrival and departure processes, duration of stay, and static capacity of each parking facility that operates in a specific zone of the city. Figure 2.6 shows the flowchart of the real time availability forecast algorithm.
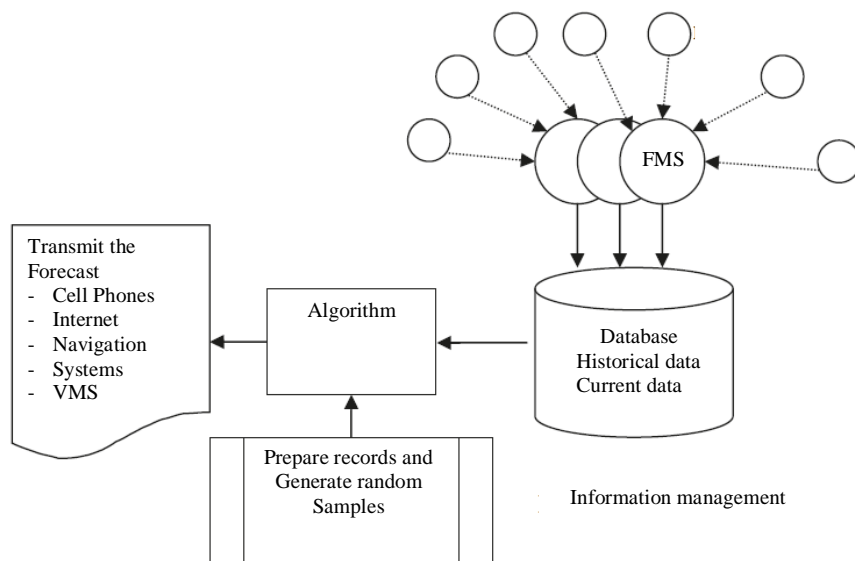


Figure 2.6. Flowchart of the real time availability forecast algorithm (Caicedo, et al. 2012)

As shown in the figure, the expected outcome of the algorithm is an availability forecast for all current parking alternatives that can be spread between users through the internet, vehicle navigation systems, or cellphones. In order to update the forecasts, the algorithm is fed over time with updated records of departures or arrivals, at each parking alternative. This information is saved in a database and is gathered from a facility management system (FMS) at each parking alternative.

In conclusion, these systems lead to a more effective parking management, and at the same time, they improve costumers' satisfaction and parking service productivity. This paper compares the proposed aggregated approach with a one-by-one simulation based forecasting algorithm, concluding that there is no significant difference between the two approaches. The algorithm was applied to a case study in Barcelona and a comparison was performed with the actual availabilities (the results showed that there was a small average error of around 3%).

*However, these models are rather weak for bigger areas (such as a whole city), due to the large amounts of required data. I.e., these models not only ignore the variations in demand for the whole city, but they are very time consuming processes.*

***Weinberger, R. (2012). 'Death by a thousand curb-cuts: Evidence on the effects of minimum parking requirements on the choice to drive'. Transport policy, Elsevier, vol. 20, pp. 93-102.***

This paper aims to understand the effects of guaranteed parking at home on the drivers' mode choice. Three neighborhoods are studied in New York City, which have few off-street parking. This research includes two levels. In the first level a survey was conducted based on the Google Earth for 2000 properties, and this survey was used as a base to estimate the on-site parking for the neighborhoods of the study. In the second an estimation was made for the maximum likelihood parameters that forecast the share of residents who use their private car. This estimation used the calculated parking availability and a generalized linear model.

In this paper, a binary *logit* model is used to forecast the on-street parking. Then a generalized linear model with a *logit* link function was designed to describe the causes for increasing or decreasing the amount of trips by car to the working areas with public transportation accessibility. The analysis is first applied to the dwellings, but at the end the unit level is the census tract. This work did not use a disaggregate mode choice model to estimate the probabilities due to the lack of data in the travel surveys. A percentage was assumed for the work trips that are done by private car as a function of average income level, car ownership, distance to subway or commuter train, and the level of on-site parking per dwelling unit, as follows:

$$y = f(u, v, w, \alpha, \beta. \gamma, \delta) \hspace{3cm} (9)$$

where y is the percentage of people who drive to work, u is a vector of characteristics of the built environment, v is a vector of socio-economic and demographic characteristics of people, w is the on-site parking per dwelling unit (study variable), and $\alpha, \beta, \gamma, \delta$ are the estimated parameters. An aggregate logit model was used to allow the usage of an ordinary least square (OLS) regression to model percentages.

$$ln\left(\frac{y_i}{1-y_i}\right) = \alpha + \beta' u_i + \gamma' v_i + \delta w_i \hspace{3cm} (10)$$

Surprisingly the results seem to show that the higher incomes are related with the lower levels of traveling by private car. The reason for this behavior is that maybe the wealthier families in New York City are living in the areas with the best public transportation offer. The model also shows a clear relationship between increasing access to parking at home and the share of driving to work in Manhattan core. Moreover, there sems to be an indirect and direct correlation between off-street parking and driving to work, with car ownership and facilitation of the car use, respectively.

*In conclusion, this study shows that in big cities with parking problems in crowded areas, cruising for parking can be strongly diminished by on-site private parking. The utility function of drivers with a secure parking place is different from that of drivers without it, and such a secure place makes the usage of private cars more attractive. Improving the parking facilities in the destination zone has always been promoted as a way to decrease the congestion of cruising and its externalities. However, facilitating parking, on the contrary, can absorb more drivers to the CBD zones of a city, thus increasing air pollution and congestion. To support decision-making considering all these aspects is, therefore, a need.*

## 2.2 Demand modeling

Demand for parking in a specific area of a city is highly related to the land use. A traveler in general makes a trip to fulfill his needs in his destination. The goals for traveling can vary from shopping to work or leisure, and the related trips can be mostly done by public transportation or private vehicles. If traveling is being done by private vehicles, the travelers will need to park their vehicles in a safe place and leave them for a short or long time, depending on the type of activity. This demand for a parking place has been studied during the years, with quite different approaches. In many of these studies, the demand itself is not a problem, but the its externalities are often a concern.

The cruising time for parking has been considered, in the past years, as one critical externality and an important research topic. The cruising time happens when the demand for parking exceeds the supply due to the level of attraction of a specific area. When the drivers cannot find a place to park they start

to search for an empty space. This search consequently leads to some extra cars in the roads and this excessive amount of cars creates an unpleasant congestion.

On the other hand, there is always another option for the travelers to park, which is off-street parking (parking garages). During the past years, this option has not been a good competitor for on-street parking to attract drivers, mainly due to the underpriced on-street parking. I.e., the price of on-street parking is too low, in such a way that the demand for this type of parking stays high, even without enough supply. Consequently, drivers prefer to spend more time to search for a cheap parking space, thus creating extra congestion. Since the total amount of on-street (curbside) parking is constant, the need for strategies to attract travelers to use off-street parking is obviously higher. Off-street parking structures are costly and till now there has been no study on incorporating their costs into the parking models.

The following studies mostly concentrate on the demand side of this problem, analyzing the relative externalities and congestion in more detail.

***Shoup, D. and Pickrell, D. (1978).'Problems with Parking Requirements with Zoning Ordinances'. Traffic quarterly, vol. 32, pp. 545-563.***

This unique theoretical work tries to show that a parking price change may lead to a substantial impact on the number of work trips made by automobile. Therefore, if by some zoning strategies the price of parking decreases (as a result of an increase in the supply), the number of trips using long term parking may increase significantly.

The paper suggests the parking problem is indirectly related to the land-use, with applying a zoning approach being a possible cause of problems, with the following potential flaws:

- normally there is a weak connection between the explicit zoning intervention in the real estate market and the ultimate consequence hoped for in the market where the real problem is supposed to be;
- a zoning solution gives the impression that something has been done about the observed problem, notwithstanding whether the relations between the zoning intervention and the observed problem are working as supposed;
- a zoning approach hides the true expenses of intervention because its costs do not show up in the public budget.

Since the 1920's zoning strategies, such as considering off-street parking for new buildings, have existed. The general idea was that the problem of traffic congestion can be lessened by preparing the

off-street facilities for the number of automobiles that drive to the site. The determination of the required space was done by simple assumptions and primary methods such as counting the number of required space per seat in a theater, per dwelling, or per square foot of office space. These assumptions are mostly based on the theory that the trip generation rate reflects the "need" to travel by automobile and is not directly a function of the price.

This paper states that planners know how to connect the parking supply to the local circumstances, but the real problems show up when taking these decisions out of the private market. I.e., some planners propose a zoning regulation to force the parking supply to be above the amount that would be provided by the private market, while others recommend an upper limit on the quantity of parking spaces to decrease the amount under which supply would be provided by the private market. In fact, more off-street parking may reduce the automobiles from the streets while they are at their destination. On the other hand, less off-street parking can help to decrease the amount of automobiles travelling to activity centers. In the first scenario, only traffic and fast parking near the building under analysis is considered, but in the second scenario the congestion of roads leading to an activity center is an important issue.

The primary idea of considering proper off-street parking for a new building is that it attracts vehicles to the area and these vehicles need to park somewhere near the building. If they do not find a proper parking place, they cruise the streets around to find a vacant on or off-street space and congestion increases. But even providing new off-street parking for a building will not necessarily eradicate cruising, while the low-priced on-street parking exists and most of the times the places are full. If the price of on-street parking is set much lower than off-street parking, there is always a motivation to cruise for an empty on-street parking spot. I.e., if the value of the expected cruising time is less than the difference between the on-street and off-street parking price, drivers will continue cruising.

Another argument for off-street parking is that commercial activities create parking requirements that may overflow into residential neighborhoods. Through an adequate strategy, residents will always find a proper place to park and will not need to park in the neighborhood's area.

The importance of additional parking spaces to encourage trade and employment in the CBD areas is the third prominent reason in favor of off-street parking. If we do not provide enough parking spaces for new constructions, the demand for parking in adjacent buildings will increase and consequently the price for those parking spaces grows up.

The paper under analysis states that if we do not provide parking spaces for a new building, simply the parking prices and level of congestion rises and "nobody goes to downtown anymore because it is so crowded". But the private market will tend to provide parking spaces downtown if there is enough demand.

41

The argument that "parking requirements are vital for absorbing people to come to downtown" is criticized by this work, as their authors believe the strategy of parking requirements for new buildings can be applied to the entire city, and consequently there will be more space to park the car in the entire city, not just downtown. The paper states that it is probably a mistake to identify the health of the downtown area by the number of vehicles that can be driven or parked there, and that there should be doubts on having a beneficial net result, if we consider the effects of an increasing number of parking spaces for all modes of transportation.

*In conclusion, these authors believe that a parking price change can have a huge impact on the number of work trips by automobiles. So, if the number of parking places increases and consequently their price is reduced, we may have a considerable growth in the number of trips requiring a long term parking. Moreover, it is possible that the number of trips using a short term parking increases. Therefore, trying to solve the congestion problem by minimizing the parking zones can have the reverse effect, by increasing the circulation and cruising for finding a parking place, in downtown areas and even in the routes that are serving those areas. In addition, air pollution and energy consumption may increase by raising the amount of automobiles in the streets.*

*March, A. (2007). 'Toward strategic planning for car parking'. Working paper, urban planning program, University of Melbourne.*

This paper states that the behavior of cars upon reaching a destination is influenced by the type, the price, the connectivity and the parking regulations, these factors clearly influencing people in what concerns their parking choices. To understand these choices, the following aspects need to be considered.

*Travel behavior and urban function:* Imposing restrictions upon on-street parking leads in general to a larger use of public transportation and a smaller use of cars. Ideally, parking supply should be neither over-supply nor under-supply, and land-use should always be taken into account. The definition of a maximum value for parking, as part of a wider transport plan, must stem from the strategic particular plan considering the desired characteristics of specific places and regions.

*Land-use and development patterns:* Imposing minimum parking requirements may act as a limit upon higher density development, while encouraging sprawl. The distribution and nature of parking play an important role in the city form. In Los Angeles a minimum parking required strategy is used, and the result was that the suburban areas are 74% as dense as the CBD, but in New York City with a maximum parking strategy (establishing a maximum parking area), the result is that the suburban areas are just 12% as dense as the CBD.

*Direct consumption of land and resources:* aesthetic, function, safety, and street life – these problems can be solved by two main categories of actions: improved design and improved management solutions.

According to the work under analysis, there are five main principles to move to a strategic parking approach. The first principle is using parking maxima as a primary control in all cases. In a second approach, all areas in the region must be covered with maxima. In a third approach, homogeneous standard rates must not be used, and instead a strategic justification is provided for parking maxima (in policy and regulations). The fourth approach is based on involving local plan-makers or development proponents in helping design and demonstrate the quality and benefits of parking policies and regulations. Finally, a strategic analysis should form the basis of balanced transport objectives, and create urban functions to complement the desired characteristics and functions of individual places.

*Wider questions are raised by this paper regarding transport modes in various urban forms and public transport types, vehicle kilometers traveled and congestion, the economy and social vitality in various development forms, the consumption of land and resources, the production of emissions and the cost of construction.*

**Ommeren, J.V. and Russo, G. (2014). 'Time-varying parking prices'. Economics of transportation, vol. 3(2).**

This paper studies the economic consequences of changing the parking prices in terms of changes in the demand. The employees' parking demand was estimated for an organization (hospital) that changes the price of parking by day of the week. A difference-in-difference methodology for this purpose. The demand for parking was taken as deterministic, and it is shown that considering a stochastic demand does not essentially varies the welfare calculations.

In this paper, the dependent variable is defined as whether a worker makes use of the organization parking on a given day. The study excludes the observations for workers who always or never park during the analysis period (because the effects of the parking price were not identified for this group of people). The sample includes 784 workers in 384 workdays, and the average probability of daily parking is around 60%. The combination of change in the pricing regime in a specific day, differences in parking prices between peak and slack days, and a price that changes with the worker's traveling distance, are used to define the different parking prices.

Then these differences in parking prices are categorized in three types of strategies. The first strategy exploits price changing for peak days. The second strategy exploits the same type of change, but on slack days. The third strategy exploits price changes for different days of the week after a given date.

The main result is that for each strategy (or mix of strategies), the parking price (measured in Euros per day) has a (statistically significant) negative effect on the probability to park. These results are approximately the same as those obtained by Wilson and Shoup (1990) and Wilson (1992), who also calculated the effects of employer-paid parking. They also reveal that the slope of the demand function does not change between peak and slack days, possibly because a large amount of workers work on both days, and therefore the differences in daily aggregate demand are mainly based on the differences between numbers of present workers.

Another interesting result from this research is that workers with off-site work activities have a greater likelihood to park. The amount of work hours has a positive impact on the probability to park, which relies on the diminishing marginal benefit of leisure time. So, the use of slower modes such as bicycles or public transport becomes more attractive on the days when workers are planned to work fewer hours.

*Moreover, if free parking for workers is provided, the generated loss will be around 10 % of the organization parking costs, but this amount does not include any welfare costs due to an increase of travel externalities. This loss can be minimized by using peak pricing on high demand days. If a fixed parking price is defined, the minimum loss will still be around 4 % of the organization's cost. This result is in line with the recommendations of economists such as Vickery in 1954 (Vickery, H.B. 1954).*

### Gillen, D.W. (1975). 'Estimation and specification of the effects of parking costs on urban transport mode choice'. Journal of urban economics, Elsevier, vol. 4, pp. 186-199.

The main goal of this (very much cited) paper was to evaluate if parking taxes are an effective alternative for road pricing, in terms of congestion. The paper studies the effect of changing parking fees on urban transport mode choice. A binary logit analysis was used and elasticities were calculated for four policy oriented variables. Elasticities provide a measure of the bias from misidentification and describe the most effective policy variables to decrease auto use.

The paper estimates the effects of parking costs on household choice of transport mode, for trips in urban areas. First, this work characterizes the parking cost variable and incorporates it into the mode choice by households. Second, it computes the micro elasticity of mode choice with respect to the costs of parking, among and within income levels. Finally, the effects of a change in the distribution of the characteristics are evaluated. These characteristics determine the mode choice share of each person.

For the basic model, the mode choice of households is selected as the variable. To present this binary choice problem, an econometric model is derived from a choice theoretical framework developed by DeSerpa (1971). Parking is defined here as a commodity that completes the driver's trip. It is assumed that a utility function of U(Ci), with $C_i$ being the amount of transit transportation commodity i, is being

maximized subject to the following conditions (in which $P_i$ is the price of commodity i, $\bar{Y}$ is the income of the household, $X_i$ is the transit service purchased, and $\bar{\bar{T}}$ is the time available):

$$C_i = F_i(X_i, T_i) \qquad (11)$$

$$\sum_{i=1}^{n} X_i P_i = \bar{Y} \qquad (12)$$

$$\sum_{i=1}^{n} T_i = \bar{T} \qquad (13)$$

The mode choice is given by:

$$P_i = f(TSC_j, UC_k) \qquad (14)$$

where $P_i$ is the probability of choosing mode i, $TSC_j$ is the jth characteristic of the transportation system, and $UC_k$ is the kth characteristic of the user (with "f" being nonlinear).

This work used the data from the 1964 Metropolitan Toronto and Regional Transportation Study home interview survey. The total number of the interviews was 84,065 and a sample with 3,012 trips was selected. 3 main criteria were considered to choose these trips: the trip should be a work trip; the origin of the trip should be in the boundaries of Metropolitan Toronto; the destination should be within the 1 square mile CBD of Toronto (due to missing or miscoded information, the final sample was only of 515 trips).

One of the conclusions from this paper is that the relative estimated parking costs (including parking fees) is higher than the relative estimated fares (in which parking fees are not included). I.e., for a given change in relative money costs, the effect of changing the "mode choice with cost" variable is larger than those effects with the "fare" variable. The former variable overestimates the expected effects on using private vehicles with, for instance, a gasoline tax. The model that includes a distinct parking cost variable can separate the effects of changes in parking costs and in running costs, on the mode choice. This is especially significant in the models with variable parking time, since parking services can be a substitute or complement for trips.

In this model, the sign of the parking variable coefficient shows that the parking services are an important factor in work trips. The values of the estimated variables show that drivers are relatively more responsive to changes in parking costs than in changes in other monetary costs, but definitely the effects of parking fees on auto use are not as big as some drivers would have believed. The elasticity of parking fees is low because changing them affects parking relocation as well as mode choice. Only those drivers who are in the boundary of parking relocation and switching modes will change their mode choice – these drivers are mostly the ones who have parked far from their destination and decide to change.

*Finally, the paper suggests that a parking policy with changes in the fees can significantly change the behavior of auto users. Moreover, parking authorities may have to implement significant alterations in parking fees due to the effects on the global associated incomes.*

**Thompson, R.G. and Richardson, A.J. (1996). 'A Parking Search Model'. Transportation research part A: policy and practice, Elsevier, vol. 32(3), pp. 159-170.**

This paper presents a model for the parking search behavior of the drivers. An outline of the procedures used in the decisions and processes of drivers when searching for a car park is presented, along with a computer simulation model for the problem.

The parking choice process includes different stages, based on a series of decisions, linked in a temporal manner. The following figure briefly presents this process. Drivers check individual car parks sequentially, while they travel to the urban center. When they find a car park area, they can either select it or go on to find another car park area.

The paper also estimates the utility function for the car park and define various cost components. The in-vehicle travel time is evaluated by calculating the minimum travel time path between the vehicle's current link and the link near to the car park. The walking time is given by the time needed to travel from the car park and the destination. A probability analysis is used to relate the cruising time to the car park's occupancy and geometric characteristics.
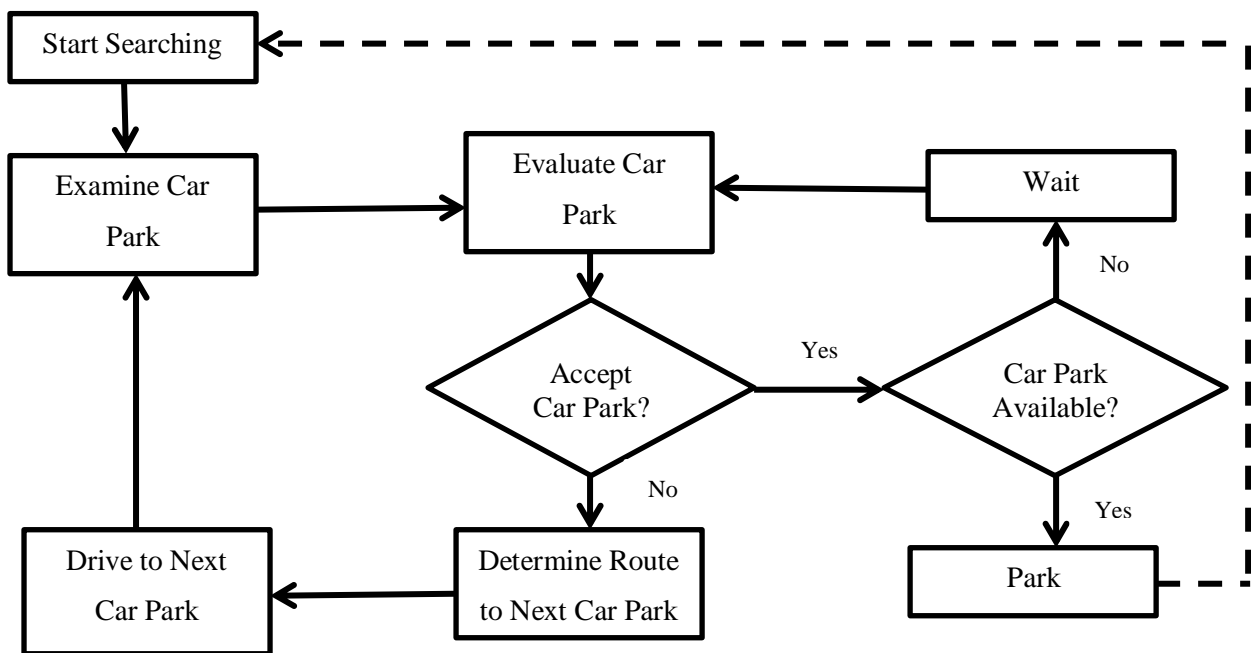


Figure 2.7. Parking choice process (Thompson, 1996)

*A final interesting result from this work is the conclusion that having experience in parking search does not necessarily lead to a better car park being selected, and this is due to the uncertain nature of the car parking system.*

**Goot, D.V.D. (1981). 'A model to describe the choice of parking places'. Transportation research part A: general, vol. 16, pp. 109-115.**

When the drivers decide to travel to the city center, there are many factors influencing their choices for parking places. This paper studied the nature and importance of those factors. Moreover, other external factors such as walking times, charges and occupation rates of parking facilities that can be controlled by the government are highlighted in this work. Results of the traffic and parking survey held in 1972 in Harlem in the Netherlands were used in the study (the data mainly include departure and arrival times, the location of the parking places, and personal characteristics and activities of the interviewed people).

The following indicators were extracted from the data: walking times, parking time restrictions, parking charges, occupation rates, accessibility factors. One of the reasons to consider accessibility factors is that the chance of selecting a parking place mainly depends on its attractiveness and accessibility to a certain driver. An assumption of this work is that the accessibility of the on-street parking places is more than that of off-street places. And another assumption is that this effect is more intense for trucks and delivery vans than for the private cars.

*This paper published in 1981 was one of the pioneers in considering a utility function in the parking problem context. Among other interesting findings, it shows that walking time has a great influence on the parking choice.*

**Hunt, J.D. and Teply, S. (1993). 'A nested logit model of parking location choice'. Transportation research part B: methodological, vol.27, pp. 253-265.**

This paper develops a nested *logit* model for a parking location choice, by using revealed preference data. These data include the behavior of travelers going to work in the CBD (central business district) of a city. Each surface lot and individual parking facility is defined as a distinct off-street alternative, along with the on-street alternatives. For the drivers who travel to the CBD, there are many options to park, and the paper proposes a nested logit model for the parking choice behavior. The study is based

on a disaggregated revealed preference observation of the traveler's behavior when going to work in the the CBD area of Edmonton, Canada.

The following figure presents the nested structure proposed in this work. The three main branches on this model are employer arranged, on-street, and off-street parking.
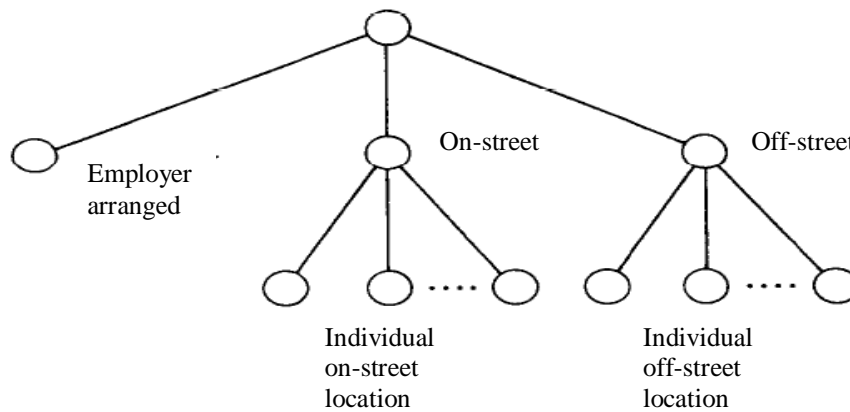


Figure 2.8. Nested structure of parking choice (Hunt and Teply, 1993)

In this paper, 10 factors are used as attributes for utility functions of the nested *logit* model: distance from the work area; waiting time for a stall; parking fee; parking surface condition (including smooth paved, rough paved with potholes or cracks, gravel or dirt); related position to the trip like the trip from home to work or work to home; type of winter provision; safety of the driver; protection of the driver's vehicle; cleanliness of facility containing stall; and noticeability of the facility.

The estimation of the coefficients of the nested *logit* model is done by a stepwise technique, with all the coefficients of the different levels of the nests being determined in a step wise fashion, where, at each level, the computed values are used to estimate the composite utility values applicable for the next higher level. The estimation of each level was done by a maximum likelihood procedure based on McFadden (1974).

*In conclusion, we might say that when we are modeling the parking spaces with different options such as on-street and off-street parking, it is appropriate to use the nested logit models, as the alternatives are totally different, with unequal characteristics. Moreover, in addition to the parking costs and the proximity to the final destination, there are other important parking choice factors such as parking surface and weather. By including these factors in the models, the goodness of fit of parking location choice behavior can be significantly improved. Although the nested logit model works well for small scale problems, it may be quite time consuming and have difficulties in the model calibration, for the case of large, realistic, city cases.*

*Arnott, R. and Rowse, J. (1998). 'Modeling parking'. Journal of urban economics, vol. 45, pp. 97-124.*

This paper proposes a simple model of parking congestion, that focus on drivers' search for an empty parking space in a spatially homogeneous metropolitan area. The model assumes that the average density of vacant parking spaces is internal, and a parking externality appears since the drivers are inattention to the effects of their parking on this average density. Stochastic stationary state equilibrium and optimum are tested, but because of the nonlinearities in the model, it is possible that multiple equilibria exist and the effects of parking fees can be complex. Therefore, several scenarios and extensions are studied, such as estimating the social value of a specific parking information system.

The paper mostly focus on the stochasticity of the empty parking spaces, as this is one of the main reasons why drivers cruise to find a parking space. It has been claimed that for the big cities, more than on-half of the drivers in downtown in rush hours are cruising for an empty parking space. Searching for parking, in addition to frustration and time consumption, leads to significant traffic congestion by slowing traffic down and inducing traffic volume. Moreover, to evaluate parking information systems, to consider the stochasticity of vacant parking spaces is also needed. And studies such as Noland (1995) concluded that unanticipated travel time may be quite expensive when trying to find a parking spot.

In the basic model, the city is located at the outside of a circle and is spatially symmetric. The amount of parking spaces per unit distance does not change, and the demand for the trips is the source of demand for parking. The trip generation system is an exogenous, stochastic, time-in-variant process, and assumes that first an individual is at home. By receiving an opportunity, he decides to accept it or not, and if he accepts, he chooses the mode of transportation. If he drives, he will decide where he is going to start cruising for an empty parking space, and then he takes the first available space and walks to his destination. The expected walking distance is related to the endogenous average density of free parking spaces. In this process, individuals collectively ignore the effect of their parking on this average density, and consequently parking externalities start to become awaken.

The basic model includes four modules: the spatial structure, a trip generation system, a system for parking and travel, and a set of stationary state conditions. The city is assumed to be spatially symmetric and on the circumference of a circle with a large radius r. It has a  spatial structure in each location as shown in the following figure. Population density and the density of parking spaces are represented by D and Γ, respectively. There are two travel modes: walking and driving. In the figure, X represents the shortest distance around the circle of a trip opportunity from home. Home, trip destination, starting point for cruising, parking location, and cruised distance are represented by O, R, Q, S, and y, respectively.
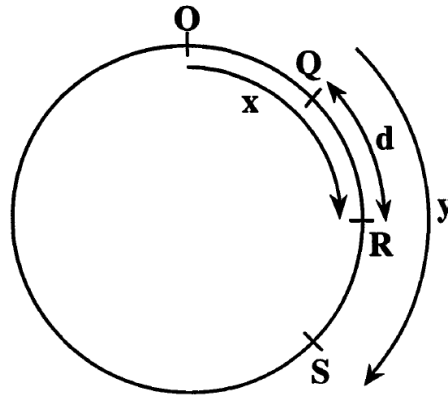
Figure 2.9. Simplified shape of the city (Arnott and Rowse, 1998)

In the model, all the parking spaces are given and operated by the planner. The land for roads can be used for traffic or for on-street parking. Assigning more land to the on-street parking can automatically increase the availability of these types of parking, but at the same time it also intensifies the traffic congestion. Land for other uses can be assigned to housing or to off-street parking. Increasing building of off-street parking can result in house construction with higher density, leading to an increase in the housing costs – there is here room for a possible optimization.

In the model, traffic congestion is ignored. To solve this problem, it is possible to assume that travel speed in regular traffic is related to the density of cars in that traffic. Moreover, the effective capacity of a road depends on the number of on-street parking places, the entering and leaving rate of the cars to an empty parking space, the density of cars that are cruising for parking, and pedestrian density. Other forms of congestion that can be considered in the parking problem are parking entry and exit congestion, and intersection congestion.

*In conclusion, the model was developed with four main concerns: to have a rough, not detailed model; to tackle the complexities of the parking problem; to ensure conceptual bases for welfare analysis, through a general equilibrium model; and to consider the stochastic behavior of cruising and parking.*

*This model has some weaknesses such as not including the costs structure of parking and of the parking assignment system, but its main problematic aspect, despite several simplification assumptions, is its complexity (that seems to be somehow unavoidable).*

*Shoup, D. (1997). 'Evaluating the effects of cashing out employer-paid parking: eight case studies'. Transport policy, Elsevier, vol. 4, pp. 201-216.*

This paper studies the effects of the law enacted in California in 1992 that forced several employers to give the workers the option to get cash instead of any offered parking subsidy. As a result, for a total of 1,694 employees in 8 companies, the number of drivers who drove alone decreased by 17 %. The number of travelers that used public transportation, carpooling, and walking or biking increased by 64, 50, and 39 %, respectively. In addition, the amount of total vehicle-mile and yearly carbon dioxide emissions for traveling to the 8 firms, was reduced by 12 % and 367 kilograms, per employee.

This law changed the employer paid parking system, from a matching grant for driving into a block grant for commuting. The cases studied by this paper show how cashing out affects travelers' mode choices, vehicle trips to work, vehicle-miles traveled to work, vehicle emissions from the work trips, gasoline consumption for the work trips, and employer's spending for subsidizing commuting.

*These cases are not from a random sample and do not represent all drivers and all employers, but they still give us some useful interesting information, even if these data are from 1990, and obviously several new parking systems and strategies have emerged during the past decades.*

*Shoup, D. (2004). 'The ideal source of local public revenue'. Regional science and urban economics, Elsevier, vol. 4, pp. 753-784.*

This paper tries to describe all relevant aspects in the parking problem. Here I mention some of the most important contributions of this work are briefly presented.

Cruising for parking creates an unknown queue of cars that ned to wait for an empty on-street parking. But there are few studies on how many cars are actually in the queue, and how long does it take to find a vacant space. These few studies analyzed the video images of the traffic flows, and made interviews with the drivers who park on-street, and search for a vacant parking space.

The following table shows the results of the 16 cruising studies in 11 cities.

Table 2.1. Results of cruising studies in 11 cities (Shoup, 2004)

| Year | City | Share of traffic cruising (%) | Average search time (min) |
|------|------|------|------|
| 1927 | Detroit (1) | 19 | |
| 1927 | Detroit (2) | 34 | |
| 1933 | Washington | | 8 |
| 1960 | New Haven | 17 | |

| 1965 | London (1) | | 6.1 |
|---|---|---|---|
| 1965 | London (2) | | 3.5 |
| 1965 | London (3) | | 3.6 |
| 1977 | Freiburg | 74 | 6 |
| 1984 | Jerusalem | | 9 |
| 1985 | Cambridge | 30 | 11.5 |
| 1993 | Cape Town | | 12.2 |
| 1993 | New York (1) | 8 | 7.9 |
| 1993 | New York (2) | | 10.2 |
| 1993 | New York (3) | | 13.9 |
| 1997 | San Francisco | | 6.5 |
| 2001 | Sydney | | 6.5 |
| Average | | 30 | 8.1 |

The motivation to cruise for parking is being created in the cities when the price of *on-street* parking is much lower than the *off-street* parking in the neighborhood. To show how strong is this incentive, table 2.1 shows the price of on-street and off-street parking in the City Hall of 20 American cities. This table presents the hourly on-street (curb) and off-street parking prices their difference.

Moreover traffic engineers usually suggest that about 15 % of on-street parking spaces should be empty to guarantee the easy entering to and departing from the parking places (Brierly 1972; May 1975; Withford and Kanaan 1972). This rate can eliminate the need of search and cruise to find an empty parking place. If we accept this rule, the right price for on-street parking will change during the day. Figure 10 describes this occupancy rate related to the demand, and this rate is shown by a vertical line and is considered here equal to 85%. The intersection points are the satisfactory points for the occupancy rate. If the parking price becomes lower than those points, the result will be overcrowded parking. If the parking price stays higher than those points there will be many vacant, not used places, this meaning a waste of valuable parking space (three scenarios are considered for the demand: high (D1), moderate (D2), and low (D3)).

Table 2.2. Price of on-street and off-street parking in the City Hall of 20 American cities (Shoup, 2004)

| City | State | Price $/hr | | Saving from curb parking $ |
|---|---|---|---|---|
| | | curb | off-street | |
| Baltimore | MD | 2 | 6 | 4 |
| Berkeley | CA | 0.75 | 0 | 0 |
| Boston | MA | 1 | 11 | 10 |
| Buffalo | NY | 1 | 3 | 2 |
| Cambridge | MA | 0.5 | 4 | 3.5 |
| Chicago | IL | 1 | 13.25 | 12.25 |
| Houston | TX | 0.25 | 1.5 | 1.25 |

| | | | | |
|---|---|---|---|---|
| Long Beach | CA | 2 | 2 | 0 |
| Los Ageles | CA | 1.5 | 3.3 | 1.8 |
| New Orleans | LA | 1.25 | 3 | 1.75 |
| New York | NY | 1.5 | 14.38 | 12.88 |
| Palo Alto | CA | 0 | 0 | 0 |
| Pasadena | CA | 1 | 6 | 5 |
| Philadelphia | PA | 1 | 3 | 2 |
| Portland | OR | 1 | 1.5 | 0.5 |
| San Diego | CA | 1 | 6 | 5 |
| San Francisco | CA | 1 | 1.5 | 0.5 |
| Santa Barbara | CA | 0 | 5 | 5 |
| Santa Monica | CA | 0.5 | 4.2 | 3.7 |
| Seattle | WA | 1 | 8 | 7 |
| Average | | 1.11 | 5.76 | 4.7 |
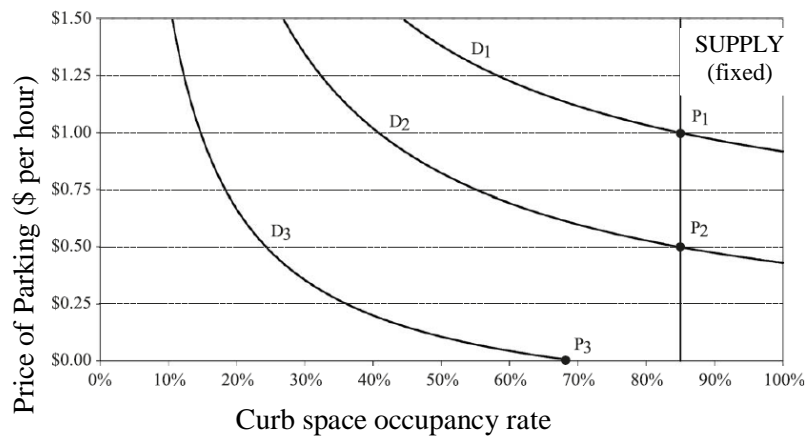


Figure 2.10. Occupancy rate related to the demand (Shoup, 2004)

*As a conclusion, we might say that to solve or remove the "parking problem" we need to: change the market price for on-street parking; use the revenues to finance neighborhood public improvements; and to satisfy the off-street parking requirements.*

**Caicedo, F. (2011). 'Changing parking by the minute: What to expect from this parking pricing policy?'. Transport policy, vol.19, pp. 63-68.**

This paper specifically concentrates on charging for parking based on time intervals. It is obviously possible to calculate parking charges in seconds, so basically the strategy of parking pricing is a political decision. Operators may not need to be fully aware about the effects of this measure on their benefits.

But businesses are clearly interested to know its impacts on the travelers' perceptions and motivations, because they are directly affected by them.

The paper introduces the concept of willingness to add time to the duration of a stay, as some drivers may require increasing their parking period (this is modeled by a dichotomous variable). When a driver parks his car, the parking time is calculated based on his activity time in the destination and on the walking time, from the car to the activity place. If, in the meanwhile, his single activity trip changes to multiple activities, the parking duration time can easily increase. It is at this point that the driver analyzes the trade-off between the extra activity time and the amount of extra parking costs, thus deciding whether or not he will extend his staying time.

The paper models the operation and the behavior of clients in urban parking garages, estimating the effects of charging the parking time by a minute interval. The model shows that charging this way, instead of charging hourly, decreases the probability of adding extra time to the duration of the stay. These extra times are normally added to the time other vehicles are waiting in the parking garages to find an empty space. Therefore, the strategy of charging by minutes can decrease the number of cars cruising for parking and increase the parking benefits.

*In conclusion, although these ideas are not new, there are few numerical case studies in this area. And it seems this approach has a considerable potential to improve the parking system, and possibly decrease cruising time and congestion.*

*Ommermen, J.V., Wentink, D., Dekkers, J. (2011). 'The real price of parking policy'. Journal of urban economics, vol. 70, pp. 25-31.*

This paper empirically studies the resident's willingness to pay for an *on-street* parking allowance, and examines the cruising costs in Amsterdam. In order to characterize the cruising costs of the residents, the idea is that they do not need cruising to use private parking spaces, but using the on-street parking requires cruising. Focus is put on the outside private parking space as parking garages do not have the same characteristics as on-street parking. Focus is also put on paid parking districts, where parking permits are just issued for the residents without private parking, and residents with private parking have no right to the parking permits.

A first main result is that an outside parking space increases the price of housing by 6% in areas with paid parking but not in a waiting lists district (districts with parking permits waiting lists).

A second result of this paper is that the lack of outside parking space can increase the price of housing up to 13% for the houses in a waiting lists district. The residents in households without private parking, in the areas with paid parking, can obtain *on-street* parking permits, but in some areas of Amsterdam

they would need to wait for around 3 years to receive the permit. The paper assumes that the costs of waiting for parking permits are capitalized in to housing prices, and by this strategy the residents' willingness to pay for on-street parking permits was computed – around 10 Euros per day, which is much higher than the residents' parking permit's tariff, and is much lower than *on-street* tariffs for the non-residents.

*These results show large efficiency losses of parking policies related to the usage of on-street parking space. In 2011, a considerable number of residents were using on-street parking, this leading to an inadequate number of on-street parking places for non-residents. If we consider that the on-street parking price is a good indicator of the economic costs of parking, then the welfare costs of policies that provide parking licenses to residents are considerable.*

**Arnott, R. and Rowse, J. (2008). 'Downtown parking in auto city'. Regional science and urban economics, vol. 39, pp. 1-14.**

This paper aims to combine 3 previously published models of curbside parking, garage parking, and traffic congestion, and test an *on-street* parking policy with a numerical example. A model is used to define the equilibrium of parking and traffic flow in the downtown area of a large city. Some assumptions were for simplification reasons, such as the downtown area is spatially isotropic and the drivers are homogenous. Travelers drive to the downtown area with an exogenous uniform rate per unit area-time, and their destinations are uniformly distributed across the unit. Moreover, each traveler has a fixed travel distance in downtown, and after he/she reaches the destination, then he/she will decide to park *on-street* or in parking garages. *Off-street* parking is assumed to be run by a private party and it has a fixed cost, while the curbside parking is managed by an authority, with a number of places that can vary.

The paper assumes the curbside parking fee is lower than the parking garages, and that its level of saturation is so high that cars start to cruise for parking space. Then, the share of the cars that are cruising is adjusted in a way that their cost of parking (cost of cruising time plus the parking price) equals the parking garages payments. However the paper neglects the subsidization of parking that can be an important component of the problem. There are several employers who provide parking facilities and subsidize their employee's garage parking. This parking subsidization decreases the garage parking prices and, consequently, it decreases the cruising time.

One important assumption in this study is that the parking garage's location and capacity are fixed, based on the observation that the parking garages are very costly to relocate or expand. This assumption, and considering an inelastic demand are two main weaknesses of this work.

One interesting result is that, by increasing the parking meter rate by a small amount, the cruising time decreased. This happens because this change seems not to affect the total cost of the trip (cruising time plus parking cost), the cruising time decreases, and the traffic congestion also.

Another interesting result is that, if the government can change the amount of *on-street* parking, the higher the meter rate, the more space should be assigned to *on-street* parking. This happens because the paper assumes demand is totally inelastic, that the price of *on-street* parking is under the off-street parking, and that there is no change in the number of *off-street* parking places. Some of these assumptions and simplifications are hard to justify in real situations, but our work is going to tackle these complications with a hopefully more comprehensive and performant methodology.

### *Su, Q. and Zhou, L. (2011). 'Parking management, financial subsidies to alternatives to drive alone and commute mode choices in Seattle'. Regional science and urban economics, vol. 42, pp. 88-97.*

This paper introduced a nested *logit* model to test the effect of parking management, travel demand management strategies, and financial subsidies to alternative modes of transportation, on people's travel mode choice in the city of Seattle. One of the main results of this work is that the travelers' mode choices can be affected by different public policy tools. In particular, the rate of driving alone from home to work decreases by increasing the parking charges for single occupancy vehicles. Moreover, discounting on parking fees for high occupancy vehicles and lowering the on-site parking ratio can drop the number of alone drivers. Empirical evidence is provided on how financial motivations by employers can affect the travelers' mode choice decision.

Two types of variables have been defined. Among these variables are the policy tools applied by the employers, including parking management measures, financial subsidies, and the employers' commute trip reduction promotional activities and supporting strategies. Another type of variables are the control variables classified in four groups: amenities and land use characteristics at the specific area; travelers' personal information and other travel behavior characteristics; employment and residential density measures at home and work place; and employers' characteristics.

The used nested *logit* model is used to calculate the determinants of mode choices for the employees who are affected by commute trip reduction. This choice is based on the test whether the IIA (independence of irrelevant alternatives) property is violated by applying a multinomial regression. The *multinomial logit* model was rejected, at the level of 0.01 by the Hausman specification test, so a *two level logit model* was chosen. The first level encompasses transit, motor, and non-motor; and in the second level, the motor branch is divided into "drive alone" and "shared ride". For normalization

purposes, the scale parameter in the second level was set equal to 1. Figure 11 shows the structure of the *nested logit model* and the result of the share of mode choice for each type.
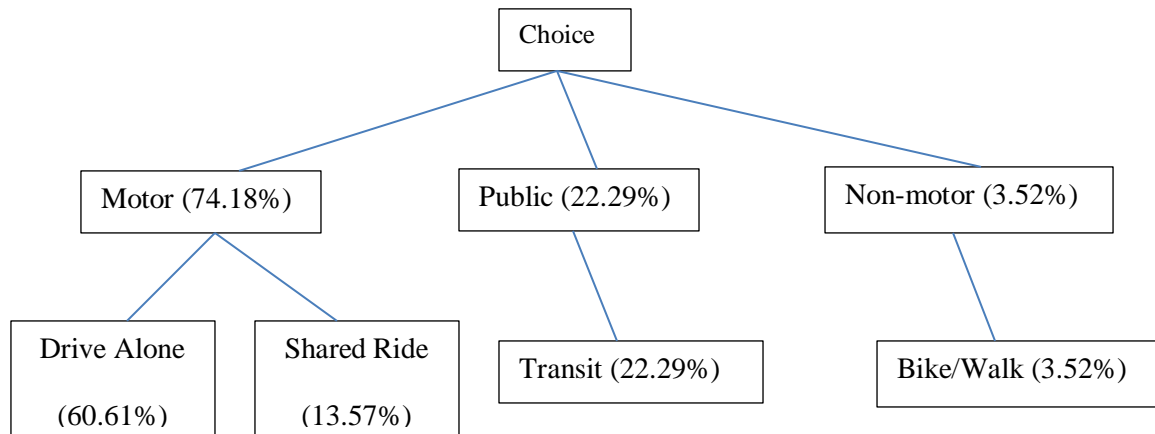
```
                              ┌──────────┐
                              │  Choice  │
                              └──────────┘
              ┌──────────────────────┼──────────────────────┐
      ┌───────────────┐      ┌───────────────┐      ┌────────────────────┐
      │ Motor (74.18%)│      │Public (22.29%)│      │Non-motor (3.52%)   │
      └───────────────┘      └───────────────┘      └────────────────────┘
        ┌────────┴────────┐          │                        │
┌──────────────┐ ┌──────────────┐ ┌────────────────┐ ┌────────────────────┐
│ Drive Alone  │ │ Shared Ride  │ │Transit (22.29%)│ │ Bike/Walk (3.52%)  │
│              │ │              │ └────────────────┘ └────────────────────┘
│  (60.61%)    │ │  (13.57%)    │
└──────────────┘ └──────────────┘
```

Figure 2.11. Structure of the *nested logit model* and the result of the *share of mode choice (Su and Zhou, 2011)*

*The approach proposed by this paper has a considerable potential, but also presents some considerable limitations. The model was developed for the city of Seattle and is not applicable to other cities with lower levels of travel services. Some transit facilities are specific of Seattle, and the unavailability of park and ride systems in smaller cities can be a problem. Moreover, the implementation of the proposed policies is in the hand of employers, and in other places and contexts, employers may possibly not be willing to apply these policies. So, in my point of view a broader and more applicable policy is needed to adequately handle the current parking problems.*

**Barter, P.A. (2011). 'Off-street parking policy surprises in Asian cities'. Cities, vol. 29(1), pp. 23-31.**

This paper provides an international view on non-residential *off-street* parking policies in East, South, and Southeast Asia (and in some western cities). In these selected areas the parking problems are intense and widespread. Parking policy approaches for 14 large metropolitan areas are categorized into 3 groups named as conventional, parking management, and market oriented. Most of these areas have low car ownership, high density development, and high percentage of public transit usage; but their parking systems are conventional, and the parking policies are mostly based on a minimum parking requirement, and do not have a specific parking management strategy.

In the *conventional* approach, the key point is to provide the minimum parking standards and avoid any type of spillovers in *on-street* parking, and *off-street* parking is considered as an auxiliary service. In the *parking management* approach, parking is seen as a section of the transport infra-structure and it is

a potential tool for a broader parking policy and urban planning goals. This approach may tackle issues such as efficiency, decreasing parking conflicts, profit, urban regeneration, and mobility management.

The *market oriented* approach ensures that demand, supply, and prices are responsive to each other. This approach is rarely adopted by policy makers and, as mentioned by Shoup (2005), should be able cope with three problems: demand-responsive charges for parking spaces; revenues for civic improvement; and abolishing the planning requirement for *off-street* parking.

Table 2.3 summarizes parking policy paths in Asia, according to this paper. In an *auto-centric conventional* approach, the main goal is to avoid parking scarcity. In this approach, supply is planned to cover demand based on auto-dependent assumptions, such as zero prices. In a *demand-realistic conventional* approach, in addition to avoiding parking scarcity, one of the main goals is to prevent wasteful surplus. Supply is planned to meet the demand, and it is estimated based on the actual context.

Another approach is *multi-objective parking management* which tries to plan parking, to serve wider urban and transport goals. In this approach, both supply and demand can be planned or managed. However, in a *constraint-focused parking management* approach, the main goal is to limit the car travels to certain locations, and bounding parking supply is an important demand management tool. Finally, in a *market based* approach, the central goal is to combine demand, supply and prices in a way that they interact with each other. The supply and the demand in this method are formed by market actors' performance.

Table 2.3. Summary of parking policy paths in Asia and some western (Barter, 2011)

| Country | Overall parking policy approach. |
|---|---|
| USA<br>Australia | Suburbs: auto-centric conventional approach.<br>Inner urban district: semand realistic conventional or multi-objective parking management.<br>CBD area: constraint-focused parking management and priced, commercial parking in some areas. |
| Bangkok<br>Jakarta<br>K. Lumpur<br>Manila | Auto-centric conventional parking approaches.<br>In some CBD areas commercial priced parking.<br>Price controls in Jakarta. |
| Dhaka<br>Ahmedabad<br>Hanoi | Focus on minimum requirements and government supply.<br>Weak on-street parking control and low prices.<br>Price control in Hanoi. |
| Beijing<br>Guangzhou | Conventional parking requirements.<br>Government provided parking.<br>Controls in on-street parking are increasing.<br>Tendency to multi-objective parking management. |
| Northwest<br>Europe | In suburban areas: demand-realistic conventional and some auto-centric conventional.<br>Inner urban areas: multi-objective parking management.<br>CBD areas: constraint-focused parking management. |
| Singapore<br>Seoul<br>Honk Kong<br>Taipei | Conventional parking policy.<br>Moderate parking standards.<br>Tendency to promote a parking management approach.<br>Pricing of commercial parking in CBD areas. |
| Tokyo | Conventional parking policies.<br>A market-oriented parking system has emerged recently. |

*In conclusion, this paper makes a comparative analysis of different parking policy approaches, in different parts of the world. Obviously, different cities have different approaches. It is clear that till now no comprehensive approach exists to include all the parking difficulties and concerns around the world.*

**Bendor, T., Westervelt, J., Song, Y., Sexton, J.O. (2012). 'Modeling park development through regional land use change simulation'. Land use policy, vol. 30, pp. 1-12.**

The model described in this paper was developed to interface the *regional urban growth land use* model by Westervelt (2011). The region urban growth model is an extendable simulation that estimates the comparative attractiveness of a region for residential growth. In this model there are some development attractors such as roads, highways, natural amenities, and current dense development. This model assesses the development attraction for every location in a landscape based on the proximity to the development attractors. The model relates the parking demand to the population, and subsequently locates parking in the urbanizing landscape. Scenarios have been set for three fast growing counties of North Carolina in the USA.
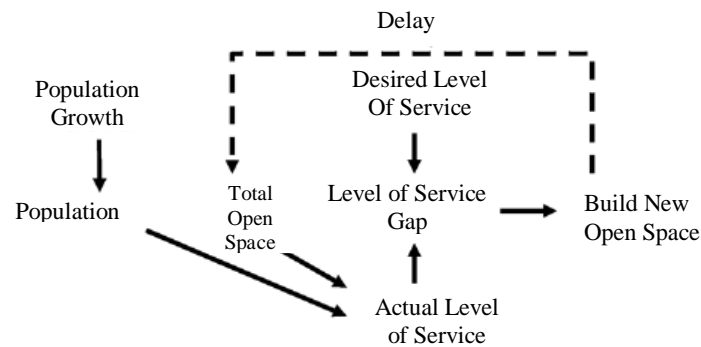


Figure 2.12. Negative feedback loop (Bendor, 2012)

The demand model in this work is based on a System Dynamics approach. System Dynamics models are mathematically described by a coupled set of nonlinear, ordinary deferential equations, that define an accumulated state of the system. In this paper, the system state variable is the total amount of open space in a jurisdiction, and it increases with time through an open space generation rate. The population is assumed to be constant, and increasing the space generation rate will lead to an increase in the level of services that is provided to the residence. The growth of parking demand through the urban population creates a negative feedback (see figure 2.12) – the residents ask policy makers more parking spaces, inducing some political feedback.

The paper examines different delays in parking planning, land purchasing and in construction, for different parking sizes, and how increasing the investment level can help on the level of services to the drivers. The model tries to simulate the urban parking growth with the urban residential development, suggesting that, while significant growth is expected in the town under study, over the next 20 years, efforts to increase parking investments may not necessarily suggest an equal increase in the level of service, due to delays in parking land purchase, planning and operation. So, the stochastic nature of actual parking construction may repeatedly under-supply parking space, as the planners do not necessarily react pre-emptively to the pressure of residents to enlarge the parking spaces.

*The paper also suggests that the fast growing municipalities should try to, not only predict the expected level of servics scenarios, but also to minimize the delays in parking planning purchase and implementation. This research (based on System Dynamics) is one of the few works on the construction costs of the parking spaces. However, it is more a conceptual work, lacking several important issues such as parking pricing and cruising time.*

*Jansson, J.O. (2010). 'Road pricing and parking policy'. Research in transportation economics, Elsevier, vol. 29, pp. 346-353.*

The main goal of this paper is to discuss parking policies, in order to understand and study the potential for increasing benefits. This benefit enhancement can be achieved by extending the congestion charging from the travelers to the internal city center, from the rush hours to the whole work day. For this reason a tariff at parking meters, with two parts, is used in the center of the CBD: a static part for the trip and a time relative part for the parking. In addition, the Swedish policy of marginal benefit taxation of free parking at the workplace is also studied.

The paper mentions two different reasons for parking: the need of parking the vehicle (on-street or off-street) while the goal of the trip is being materialized; and the need for parking during the night or at home garages, in a more long-term perspective.

The paper mentions that there is an irrational political resistance against road pricing. Moreover, congestion charges are too high in cities such as London and Stockholm, while their net social benefit seem to be comparatively low.

*In conclusion, this paper analyzes statistical data related to European cities, such as London and Stockholm, and concludes that a proper parking policy can positively replace congestion charging. Moreover, such policies would possibly need to divide the parking price into two different components (fixed and a time varying part.*

## 2.3 Flexibility

As it was mentioned earlier, *flexibility* does not have a single definition and it varies according to the area under study. Maybe the only characteristic of flexibility that has been considered in parking studies is the active attitude towards sudden changes. This characteristic has been seen mostly analyzed at a micro scale in parking studies, and specifically in the SFpark system in San Francisco. This system receives real time data and assigns the drivers to the parking spaces, considering the possible changes in the empty spaces. There are also a few other parking flexibility studies in urban networks and system dynamics. Most of the studies on urban network define small networks with few nodes, and try to find the best paths to the nearest parking spot.

*Mackowski, D., Bai, Y., Ouyang, Y. (2015). 'Parking space management via dynamic performance-based pricing'. Transportation research procedia, Elsevier, vol. 7, pp. 170-191.*

In urban areas with a high level of congestion, decreasing the number of unnecessary vehicles that are cruising for a parking space is a challenge. Moreover, if we decide to maximize parking space utilization and, at the same time, improve the cruising situation, the challenge is obviously bigger. Based on the new information technologies available for drivers, this work developed a dynamic non-cooperative bi-level model to set parking prices, in real time, for effective space utilization and parking access. The model is part of an integrated parking pricing and management system that assures the availability of proper spaces at equilibrium market prices. Numerical examples are presented to show that the model has the potential to virtually remove cruising for parking.

The paper considers variable pricing (as used in San Francisco parking system, SFpark), an on- and off-street parking reservation system (like those at Xerox and ParkWhiz), downtown parking economics and game theory. A dynamic, demand based real-time pricing model is developed, to optimally set parking spaces in busy urban areas, thus decreasing congestion and other negative economic and environmental costs. The system is an *online* system and can react to real-time demand variations. By considering user competition and market equilibrium, the system allows a parking agency to set optimal pricing policies, in order to minimize congestion, maximize economic surplus or maximize revenue.

The model was applied to the San Francisco smart parking system (SFpark) for illustration purposes. The area of study is a network with 20 parking areas, including 282 parking spaces on 19 on-street block faces and 205 spaces in a large parking garage. One of the assumptions used by the model was that the origins were aggregated at the access points to the parking neighborhoods. For this reason, users are assumed to have already made their mode choice and are only sensitive to local driving time within the neighborhood. Destinations were aggregated at the city block level.

Four different parking management scenarios were studied. In the first traditional scenario, drivers have no information at all. In the second scenario (static information scenario), drivers check the parking availability and pricing information just when they start their journey. In the third (dynamic information) scenario, drivers receive updated information on the parking space availability while they are driving. And in the fourth scenario (dynamic pricing scenario), drivers can be informed by near real-time availability information, and prices can change at every time interval. In the first three scenarios, a normal day was divided into three periods, morning (9:00 am to 12:00 pm), early afternoon (12:00 pm to 3:00 pm), and early evening (3:00 pm to 6:00 pm).

*In conclusion, this paper introduces and develops an interesting dynamic pricing model to decrease cruising for parking in busy urban areas. However, the model has a few significant limitations, in particular, the omission of competition with other parking agencies. If the location, prices and capacities of the other parking lots are fixed and given, it is obvious how to incorporate that information in the model, but considering are multiple agencies making pricing decisions at the same time would be a major challenge. Another natural extension of the model would be to consider multiple vehicle types, such as motorcycles, compact or electric vehicles, etc. or user types such as shoppers and tourists. Moreover, before this model can be used by parking agencies all the parameters of the model must be calibrated with empirical data.*

*Qian, Z. and Rajagopal, R. (2014). 'Optimal dynamic parking pricing for morning commute considering expected cruising time'. Transportation research part C: emerging technologies, vol. 48, pp. 468-490.*

This paper explores how dynamic parking pricing and information provision can be used in managing recurrent parking demand in the morning commute. It is assumed that travelers are aware of time-varying pricing data and time-varying expected occupancy, to make their parking choices. They gain this information by day to day experience or online information provision. The paper starts by using a Variation Inequality (VI) approach, formulating the parking choices under the user equilibrium conditions. In addition, the system optimal parking flow problem and system optimal parking prices problem are solved by linear programing. Their flow pattern unit is not unique and it offers flexibility for operators to achieve different management goals.

The idea is to handle the recurrent parking choices by time–varying prices, with these prices being estimated based on the daily average demand. The historical information of time-varying average parking occupancy and parking prices were provided to the drivers, who have three main concerns to choose the space: prices, parking cruising time, and parking space convenience. The parking setting considered here is similar to SFPark in San Francisco, but considering only the morning commute.

The model uses a "day to day average parking occupancy" computed for parking garages based on the experience of users. This means that, if a user had a bad experienced on going at a certain time to the parking because of the amount of cars there, he/she would change the time of his/her next trip. So, the assumption here is that the daily average gives the time-varying commuting demand for parking, and it does not change from day to day.

Another assumption of the model is that the morning commute parking is recurrent and commuters choose the same location every day, and that none of the vehicles that parked during the morning commute will leave its space in the morning. Travelers have an understanding from the day to day cruising time to make their recurrent parking choices, but for any specific day the realized cruising time is a random variable. Moreover, the expected cruising time of a parking area is assumed to be dependent on the data type that is prepared for the travelers, and on the cumulative arrivals to that area. But the expected parking searching time function with respect to the occupancy is assumed to be strictly monotone and convex.

Based on the network setting and mentioned assumptions, the paper proposes an user equilibrium model for the travelers' recurrent parking location choices. In any circumstances and in any time, are the drivers aware of the time-varying occupancy of each area, of the time-varying parking prices, and of the time-varying expected cruising time. The flow patterns are such that, if all the travelers departure at the same time they will have the same generalized travel cost, and the drivers cannot unilaterally change their parking location choice to decrease this cost.

The time-varying occupancy information helps drivers to recognize and choose, in real time, the area that results in a lowest expected travel cost, and at the same time it makes them sure that they will have a stabilized flow pattern after day to day. Moreover, the drivers' parking choices are assumed to be completely rational (like they always choose an area with the lowest generalized travel cost), and a user equilibrium recurrent parking pattern is searched for. Therefore, different parking fees lead to different flow patterns, and the network performance can be assessed by the total travel cost (just parking cruising time and road travel time).

It is worth mentioning that all the collected parking fees are considered as part of the social welfare and are not included in the total system cost. The main concern here is on the system pricing that can lead to minimal total costs in the future.

The studied parking network is shown in figure 13. The drivers depart from the same origin, park in the same area, and select the same roadway route. In this network problem routes are managed so that the total network costs are minimized. As the case study they applied their model to the real parking network of the campus of the Stanford University.
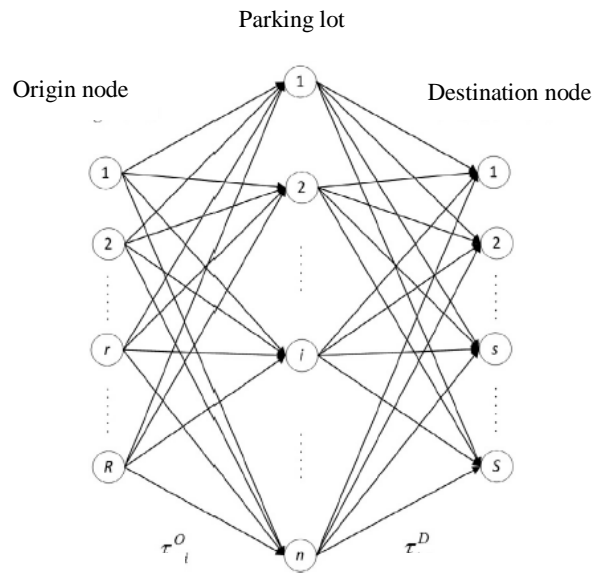
Figure 2.13. The parking network (Qian and Rajagopal, 2014)

*The paper investigated the parking pricing problem based on a network model, assuming that the drivers have knowledge about the parking prices in all areas and about the occupancy level of the parks in a specific area, and that they try to minimize costs. In addition to the lack of a standard demand model to evaluate changes in demand, the construction cost of the parking and the parking costs were ignored in the model. However, this work is very interesting in terms of providing a network view to the parking problem at a micro scale, and introducing useful ideas on user equilibrium.*

**Pierce, G., Willson, H., Shoup, D. (2015). 'Optimizing the use of public garages: Pricing parking by demand'. Transport policy, vol. 44, pp. 89-95.**

This paper tries to describe the way U.S. cities are managing and controlling their *off-street* parking structures, discussing also how this style of management can violate the logic of economics and public benefits. To understand how cities should manage their *off-street* parking facilities for maximizing the public benefits, a conceptual case has been constructed, and tests were made using the data from 14 parking garages in San Francisco SFpark program. SFpark decreased the average price for the drivers, with an increase in the usage of off-street parking, keeping the revenue for the city.

There are normally three approaches for park pricing in cities: price at the marginal cost; price at the market rate; and price to reach a specific revenue. Free *on-street* parking is the best example of the first approach, with planners considering, for so many years, *on-street* parking as a free service. Pricing based on the responses of demand is an example of the second strategy – if on-street parking charges

become higher than collection and maintenance costs, there will be a considerable revenue for the city. Projects such as SFpark, aiming at maximizing the occupancy and not the total revenue, fall into the third approach.

For *off-street* parking spaces, cities normally set some revenue targets, given that *off-street* parking garages imply high costs of construction and operation. A recent study (Shoup, 2011) about the construction costs of *off-street* parks in 12 American cities has shown that the average cost of *off-street* parking garages is 24,000$ per aboveground place, and 34,000$ per underground place. Pricing *off-street* parking spaces for covering this cost, without considering the demand, can lead to a significant number of vacant places. If these structural and operational costs are given, the owner should be able to maximize the revenues and profits through the occupancy rate. At this rate, there will be no extra benefit by reducing the parking price to attract more people.

Given the random nature of arrivals and departures, cities should have the following goals, for setting garage occupancy targets: *ready availability* (every garage should have space so that every driver can easily find a vacant place to park); *high occupancy* (parking spaces are well-used and many customers are being served); *revenue* (so that at least all construction and operational costs are covered.

*In conclusion, currently the SFpark program seems to be working well in terms of occupancy rate (60 to 80 percent). This example shows that the occupancy rate is an important research topic, but there is still a need for a system that additionally includes the structural and operational costs.*

## 2.4 Environmental issues

In evaluating major infra-structure projects, policy concerns are obviously different from the concerns of the private sector. For instance, for a private entity, building a road or a park will only be interesting if the expected tolls are higher than the construction and maintenance costs. Financial matters are are key in the analysis of these type of projects. What are the costs and revenues? Am I financially secured in this project?

In this context, a broader economic analysis clearly needs to include the short and long term impacts of a project on the local economy. Since any big scale project will always require some sort of public acceptance, the nature and magnitude of these economic impacts need also to consider the willingness of public authorities and governmental bodies to support or grant approvals for the project.

On the other hand, the public sector, which is responsible for different kinds of infrastructure systems, has a perspective in identifying needs and evaluating potential projects that is totally different from the perspective of the private sector. Here, the motivation is not to earn more money, but it is to fulfill public needs to help the economy grow. This does not mean that in the public sector the financial

benefits are not important, but rather that they are not necessarily central. Social and environmental impacts are the dominant non-monetary objectives in the public evaluation process, and equity will be critical in the distribution of costs and benefits.

There are complex relationships between what can be considered as the natural world and the man-made world, and any project can significantly change those relations. For instance, construction activities require materials such as wood, concrete and steel, possibly changing in the environment in a significant way. The following aspects are some of the key environmental concerns in this context:

- ecosystems;
- pollution;
- wetlands, aquifers, and drainage;
- wildlife habitat;
- renewable versus nonrenewable resources;
- climate change.

Ecosystems can be destroyed in quite different ways, as it is the case of pollution. Pollution is normally associated to the introduction of foreign elements into the water, air or soil, that can lead to the death of some species of plants and animals. Toxic chemicals are another type of pollution that are poisonous for some sort of species and can make the water quality, in the sea or in rivers, unsustainable for some types of fish. There are several key concerns in the environmental impacts of projects, such as: the usage of certain materials in operation or construction activities; pollution and impacts on the air, water and soil quality; loss of habitat and damaging the ecosystems, or impacts on plants and wild life; or effects such as noise, shade and aesthetics.

Special environmental impacts of projects are related to air and noise pollution. The health risks of traffic related noise and air pollution have been broadly recognized by several epidemiological studies. Increasing risks of heart attacks, the exacerbation of asthma among children, and the drop in life expectancy are some examples of these risks. These health risks generate huge external costs for society and they are not reflected in the market price of transportation or counted in the distribution of economic resources (Martland 2011, Bamberger and Hewitt 1986, Akitoby et al. 2007, Transport Canada's Urban Emission Calculator 2006).

## 2.5 Integrated demand optimization

The parking problem is so complex that it can never be solved by a single approach. Research attempts based on simple single approaches rapidly led to rather complex models that in turn forced people to consider, for the sake of simplicity, assumptions about fundamental aspects of the parking problem. To

avoid ignoring some of these basic aspects, it is necessary that a comprehensive approach to the problem includes both the demand side and the supply side.

In fact, during so many years, there is just a couple of research works including both the demand side and the supply side. However, these studies consider the demand is an inelastic entity, and they assume the number of *off-street* parking places is fixed. In these studies, demand does not change in any way. Moreover, in the supply side, optimization models are sometimes considered, mostly trying to minimize the travel costs for the travelers (based on their cruising time).

*Inci, E. and Lindsey, R. (2015). 'Garage and curbside parking competition with search congestion'. Regional science and urban economics, Elsevier, vol. 54, pp. 49-59.*

This paper studies a parking market with publically operated curbside parking, privately operated parking garages, and drivers who have different parking durations. Downtown parking markets are considered, where nonlinear parking pricing, spatial competition between curbside parking and garages, and generated congestion by curbside parking search, are simultaneously playing a role. To reduce the difficulties of the analysis, the total demand is assumed to be fixed, traffic congestion is ignored, and just two types of individuals (with different parking times) are considered. There is a situation in which congestion related to the parking search creates a link between parking submarkets and non-convexities in garages' profit, and the paper discusses how to find an equilibrium for the market in this scenario.

The paper addresses questions such as: How is the competition between parking garages when a substitute such as curbside parking exists? How can garage parking fee schedules be defined? How should curbside parking be priced in order to compete with the parking garage market and to control cruising congestion? In terms of time, should hourly fees change by parking duration or should a uniform hourly price be better? Is it necessary to regulate garage parking to reach a social optimum, or can curbside parking prices do the job?

Given the similarities between the mentioned issues and parts of our research in this thesis, we will analyze this paper in more detail . However, the perspective of the paper is different from ours, as the paper mostly concentrates on the micro scale of the problem rather than considering it as a wider problem.

First of all, the paper assumes that there is a fixed set of drivers with different destinations and durations of stay. The different parking lengths are characterized, and the specific benefits for each length identified. In the model, a given destination is assumed for each driver, distributed uniformly in a circle with different densities for short-term and long-term drivers. Curbside parking (operated by public entities) is distributed continuously around the circle. The location of parking garages is fixed, and each

garage is being operated by a private company. Curbside parking prices can change, to allow price discrimination and to use curbside parking prices to improve efficiencies. Some constraints are defined to characterize short time and long time parking, and how drivers try to secure their space.

Later, the paper goes through market equilibrium issues. In this equilibrium, each garage competes for each type of driver, either with its closest neighbor garage, or with curbside parking, and several types of market configurations are considered. Since total parking demand does not change, the social optimum is linked to a total cost minimum. Total costs are estimated by the total number of drivers who park in both garages and curbs. The paper then tests the model with a numerical example specifically created for that purpose.

The analysis presented in this work can be extended in different directions. One of its limitations comes from considering just two types of drivers, with specific parking times. This should be extended to multiple times or even to a continuum time description. This would lead to more realistic results (through a more detailed analysis of price discrimination according to parking durations). Another possible extension of the model would be in the parking costs. Right now parking duration is not considered to be related to the price, but the parking price is a function of the parking duration. Moreover, the model does not consider any garage capacity constraint, apparently due to the difficulties in modeling the objective function.

Another weakness of this work is related to the alternative market structures, with one possibility being the monopoly control of garage parking. The paper considers the perfect competition situation implausible, because of barriers such as scale of the economy or substantial construction costs. But shortage of space and zoning regulations are two other known barriers in this context.

In conclusion, this paper has developed and tested a simple spatial parking model, where the drivers (of two types) ride downtown with destinations that are distributed uniformly around a circle. Parking garages are privately owned, and they compete with each other and with publically operated curbside parking. Another assumption in this model is that parking garages have no congestion, and that finding a curbside parking is rare, requiring drivers an additional extra search effort.

There are some considerable differences between the standard utility and demand models presented in the paper, and those we are going to use in our work. Unlike the other spatial competition models, the paper derives the utility from the curbside parking considering it endogenous, with a separate computation formula for short time parking and longtime parking (and a fixed demand for each of these parking types). This means the utility drops with the number of drivers that use a given space. In this way, connections were assumed between parking garages, and when a parking garage increases the parking price, congestion for the other parking garages are affected.

*Unfortunately, having problems with the definition of parking garage construction costs, the paper has changed the standard format of demand and utility models in such a way, that practically the model became a cluttered mathematical combination of the utility concept, a fixed demand, and long-term or short-term parking estimations.*

**Arnott, R., Inci, E., Rowse, J. (2014). 'Downtown curbside parking capacity'. Journal of urban economics, Elsevier, vol. 86, pp. 83-97.**

This paper tries to understand how much curbside parking is assigned to drivers, when parking garages are owned by the private sector. Two main scenarios have been defined. In the first scenario, no cruising for parking occurs, and when the demand is lower than the street capacity just curbside parking is provided. For intermediate values of the demand, both curbside parking and garage parking are provided, but for the case of high demand, just garage parking is provided. In the second scenario, curbside parking is underpriced, and cruising for parking happens only when both curbside and garage parking are available.

At first, the paper considers that there is no parking price, and that the use of parking is free. In this case, the user travel cost on a trip (UC) is given by the trip length, $m$, multiplied by the travel time per mile, $t$, and by the value of time, $\rho$: UC = $\rho$mt.

The travel time per mile is an increasing function of the density of traffic per unit area, V. The full price of a trip (F) is equal to the user cost plus toll, $\tau$: F = UC + $\tau$  .

The demand for trips per unit area time is stable and given by D, as a function of the full price of a trip: D = D(f).

The steady state number of trips per unit is given by r (the traffic density divided by the length of time each car spends in traffic, $mt$: $r = \frac{V}{mt(V)}$ .

In the paper, four optimization models are proposed for a scenario with only curbside parking, and three scenarios of both curbside and garage parking. The objective functions of these models try to maximize the social surplus, by considering the negative effects of cruising time. The single decision variable of these functions is the social benefit of throughput $r$ per unit area time, and the cost component of the objective function is the value of time multiplied by the density of cars in transit.

There is in the paper a strong contradiction between the considered assumptions and definition of the objective function. The question arises when the paper assumes that the optimum benefit happens when the price of the curbside parking and garage parking are equal, and consequently the effects of parking prices in maximizing the social benefits (objective function) of drivers are ignored. One of the

assumptions of the paper is, in fact that, because of cheaper curbside parking, drivers first fill all the curbside parking spots and then they go for garage parking. But in the equilibrium referred in the paper (equal curbside and garage parking prices) drivers first choose the parking garage because it does not include cruising time. Moreover, considering and formulating the cruising time as a negative social effect in the objective function (due to a lower curbside parking price) seems problematic – we might, for example, say the ideal maximum social benefit for a group of drivers happens when garage parking price is free, and so drivers do not need to cruise for parking space, and at the same time do not pay for it.

According to the paper, this may possibly happen because the parking garages are owned by private entities, with operation costs associated. But, still in this case there are possible business models for garage owners to keep the parking prices lower than those of curbside parking. So, in any case, ignoring the parking price for maximizing the social benefits of a group of drivers is a relevant issue.

In conclusion, parking should be viewed as an essential part of the city transportation problem, and having a good parking policy can help to decrease the downtown congestion. This paper assumes that the private sector has the control of parking garages and that their prices are always higher than the curbside parking. Basically the paper tries to understand if curbside pricing should be considered as exogenous, and how much curbside should be allocated to the parking. In this line, the paper provides a set of formulations based on ideas such as the traffic jam density explaining part of the curbside parking, or the connections between the traffic flow and the social benefits of a group of drivers. But, by equalizing the curbside and garage parking fees, all the effects of the parking prices are practically eliminated, and focus is given to the effects of cruising time and traffic jam congestion.

*The methodology used in this paper is, among those found in the literature, the closest to the methodology adopted in the current thesis. However, in terms of techniques used, demand functions, and optimization procedures, several substantial differences exist in our work. Ignoring the parking prices and the construction costs of parking garages, are two main weaknesses of the paper under analysis.*

## 2.6 A summary of the literature review

In this chapter we have reviewed 39 books and articles on the parking problem subject, trying to cover most of the important studies. These works have quite different natures and are based on quite diverse approaches. We believe therefore that this comprehensive review allowed us to identify the main gaps in this area of study.

One interesting observation is that there is no uniformity between these studies. There are quite different approaches to similar problems, and none of them can completely present a comprehensive solution for a more general parking problem. So, one of the main research gaps is the need for a detailed framework to unify the studies in this area. None of the presented approaches in the reviewed articles is comprehensive enough to simultaneously cover all the important aspects of the problem.

In addition, most of the presented approaches assume that demand or/and supply are given and deterministic, with fixed locations. This means that primarily we need a basic approach with a flexible, general model, and this approach should have the ability to include all the different aspects of parking problem. The following table summarizes the reviewed approaches, with their pros and cons.

In this thesis we are going to tackle most of these identified gaps, by introducing a comprehensive framework to tackle the problem. This framework includes the demand side and the supply side at the same time, and tries to consider all the key aspects of the parking problem. Table 2.4 summarizes the articles and papers reviewed in this chapter, and highlights their strong points and weaknesses. As we mentioned before, there is no unified approach to the parking problem and having a comprehensive framework to cover its most important aspects can, therefore, be extremely useful.

Table 2.4. (a) Summary of the papers presented in chapter 2

| Articles | Category | Weaknesses | Strong points |
|---|---|---|---|
| Paying for parking *(Roth, 1965)* | Optimization | - mathematical modeling<br>- lack of details | - basic principals<br>- problem description<br>- framework |
| A temporal and spatial equilibrium analysis of commuter parking *(Arnott. et al. 1990)* | Optimization | - CBD is a Point not area<br>- just for morning rush hour<br>- fixed demand | - comparing road tolls and parking fees<br>- effects of parking in congestion |
| Parking fees and congestion *(Glazer and Niskanen. 1992)* | Optimization | - lack of supply side studies<br>- no construction cost studies<br>- no specific demand modeling | - short time and longtime parking<br>- road pricing and parking pricing<br>- relation between parking and congestion<br>- seeing both parkers and through drivers |
| Cruising for parking *(Shoup. 2006)* | Optimization | - lack of study in demand side or supply side<br>- just in drivers point of view<br>- no framework<br>- missing the management point of view | - comprehensive study in cruising for parking<br>- simple and practical formulation in cruising<br>- applicable mathematical modeling |
| Class of comprehensive optimization of congested road-use pricing and parking pricing *(Feng et al. 2009)* | Optimization | - fixed demand<br>- fixed supply<br>- no framework | - view parking problem as a network<br>- concentrate on park and ride<br>- minimizing the cruising time |
| Congestion pricing: A parking queue model *(Larson and Sasanuma, 2007)* | Optimization | - a mathematical formulation for the model a framework<br>- considering off-street parking<br>- flexibility in theories | - comparing road pricing and parking pricing policies<br>- comprehensive definition of demand and supply sides in parking problems |
| The evidence base for parking policies *(Marsden, 2006)* | Optimization | - a mathematical formulation for the model a framework<br>- considering off-street parking<br>- flexibility in theories | - designing parking policies that contain efficient use of the transport network, lower emissions, higher densities, and better and more inclusive design |

Table 2.4. (b) Summary of the papers presented in chapter 2

| Articles | Category | Weaknesses | Strong points |
|---|---|---|---|
| The economics of pricing parking<br>*(Anderson and de Palma, 2002)* | optimization | - a clear strategy about externalities of cruising<br>- a framework<br>- considering off-street parking<br>- flexibility in formulation | - how parking is located far from the CBD<br>- divided parking costs in details |
| Parking prices in the central business district<br>*(Brown and Lambe 1971)* | Optimization | - concentrate on walking distances instead of parking price<br>- the demand is fixed<br>- the supply is fixed | - study in parking price and the distribution of parking space<br>- establishing parking price based on the effective walking time of travelers |
| An integrated model of downtown parking and traffic congestion<br>*(Arnott and Inci, 2005)* | Optimization | - a realistic interval for cruising<br>- a framework<br>- considering off-street parking<br>- flexibility in formulation | - simple model for interaction between traffic flow and cars that are cruising for parking |
| Optimization models for the urban parking pricing problem<br>*(Gallo et al. 2005)* | Optimization | - a good model for externalities<br>- a real case study<br>- a framework<br>- considering off-street parking<br>- flexibility in formulation | - adoption of spatial parking policies with origin-destination pairs<br>- includes externalities<br>- minimizing net cost revenue |
| The planning model for locating urban parking facilities and the design of genetic algorithm<br>*(Jun and Wei, 2003)* | Optimization | - parking pricing strategy<br>- considering distributed demand<br>- a framework<br>- flexibility in formulation | - subdividing the planning zone in smaller areas<br>- designed under different conditions of land use |
| A new heuristic for solving the parking assignment problem<br>*(Abidi. et al. 2015)* | Optimization | - lack of proper strategy for cruising time<br>- no sign of demand | - parking assignment based<br>- genetic algorithm |
| Spatial competition between parking garages and downtown parking policy<br>*(Arnott, 2006)* | Optimization | - lack of value of time, travel distance, parking duration<br>- lack of construction costs and interaction with public transportation | - spatial competition between parking garages<br>- economic view of the parking problem |

Table 2.4. (c) Summary of the papers presented in chapter 2

| Articles | Category | Weaknesses | Strong points |
|---|---|---|---|
| A multilayer model to simulate cruising for parking in urban areas *(Gallo et al. 2011)* | Optimization | - applicable for very small areas<br>- fixed demand and supply<br>- no sign of construction costs<br>- no sign of externalities | - network view to the parking problem<br>- parking assignment method<br>- effects of cruising time and walking time on parking problem |
| Prediction of parking space availability in real time *(Caicedo et al. 2012)* | Optimization | - fixed demand<br>- time consuming process<br>- no strategic view to the problem | - real time study<br>- intelligent parking reservation systems<br>- costumers satisfaction view |
| Death by a thousand curb-cuts: evidence on the effects of minimum parking requirements on the choice to drive *(Weinberger, 2012)* | Optimization | - a focused view on a specific type of parking<br>- fixed supply side<br>- lack of comprehensive approach to the parking problem | - effects of guaranteed parking in parking studies<br>- cruising for parking in a big city |
| Problems with parking requirements with zoning ordinances *(Shoup and Pickrell. 1978)* | Demand | - a brief look at externalities of parking<br>- no specific solution for parking problem | - effects of parking price in work trips<br>- impacts of zoning in long term parking |
| Toward strategic planning for car parking *(March, 2007)* | Demand | - a mathematical formulation for the model<br>- no framework<br>- considering off-street parking<br>- flexibility | - describing behavior of cars that is influenced by type, price, and the regulation of parking |
| Time varying parking prices *(Ommeren and Russo, 2014)* | Demand | - fixed supply side<br>- lack of some important aspects in parking problem such as cruising for parking<br>- lack of study in externalities | - studies the interaction of demand and parking price<br>- suggestion of varying parking price for different times of day |
| Estimation and specification of the effects of parking costs on urban transport mode choice *(Gillen, 1975)* | Demand | - lack of framework for parking studies<br>- lack of some important aspects in parking problem such as cruising for parking<br>- lack of study in externalities | - studies parking taxes<br>- importance of parking services<br>- studies the effects of parking price in demand |

Table 2.4. (d) Summary of the papers presented in chapter 2

| Table 2.4. (d) Summary of the papers presented in chapter 2**Articles** | Category | Weaknesses | Strong points |
|---|---|---|---|
| A parking search model *Thompson. R. G. and (Richardson, 1996)* | Demand | - no demand and supply side<br>- no construction cost<br>- concentrate just in cruising externality | - parking search behavior<br>- a framework for cruising<br>- a decision process<br>- uncertainty nature of car park system |
| A model to describe the choice of parking places *(Van Der Goot, 1981)* | Demand | - fixed parking spaces and no solution for excessive demand<br>- no environmental externalities | - importance of parking in choosing travel destination<br>- chance of selecting a parking place<br>- effects of walking time |
| A nested logit model of parking location choice *(Hunt and Teply, 1993)* | Demand | - the model is good for small scales not a big city<br>- lack of variation in the supply side<br>- no assignment system | - a nested logit model<br>- behavior of drivers in parking choice |
| Modeling parking *(Arnott and Rowse. 1998)* | Demand | - inflexible supply side<br>- no construction cost<br>- no parking assignment system<br>- complexity | - model for parking congestion<br>- proposing different scenarios<br>- focus on the stochasticity of vacant parking spaces |
| Evaluating the effects of cashing out employer-paid parking: eight case studies *(Shoup. 1997)* | Demand | - random sample of the drivers that do not represent all of them | - comparing several case studies<br>- effects of offering parking facilities by employer to employees<br>- environmental concern |
| The ideal source of local public revenue *(Shoup, 2004)* | Demand | - lack of solution for parking problem<br>- lack of solution for construction costs | - comprehensive parking study<br>- including important aspects such as cruising time<br>- analytical study |
| Changing parking by the minute: what to expect from this parking pricing policy? *(Caicedo, 2011)* | Demand | - Concentrate on a small aspect of the parking problem<br>- No sign of parking price itself, just the time intervals for charging them | - Study on parking charges' time intervals<br>- Effects of charging by minutes or hours on demand side |

Table 2.4. (e) Summary of the papers presented in chapter 2

| Articles | Category | Weaknesses | Strong points |
|---|---|---|---|
| The real price of parking policy *(Ommermen et al. 2011)* | Demand | - lack of any consideration in off-street parking<br>- no framework for parking studies | - willingness to pay for on-street parking<br>- cruising time<br>- pre-paid parking |
| Downtown parking in auto city *(Arnott and Rowse, 2008)* | Demand | - fixed off-street parking facility and price<br>- keeping on-street parking price always lower than off-street parking price<br>- no cruising time, no externalities | - proposing on-street parking policy<br>- demand allocation |
| Parking management, financial subsidies to alternatives to drive alone and commute mode choices in Seattle *(Su and Zu, 2011)* | Demand | - not an applicable model for other cities<br>- proposed policies for employers that may not accept it | - a nested *logit* model to test the effects of parking management<br>- financial subsidies for parking<br>- variables of interest and variables of controls |
| Off-street parking surprises in Asian cities *(Barter, 2011)* | Demand | - not proposing any specific model<br>- no mathematical formulation | - study in non-residence off-street parking policy<br>- 14 case studies in Asia<br>- parking policy categorization |
| Modeling park development through regional land use change simulation *(Bendor, et al. 2012)* | Demand | - just concentrating on the harmful effects of the delay in building an off-street parking<br>- not considering parking price in models | - regional urban growth model<br>- system dynamics<br>- relating parking demand to the population growth |
| Road pricing and parking policy *(Jansson, 2010)* | Demand | - just for European cities<br>- no framework for parking problem<br>- no specific demand or supply model<br>- | - study the parking market<br>- discussion about the current parking policies' potential<br>- comparison with congestion charging |
| Parking space management via dynamic performance-based pricing *(Mackowski et al. 2015)* | Flexibilities | - lack of pricing by multiple agencies in the real time<br>- no futuristic solution for parking problem such as new parking structures<br>- the model is mostly informative, not supporting decision making | - real-time parking pricing<br>- efforts to virtually remove cruising for parking<br>- different scenarios of drivers information |

Table 2.4. (f) Summary of the papers presented in chapter 2

| Articles | Category | Weaknesses | Strong points |
|---|---|---|---|
| Optimal dynamic parking pricing for morning commute considering expected cruising time *(Qian and Rajagopal, 2014)* | Flexibility | - applicable for small case studies<br>- drivers should have the knowledge of parking price in all areas<br>- fixed demand<br>- fixed supply | - dynamic parking pricing<br>- optimal parking flow<br>- optimal parking price<br>- network of parking |
| Optimizing the use of public garages: pricing parking by demand *(Pierce et al. 2015)* | Flexibility | - it is a real time study and does not propose a specific framework<br>- cannot include futuristic view in changing the off-street parking<br>- fixed number of parking | - analyzing US off-street parking management<br>- proposing a scenario for maximizing the benefits of off-street parking in US<br>- important information about occupancy rates of off-street parking |
| Garage and curbside parking competition with search congestion *(Incie and Lindsey, 2015)* | Integrated Demand-Optimization | - demand for every type of parking is fixed<br>- consider two types of parking time<br>- the supply side is fixed<br>- there is no standard utility model for demand | - tries to involve both demand side and supply side<br>- finding equilibrium based on the cruising time |
| Downtown curbside parking capacity *(Arnott et al. 2014)* | Integrated Demand-Optimization | - no parking pricing<br>- assumption of on-street parking price must be lower than off-street ones<br>- no idea about construction costs<br>- number of off-street parking in supply side is fixed and does not change | - tries to allocate on-street parking<br>- cruising time |

# 3   Methodology

## 3.1   Introduction

In this chapter we comprehensively describe the methodological approach we propose to deal with the problems previously described. A set of general concepts, principles and techniques, such as a demand-supply based approach and mathematical programming models, are described.   Then, different techniques are put together and a base model is proposed to tackle the parking problem. The main model is an optimization model, with an objective function designed to maximize the revenue. A demand-supply based approach is used as an input for this optimization model. This approach will allow the control of the demand, through the control of the supply.

A comprehensive methodology should cover the demand side of the problem as well as the supply side. In congestion studies, a trip happens when there is an attractive activity or goal for a commuter in the specific area of a city. Such reasons are often concentrated on the central business district (CBD) of a city, therefore generating a considerable number of trips. These trips are normally done by private vehicles or public transportation. Selecting between these modes depends on several factors, such as travel time and travel cost. This means that, normally, a rational traveler chooses the cheaper and faster way to the destination (Jun and Wei, 2003; Larson and Sasanuma, 2007).

If we consider travel costs and travel times of a traveler who drives alone, one substantial part of these times and costs is related to parking. The response of drivers to the parking price is different, and is partially related to the urgency of work and the length of activity. In general, we assume that drivers need to park their car in their destination zones. If they find an empty place, they will park there, and if they cannot, they will park their vehicle in other neighbor zones or they will not travel by car, using another transportation mode (Gillen, 1975; Shoup, 2006).

Another important factor to include in our model is the type of parking. There are two main types of parking, that are fundamentally different: *on-street* (curbside) parking and *off-street* (garages) parking. *On-street* parking is normally known as a cheap way to park, and it is proper for short time parking, such as shopping. The nature of this type of parking attracts drivers and creates congestion. This congestion becomes a more critical issue when all the parking spaces are full, and drivers start to search, at a low speed, an area with empty space. On the other hand, *off-street* parking is normally more expensive, and therefore a more inconvenient choice for the drivers. Parking garages are the last choice for many derivers, as they usually have available places but they are expensive. Unlike on-street parking, parking garages do not create excessive congestion and are more adequate to long time parking (Van Der Goot, 1981; Shoup, 2004).
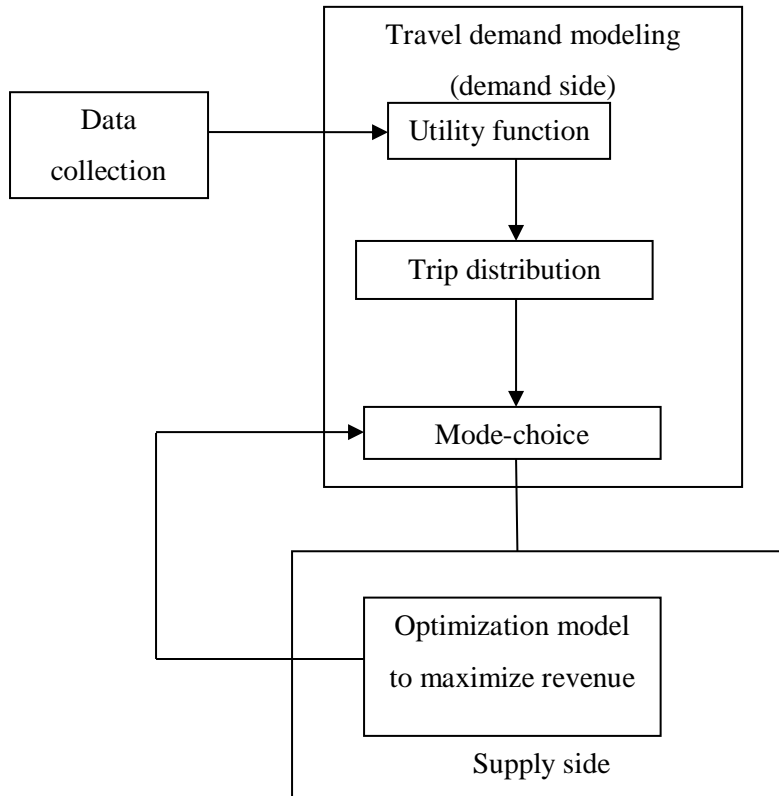
Figure 3.1 presents our integrated approach, showing the interaction of the demand-supply based approach with the optimization model. The system starts with data collection and then the classical 4-step travel demand modeling procedure is used as demand forecasting method. These forecasts and the mode-choice stage of the travel demand model are used as an input for the optimization model.

The optimization model has the supply side variables, and revenues are maximized by applying this model. These variables are parking prices, parking locations and the number of parking places.

A case study will be be used to validate this model. As referred, in this framework, the outputs from the mode choice model are inputs to the optimization model. This means that mode choice is affected by the price of the parking places and this price is optimized by the optimization model used to maximize revenue.

Figure 3.2 shows a simplified version of the approach. There are several complexities in the parking problem, and our goal is to design an approach comprehensive enough to cover many of its aspects. One of these aspects is related to the cruising time. As mentioned before (Shoup, 2006; Ommermen et al. 2011) cruising time t is one of the main reasons for congestion and it can be analyzed in the demand side. Cruising for parking happens when drivers notice underpricing in *on-street* parking when

compared with an expensive off-street parking alternative, and then decide to search for an empty place. This search continues until they find a vacant place or until they change their mind and decide to go to the nearest off-street parking. So basically the cruising time is not a linear entity itself, and this has therefore been a natural research topic. This issue is handled in a specific step of our approach.

Another related item is parking duration that changes based on the goal of the trip. For instance, shopping trips normally need a short time parking, while work trips may need a parking spot for the whole day. From a congestion point of view, the *on-street* parking is more convenient for the trips with the short time goals, and parking garages are more proper for long term parking. On the other hand, travelers, who decided to park for a long time, search for vacant, cheaper *on-street* parking in underpriced conditions (Brown and Lambe, 1971; Anderson and de Palma, 2002; Inci and Lindsey, 2015). As referred, our approach to the parking problem includes a specific step for parking duration.
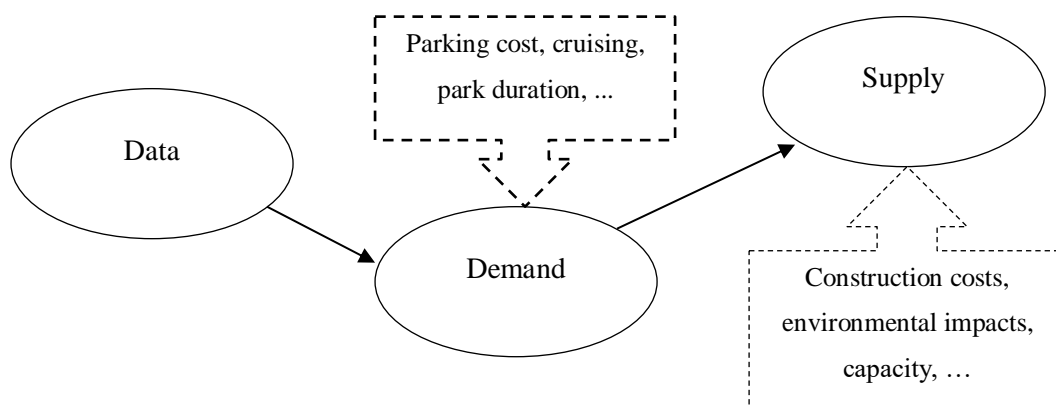


Figure 3.2. Simplified version of our approach

Our approach is innovative in different aspects. First, the demand in this study is not static. Different items such as travel costs and parking prices affect the demand for traveling by private vehicle, and our approach will explicitly consider dynamic demand through these aspects. Second, another major difference in this thesis is related to the construction costs of *off-street* parking. These costs have always been ignored by researchers, being considered as huge, and without any economic planning. Therefore, most of the studies do not include any changes in the capacity, or any possibility of building a new *off-street* parking. As shown in figure 3.2, the construction costs of *off-street* parking are explicitly included in the supply side of our approach.

## 3.2 A demand-supply approach

In our system, the demand-supply component is based on the assumption that there should always be a balance between demand and supply. There are four main principles connecting demand to supply:

a) if demand increases and supply stays untouched, then a higher equilibrium price is achieved;

b) if demand decreases and supply stays untouched, then a lower equilibrium price is achieved;

c) if demand stays untouched and supply increases, then a lower equilibrium price is achieved;

d) if demand stays untouched and supply decreases, then a higher equilibrium price is achieved.



Figure 3.3. Demand and supply interactions

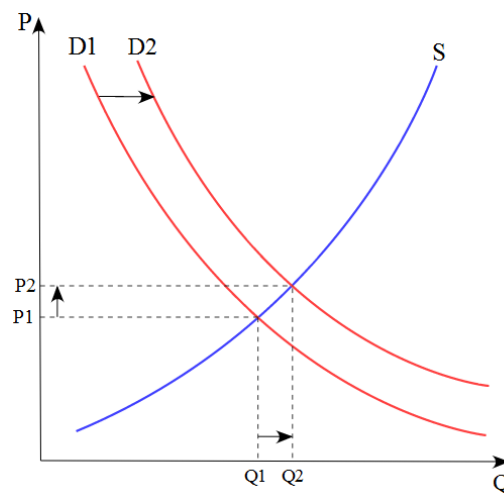Figure 3.3 shows the interactions between the demand and the supply, in several situations. The price P of a product (in our case the parking price) is determined by a balance between a supply at a given price (supply S) and the desires of those with purchasing power at a given price (demand D). The diagram describes a positive move in the demand from D1 to D2, resulting in an increase in the price (P) and in the quantity sold (Q) of the product (Ben Akiva and Lerman, 1985; Martin and McGuckin, 1998; McNally, 2000; McNally, 2007).

As mentioned by *Larson (Larson and Sasanuma, 2007)*, parking problems involve both demand and supply. First, we need to scale the problem, and divide the geographic area of study into small zones. In every zone, parking demand is related to the amount of shoppers, workers and residences. Besides, there is always additional demand for zones that are adjacent to zones where there is no remaining empty space for parking. The geographic distribution of origin trips, and the situation of public transport in every zone are other important aspects to be considered in the demand side. On the other hand, the supply side refers to the amount of *on-street* parking, *off-street* parking, and the capacity of the different types of public transportation to satisfy demand.

### 3.2.1 The demand side problem

Current demand estimation methods for parking are mostly developed for new, suburban sites with unpriced parking. This often leads to extreme results in urban areas, with better public transportation systems (Brown and Lambe, 1971; D'Aciento et al. 2005). Similarly, these inflexible demands do not change, simply by improving existing parking systems or public transportation services. Therefore,

instead of pre-defined demand for parking, we need to estimate demand based on different scenarios of parking pricing and different offers of public transportation.

The demand itself includes different complexities. One of these complexities is that it is not a uniform entity, and differs according to the goal of the trip in the destination (Arnott and Rowse 2008). For instance, shoppers or buyers make their trip to a specific zone for one or two hours, and they leave the zone after they finished their activity. On the other hand, workers reach their work early in the morning, and they leave the place late in the afternoon. There are some differences between these two types of travelers, in terms of parking (Inci and Lindsey, 2015).

Another complexity concerning demand is the nonlinearity of the travel mode selection process (Gillen, 1975). Demand for the different types of transportation change based on the travel cost and travel time in general, and changes in any of these items can affect the mode choice. When parking is underpriced and cruising to find an empty parking place happens, the total travel time and travel costs will be affected. This effect is also nonlinear because, by wasting more time in the traffic, the willingness to pay for a parking spot changes, and therefore this problem becomes even more complex (Arnott and Rowse, 1998; BenDor et al. 2012; Inci and Lindsey, 2015).

Also the attitude of different people towards changes in price is different depending on their goal of travel. Shoppers or buyers may need to use their private vehicles more than workers, because of carrying the purchased items. So the flexibility of one group of travelers can differ from the other travelers with different goals (Roth, 1965; Arnott et al. 1990; Anderson and De Palma, 2002).

As described below (see section on techniques), the trip distribution and mode choice stage of the 4-step travel demand model was chosen for this study. 4-step travel demand modeling includes four main stages (trip generation, trip distribution, mode split, and trip assignment), and in this dissertation we are using the trip distribution and mode choice stages of this model. In the *trip generation* stage, the total number of trips generated by a zone is assumed to be only a function of attributes of the zone, such as population and employment. Therefore, at this stage, it is not possible to consider attributes such as travel time, travel costs or parking prices in the destination zone, which would require information on both the origin and the destination of a trip. However, to estimate trip attraction at this stage, it is possible to apply the effects of land-use and specially of parking pricing and of the improvement of public transportation modes. This can be done by using methods such as regression or cross-classification (Ben Akiva and Lerman, 1985; Martin and McGuckin, 1998; McNally, 2000; McNally, 2007).

In the *trip distribution* stage, we estimate the most likely origin-destination trips. This stage matches trip-makers' origin and destination as a way to develop origin-destination (OD) matrices. An OD matrix can be estimated by two different ways. The first way is deducing direct paths through OD surveys, and

asking drivers about their origin, destination, frequency, and motivations. A second, cheaper and faster way to do trip distribution is based on the total number of trips and trip generation indicators for each zone. Typically, the models that estimate trip distributions are known as *gravity* models. Gravity models include trip attraction parameters reflecting the effects of parking pricing and public transportation development, from the beginning (Allen, 1984; Ben Akiva and Lerman, 1985; Martin and McGuckin, 1998).

The third stage of the procedure is *mode split*. There are two main methods for performing mode split: trip-end models; and trip interchange models. Trip-end methods are applied before trip distribution, considering socio-economic variables such as income, and car ownership. Level of service attributes such as travel time, cost, and parking cost cannot be included in trip-end methods, because OD flows are not known yet. On the other hand, trip interchange methods are applied after trip distribution and OD flows are known, and it is, therefore possible to consider level of service attributes (Ortuzar, 2001; McNally, 2007). In this dissertation the trip interchange model will be used.

### 3.2.2 The supply side problem

From the reviewed literature, we can state that there are two main parking problems related to the supply side. The first problem is inadequate *parking capacity* in a zone. This problem can be tackled by building an off-street parking site, or by improving the current public transportation system in that zone – obviously these solutions may be quite costly (Arnott, 2006), requiring the optimization of construction costs, and of the costs of public transportation enhancements.

Parking capacity refers to the total parking space in a specific zone of a city. This space includes *on-street* (curbside) parking and *off-street* (garage) parking. In general, the policies related to *on-street* parking are in the hands of the government and public entities, and they include pricing and capacity management. If we assume the total number of the streets of a city is fixed, we can conclude the maximum capacity of the *on-street* parking for a city is constant. However, the minimum *on-street* parking capacity depends on the policy-maker decisions (Shoup and Pickrell, 1978; March, 2007; BenDor et al. 2012).

On the other hand, *off-street* parking buildings (garages) are always assumed to be owned or managed by private entities. Usually they cannot compete with the low-offered price of the *on-street* parking. In general, the private sector cannot find a reasonable solution to tackle the high price of the buildings of *off-street* parking. In addition, these private entities do not have a proper understanding of the details of congestion studies (promoted by the government) and they cannot adopt the resulting policies (Roth, 1965; Feng et al. 2009; Larson and Sasanuma, 2007; Arnott and Rowse, 2008). It seems therefore that a uniform strategy, desirably with a single operator entity (public or private), should apply for the *on-street* and *off-street* parking.

Another relevant problem is inappropriate *parking pricing*. Parking pricing controls congestion, and balances supply and demand. Parking prices have a direct impact on travel costs, and can play an important part in the decisions of the commuters. In general, these prices are calculated for *on-street* and *off-street* parking, in two separate and unrelated processes by government and private parties. For instance, the government adopts and implements a policy of minimizing cruising time for *on-street* parking in a city. At the same time, parking garage operators, to cover their expenses and maintenance costs, make decisions aiming to maximize their revenue. As a result, we will have a slight increase in the *on-street* parking prices, and a more substantial raise in the *off-street* parking prices. This shows again a lack of a uniform and integrated approach to the problem (Shoup, 2006; Arnott et al. 2014; Arnott and Rowse, 2008; Ommermen et al. 2011; Shoup, 2004). These issues clearly justify the design of new multi-objective optimization models, where one of the objectives is the maximization of net cost revenues.

## 3.3 Main adopted techniques

In this dissertation we are going to use an integrated approach comprising two main techniques: travel demand modeling; and optimization and mathematical programming. These techniques will be used in different phases of the study, separately or in an integrated way (see Figure 3.4).
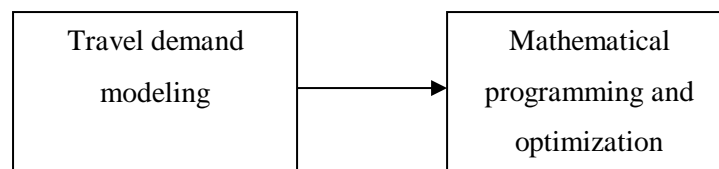


Figure 3.4. Techniques to be used for the parking problem

As mentioned before, the price of parking (both *on-street* and *off-street*) is a problem involving both demand and supply (Shoup, 2006; Arnott et al. 2014; Arnott and Rowse, 2008; Ommermen et al. 2011; Shoup, 2004). So, the main goal of our model should is to find a proper parking price, covering most of the different important aspects of the problem. Based on the mentioned effects of the parking price in travel demand, this price should be a way to control traffic congestion, by moving a part of this congestion to the public transportation. At the same time, this price should be set in a way that it covers the expenses of the parking operators. To include and evaluate the effects of this price on traveler's decisions, we followed the decision rules and method first proposed by Ben Akiva and Lerman, 1985. This method has been used in most of the demand related articles in transportation recently (as for example: Hunt and Teply, 1993; Feng et al. 2009; Su and Zhou 2011; Weinberger 2012) and we will comprehensively explain it later it in this chapter.

As *on-street* parking and *off-street* parking have quite different characterizations, we defined different variables for these two types of prices. The process is rather simple. First, the different parking prices are entered into the demand model, so that there is a balance between the amount of trips by private vehicles and public transportation. The output of this first stage is a distribution of trips by private vehicles (with alone drivers) between zones of the case study. This output changes with the parking prices, and is used as an input for subsequent stages of the method.

This second stage of the model tries to manage the parking capacities. As mentioned before, one of the main problems from the supply side is the costly structures of off-street parking. These costs do not allow the private entities to compete with the *on-street* parking prices, and lead to congestion and inappropriate standard parking capacity. So, one solution for this problem is to allocate the incomes of the parking tariffs to invest in new structures. Very few authors have mentioned the construction of a new parking structure as a possibility (e.g., Shoup, 2006; Pierce et al. 2015) and normally this option has been rejected without any scientific or mathematical reason. Parking structures are viewed as expensive structures to build, and consequently they are assumed as fixed supply facilities in the destinations of the trips.

However, in this dissertation we will show that it is possible to collect parking tariffs and spend them on building new parking structures, while having extra benefits. In addition, by formulating an optimization model, we will try to find an optimum parking tariff to maximize the revenue taking changes in the demand into account. Therefore, an optimization model is defined that uses the parking price-related outputs of the demand model, to maximize the revenue. This optimization approach and its techniques will be described later in this document. This approach obviously assumes there is a uniform management policy, led by a unique entity.

### 3.3.1 Travel demand modeling

Urban transportation planning is often used to support decision-making (by elected officials or their representatives) in the selection of transportation policies and programs. In such processes, planners build up information about the impacts of applying alternative courses of action, including transportation services and structures, such as new highways, bus route changes, or parking limitations.

These processes depend on travel demand forecasting, including foreseeing the effects that different policies and programs will have on traveling in a given urban or metropolitan area. A forecasting procedure should offer comprehensive information, such as traffic volumes, bus patronage, and turning movements, to be used by planners and engineers in their designs. A travel demand forecast could also comprise the number of cars on a future highway or the number of passengers on a new express bus service. In addition, it might foresee a decrease in the utilization of automobiles, as a response to a new policy imposing taxes on central parking sites.

There are two main popular approaches to estimate demand in transportation studies: the 4-step travel demand modeling; and activity based travel demand modeling. Probably the most important reason for choosing a 4-step model is that the activity based approach needs a very detailed time use survey – this is normally very costly and difficult to gather. However, the 4-step method is weaker in what concerns the need for the demand of the trips rather than activities. In this doctoral project, a 4-step travel demand modeling will be used to estimate travel demand between origins and destinations.
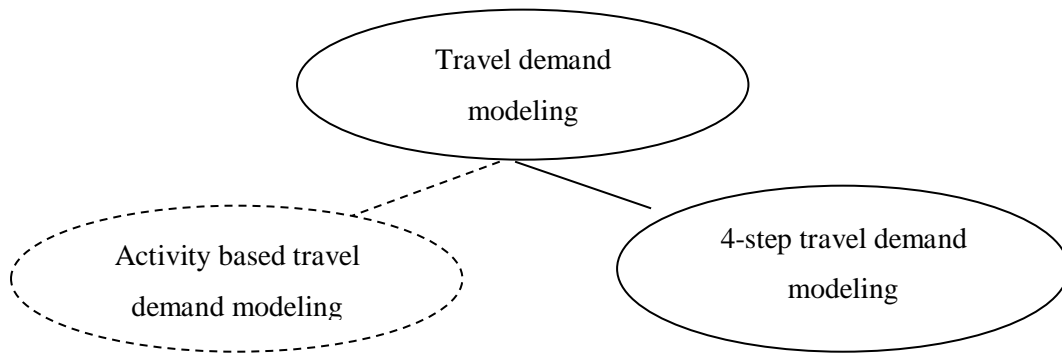


Figure 3.5. Travel demand modeling methods

The first stage of the 4-step model *(trip generation)* is the procedure by which urban activities are used to estimate the number and type of trips. For instance, the number (and pattern) of trips that are generated by a shopping center is rather different from the number of trips generated by an industrial complex (even if they occupy about the same amount of space).

After trip generation, we know the number of trip productions and trip attractions for each zone. But there are still several interesting issues to study: where exactly do trips in a given zone start or finish, or what are the travel volumes between zones. The *trip distribution* process aims at determining where the produced trips in each zone will go, and how they will be split between all other zones in the study area. The result is a set of tables that show the travel flows between each pair of zones.

The *mode split* phase forecasts people's decisions concerning the mode of travel. In this procedure, mode usage comes naturally after trip distribution. Even if it can be done at different points in the forecasting process, the mode split analysis is frequently performed after trip distribution, since the information on where trips are going allows us to compare the alternative transportation services, competing for users.

### 3.3.1.1 Utility and binary choice model

In general, making a choice from a set of two or more alternatives requires the use of a pre-defined decision rule. Such a rule defines the mechanisms for the decision maker to analyze the available

information and reach a unique choice. A wide variety of decision rules has been proposed in the transportation and mobility contexts (see, e.g., Ben Akiva and Lerman 1985) and these rules are based on four main classes of approaches – dominance, satisfaction, lexicographic rules, and utility.

In this dissertation our approach is based on the *utility* concept. This class of decision rules assumes that the attributes are comparable, this meaning that the attractiveness of an alternative is defined by a vector of attributes values, and that it can be turned into a scalar. This defines a single objective function that explains the attractiveness of the alternative in terms of its attributes. This "index" of attractiveness is called "utility", a measure that the decision maker tries to maximize.

We base our approach on the so-called "economic consumer theory", that aims at providing the tools for transforming the assumptions about desires into a demand function (this function describing the actions of consumers, under given circumstances).

Another important related technique is the "random utility approach" first formalized by Manski, 1977. In this approach, the observed inconsistencies in choice behavior are assumed to be a result of observational deficiencies related to the analysis process. It is also assumed here that the individual always chooses the alternative with the highest utility, but as we cannot know the utilities with certainty, these utilities are viewed as random variables – the choice probability of alternative $i$ is equal to the probability that the utility of alternative $i$, $U_{in}$, is greater than or equal to the utilities of all other alternatives in the choice set:

$$P(i|C_n) = \Pr[U_{in} \geq U_{jn}, all\ j \in C_n] \qquad (18)$$

where C is a universal set alternative, and the constraints faced by an individual decision maker $n$ determine his/her choice set $C_n \subseteq C$, and $U_{in}$ is the utility index associated with the alternatives.

In the *binary choice model,* the individual decision maker is faced with a set of feasible discrete alternatives, and tries to maximize his/her utility. The utility of any alternative is viewed as a random variable (as in equation 18 above). In a binary choice, the choice set $C_n$ has two elements {i,j} – in this dissertation, the alternative $i$ is the option "driving", and the alternative j is using the "public transportation". The probability of a person $n$ choosing the alternative i is given by:

$$P_n(i) = \Pr(U_{in} \geq U_{jn}) \qquad (19)$$

and the probability of choosing the alternative j is:

$$P_n(j) = 1 - P_n(i) \qquad (20)$$

Since $U_{in}$ and $U_{jn}$ are random variables, we can divide them into two additive parts as follows:

$$U_{in} = V_{in} + \varepsilon_{in} \qquad (21)$$

$$U_{jn} = V_{jn} + \varepsilon_{jn} \qquad (22)$$

$V_{in}$ and $V_{jn}$ are called the systematic or representative components of the utility for $i$ and $j$; with $\varepsilon_{in}$ and $\varepsilon_{jn}$ being the disturbances or random components.

*Binary choice models* are usually classified as: the linear probability model; the binary *probit* model; and the binary logit model. In the *linear probability model,* the difference in disturbances, $\varepsilon_{in} - \varepsilon_{jn}$, is uniformly distributed between two fixed values. Given the limitations of this model (and its unrealistic forecasts), more realistic assumptions about the disturbances have been tried. One of these assumptions was to consider the disturbances as the sum of several unobserved but independent components. In the *probit model*, $\varepsilon_{in}$ and $\varepsilon_{jn}$ are assumed to follow normal distributions (Ben Akiva and Lerman 1985, Ortuzar and Willumsen 2011).

### 3.3.1.2  Binary logit model

The *binary probit model* considers some assumptions about the distribution of $\varepsilon_{in}$ and $\varepsilon_{jn}$. However, this distribution does not have a closed form (in terms of $\varepsilon_{in} - \varepsilon_{jn}$), and the choice probability must be expressed as an integral. That is why the *binary logit* was proposed, as a probit-like model that is analytically more convenient. This model assumes that $\varepsilon_n = \varepsilon_{in} - \varepsilon_{jn}$ is logistically distributed, as follows:

$$F(\varepsilon_n) = \frac{1}{1+e^{-\mu\varepsilon_n}} \quad , \quad \mu > 0, -\infty < \varepsilon_n < +\infty \qquad (23)$$

$$f(\varepsilon_n) = \frac{\mu e^{-\mu\varepsilon_n}}{(1+e^{-\mu\varepsilon_n})^2} \qquad (24)$$

where $\mu$ is a positive scale parameter. Under these assumptions, and equations 19, 21 and 22, the probability of alternative i is given by:

$$P_n(i) = \Pr(U_{in} \geq U_{jn}) = \frac{1}{1+e^{-\mu(v_{in}-v_{jn})}} \qquad (25)$$

If we assume that $V_{in}$ and $V_{jn}$ are linear with their parameters, we have:

$$V_{in} = \beta_i X_{in} \quad and \quad V_{jn} = \beta_j X_{jn} \qquad (26)$$

and consequently we can write the *logit* model as follows (Ben Akiva and Lerman 1985, Ortuzar and Willumsen 2011):

$$P_n(i) = \frac{1}{1+e^{-\mu\beta(X_{in}-X_{jn})}} \qquad (27)$$

For the demand part of parking modeling, we will use the *binary logit model* to estimate the mode choice and to evaluate the effects of the parking prices in the mode split. As explained before, this model is based on the rational and behavioral actions of travelers, and seems to be a proper and valid choice for modeling demand in the parking problem context.

### 3.3.2 Mathematical programming and optimization

Basic economic decision analysis includes identifying the action that achieves the best value for the desired goal or objective, i.e., the action that optimizes the value of an objective function (maximization or minimization). For instance, we might be interested in evaluating the price level that maximizes profit. In a production problem, the target can be to find out the combination of inputs that minimizes the cost of producing a desired level of outputs. To solve problems such as these, there are many techniques. Optimization techniques are a strong set of tools that can be very useful in supporting managing an investor's resources and therefore in maximizing shareholders' wealth.

The general form of these problems involves recognizing the alternative means of attaining a given objective and then choosing the alternative that fulfills the objective in the most efficient way, subject to constraints on the used resources. In mathematical programming terminology, optimizing the value of some objective functions is the problem, and this should be subject to constraints such as environmental and behavioral restrictions (Bradly et al. 1977).

In the *supply side* of the parking problem, there is a set of variables whose values can be found by optimization models. The first variables are the prices of parking places, and a second set of variables is related to the location of each parking site. The geographical area being studied will be divided in zones, and each zone will have a value of an *index* for the variables of the optimization model. These variables will therefore be associated with the parking locations, and they will represent the locations with lack of parking places or the locations that have extra *on-street* parking. A third set of variables is related to the number of parking places required to handle the demand for a specific zone. For example, in terms of *on-street* parking that occupies the street sites, it is possible to decrease the number of parking places and use those empty spaces for more beneficial business.

For complicated, hard optimization problems, we typically use heuristics. Heuristic algorithms use the structure of the problem to produce satisfactory solutions in an efficient way (Glover, 1977). The main common characteristic of heuristic optimization is that heuristics begin with an arbitrary initial solution, iteratively create some new solutions by some generation rules, and evaluate these new solutions, and finally report the best solution found during the search process. This iterated search procedure is normally stopped under some conditions, e.g., when there is no improvement over a fixed number of iterations, when the found solution is good enough, or when the CPU time reaches a given limit.

The number of heuristic techniques is rapidly growing, and here we highlight some main features of these algorithms. First, a new solution can be generated, for example, by modifying the current solution, according to a given "neighborhood scheme". For this purpose, we can use a deterministic rule, a random guess or a combination of both. This exploration will create a "path" in the solution space that will typically lead to a local optimum, this meaning no better neighbor solution can be found. Therefore,

in order to overcome local optima, these methods may temporarily move to "worst" solutions, as a way to increase the probability of reaching better zones of the solution space (this is the case of the Simulated Annealing or the Tabu Search meta-heuristics).

Another important characteristic of a specific heuristic algorithm is its degree of generality. When designing a new heuristic, there is a clear trade-off between doing it so that a broad class of problems can be tackled probably in a not so efficient way, or rather take advantage of specific characteristics of more limited set of problems to efficiently produce very good solutions.

In addition, meta-heuristics are a generalization of local search, and in fact these algorithms can be viewed as sophisticated improvement heuristics. In our case, the objective function of the optimization problems will be non-linear and heuristics and meta-heuristics will be helpful in solving these problems (Osman and Kelly, 1996; Taillard et al. 2001; Michalewicz and Fogel, 1999; Aarts and Lenstra, 2003; Winker and Gilli, 2004).
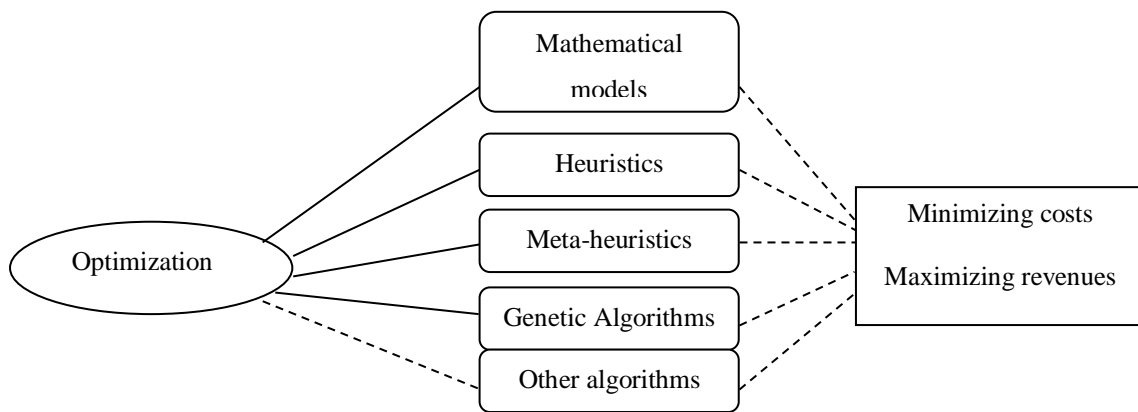


Figure 3.6. Optimization methods

In addition, Genetic Algorithms (GA), recombining solutions, and working with populations of solutions, can be another interesting approach to tackle the problems we are interested in. This possibility should be explored, also because in our case, solutions can be totally (or partially) naturally coded by binary streams. Exploring the multi-objective nature of these problems would also be natural by using GA.

## 3.4  An integrated model

This dissertation tries to combine both the demand and the supply sides, to achieve a comprehensive and integrated approach for the parking problem. The problems related to the parking are numerous and

the goal of this integrated approach is to provide a comprehensive and flexible mathematical model based on the combination of demand modeling with optimization.

In the demand side, first we assume there are two modes of transportation: "drive alone" and "travel by bus". The reason for this choice is that we are trying to build a fundamental base for a more detailed study of the parking problem. Traveling by car or bus can be viewed as a good representation for two important means of transportation. By this categorization, we are also trying to divide the whole demand into private and public transportation, which have substantial differences in their characteristics. However, other modes such as walking or bicycle normally have an important share of commuters' daily trips.

For the car owners, traveling by car is usually an easier option than traveling by bus. A car has unique features that none of the other modes of transportation can compete with. You can drive the car from home without the need of walking to any station, and it is in general a more comfortable option. You do not need to be in a crowded small space of a bus in the rush hours, and you can calmly listen to the music or radio channels that you like. You can choose where to go or change your destination when you want. You can find and choose the nearest possible place to the destination to park and do not need to walk from the station to the destination. However, there is a big con in this story, the cost. The trip cost is a key issue that makes the difference between traveling with a private vehicle or by bus. This cost can be a monetary cost or a time cost, and in this study we considered it as a key variable for mode choice.

Taking all these issues into account, in our work we assume that for the base model, the travel cost is obtained by adding the fuel cost and the parking price. The parking cost itself includes the cruising cost, the parking tariff, and the "walking cost" between the parking place and the destination. However, as a first approach, in the demand model we only consider the parking tariffs and the fuel cost. In the extensions of the model, we will apply other costs.
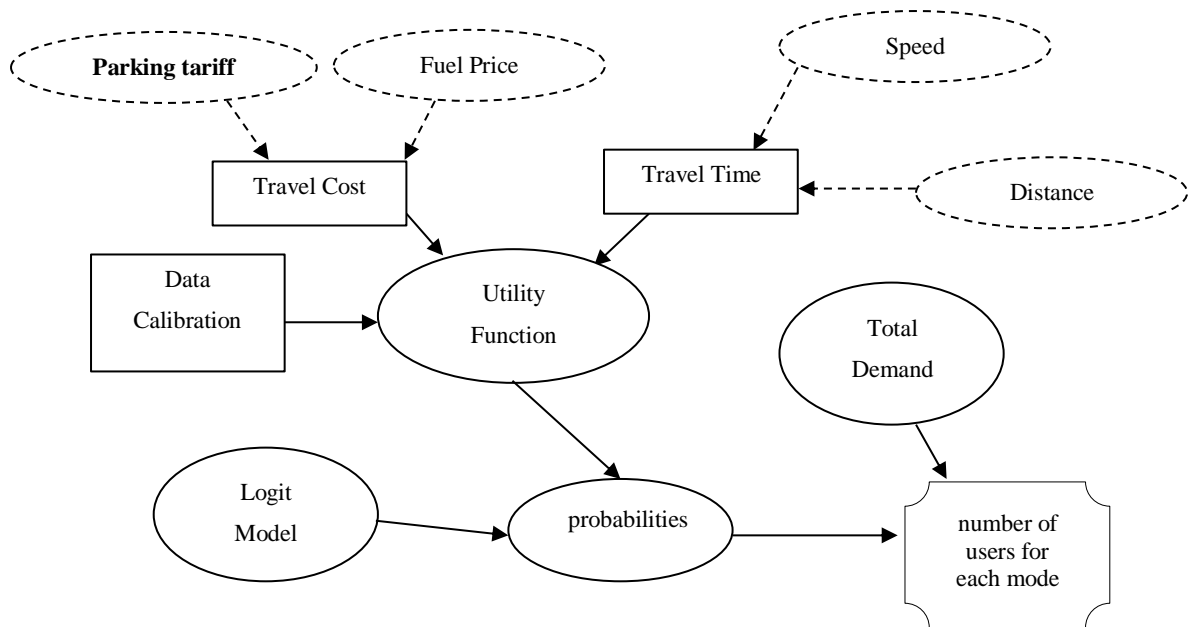
Figure 3.7. A first architecture for the parking problem base model

Choosing between the car and the bus is a binary choice. To estimate the probability of choosing each of these modes, we need to define their utility function. In the base model, this function includes two variables for cost and time. The definition and the calculation method of the travel costs for the "alone drivers" in the base model was already presented, and for the travelers who are commuting with bus, it is assumed to be equal to the bus fares. These utility functions will be calibrated with real data.

The step after the estimation of utilities is the computation of the probabilities for mode selection by the travelers. In this stage we will use a *logit* model to compute the probabilities. Based on the specific parking tariff from the first phase, these probabilities will reveal the behavior of travelers in choosing a specific mode. Then these probabilities will be used together with the total demand to find out the share of each mode, based on the specific conditions under analysis. This process is the first mechanism we are using in our base model to tackle the parking problem (see figure 3.7).

The next component of this approach is related to the assignment or allocation of the demand flows to parking spots. For this purpose, we try to maximize the revenue, by changing the number of parking spots. First, in the basic model, we try to assign all the parking demand to the destination zones. This means all cars must find a parking space. If there is enough capacity for the cars, there is no need to build a new *off-street* parking. Otherwise, investments are needed to build a new *off-street* park or expand current ones.
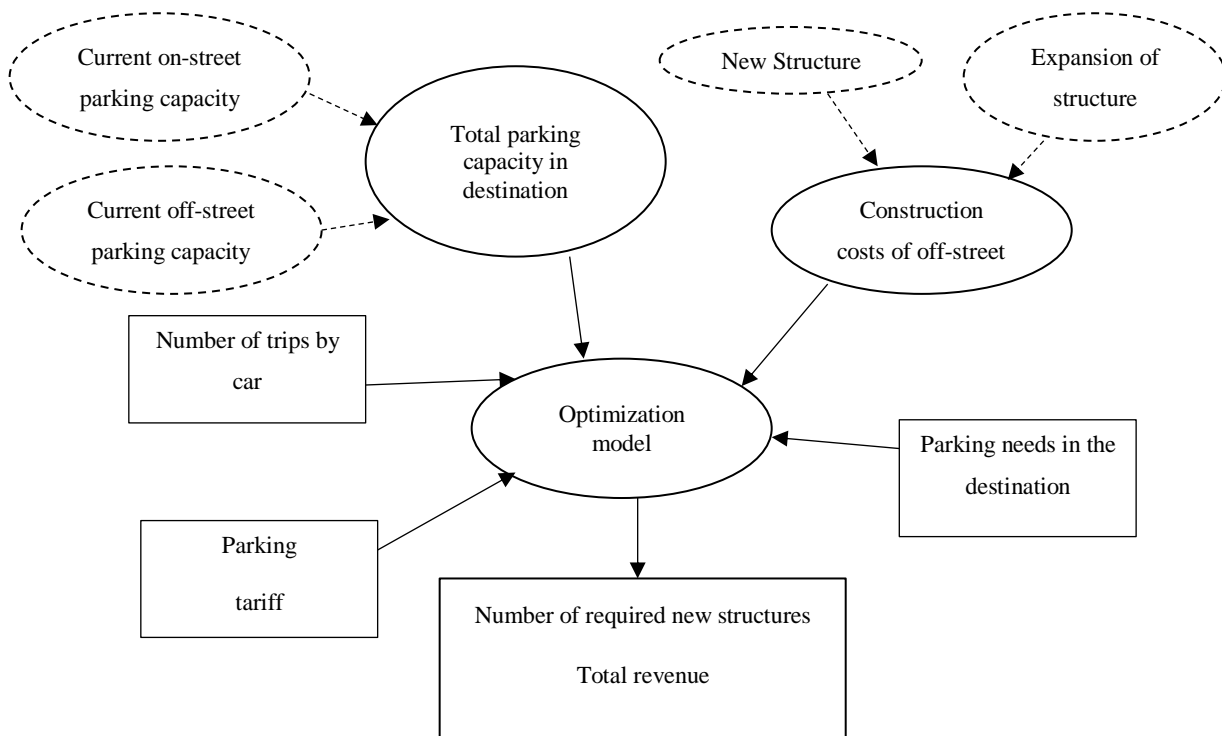
Figure 3.8. Second component of the base model

This assignment is done while the total revenue of the parking is estimated from the parking tariffs and by considering the negative effects of construction costs. In fact, in the base model, we try to estimate the feasibility of covering the construction costs of the *off-street* parking by parking tariffs. Basically, we try to compute the revenue if we spend all the money generated by the parking tariffs in building new parking spaces (see figure 3.8).

To reach a comprehensive framework for the parking problem, we need to integrate these two mechanisms or components (see figure 3.9). The combination of these two mechanisms is guaranteed by the number of car trips (as a joint system sub-component).
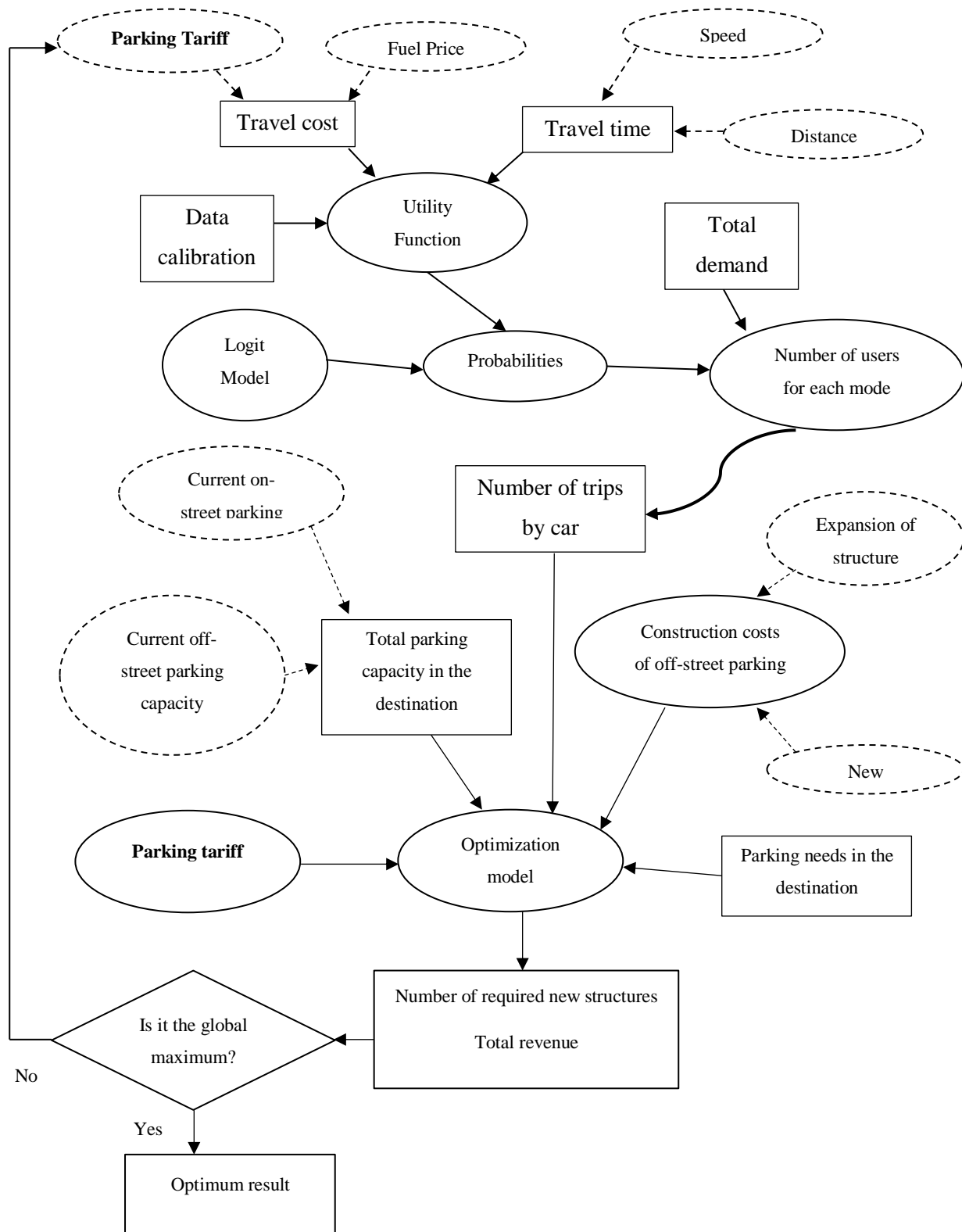
Figure 3.9. Detailed description of the base model

As shown in the figure, we first set a base parking tariff for each zone of a study area. This tariff can be a single one or differ according to the zones. Then in the first component of our approach, the distribution of trips by car is estimated, based on the specific parking tariffs – this distribution is used

as an input for the second component of the system. This input along with other parking related values such as capacity, parking tariffs, and construction costs, is the basis for the optimization model, intended to maximize the revenue.

As we see in the combined, integrated system, the parking tariffs affect the whole model in two different ways. First, they are used to estimate the mode choice and number of travelers who are using the car. In this stage, we expect that increasing these tariffs negatively affects the number of private vehicle users. This effect is nonlinear due to the *logit* model. This negative effect on the quantity of private car usage has a direct impact on the optimization model of the second system's component. Therefore, increasing the parking tariffs has a nonlinear negative effect on the maximization of the total revenue.

On the other hand, parking tariffs have a direct linear effect on the optimization model itself. The revenue function (to be maximized) is the product of the number of parkers by the parking tariff they pay. Thus, increasing the parking tariff has a positive effect on the maximization of the revenue.

These opposing effects of the parking price, with both negative and positive impacts on the revenue maximization, lead us to an integrated optimization model, that can be used to define parking prices considering most of the important aspects of the parking problem.

# 4 Optimization

## 4.1 Introduction

In this chapter we are going to present in detail our optimization approach to the parking problem, and describe the *base* model we have developed in this research. As mentioned in the previous chapter, one of our main goals in this approach is to design a flexible tool to take the costly decision of building (or expanding) a new off-street parking structure (park) into account. For this purpose, we need a model to estimate the benefits and costs of these decisions and to optimize them.

Benefits and costs in a parking problem include a vast range of different items. The main revenue of a parking space straightly comes from the parking tariffs paid by the drivers. As mentioned, *on-street* parking spaces are normally underpriced in the CBDs of big cities. Moreover, the tariffs of *off-street* parking are normally set by private entities, without any consideration of the neighborhoods' parking prices or any information on congestion. Therefore, *on-street* and *off-street* parking tariffs clearly need to be defined in an integrated manner.

The main direct costs of this problem are the structural costs of the new building for an *off-street* park. These structures can be built under or over the ground, and the costs associated to this choice have always been an obstacle for the development of a comprehensive parking approach. Another important indirect cost is related to *cruising* for parking places, in the city streets. As referred, cruising leads to extra congestion in the crowded areas of a city, due to the underpriced *on-street* parking places.

There are other indirect sources of revenues and costs in this context. An *on-street* parking space is a part of the urban land, and it has, therefore, a considerable land-use value. This means that *on-street* parking space can be used for other beneficial activities, possibly with more benefits.

Other substantial indirect benefits of parking spaces are related to public transportation. By increasing the parking tariffs, it is likely that the drivers change their mind, and use public transportation instead of private vehicles, to travel. This increase in the usage consequently upsurges the gained revenues from public transportation, and may have an indirect effect on the parking tariffs.

Finally, it should be referred that environmental impacts are also a key dimension of the parking management strategy. Decreasing cruising for parking tends to reduce congestion and consequently decreases its harmful environmental impacts.

In this chapter, we first formulate a *base* model to maximize the profits. For this reason, an objective function is defined, to increase the yearly amount of parking tariffs and to decrease the construction costs of building new off-street parks. To include both *on-street* and *off-street* parking in the models

and to take their interactions, we will assume that the public entities and the government have the supervision over the parking pricing in both curbsides and parking garages.

The base model covers the variability in the demand and the congestion effects of changes in parking prices. This problem is nonlinear in its nature, and we therefore propose another model, easier to solve, by introducing new binary variables.

In this chapter, after presenting the *base* model, we apply and validate it in a randomly generated case study, trying to find the optimum parking strategy (pricing and spaces). We will describe the characteristics of the case study (a randomly generated city) and perform a sensitivity analysis on the obtained results.

We will then propose some extensions of the model and we will finally focus on public transportation and its benefits and costs for the case study.

## 4.2   The basic model

The objective of the optimization model is to maximize total profit, by including the costs of building new *off-street* parks and considering changes in congestion. Here we introduce the sources of revenue, costs, and the constraints related to the objective function, thus defining our mathematical programming model.

### 4.2.1   Model structure

Figure 4.1 describes the structure of the *base* model. Benefits have been divided into two main sources. First we have the parking tariffs computed by multiplying the number of parking places by the parking prices (this includes *on-street* and *off-street* parking). We also consider social benefits. These benefits here are estimated as follows: when we omit some *on-street* parking spaces, we can have benefits directly from those spaces, or indirectly by devoting the associated money of to a social activity.
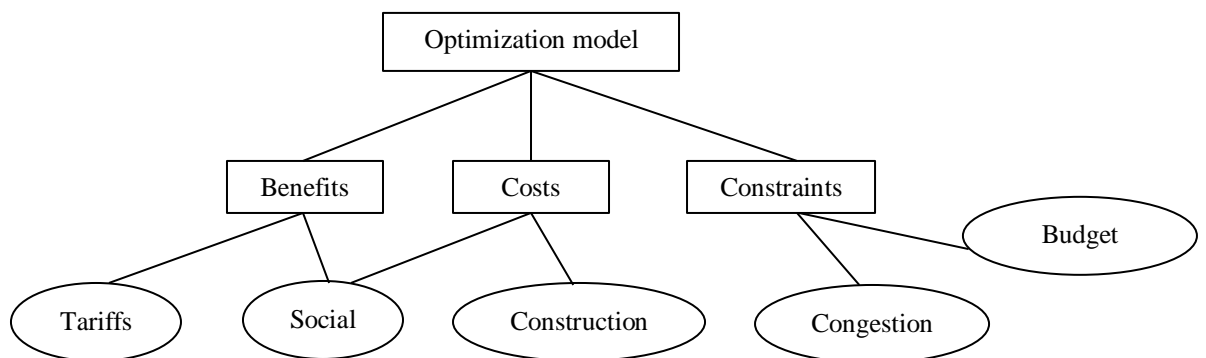


Figure 4.1. Structure and characteristics of the *base* model

As mentioned before, construction costs for new *off-street* parks will occur when we need to cover extra demand, if for a specific parking pricing strategy, the amount of users of private vehicles becomes more than the amount of current parking places.

Constraints are mainly related to congestion and budget. The congestion part includes the balance between the demand side (the number of travels by private car to a given destination) and the supply side (the number of current and future parking places in the destination). The budget constraint reflects the  global budget set by the public entities, for building new parking structures in the whole area.

This base model tries to maximize the profit (considering the mentioned revenues and costs and conceptually it can be formulated as an optimization model, as follows:

$$Maximize: \quad\quad Revenues - Costs \quad\quad\quad\quad\quad (32)$$

$$subject\ to: \quad\quad Congestion\ constraints,\ Budget \quad\quad (33)$$

$$decision\ variables: \quad Parking\ prices,\ New\ parking\ places \quad\quad (34)$$

Parking prices and new parking places are our main decision variables. Parking prices strongly determine revenues, and have an important role in the amount of congestion. As mentioned in the previous chapters, prices are one of the main items that decision-makers and politicians can use to control traffic and to establish a parking strategy. The new parking places are also computed by the model, to cover congestion and budget constraints, while the objective function is maximized.

Expressions 34 and 35 below define the revenues and costs in the base model. Revenues can be computed by multiplying the parking prices (for both *on-street* and *off-street* parking) by the demand of places, plus the social benefits of using parking space for other purposes. On the other hand, costs include the construction of new *off-street* parking places and the losses of eliminating a parking space.

$$Revenues = Parking\ tariffs * Used\ parking\ space + Social\ benefits \quad (34)$$

$$Costs = Construction\ costs + Parking\ removal\ costs \quad (35)$$

Here we assume that when a driver arrives to his destination zone, he first needs to decide where to park. He will choose between *on-street* parking (curbside) and *off-street* parking (garages), based on several conditions. We also assume that a driver will choose *on-street* parking first (because of comfort and easy access) and if these parking spaces are full, he will go for the *off-street* parking. This seems to be a rational assumption, due to congestion problems and cruising for finding a cheaper parking space. Of course, this can be true while there are no big differences between the *on-street* and *off-street* parking

prices. But it is obvious that if the *on-street* parking price is set higher than the *off-street* parking price, the choice will change.

Therefore, to find the optimum prices for *on-street* and *off-street* parking, with a correct allocation of drivers to the parking places, we consider one main scenario for the *base* model, where the first priority of the driver is parking in the curbsides.

### 4.2.2 Algorithms and mathematical details

We consider the city is divided into a set of different zones, well representing the main origins and destinations. Based on this partitioning, we first describe our objective function. As explained before, we aim at covering the expenses of building new off-street parks in different parts of the city, to satisfy the non-satisfied parking demand for private vehicles. This leads to an objective function that maximizes profit (revenues minus costs).

We assume we have two main sources of revenues and two sources of costs. The first source of revenues comes from the parking tickets, and is straightly earned from the drivers when parking. To estimate these revenues we simply multiply the parking prices by the number of parkers – these two items have different values for *on-street* and *off-street* parking. The parking prices are decision variables that can be set by the government and the public entities for *on-street* and *off-street* parking separately. On the other hand, the quantity of *on-street* and *off-street* parkers are variables of the model that are computed by the demand models explained later in this section.

Providing parking spaces has its own costs. These costs vary from maintenance to upgrade or building new facilities, to indirect costs such as environmental harms. In our *base* model, we assume one critical component is the construction costs of the new parks. These costs are incurred when the demand for parking in a specific part (zone) of the city exceeds the total amount of current existing places including both *on-street* and *off-street* parking. A city has a certain number of streets and roads, and therefore we can assume that the maximum number of *on-street* parking places (curbsides) is limited. Thus, the only remaining option for public entities will be providing (building) new parking facilities and garages (*off-street* parking) if costs are reasonable. However, normally these costs are huge. In our *base* model, these costs are computed as yearly costs – we estimate the cost of building a medium size *off-street* park, and divide this cost into a specific number of years, based on the interest rate. In the objective function, we consider the yearly cost for a new parking place, multiplied by the number of necessary new places.

In the objective function, we will also consider what will happen if we allocate the revenues of some *on-street* parking space to obtain some additional social benefits. Obviously, the first direct effect of such a decision is decreasing the revenues from the parking tariffs. By dropping the revenues of some parking places, we consequently decrease the value of the objective function. On the other hand, this

money can be spent in other social benefits, including, for example, the improvement of the sidewalks to setting up new businesses.

In our optimization model, constraints are used for the allocation of cars to parking spaces, to model the effects of parking prices in congestion, and to take into account the available budget. To set up these constraints, some pre-processing needs to be done (as explained later in this section).

A first set of constraints handles the allocation of cars to the parking spots, considering that drivers primarily park *on-street* as this is, in general, a more convenient option. For this purpose, we need to estimate the correct amount of congestion for different parking prices. Figure 4.2 briefly presents the pre-processing algorithm used to allocate the demand to the parking places.
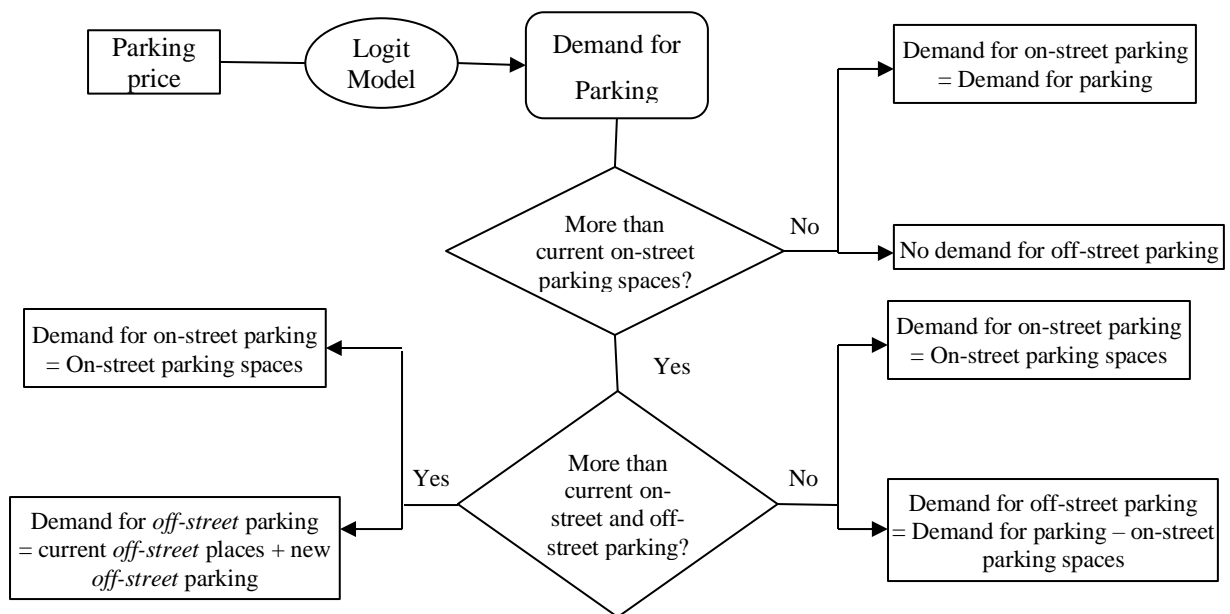
Figure 4.2. Demand separation algorithm for *on-street* and *off-street* parking

As presented in this figure, we estimate the demand for parking by a *logit* model. This model explicitly considers the changes of parking prices. Therefore, in the objective function, we not only consider the direct effects of changes in the parking prices, but also the changes in the demand due to the parking prices. For instance, when the parking price (*off-street* or *on-street*) increases, it directly will upsurge the revenues (as we multiply it directly by the demand). However, increasing this price will affect the demand (by the *logit* model) decreasing it, and consequently revenues will be decreased. This "dichotomy" is obviously an opportunity to explore new solutions for the problem.

Following the introduction presented in the previous chapter, we now consider a generalized form of utility for using the private car (see expression 36). *The parking price is an attribute of the destination*

100

*zone of a trip,* and we directly use it in this utility function. We "normalized" parking costs and travel costs in this function, as these costs are of different nature and scale. The parking cost is a rate (for example, euros/hour) and it changes according to the the goal of the trip (short and long time activities) and to the destination zone. However, it is also possible to include this price straightly in the generalized costs, as a *direct cost of a trip*. For this reason, we need to partition the trips based on their goal, and assume different average times for the different activities. In a first approach, we have simply imported this price directly into the utility function.

The utility for decision maker $n$ from an alternative $i$ is composed by two parts. The first part $V_{ni}$ is considered to be known, and the second part is the unknown, random component $\varepsilon_{ni} - U_{ni} = V_{ni} + \varepsilon_{ni}$. Expression 36 computes the *logit* choice probability of alternative $i$ by individual $n$ as $P_{ni}$. In this function. $V_{ni} = \beta' x_{ni}$, where $\beta'$ is a vector of coefficients for $x_{ni}$, that is (as suggested in the literature – Train 2001, Ben Akiva and Lerman 1985, McFadden 1974) "*a vector of observed variables relating to alternative j*".

$$P_{ni} = \frac{e^{(V_{ni})}}{\sum_{j=1}^{P} e^{(V_{nj})}} = \frac{e^{(\beta' x_{ni})}}{\sum_{j=1}^{P} e^{(\beta' x_{nj})}} \qquad (36)$$

If we consider that "traveling by car between two zones" is one of our alternatives, the attributes of the destination zones will be a part of *variables relating to the alternative*. Two of these attributes that we are going to work with are the *on-street* and the *off-street* parking rates – these rates define two variables associated to attributes of the destination zones for the alternative "travel by car".

$$U = \alpha \ (in\_vehicle \ travel \ time) + \beta \ (travel \ cost) + \varphi \ (off\_street \ parking \ rate)$$
$$+ \ \omega \ (on\_street \ parking \ rate) + \gamma \ (discomfort \ level) + \varepsilon \qquad (37)$$

In this expression, in-vehicle travel time, travel cost, parking prices and discomfort level are the travel attributes; α, β, φ, ω, and γ are the coefficients of these attributes; and ε is the random component. For example, a change of one unit in the value of the utility function can be achieved by a change of the *in-vehicle travel time* of $1/\alpha$. The ratio of the *in-vehicle travel time* to the *travel cost* represents the monetary value of the in-vehicle travel time. Therefore, the value of *in-vehicle travel time* is equal to $\alpha/\beta$, and the value of *discomfort* to $\gamma/\beta$. In the same way, the value of the *off-street* and *on-street parking rates* for the travelers can be defined as $\varphi/\beta$, and $\omega/\beta$ respectively.

The generalized cost for "*traveling by the mode car from zone i to zone j*" is obtained by adding up the different attributes, with their units normalized (expression 38):

$$C_{ij}^{car} = a_1 TT_{ij} + a_2 \left( dl_{ij} - 1 \right) * \left( TT_{ij} \right) + a_3 Poff_j + a_4 Pon_j + F_{ij} + \delta \qquad (38)$$

where we have:

$TT_{ij}$: in-vehicle travel time between origin $i$ and destination $j$;

$dl_{ij}$: discomfort level experienced for traveling from origin $i$ to destination $j$;

$F_{ij}$: direct cost of traveling from origin $i$ to destination $j$;

$Poff_j$: off-street parking price in the destination zone $j$;

$Pon_j$: on-street parking price in the destination zone $j$;

$\delta$ : all the attributes that are not included in the generalized cost (such as safety, convenience, reliability);

$a_1, a_2$: weights attached to each disutility (expression 38) – $\alpha/\beta$ and $\gamma/\beta$;

$a_3, a_4$: weights for the off-street and on-street parking rates (expression 38) – $\varphi/\beta, \omega/\beta$.

For driving with a private vehicle, we assume that the discomfort level ($dl_{ij}$) is equal to 1, and we rewrite expression 38, as follows

$$C_{ij}^{car} = a_1 TT_{ij} + a_3 Poff_j + a_4 Pon_j + F_{ij} + \delta \qquad (39)$$

Expression 39 shows the ingredients of the direct cost for car users in our *base* model. $Poff_j$ and $Pon_j$ are the parking prices (rates) in the destination zone, normally expressed in euros (dollars) per hour. In fact, they are the attributes of the destination in our utility function and, based on expression 37, we can estimate their coefficients from the revealed preference data, by the maximum likelihood method.

As mentioned before, one of our main goals in introducing the utility function and mode choice stages is to analyze the effects of changes separately induced by the *on-street* and *off-street* parking rates on the demand for parking. For this reason, these two variables are included in the generalized costs, and considered in our demand model.

The *fuel cost* (in euros) is calculated based on the distance between the zones, and the parking cost directly depends on the destination of the trip. We assume the fuel cost and any other direct cost, such as road tolls, are included in $F_{ij}$.

The common mathematical formulation for modeling the mode choice, at an aggregate level, is the multinomial *logit* function (expression 36), and its equivalent here is as follows (expression 40):

$$P_{ij}^L = \frac{e^{(-\beta_L C_{ij}^L)}}{\sum_{N=1}^{P} e^{(-\beta_N C_{ij}^N)}} \qquad (40)$$

where $P_{ij}^L$ is the probability of choosing mode $L$ to travel from origin $i$ to destination $j$, $C_{ij}^L$ is the generalized cost for mode $L$, and $\beta$s are the coefficients.

We use this probability to estimate (expression 41) the demand for each mode (in our case studies, we have two modes – car and bus):

$$Q_{ij}^{car} = P_{ij}^{car} * Q_{ij}^{Total} \qquad (41)$$

where we have:

$Q_{ij}^{car}$ : number of car drivers from origin $i$ to destination $j$;

$Q_{ij}^{Total}$ : total number of travelers from origin $i$ to destination $j$;

$P_{ij}^{car}$: probability of choosing to drive the car for traveling from origin $i$ to destination $j$.

These expressions (36 to 41) mathematically model the parking prices' issues – see figure 4.3. Parking prices are our decision variables and they depend on the strategy of the decision maker. In a first stage, these variables are used to indirectly estimate travel demand by car, as explained above.
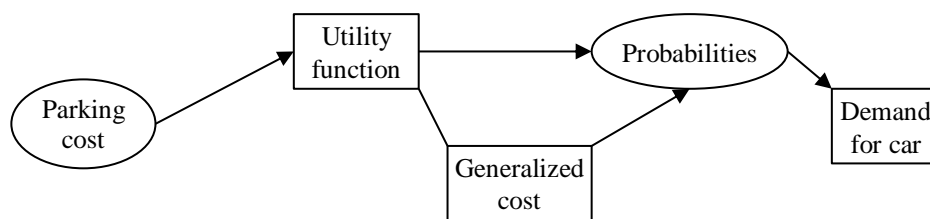


Figure 4.3. Demand estimation in the pre-processing stage

$Q_{jk}^{car}$ is the output of the demand model and this value is used as an input for our optimization model in the supply component. This demand changes with the changes in parking costs. For instance, by increasing the parking price, the generalized costs will increase, and consequently the probability of using the car and the number of travelers by this mode will decrease. This change is nonlinear because of the *logit* function, and it will straightly affect the results of the optimization model.

As mentioned, we are going to maximize the profit associated to *on-street* and *off-street* parking. The revenues are obtained from charging for parking places. On the other hand, building an *off-street* park is costly and it should be considered as such in the objective function. In addition, sometimes we can devote the space or revenues of some on-street parking to other uses, such as gardening or improving the level of services of public transportation. This should be also considered in the optimization model. So, the objective function can be written as follows (expression 42):

$$R = \sum_k ( P_k^{on} * Q_k^{on} + P_k^{off} * (Q_k^{off} + X_k^{off}) - C_k^{off} * X_k^{off} + V_k^p * X_k^{on} - P_k^{on} * X_k^{on}) \quad (42)$$

$X_k^{off}$ :  number of *off-street* parking places to be built in addition to the current ones, in zone k;

$X_k^{on}$ :  number of *on-street* parking places to be eliminated (or their benefits eliminated) in zone k, to assign the space to a more beneficial activity;

$Q_k^{on}, Q_k^{off}$:  the demand for *on-street* and *off-street* parking in zone k (as calculated by expressions 36 to 40, and the algorithm of figure 4.2);

$C_k^{off}$ :  present value for the construction cost of an *off-street* park in zone k;

$V_k^p$ :                social benefit of eliminating an on-street park (or its benefit) in zone k.

In this expression, $P_k^{on} * Q_k^{on}$ is the revenue that can be obtained from the *on-street* parking places in zone k (by multiplying the *on-street* parking rate by the amount of drivers who park in the curbsides). The second term, $P_k^{off} * \left( Q_k^{off} + X_k^{off} \right)$, represents the monetary benefits from the *off-street* parking places (by multiplying the *off-street* parking rate by the average amount of drivers who park in garages in an hour).

The third component of the objective function, $C_k^{off} * X_k^{off}$, is the construction cost of the new *off-street* park. To compute this cost we first estimate the building cost for an average size park. Then we need to define a target year and interest rate, to calculate the present value of building it. Finally, we divide that cost by the capacity of the park, and find the cost per place (to be multiplied by the number of new *off-street* places). Figure 4.4 shows this cost-calculation process.
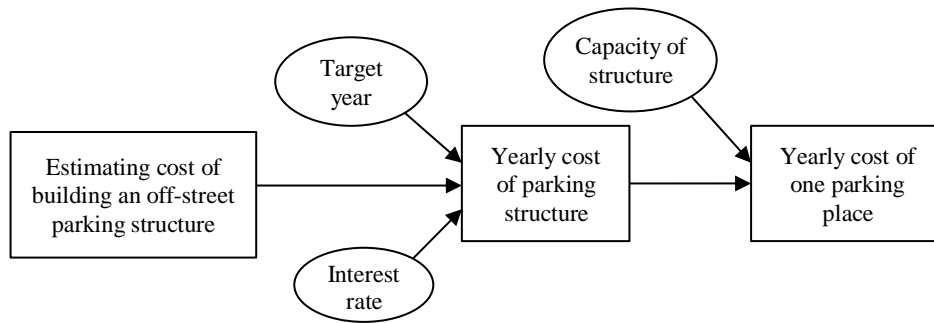


Figure 4.4. Cost-calculation process of building a new off-street park

The two final components of the objective function are related to the adopted strategy for *on-street* parking. The costs of such strategies directly come from the lack of revenues, i.e., by removing a place or allocating it to another activity we will not have these direct revenues (mathematically defining them as costs). On the other hand, these physical spaces can lead to different types of benefits that can be converted into "monetary benefits".

We estimate $Q_k^{off}$ and $Q_k^{on}$ through the pre-processing algorithm and expressions 36 to 40, with $P_k^{on}$, $P_k^{off}$, $X_k^{on}$, and $X_k^{off}$ being the decision variables.

Our model considers a  set of constraints for the capacity of both *on-street* and *off-street* parking. In addition, we assume that the cars that come to a specific zone will stay and park in the zone. Another assumption is that they first start to park in current *on-street* parking places, and then they continue with *off-street* parking spots – when these become full, the model will consider the need for additional places.

## 4.3 The model

We assume the city has been partitioned into *N* zones, with the number of travelers to each zone being computed by a multinomial *logit* model, and with a specific capacity for cars to park in each zone. We have a given budget to build new off-street parks, and we want to find parking prices to maximize the revenues along the year – we therefore want to find how many places should be built, based on our budget, on the estimated demand, and expected revenues. We also know that variations on the parking prices will tend to change the demand for using the car or the public transport.

Based on the concepts and assumptions presented along this chapter, we come to the following model:

*Maximize* :

$$\sum_{j=1}^{N} \sum_{l=1}^{M} 8 * 365 * \rho_{jl} * \pi_l^{on} * Q_{jl}^{on} + 8 * 365 * \rho_{jl} * \pi_l^{off} * \left(Q_{jl}^{off} + X_{jl}^{off}\right) - \rho_{jl} * C_j^{off} * X_{jl}^{off} \qquad (43)$$

*subject to*:

$$\sum_{l=1}^{M} \rho_{lj} = 1 \qquad\qquad \forall j \ in \ zone \qquad\qquad (44)$$

$$\rho_{lj} * \left(Q_{jl}^{car} - \left(Q_{jl}^{off} + Q_{jl}^{on}\right)\right) = X_{jl}^{off} \quad \forall j \ in \ zone \ , l \ in \ set \qquad (45)$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} X_{jl}^{off} \leq budget \qquad\qquad (46)$$

*Parameters*:

$\pi_l^{on}$: set of *on-street* parking prices with *l* elements;

$\pi_l^{off}$: set of *off-street* parking prices with *l* elements;

$Q_{jl}^{car}$: the cumulative demand for cars in destination zone *j* when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_l^{off}$ (average number of cars per hour per day);

$Q_{jl}^{on}$: the demand for *on-street* parking in destination zone *j* when the *on-street* parking rate is equal to $\pi_l^{on}$ and the *off-street* parking rate is $\pi_l^{off}$ (average number of cars per hour per day);

$Q_{jl}^{off}$: the demand for the *current off-street* parking in destination zone *j* when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_l^{off}$ (average number of cars per hour per day);

$C_j^{off}$: the construction cost of a parking place in zone *j* (euros per place per year).

*Decision Variables:*

$\rho_{jl}$ : binary variables – equal to 1 if the *on-street* parking rate is $\pi_l^{on}$ and *off-street* parking rate $\pi_l^{off}$ in the destination zone *j*, and equal to 0, otherwise;

$X_{jl}^{off}$: new *off-street* parking places necessary to be built in destination zone *j* when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_l^{off}$ (average number of spaces per hour per day).

As a first approach, we assume that the *off-street* parking price will be 90% of the *on-street* parking price ($\pi_l^{off} = 0.9 * \pi_l^{on}$) – thus, in the model, the number of elements in the set of *off-street* parking prices will be 90% of those in the set of *on-street* parking prices. We also assume that we are estimating revenues and benefits for 8 hours of traffic per day (4 pick hours in the morning, and 4 hours in the afternoon).

One of the key features in this model are the binary decision variables $\rho_{jl}$, for choosing the best price from a set of prices. Through these variables, we are sure to move along the demand line of the *logit* model, and that all changes in demand due to changes in the parking prices are being computed. From the binary variables for each zone, just one can be equal to 1 (constraints 44).

Constraints 45 are related to the balance between the demand and the parking places. They guarantee all cars that come to a specific zone will find a place in the current or in the future places. Items such as $Q_{jl}^{car}$, $Q_{jl}^{on}$, and $Q_{jl}^{off}$ are calculated in the pre-processing stages for different parking prices $\pi_l^{on}$ and $\pi_l^{on}$, thus assuring that we are moving along the demand curve.

Finally, constraints 46 is taking the budget for building new places into account – all costs of future *off-street* parking places in all zones must be less than our current budget.

This model connects all zones internally through the budget and the demand, giving us the necessary number of *off-street* parks to build and the parking prices to adopt. For example, if a specific value for the parking price gives us the maximum revenue while the amount of new parking places to build exceeds our budget, then the model may increase the parking prices to deal with this situation. By increasing these prices, the demand (calculated in the pre-processing stage) will decrease, and consequently the amount of new needed parking places will satisfy the budget. However, as the effect of the new parks on the budget is over the entire city (with those parks being related), and at the same time the demand can change (as computed in the pre-processing stages), it may happen that prices are increased in some zones and decreased in other zones. To fully explain the behavior and complexities of the model, in the next section we apply it to a simple, illustrative case study.

## 4.4  Test problem instance

To assess the performance of our model, we have applied it to a simple, randomly generated problem instance. Figure 4.5 shows some data on this small case study (with 4 zones) for which we have tried different scenarios. We assume that the drivers need parking places near the center of the destination zone.
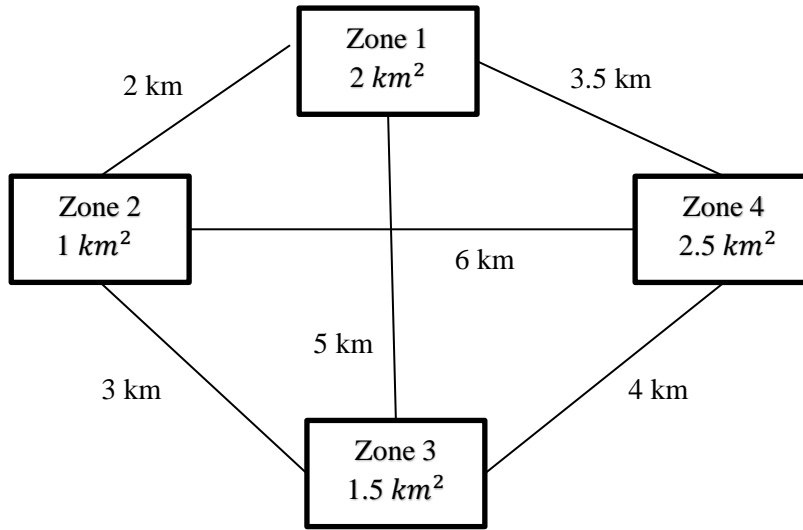
Figure 4.5. The case study – distances between zones and areas

### 4.4.1 Total demand

In a first step, we estimate the total demand between zones, i.e., how many trips are done with car and bus, from one zone to another. For this reason, we are using *a trip generation and distribution model* to estimate the total demand for the case study. The typical density for a mid-size city can be around 5,000 people per $km^2$. We have assumed that the area of the city is around 7 $km^2$, with around 35,000 people in the whole area.

We are using expression 47 to estimate the total demand between the zones. We assume that the generated trips for each zone are directly related to the area of each zone, with the bigger zones generating more demand. We also assume that, instead of the trip costs between the zones, the costs are measured using the distances between the centers of zones – higher travel costs are associated to larger distances. The total number of trips between two zones is then given by (expression 47):

$$Q_{ij}^{total} = \alpha * S_i * S_j * e^{-\beta * D_{ij}} \quad (47)$$

where $Q_{ij}^{total}$ is the total number of trips between zones *i* and *j* per hour per day. $S_i$ and $S_j$ are the areas of zones *i* and *j*, and $D_{ij}$ is the distance between these zones. The parameters α and $\beta$ are used to ensure that constraints are met – here, we have set α=150, 200, and $\beta$= -0.01, -0.05, to have a realistic value of $Q_{ij}^{total}$ (see table 7).

Table 4.1. The total number of trips for the case study

| $Q_{ij}^{total}$ | | | | |
|---|---|---|---|---|
| Zone | 1 | 2 | 3 | 4 |
| 1 | 0 | 1047 | 1693 | 2413 |
| 2 | 1137 | 0 | 860 | 1110 |
| 3 | 1223 | 827 | 0 | 2217 |
| 4 | 2793 | 1233 | 1713 | 0 |

We have also assumed that all trips inside the zones is done by walking (so, for example, the number of trips from zone 1 to zone 1 is assumed to be 0).

### 4.4.2 Travel costs

In this example, we assume that we just have two modes – private vehicles and buses. As referred, we compute the travel costs for these two modes based on the distance between zones (expression 48):

$$C_{ij}^{car} = 1 + R * D_{ij} \qquad (48)$$

In expression 48, $C_{ij}^{car}$ is the travel cost by private vehicles between zones $i$ and $j$ – $D_{ij}$ is the distance between zones, and $R$ is a random value between zero and 1.

For the case study, generating the costs in this way means the costs have a random character because of the term $R$. Moreover, their relative values seem to be rather realistic as in real life, the zones that are far away have more travel costs (basically, more fuel consumption).

Table 4.2. Travel costs for private vehicles

| $C_{ij}^{car}$ | | | | |
|---|---|---|---|---|
| Zone | 1 | 2 | 3 | 4 |
| 1 | 0 | 1.2 | 1.5 | 1.35 |
| 2 | 1.15 | 0 | 1.3 | 1.6 |
| 3 | 1.6 | 1.3 | 0 | 1.4 |
| 4 | 1.3 | 1.5 | 1.35 | 0 |

To compute the cost of travel by bus we are using expression 49. Normally the cost of using public transportation is lower than the cost of using the car, thus stimulating people to use public transportation instead of private vehicles.

$$C_{ij}^{bus} = 1 - R' * D_{ij} \qquad (49)$$

In this expression, $C_{ij}^{bus}$ is the travel cost by bus between zones $i$ and $j$. The parameter $R'$ is randomly generated between 0 and 1, and has a different value for every origin and destination $ij$.

Table 4.3 shows the travel costs by bus between the different zones. As mentioned, these values are considerably lower than those generated for car traveling (table 4.2).

Table 4.3. Travel costs by bus between different zones.

| $C_{ij}^{bus}$ | | | | |
|---|---|---|---|---|
| Zone | 1 | 2 | 3 | 4 |
| 1 | 0 | 0.7 | 0.8 | 0.75 |
| 2 | 0.65 | 0 | 0.7 | 0.8 |
| 3 | 0.75 | 0.6 | 0 | 0.75 |
| 4 | 0.75 | 0.9 | 0.8 | 0 |

### 4.4.3 Mode choice

As referred before, to compute the probability of taking the car instead of using the bus, we need to define a utility function (expression 36) that is the difference between the utility function for using the car and the utility function for using the bus. To simplify the computations, we rewrite expression 39 for the generalized travel costs as follows:

$$GC_{ij}^{car} = C_{ij}^{car} + 0.5 * P_j^{on} + 0.5 * P_j^{off} \qquad (47)$$

$$GC_{ij}^{bus} = C_{ij}^{bus} \qquad (48)$$

$$DC_{ij} = C_{ij}^{car} + 0.5 * P_j^{on} + 0.5 * P_j^{off} - C_{ij}^{bus} \qquad (49)$$

In these expressions, $GC_{ij}^{car}$ and $GC_{ij}^{bus}$ are the generalized costs of traveling by car and by bus, and $DC_{ij}$ is their differences.

The first part of expression 47 is the simplified version of the generalized cost for using the car (expression 38), $C_{ij}^{car}$. To complete that expression, we assume that the *impact* of parking in an *on-street* park or in an *off-street* park is half of the travel cost by car in the utility function (in practice, the real value can be directly estimated by a travel survey). This means that, in the generalized costs for traveling by car, $C_{ij}^{car}$ should be twice the value of *on-street* and *off-street* parking prices.

To use the differences between costs in the binary *logit* model, we use expression 49, and estimate probabilities by expression 50. $P_j^{on}$ and $P_j^{off}$ are obtained from the values in the sets $\pi_l^{on}$ and $\pi_l^{off}$, where $\pi_l^{on}$ ($\pi_l^{off}$) is the set of prices for an *on-street (off-street)* parking place per hour in the destination *j*, with *l* elements. Table 4.4 shows the values for $DC_{ij}$ for a scenario with $\pi_l^{on} = 1$ and $\pi_l^{off} = 2$ for zone *j* (we have assumed that in all destinations the parking prices are the same).

| Zone | 1 | 2 | 3 | 4 |
|------|------|------|------|------|
| 1 | 0 | 2 | 2.2 | 2.1 |
| 2 | 2 | 0 | 2.1 | 2.3 |
| 3 | 2.35 | 2.2 | 0 | 2.15 |
| 4 | 2.05 | 2.1 | 2.05 | 0 |

To compute the different portions of the total demand for each zone, we use the binary *logit* concept. As mentioned before, for this (randomly generated) case study, we assumed that the utility of each mode just results from the travel costs. We have computed $DC_{ij}$ as the differences between utilities. Then, based on the *logit* model, the portion of $Q_{ij}^{total}$ that travel by car from zone $i$ to zone $j$ (and similarly for buses) is computed as follows:

$$Q_{ij}^{car} = \frac{e^{\mu * DC_{ij}}}{1 + e^{\mu * DC_{ij}}} * Q_{ij}^{total} \qquad (50)$$

In this expression, µ is the coefficient for the regression of $DC_{ij}$, and it was made here equal to -0.3 – its negative sign means that the utility of driving by car is less than that of using the bus.

Cost in general is a "disutility" because when the travel cost increases, the utility of that mode decreases, as people are not interested in paying more. To have this negative utility, we take µ as negative. Moreover, the exponential function (that is multiplied on $Q_{ij}^{total}$) is based on the binary *logit* models that better reflect people's behavior. Table 4.5 shows the car usage share from the total $Q_{ij}^{total}$.

Table 4.5. Car usage share from the total $Q_{ij}^{total}$ for traveling from zone $i$ to zone $j$ (with $\pi_i^{on} = 1$ and $\pi_i^{off} = 2$ for all zones).

| Car usage share (in %) | | | | |
|------|------|------|------|------|
| Zone | 1 | 2 | 3 | 4 |
| 1 | 50 | 35 | 34 | 35 |
| 2 | 36 | 50 | 35 | 33 |
| 3 | 33 | 34 | 50 | 34 |
| 4 | 35 | 35 | 35 | 50 |

To find the total demand for a given destination zone, we need to sum the demand from all zones to that specific zone. So we define $Q_j^{car}$ and $Q_j^{bus}$ as a total demand (for car and bus) in the destination zone, as follows:

$$Q_j^{car} = \sum_{i=1}^{4} Q_{ij}^{car} \qquad (51)$$

$$Q_j^{bus} = \sum_{i=1}^{4}(Q_{ij}^{total} - Q_{ij}^{car}) \qquad (52)$$

Table 4.6 shows these values. The share of each mode depends on the general costs and the parking prices (expressions 49 and 50). We have assumed the price for *on-street* parking is 1 euro per hour per place, and for *off-street* parking is 2 euros per hour per place.

Table 4.6. Mode share on destination zone $j$
(for $\pi_l^{on} = 1$ and $\pi_l^{off} = 2$ equal for all zones).

| Destination zone | Bus share | Car share |
|:---:|:---:|:---:|
| 1 | 0.65 | 0.35 |
| 2 | 0.66 | 0.34 |
| 3 | 0.66 | 0.34 |

### 4.4.4 Effects on the demand of changes in parking prices

To help us understand the effects of the parking prices on the mode share of the demand, we have created a new scenario, doubling the *on-street* and the *off-street* parking prices (see table 4.7).

Table 4.7. Mode share on destination zone $j$
(for $\pi_l^{on} = 2$ and $\pi_l^{off} = 4$ equal for all zones)

| Destination zone | Bus share | Car share |
|:---:|:---:|:---:|
| 1 | 0.75 | 0.25 |
| 2 | 0.75 | 0.25 |
| 3 | 0.75 | 0.25 |
| 4 | 0.74 | 0.26 |

As we can see in table 4.7, the share of car use decreases by increasing the parking prices. In the first scenario (with $\pi_l^{on} = 1$ and $\pi_l^{off} = 2$), this share was around 35 %. In the second scenario, we doubled parking prices, and the result was around 25 %.

### 4.4.5 Current capacity of *on-street* parking

Other parameters have been defined, as it is the case of the *current capacity of on-street parking* for each zone. *On-street* parking places are those beside the roads and streets, and every zone has a specific capacity for *on-street* parking. To simplify the computations, we multiply the area of each zone by a random multiplier, to get the the number of *on-street* parking places.

The area of each zone, $S_j$, is used to compute the maximum capacity of *on-street* parking places $Z_j^{on}$ – this seems reasonable as it does not depend on the parking prices, but only on the associated area:

$$Z_j^{on} = (0.3 + 0.55 * R") * 300 * S_j \qquad (53)$$

In this expression, the random parameter $R"$ takes a value between 0 and 1, as a way to generate a random capacity for each zone. The values of 0.3, 0.55 and 200 were chosen to provide more realistic capacities – see table 4.8.

Table 4.8. Capacity of on-street parking (number of places).

| Zone | $Z_j^{on}$ |
|------|-----------|
| 1 | 312 |
| 2 | 302 |
| 3 | 297 |
| 4 | 323 |

## 4.4.6   Current capacity of *off-street* parking

Another parameter that needs to be defined for each zone is the current capacity of *off-street* parking. To simplify the computations, we consider the 80% of the maximum *on-street* parking capacity in each zone, as a measure for current *off-street* parking places. Table 4.9 shows the current capacity of off-street parking places in each zone, $Z_j^{off}$.

Table 4.9. Capacity of off-street (number of places).

| Zone | $Z_j^{off}$ |
|------|-----------|
| 1 | 191 |
| 2 | 182 |
| 3 | 177 |
| 4 | 201 |

## 4.4.7   Construction costs of an *off-street* park

Finally we need to define the costs of building *off-street* parks. Off-street parking buildings are costly structures, and, for our model, we have to compute the present value of constructing these buildings.

In average, and as a first approximation, we might say that an *off-street* park with 5 floors and 250 places per floor will cost around 6 million euros. This means 4,800 euros per place. The present value for 30 years, with an average interest rate of 0.05, will therefore be 1,111 euros per place per year – in our example, we will use this value. This value will be "randomized" by a parameter of $R'''$ (taking values between 0 and 1). The *off-street* parking construction costs $C_j^{off}$ for each zone are then computed as follows (see table 4.10):

$$C_j^{off} = 1111 * (1 + 0.1 * R''') \qquad (54)$$

| Zone | $C_j^{off}$ |
|------|-------------|
| 1 | 1214 |
| 2 | 1191 |
| 3 | 1209 |
| 4 | 1140 |

### 4.4.8 Results for the case study

We now apply our approach to solve the illustrative, small case study. As mentioned before, we are going to set a parking price to assign the demand to each zone, in order to maximize profit. As constructing an off-street park is rather costly, our objective function maximizes profit, by carefully defining the different revenues (benefits) and the costs.

As referred, we have defined two different sets of variables. The first set, $X_{jl}^{off}$, is related to the number of *off-street* parking places we need to add to each zone to balance the demand side with the supply side (parking places), maximizing profit. We therefore need to estimate the demand for *on-street* and *off-street* parking separately, based on the different scenarios of parking prices – the algorithm presented before was used for this purpose.

We used expression 55 to define the set of *on-street* parking prices, and assumed that *off-street* parking prices are 90% of those prices. So, we have run the model with the prices of expression 55 – results are presented in table 4.11 below.

$$\pi_l^{on} = \{2, 2.1, 2.2, 2.3, \dots, 4\} \qquad (55)$$

Table 4.11. Results for the case study with an unlimited budget

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|------------|-----|--------------|---------------|----------------|
| 1 | 11 | 3 | 2.7 | 274 |
| 2 | 10 | 2.9 | 2.61 | 7 |
| 3 | 12 | 3.1 | 2.79 | 141 |
| 4 | 11 | 3 | 2.7 | 323 |

As we see in table 4.11 for the case study, if there is no budget constraint, *on-street* parking prices should be set at the values 3, 2.9, 3.1, 3 euros per hour, for zones 1 to 4, respectively. An amount of 274, 7, 141, and 323 new *off-street* parking places need to be built for those zones, respectively. In this scenario, the total achieved value for the revenues per year is 21,755,023 euros.

We now assume that we have a limited budget to build 500 *off-street* parking places in all the zones of the case study. This means that the previous solution (with more than 700 *off-street* parking places) is not feasible anymore. We applied this constraint to the model, with the results shown in table 4.12.

Table 4.12. Results for the case study and with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 15 | 3.4 | 3.06 | 157 |
| 2 | 11 | 3 | 2.7 | 0 |
| 3 | 13 | 3.2 | 2.88 | 116 |
| 4 | 14 | 3.3 | 2.97 | 225 |

With the budget limit, the number of new parking places is 498 (less than 500) – see table 4.12. This solution is associated to increasing the parking prices. I.e., if in the first scenario the optimum *on-street* parking price for zone 1 was 3 euros per hour, with the budget limitation this price has been increased to 3.4 euros per hour. What is the reason for this increase? In fact, in the pre-processing stage of the model (demand component), by increasing the parking price, the total number of car drivers decreases for all zones. Therefore, with a lower number of travelers using the car, the number of places needed to be built also decreases, and consequently we can meet the budget. Naturally, when the parking prices in a specific zone increases, people tend to use public transportation – see expressions 56 and 57. From expression 49, when variables $P_j^{on}$ or $P_j^{off}$ increase their value, the value of $DC_{ij}$ also increases.

$$Q_{ij}^{car} = \frac{e^{\mu*DC_{ij}}}{1+ e^{\mu*DC_{ij}}} * Q_{ij}^{total} \qquad (56)$$

The term multiplied by $Q_{ij}^{total}$ in this expression can be written as:

$$\frac{e^{\mu*DC_{ij}}}{1+ e^{\mu*DC_{ij}}} \quad = \quad \frac{e^{\mu*DC_{ij}}+1-1}{1+ e^{\mu*DC_{ij}}} \quad = \quad 1 - \frac{1}{1+ e^{\mu*DC_{ij}}} \qquad (57)$$

We know that μ is negative. So, when $DC_{ij}$ increases, $\mu * DC_{ij}$ and $1 + \mu * DC_{ij}$ also decrease. When this happens, $\frac{1}{1+ e^{\mu*DC_{ij}}}$ will increase, and $1 - \frac{1}{1+ e^{\mu*DC_{ij}}}$ will decrease. So, the term multiplied by $Q_{ij}^{total}$ will decrease, and $Q_{ij}^{car}$ will also decrease. Therefore, when we increase the parking prices ($P_j^{on}$ or $P_j^{off}$), the car share of the demand decreases, and the demand for using other modes (such as bus, $Q_{ij}^{bus}$) will increase (equation 56).

In addition, we can observe that the increase in the prices is not linear, with the changes due to the travel costs in the zones and to the effects of the *logit* model. For example, while in zone 1, the price increases 0.4 euros, in zone 2 this increase is equal to 0.1 euros.

Limiting the budget also impacts the yearly profit. In this second scenario, the objective function value is 21,649,816 euros per year, less than in the first scenario. This means that lower budgets will lead to lower revenues and profits.

### 4.4.9 Sensitivity analysis

To have a better understanding of the model and how it works, here we perform some sensitivity analyses, by using different values for the different parameters of the model, and checking the impact of these changes in the results.

We start by changing the current capacity of the zones, in terms of parking places – we have increased these capacities by 20% (see results on table 4.13).

Table 4.13. Results for the case study by increasing current capacity by 20%, with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 12 | 3.1 | 2.79 | 143 |
| 2 | 8 | 2.7 | 2.43 | 0 |
| 3 | 12 | 3.1 | 2.79 | 46 |
| 4 | 11 | 3 | 2.7 | 218 |

Comparing table 4.13 with table 4.12, we find out that the parking prices are lower, and the number of required parking places is also lower. This means that if we have more parking places, the parking price for getting the maximum revenue should be lower. Moreover, the objective function value in this case is equal to 22,345,489 euros per year, which is higher than that in the previous case.

On the other hand, to analyze the effects of changing the number of current parking places, we have assumed that these places are 20% less than those of the the original case – see results on table 4.14.

Table 4.14. Results when we decrease the current capacity by 20% with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 17 | 3.6 | 3.24 | 205 |
| 2 | 16 | 3.5 | 3.15 | 0 |
| 3 | 19 | 3.8 | 3.42 | 80 |
| 4 | 18 | 3.7 | 3.33 | 215 |

As shown on table 4.14, when we start with a lower number of current parking places, the parking prices and the number of required places increase. But the revenue decreases to 20,493,058 euros per year. The changes shown in these tables are reasonable, and they show the model has an expected, balanced behavior, when changing the number of current parking places.

Next we analyze variations to the coefficients of $P_j^{on}$ and $P_j^{off}$ (in expression 47). These coefficients result directly from the statistical analysis and the *logit* model. So, in each case they are based on the specific gathered travel data. In expression 47, we assumed that these coefficients are equal to 0.5, and here we analyze the impact of increasing or decreasing this value by 0.05 (see table 4.15).

Table 4.15 Results for the case study by decreasing
parking price coefficients to 0.45, with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 18 | 3.7 | 3.33 | 176 |
| 2 | 14 | 3.3 | 2.97 | 0 |
| 3 | 17 | 3.6 | 3.24 | 107 |
| 4 | 18 | 3.7 | 3.33 | 216 |

As mentioned before, these coefficients come directly from the utility function, and they reflect the importance in people's behavior towards the prices. Decreasing these coefficients (and keeping the other coefficients fixed) in the generalized cost equation, shows a decrease of travelers' reaction towards the parking prices, when compared to the other costs. This interpretation is in line with the results of the model. In table 4.15, the optimum parking prices are higher than those in table 4.12, this showing that to maximize profit, we can increase the parking prices. In fact, decreasing the coefficients leads to an increase of the parking prices, with low effects in the demand. Obviously, there is also, in the objective function, another interaction of the parking prices and the demand, that leads to choosing the higher parking price for maximizing revenue.

Table 4.16. Result for the case study by increasing parking
price coefficients to 0.55, with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 12 | 3.1 | 2.79 | 154 |
| 2 | 8 | 2.7 | 2.43 | 0 |
| 3 | 10 | 2.9 | 2.61 | 119 |
| 4 | 11 | 3 | 2.7 | 225 |

Table 4.16 shows the results, when the coefficients of the parking prices are increased to 0.55. This increase means people are more sensitive to the parking prices than in the cases with lower coefficient values. This interpretation is in line with the results of the model. Increasing the importance of the parking prices, and their effects on the mode choice, has a direct impact on the optimal solution and in the revenues.

If, for instance, we increase the coefficient of one parking price, the demand for using the car decreases (by the exponential function), and when the demand decreases the optimum solution of the optimization

model changes (as the parking price is multiplied by the rate of change in demand). As mentioned before, the coefficients of the parking prices are computed statistically, and based on a travel survey.

We finally address changes in the total demand (see table 4.1 for an estimation of its value). Here, we change the total demand to values that are 10% less and 10% more than the values used in the base version – see tables 4.17 and 4.18.

Table 4.17. Results for the case study by decreasing the total demand by 10%, with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 12 | 3.1 | 2.79 | 169 |
| 2 | 8 | 2.7 | 2.43 | 0 |
| 3 | 12 | 3.1 | 2.79 | 79 |
| 4 | 11 | 3 | 2.7 | 239 |

By comparing the values in table 4. 17 (demand decreased by 10%, and all other parameters kept equal) to the values in table 4.12, we can see that the parking price to reach the optimum revenue has decreased. This change is rational, showing that when we have a lower total demand for a zone, the optimum parking price is lower than when we have a higher one.

Table 4.18. Results for the case study by increasing the total demand by 10%, with a budget limited to 500 places

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|
| 1 | 17 | 3.6 | 3.24 | 165 |
| 2 | 13 | 3.2 | 2.88 | 0 |
| 3 | 16 | 3.5 | 3.15 | 99 |
| 4 | 16 | 3.5 | 3.15 | 235 |

Finally, comparing table 4.18 (demand increased by 10%) with table 4.12, we see that to control excessive demand, we need to increase the parking price. By increasing this price, the share of the car demand decreases, but this share will be multiplied by the total demand (that was increased itself in this scenario), thus balancing the effects in the maximization objective function.

The different sensitivity analyses performed in this section clearly show the potential of the model (partially due to the interactions of components and the preprocessing stage) in supporting decision-making. In the next section, we present some extensions to this base model, thus trying to improve it.

## 4.5 Model extensions

We now present some extensions of the above model, that aim at potentially improving its practical usefulness. The base model has room for several developments, and we have therefore considered some

other important aspects such as social and environmental concerns, as explained in the following sections.

### 4.5.1 Environmental concerns

Our first extension to the model is related to environmental issues. Environmental concerns such as air pollution have become one of the priorities in the modern world, and it is crucial in practice to set policies or develop tools regarding these concerns. For this reason, we have defined a new constraint (expression 58) to control the environmental damages of using private cars.

*Maximize* :

$$\sum_{j=1}^{N} \sum_{l=1}^{M} 8 * 365 * \rho_{jl} * \pi_l^{on} * Q_{jl}^{on} + 8 * 365 * \rho_{jl} * \pi_l^{off} * \left(Q_{jl}^{off} + X_{jl}^{off}\right) - \rho_{jl} * C_{jl}^{off} * X_{jl}^{off} \qquad (43)$$

*Subject to*:

$$\sum_{l=1}^{M} \rho_{lj} = 1 \qquad\qquad \forall\, j\; in\; Zone \qquad\qquad (44)$$

$$\rho_{lj} * \left(Q_{jl}^{car} - \left(Q_{jl}^{off} + Q_{jl}^{on}\right)\right) = X_{jl}^{off} \quad \forall\, j\; in\; Zone\,, l\; in\; set \qquad (45)$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} X_{jl}^{off} \;\leq\; Budget \qquad\qquad (46)$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} \boldsymbol{\rho_{lj}} * \boldsymbol{Q_{jl}^{car}} \;\leq\; \boldsymbol{Environmental\; bound} \qquad\qquad (58)$$

With inequality 58 we impose a bound to the global demand in all zones. This constraint helps us to limit the total number of private vehicle travels in the entire city, thus controlling the hazardous effects of the air pollution.

For instance, for our case study (see previous section and the results in table 4.12), the number of car travels in each zone is shown in table 4.19.

Table 4.19. Total number of car travelers
(computed with the model results in table 12)

| Zone | $Q_{jl}^{car}$ |
|------|------|
| 1 | 660 |
| 2 | 471 |
| 3 | 590 |
| 4 | 749 |
| Total | 2470 |

This table shows the number of travelers by car, obtained with the model specifications that lead to the results in table 12. In total, we have 2470 per hour. If we want to bound the total number of vehicles in the city to 2000, thus decreasing the resulting air pollution, the extended model will lead to the results presented in table 4.20 as follows:

Table 4.20. Results of the model with environmental concerns (maximum 2000 cars)

| Zone ($j$) | $l$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $X_{jl}^{off}$ | $Q_{jl}^{car}$ |
|---|---|---|---|---|---|
| 1 | 20 | 3.9 | 3.51 | 32 | 535 |
| 2 | 15 | 3.4 | 3.06 | 0 | 400 |
| 3 | 18 | 3.7 | 3.33 | 5 | 479 |
| 4 | 20 | 3.9 | 3.51 | 58 | 582 |
|  |  |  |  | Total | 1996 |

By comparing this table with tables 4.12 and 4.19, we can observe that, in the optimum solution, the model has increased the parking prices, as a way to satisfy the environmental constraint. By this increase, the model decreased the number of travels by car (in the pre-processing stage) to 1996 instead of 2470, thus satisfying the environmental constraint.

On the other hand, this increase in the parking prices has a negative impact on the revenues (and on the objective function). From a previous value of 21,649,816 euros per year, in the model with environmental concerns, this value decreased to 20,922,628 euros per year. So, to reach our ideal environmental situation (in this case by limiting the maximum number of car travelers to 2000) is a costly decision, and this extended model can evaluate the monetary pros and cons of different alternatives (obtained, for example, by testing different values for the bound).

### 4.5.2 Independent *off-street* parking prices

In this section we are going to rewrite the model to consider that *off-street* parking prices are set separately, thus being independent from the *on-street* parking prices. In the previous sections we assumed that *off-street* prices were 90% of the *on-street* prices. Here, we consider another set of *off-street* parking prices, $\pi_k^{off}$, adding the index $k$ to the model:

$$\pi_k^{off} = \{2.5, 2.6, 2.7, 2.8, \dots, 4.5\} \qquad \pi_l^{on} = \{2.5, 2.6, 2.7, 2.8, \dots, 4.5\} \qquad (59)$$

The model with the new indices is as follows:

*Maximize* :

$$\sum_{j=1}^{N} \sum_{l=1}^{M} \sum_{k=1}^{K} 8 * 365 * \rho_{jlk} * \pi_l^{on} * Q_{jlk}^{on} + 8 * 365 * \rho_{jlk} * \pi_k^{off} * \left( Q_{jlk}^{off} + X_{jlk}^{off} \right) - \rho_{jlk} *$$
$$C_j^{off} * X_{jlk}^{off} \qquad (60)$$

*subject to*:

$$\sum_{l=1}^{M} \sum_{k=1}^{K} \rho_{jlk} = 1 \qquad \forall j \text{ in zone} \qquad (61)$$

$$\rho_{jlk} * \left( Q_{jlk}^{car} - \left( Q_{jlk}^{off} + Q_{jlk}^{on} \right) \right) = X_{jlk}^{off} \quad \forall j \text{ in Zone}, l \text{ in set}, k \text{ in set} \qquad (62)$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} \sum_{k=1}^{K} X_{jlk}^{off} \leq budget \qquad (63)$$

$$\sum_{j=1}^{N} \sum_{l=1}^{M} \sum_{k=1}^{K} \rho_{jlk} * Q_{jlk}^{car} \leq environmental\ limit \qquad (64)$$

119

$$\rho_{jlk} * \pi_k^{off} \geq 0.75 * \rho_{jlk} * \pi_k^{on} \qquad \forall \, j \, in \, zone \, , l \, in \, set, k \, in \, set \qquad (65)$$

$$\rho_{jlk} * \pi_k^{on} \geq 0.75 * \rho_{jlk} * \pi_k^{off} \qquad \forall \, j \, in \, zone \, , l \, in \, set, k \, in \, set \qquad (66)$$

$Q_{jlk}^{car}$: the cumulative demand for cars in destination zone $j$ when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_k^{off}$ (average number of cars per day);

$Q_{jlk}^{on}$: the demand for *on-street* parking in destination zone $j$ when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_k^{off}$ (average number of cars per day);

$Q_{jlk}^{off}$: the demand for *current off-street* parking in destination zone $j$ when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_k^{off}$ (average number of cars per day);

$C_j^{off}$: the construction cost of a parking place in zone $j$ (euros per space per year).

*Decision Variables:*

$\rho_{jlk}$: binary decision variables – 1, if the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_k^{off}$ for destination zone $j$; 0, otherwise;

$X_{jlk}^{off}$: number of new *off-street* parking places to be built in destination zone $j$ when the *on-street* parking rate is $\pi_l^{on}$ and the *off-street* parking rate is $\pi_k^{off}$ (average number of places per day).

As referred, one difference in this "extended" model is that we have the new index *k*. Moreover, we have introduced a set of additional constraints (equations 65 and 66). Constraints 65 control the differences between the *on-street* and the *off-street* parking prices. As mentioned before, in the pre-processing stage we assume the drivers prefer to first park *on-street*, and only then do they search for the *off-street* parking. This situation may not happen if the *off-street* parking becomes much cheaper than the *off-street* parking. Therefore, we assume that, for all the zones, the *off-street* parking prices cannot be more than 75% cheaper than the prices of *on-street* parking. Moreover, constraints 66 aim at preventing the excessive *cruising* for *on-street* parking, thus keeping prices in an acceptable range for drivers to change their type of parking – see table 4.21 below.

Table 4.21. Results of the model with separate parking
sets, no environmental limit, and a budget limited to 2000 places.

| Zone ($j$) | $l$ | $k$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $Q_{jlk}^{car}$ | $X_{jl}^{off}$ |
|---|---|---|---|---|---|---|
| 1 | 3 | 12 | 2.7 | 3.6 | 683 | 180 |
| 2 | 9 | 1 | 3.3 | 2.5 | 461 | 0 |
| 3 | 16 | 6 | 4 | 3 | 483 | 9 |
| 4 | 1 | 9 | 2.5 | 3.3 | 829 | 305 |

The objective function value for this scenario is 22,190,890 euros per year. This value is higher than the one in table 4.12, and the reason is that here we are choosing *off-street* parking prices from a separate set, with a flexible range of 75% movements between *on-street* and *off-street* parking price differences.

Table 4.22. Results of the model with separate parking
sets, with a environmental limit, and a budget limited to 2000 places.

| Zone ($j$) | $l$ | $k$ | $\pi_l^{on}$ | $\pi_l^{off}$ | $Q_{jlk}^{car}$ | $X_{jl}^{off}$ |
|------------|-----|-----|--------------|---------------|-----------------|----------------|
| 1 | 20 | 9 | 4.4 | 3.3 | 501 | 0 |
| 2 | 20 | 9 | 4.4 | 3.3 | 304 | 0 |
| 3 | 18 | 8 | 4.2 | 3.2 | 441 | 0 |
| 4 | 3 | 12 | 2.7 | 3.6 | 744 | 220 |

When we consider the environmental limit (equation 64), the parking prices change in a way that the total number of car drivers does not exceed 2000. However, the profit decreases to 21,449,775 euros per year. These changes are not obvious – for instance, for zone 1, the *on-street* parking price has increased 1.7 euros per hour, but the *off-street* price has decreased 0.30 euros. These changes are different among the different zones, and they result both from the pre-processing stage and the optimization model of our approach.

The above examples clearly show the flexibility of the model in tackling different scenarios, and in becoming an interesting decision support tool. The decision maker plays an important role here, in analyzing *trade-off* solutions considering criteria such as the budget or the environmental impacts.

## 4.6  Conclusion

In this chapter of the dissertation, we described in detail the mathematical models we have developed for the parking problems under study. These models were based on the methodological approaches presented in chapter 3, aiming to consider the structural costs of *off-street* parking in a flexible approach. We started by designing a *base* model, and have later developed some extensions to that model.

In the base model, we have assumed the drivers will surely park in their destination zones. Binary variables are used to model the *on-street* parking prices and the number of new off-street parking places – these variables connect the optimization model to the demand model and to the pre-processing stage. The objective is simply the maximization of profit.

In this model, changing the parking prices has several effects on the optimization model – on the demand estimation, and on the parking prices to be used in the objective function of the optimization model. The constraints of the optimization model assure that the demand and the supply are equal, and that the total budget is respected.

In order to validate and assess our approach, we randomly generated a small case study (a small city with 4 zones). The application of the approach to this case showed its flexibility and the potential to support decision-making. This conclusion was reinforced by performing some sensitivity analyses, used to find the best prices for *on-street* and *off-street* parking in the different zones.

We later extended our *base* model, by considering bounds for the total number of car drivers, as a way to include environmental concerns into the model. The goal here was to help decreasing the harmful effects of the particles in the air. Finally, we have extended the model to separately consider *on-street* and *off-street* parking prices.

From these first experiments of our integrated approach (based on a small, illustrative case study), we can conclude that *on-street* and *off-street* parking need to be priced carefully, to attract people towards parking garages, and thus decrease the traffic resulting from cruising for parking spaces.

To apply this model to a real city, we need to carefully analyze the demand and the supply sides of the problem. For the demand, we will need a travel survey to feed the binary *logit* model used to define the use of cars and buses. In addition, data related to the geographical characteristics of the area under study has to be collected.

We believe the approach has a considerable potential to handle other several interesting issues. For instance, we should be able to support the design of a more advanced and integrated policy for parking prices, for all zones of a city, with flexibility to cope with different scenarios, considering different budgets or environmental constraints. It should be mentioned that some important aspects that can affect parking prices such as the public transportation price could have been included in our models, but for keeping models simpler to solve, we did not consider those aspects.

In the next chapter, we apply and explore our integrated approach with the county of San Francisco, in California, as a larger, more realistic case study.

# 5 Case study

## 5.1 Introduction

In this chapter we are going to apply the approach developed in this research project to a real case study, explaining the models in detail and showing their potential.

The case study was designed for the county of San Francisco, in California, USA. One of the reasons to choose this case was the availability of data. In previous years, several studies on transportation and mobility have been done in the area of the San Francisco Bay, and lots of valuable data have been gathered for this region. Census data from the San Francisco Bay area, and the transportation 2035 plan for this area, are two important sources of data that we have used to calibrate and test our framework and models.

Here we first go through the history of the transit in the area of the San Francisco Bay, that involves main six modes briefly described in the following paragraphs.

*Cable Car*

In September 1873, the Clay Street Hill railroad started a cable car service in Clay, from Leavenworth to Kearny. The line became popular and profitable very fast, and allowed the development of the area that previously had been largely undeveloped. The success of this line led to the implementation of other cable car systems. In 2011, the fare revenue of the cable car was around 25 million dollars, and today, it stands as the world's last manually operated cable car system.

*Street Car*

The regular service for the San Francisco's and San Mateo's first electric streetcar line started in April 1892. The line ran from Steuart and Market, to the Holy Cross Cemetery in what is now Colma, San Mateo County. The streetcar is the second oldest type of vehicle in the San Francisco system and operates now on Market Street and Embarcadero.

*Motor Bus*

The 1st September 1917 was the first day of motor bus transit service in San Francisco, operated by Muni. The first routes were temporary and were meant to help people without transit service. Nowadays, Muni operates approximately 80 routes throughout San Francisco, with stops within 2 blocks of 90% of all residences in the city, and more than 200 million annual passenger miles.

*Trolley Bus*

The trolley bus line in San Francisco started in October 1935. This was the first trolley bus service in the city. The line was a transformation of the the streetcar operation over Twin Peaks, that had been in

service since November 1894. The trolley buses are not only cleaner and more energy efficient, but also operate better in the hilly terrains that are common in the city. Today San Francisco has the largest trolley bus fleet of any transit agency in the US and Canada.

*Light Rail*

In December 1980, the K, L, M and N metro lines began full weekday service. Although "Muni Metro" and "Light Rail Vehicle" were new terms, many people thought that this service is a modernized version of the old streetcar system, and they did not accept it as an entirely new system. Muni metro was operating a fleet of 151 light rail vehicles, with the top speed of 35 mph, having over 170,000 daily ridership.

*Heavy rail*

The population of the counties of Alameda, Contra Costa, and San Francisco, voted for the approval of a 792 million bond issue for the Bay Area Rapid Transit (BART) construction in November 1962. BART began service in September 11, 1972, with more than 100,000 passengers in its first five days of operation. This heavy rail is the youngest fleet in the system, and it has proven to be a worthwhile investment, serving the bay area residents quite well. This system has a fleet of 669 vehicles.

In the next sections, we present the application of our framework to the real case study, explaining how it was changed and tuned to become fully functional. The travel survey that we are going to use to calibrate our demand model was gathered by the Metropolitan Transportation Commission. This data divided the San Francisco county into 190 zones. This databank contains 10,744 lines of valid data, each line being one trip.

## 5.2 Model

As mentioned above, in general, we consider that the drivers park their cars in their destination zone. Figure 5.1 presents our integrated approach, showing the interaction of the demand-supply component with the optimization model. The system starts with data collection, and then a travel demand modeling procedure is used to forecast demand. The demand component of the approach and the mode-choice stage of the travel demand model are used as an input for the optimization model. The optimization model maximizes profit, and includes the supply side decision variables. These variables are parking prices, parking locations, and the number of parking places.
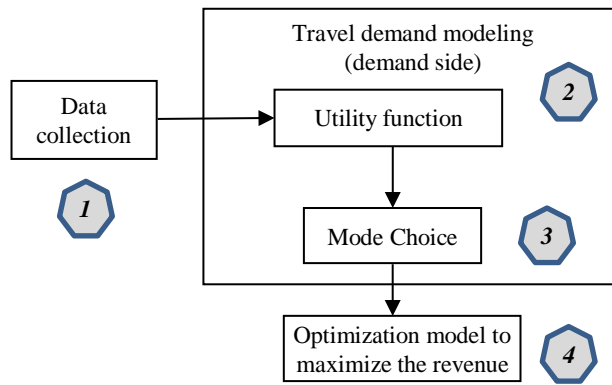
Figure 5.1. General structure of the model

### 5.2.1 Data collection

In a first step of the approach, data is collected and gathered, to be used as an input for the model. These data include travel surveys, geographical data and park capacities related to the zones of study.

#### *5.2.1.1 Total number of generated trips and trip table*

The total number of trips for a given area is forecasted based on different parameters such as activity and land-use in the area – it shows, in an aggregated way, the total number of trips that take place there. This data contains the total *home-based* and *non home-based* trips with different goals such as work or shopping. The source for this numerical data was the *Transportation 2035 Plan for the San Francisco Bay Area (Travel forecasts data summary, pages 58-61)*. This document (published in December 2008), predicts the total number of county to county *home-based work* and *non-work* trips until the year 2035. For the San Francisco county, and for 2010, the total number of daily trips (for an average day) was calculated as 1,759,578 (this does not include walking trips).

Figure 5.2 shows the zones in the San Francisco county. This zoning system (known as TAZ1454) includes San Francisco and the whole bay area, and has 1454 zones (with190 zones in the San Francisco county).
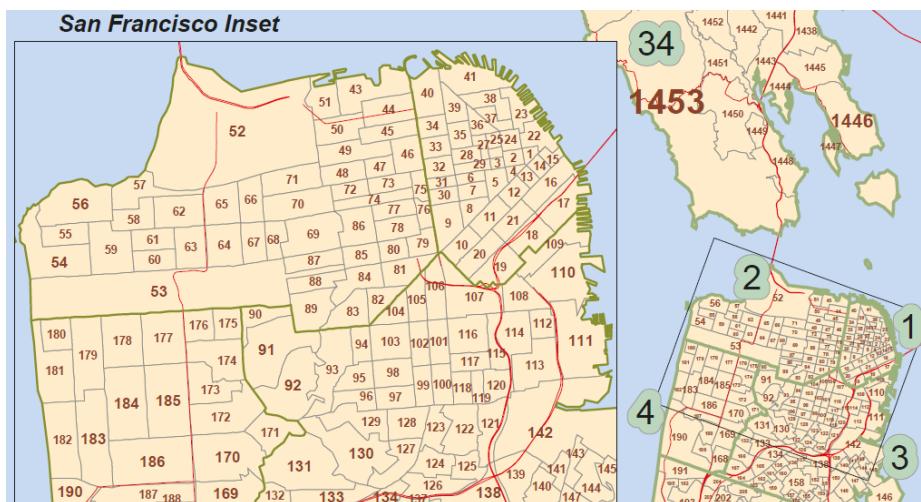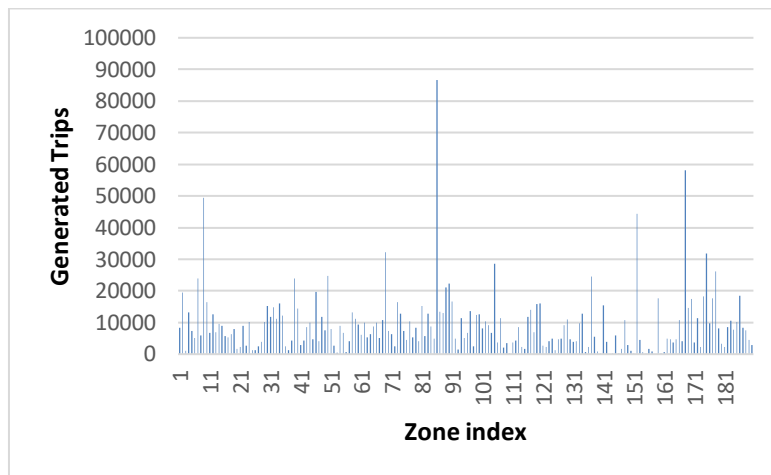


Figure 5.2. Zoning map of San Francisco county (TAZ1454).

The trip tables used in this work were available in the website of the *Metropolitan Transportation Commission* for the San Francisco county and the bay area. Graph 5.1 is directly extracted from those tables, and shows the trips for each of the 190 zones.



Graph 5.1. Generated daily trips for the San Francisco county, for the 190 zones.

As we can see in this graph, zone 86 generates the highest number of trips per day (86,719). Zones such as 168, 9, and 152 are among those with the highest generated trips.

Graph 5.2 shows the number of attracted trips for each zone. These numbers represent the demand in each zone, being the daily total number of trips towards each zone.
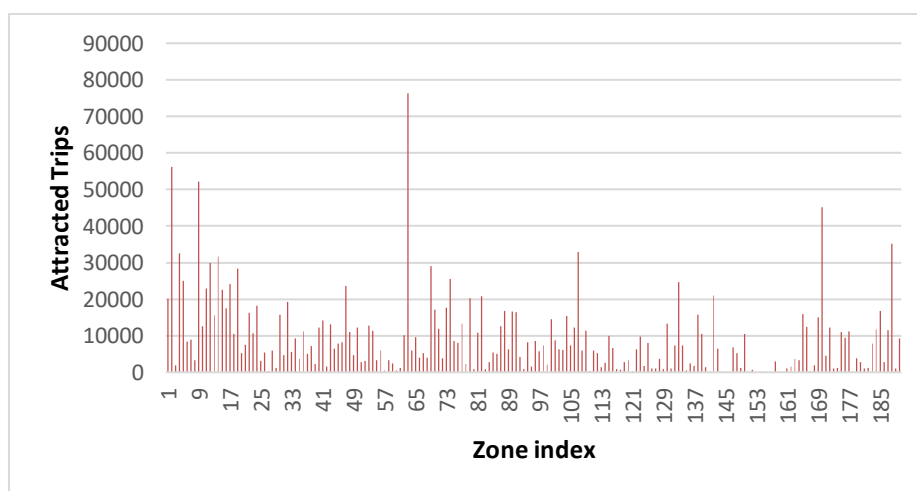


Graph 5.2. Attracted trips for each of the 190 zones.

The trips in this graph are, for each zone, the summation of all the trips generated in the different zones, with that specific destination. For instance, zone 63 with 76,368 trips per day has the maximum demand.

A simple analysis shows that this zone has several businesses and points of interest for the travelers, thus attracting more people than the other zones.

Other zones such as 2, 9, and 170 also "attract" many trips during the day, and in fact they are viewed as crowded zones in the San Francisco county. Moreover, zones from 1 to 20 attract many trips and they are neighbors of the CBD area of San Francisco. On the other hand, zones such as those from 153 to 157, do not attract any trip from other zones.

### 5.2.1.2 Distance between zones

The study area was divided into zones, based on the land-use of the different areas. The distances were computed by Google maps, as the distances between the center of the zones (in kilometers). The zoning system used here is the 1454 zone system of the San Francisco Bay Region, that is based on the 2000 census tracts.

As referred, this zoning system divided the San Francisco county into 190 zones (and 4 "super-districts").

### 5.2.1.3 Current number of on-street parking

The total current number of *on-street* parking places in each zone is estimated by the total length of the roads and streets for each zone, divided by an average length of a car. To compute these numbers, we used the length of the streets in four different zones (in four "super-districts"). We then divided these values by the total area of the zones, to compute the average number of *on-street* parking for square kilometer. Finally, we multiplied this ratio by the area of each zone, thus estimating the number of *on-street* parking in each zone.

### 5.2.1.4 Current number of off-street parking

The current number of *off-street* parking places was estimated for each zone, by the number of currently existing private or public parking garages and parking buildings. This data was based on the 2000 census tracts and on Google maps.

For the San Francisco county, over 1397 *off-street* parking (public or private) garages were identified. They were distributed at the level of the *super-districts,* and then the average number of the *off-street* parking places was calculated for each zone in every *super-district.*

### 5.2.1.5 Present value for the construction costs of an off-street parking

*Off-street* parking buildings (garages) are costly structures. We therefore tried to carefully estimate the present economic value of the construction costs of an average size *off-street* park, with 5 floors and 250 places in each floor. These costs may be around 6 million dollars, this meaning a value of around 4800 dollars per place. The present value for 30 years and an interest rate of 0.05 is, therefore, 1111 dollars per place per year.

127

However, this cost is an average cost, and depending on the different land uses, it can be higher or lower. This means that in zones in the CBD area, the price of land is obviously higher than in the zones with lower levels of attraction. Therefore, we cannot consider the average calculated cost for all the zones, and we have modified the price of the new *off-street* parks for each zone, based on its land use and on its demand. For this purpose, a ratio to the base price was applied.

### 5.2.1.6 *Fuel price and fuel usage for a normal car per kilometer*

The amount of fuel used by an average car per kilometer was considered to be 9 liters per 100 kilometers, with a fuel price of 2 dollars per litter.

Obviously, these values can be quite different in other contexts and situations, thus requiring a careful estimation. However, this should not negatively impact the validation of our approach.

### 5.2.1.7 *A travel survey*

A trip survey is also required for the area of study. This survey should contain the *origin* and the *destination* of each trip, the *mode* of transportation, and the *travel cost* and *travel time* for the trip. The travel cost can be computed in different ways, the most natural way being to calculate the distances for each trip and then multiplying these distances by the fuel costs.

In our case study we have used the data from the travel survey done in 1998 for the San Francisco Bay area, by the Metropolitan Transportation Commission MTC.

## 5.2.2 Mode choice

The next step of our approach is the mode choice stage of the travel demand modeling process. In this step, we use the estimated distributed demand between zones and the travel survey, to estimate the mode travelers will choose for their trips. Here we assume that there are just two modes of transportation: private cars and bus.

In this step, a travel survey is used as a sample for the travelers driving between the different zones, and for the travel costs, travel times and parking costs. This data is used to define the utility function. For travel demand modeling a *Logit* model is used. The utilities and probabilities of making a choice are then computed as follows:

$$V_{car} = \alpha * P^{off} + \beta * P^{on} + \gamma * COST + \delta * TIME + \theta \tag{67}$$

$$V_{bus} = \gamma * COST + \delta * TIME \tag{68}$$

$$P_{car} = \frac{e^{V_{car}}}{e^{V_{Bus}} + e^{V_{car}}} \tag{69}$$

$$P_{bus} = 1 - P_{car} \tag{70}$$

$V_{car}$: utility of choosing the car as the travel mode;

$V_{bus}$: utility of choosing the bus as the travel mode;

$P_{car}$: probability of choosing the car as the travel mode;

$P_{bus}$: probability of choosing bus modes (not the car);

$P^{off}$: *off-street* parking price;

$P^{on}$: *on-street* parking price;

$\alpha, \beta, \gamma, \delta$: model parameters estimated by the *Nlogit* software, from the travel survey;

$\theta$: a constant of the model.

The utility function of using the car is calculated by the *Nlogit*, having as input a restructured version of the travel survey.

```
+------------------------------------------+
| Discrete choice and multinomial logit models|
+------------------------------------------+
Normal exit from iterations. Exit status=0.
+------------------------------------------+
| Discrete choice (multinomial logit) model   |
| Maximum Likelihood Estimates                |
| Model estimated: Jun 16, 2016 at 11:01:41AM.|
| Dependent variable              Choice      |
| Weighting variable                None      |
| Number of observations            1111      |
| Iterations completed                 6      |
| Log likelihood function      -468.1911      |
| Number of parameters                 5      |
| Info. Criterion: AIC =         .85183       |
|   Finite Sample: AIC =         .85188       |
| Info. Criterion: BIC =         .87439       |
| Info. Criterion:HQIC =         .86036       |
| R2=1-LogL/LogL*  Log-L fncn  R-sqrd  RsqAdj |
| Constants only.  Must be computed directly. |
|                Use NLOGIT ;...; RHS=ONE $ |
| Chi-squared[ 4]        =    152.39486       |
| Prob [ chi squared > value ] =   .00000     |
| Response data are given as ind. choice.     |
| Number of obs.= 1111, skipped   0 bad obs. |
+------------------------------------------+


+------------------------------------------+
| Notes No coefficients=> P(i,j)=1/J(i).     |
|       Constants only => P(i,j) uses ASCs   |
|         only. N(j)/N if fixed choice set.  |
|          N(j) = total sample frequency for j |
|          N    = total sample frequency.    |
|        These 2 models are simple MNL models. |
|        R-sqrd = 1 - LogL(model)/logL(other) |
|        RsqAdj=1-[nJ/(nJ-nparm)]*(1-R-sqrd)  |
|          nJ   = sum over i, choice set sizes |
+------------------------------------------+
+--------+-------------+---------------+--------+--------+
|Variable| Coefficient | Standard Error |b/St.Er.|P[|Z|>z]|
+--------+-------------+---------------+--------+--------+
A       |   -.28295376    .13092444     -2.161   .0307
B       |   -.50694286    .31454498     -1.612   .1070
C       |   -.92494060    .09154901    -10.103   .0000
D       |   -.22785316    .09510038     -2.396   .0166
CONST   |   9.15050094    .98513603      9.289   .0000
```

Figure 5.3. Software output for the discrete choice model

The travel survey is a *revealed preference* data, and each line of its file describes a trip by bus or by car (this data was restructured by the SPSS Statistics 19 version, leading to two lines for each trip). After testing the different generic or specific coefficients, the model is calibrated, and expressions 71 and 72 can be written as follows:

$$V_{car} = -0.28295 * P^{off} - 0.5069 * P^{on} - 0.9249 * COST - 0.2278 * TIME + 9.1505 \qquad (71)$$

$$V_{bus} = \qquad\qquad -0.9249 * COST - 0.2278 * TIME \qquad\qquad (72)$$

Figure 5.3 presents the output of the *Nlogit* model, with the associated tests.

The travel survey (done, as referred above, in 1998) includes 11,527 trips for the 190 zones. The variables of the *Nlogit* model are travel costs, travel times between zones, and *on-street* and *off-street* parking prices (the likelihood test and t-tests were used in the model).

For applying the mode choice models to the San Francisco county (data for 2010), we need to have distributed trips for that year, the distances and travel costs between the zones (as explained in the previous section).

Finally, we need to have the travel costs and the travel times. Two main travel costs (prices) exist: fuel consumption and trip tolls. For our case study, these prices were computed for the year 2010. From the *Transportation 2035 Plan for the San Francisco Bay Area* (Travel forecasts data summary, page 49), the fuel cost was 3 dollars per gallon, and the tolls are increased by 2.9% per year – see expression 73. In addition, the travel time between two zones can be approximately computed dividing the distance by the average speed.

$$Travel\ cost\ between\ zones = Fuel\ costs + Tolls \qquad\qquad (73)$$

$$Travel\ time\ between\ zones = \frac{Distance}{Average\ speed} \qquad\qquad (74)$$

Expression 71 then gives us, for all the zones, the utility of using the car. With the *logit* model and equations 69 and 70, we compute the probabilities of using the car or other mode of transportation, based on the travel survey mentioned above. These probabilities are then multiplied by the distributed demand data.

The demand for 2010 was computed as the average daily demand. To estimate the demand for the peak hours of the day, the values in table 5.1 were used.

Table 5.1. Share of average weekday vehicle miles of travel

| Time Period | Share of travel |
|---|---|
| 00:00 - 06:00 | 5.80% |
| 06:00 - 10:00 | 25.00% |
| 10:00 - 15:00 | 27.90% |
| 15:00 - 19:00 | 28.70% |
| 19:00 - 24:00 | 12.60% |

From 6:00 am to 10:00 am (AM peak period) the share of travel is 25%, and the peak period of the afternoon is considered to be from 15:00 am to 19:00 am. So, at the peak hours, the number of travelers that will use the car is obtained by multiplying the probability by the corresponding share of the travel demand.

$$Demand\ for\ car = \quad Share\ of\ travel\ (peak\ hour) * Probability\ of\ using\ car *$$
$$Distributed\ demand\ for\ car\ and\ transit \qquad (75)$$

The following expressions are then used to compute the different costs:

$$Fuel\ cost\ for\ car = \frac{3\left(\frac{\$}{gal}\right) * 1(km) * 0.1\left(\frac{lit}{km}\right)}{3.7854\left(\frac{lit}{gal}\right)} = 0.079\ \$/km$$

$$Travel\ time\ by\ car = \frac{1\ km}{40\ km/h} = 0.025\ hr$$

$$Travel\ cost\ by\ bus = 0.5\ \$\ for\ 1\ kilometer\ trip$$

$$Travel\ time\ by\ bus = \frac{1}{20\ km/h} = 0.05\ hr$$

We have assumed that the average speed of a car is 40 kilometers per hour, and that of a bus is 20 kilometers per hour. The travel cost for a bus kilometer trip is assumed to be 0.5 dollars.

### 5.2.3 Optimization model

The next component of the approach is the optimization model, dealing with the supply side. The travel demand by car is used as an input for the assignment of the parking places. Accordingly, the objective function of our model aims at maximizing the revenues of the parking places minus the construction costs of the new parks. Constraints on the demand and on the supply are considered in the model.

The revenue component of the objective function considers the ticket prices and the number of parking places that are going to be built. This revenue is yearly, and computations are done for the peak periods of the day.

In addition, the model has a specific process to assign the demand to the parking areas: first, the total current parking places in each zone are calculated, and then compared with the total future demand. If the current places are more than the total future demand, the required number of *off-street* parking places is set to 0, i.e., there will be no need to build a new *off-street* park. Otherwise, we need to build new

spaces, assuming that first the current *on-street* and *off-street* parking places become full, and then the extra demand will use the new parking places.

As mentioned, two different types of decision variables were defined. The first variables $X_j^{off}$ are the number of *off-street* parking places in each zone, that need to be added to balance the demand with the supply. This is, how many *off-street* parking places do we need to build to satisfy the future demand and maximize the revenues.

In addition, we have defined binary variables $\rho_{jl}$ to choose one specific parking price for zone $j$, from a set of prices (a set with $k$ elements). Considering a time horizon of one year, to maximize the net profit, we finally have the following model:

*Maximize* :

$$\sum_{j=1}^{N}\sum_{l=1}^{M} 365 * 4 * \rho_{jl} * \pi_l^{on} * Q_{jl}^{on} + 365 * 4 * \rho_{jl} * \pi_l^{off} * \left(Q_{jl}^{off} + X_{jl}^{off}\right) - \rho_{jl} * C_{jl}^{off} * X_{jl}^{off} \qquad (76)$$

*subject to*

$$\sum_{l=1}^{M} \rho_{lj} = 1 \qquad\qquad \forall\, j\ in\ Zone \qquad\qquad\qquad (44)$$

$$\rho_{lj} * \left(Q_{jl}^{car} - \left(Q_{jl}^{off} + Q_{jl}^{on}\right)\right) = X_{jl}^{off} \quad \forall\, j\ in\ Zone\,, l\ in\ set \qquad\qquad (45)$$

$$\sum_{j=1}^{N}\sum_{l=1}^{M} X_{jl}^{off} \ \leq\ Budget \qquad\qquad\qquad\qquad (46)$$

$$\sum_{j=1}^{N}\sum_{l=1}^{M} \rho_{lj} * Q_{jl}^{car} \ \leq\ Environmental\ limit \qquad\qquad\qquad (58)$$

The only difference between this model and the one presented in chapter 4 is that the new objective function (expression 76) considers 4 peak hours (instead of 8). So, the values of $Q_{jl}^{on}$, $Q_{jl}^{off}$ and $X_{jl}^{off}$ are average hourly amounts.

In the next section we present and discuss the results obtained for this real case study, in three different scenarios.

## 5.3 Results for the case study

In this section we present and analyze the results obtained for the San Francisco county case study, in three different scenarios. In the first scenario, we assume there are no budget or environmental bounds. Then, we add a budget constraint, and finally, we take the environmental constraints into account.

In the small illustrative case of the previous chapter, to solve the models we have used a student version of the optimization software Xpress IVE, version 7.9. Due to the limitations of this software for the real

case study, we have moved to the full version of Cplex 12.5.1, rewriting the models accordingly. Complementary code was written in Java.

In this setting, and with the model applied to the San Francisco county case study (for all the 190 zones), each run of the software was taking between 1 to 2 minutes. In fact, this new implementation of the model helped us to significantly improve the previous time consuming method for parking pricing.

### 5.3.1    First scenario (with no additional constraints)

In the first tested scenario, we do not include any budget constraint or any environmental bounds. We assume we have an unlimited budget to build the *off-street* parks, and at the same time we do not consider any environmental concerns. In this case, the model works separately for each zone, computing the ideal parking prices for the 190 zones of the city, based on people's behavior and their willingness to pay, and on the costs of new parks. The model maximizes the difference between the revenues from the parking tickets and the costs of new parks, taking changes in the demand into account. The set of parking prices is as follows

$$\pi_l^{on} = \{0.25, 0.5, 0.75, 1, 1.25, \ldots, 10\}, \quad \pi_l^{off} = 0.9 * \pi_l^{on} \qquad (76)$$

The results for this first scenario are shown on graph 5.3, with the hourly parking prices for all the 190 zones of the San Francisco county case study (in dollars).
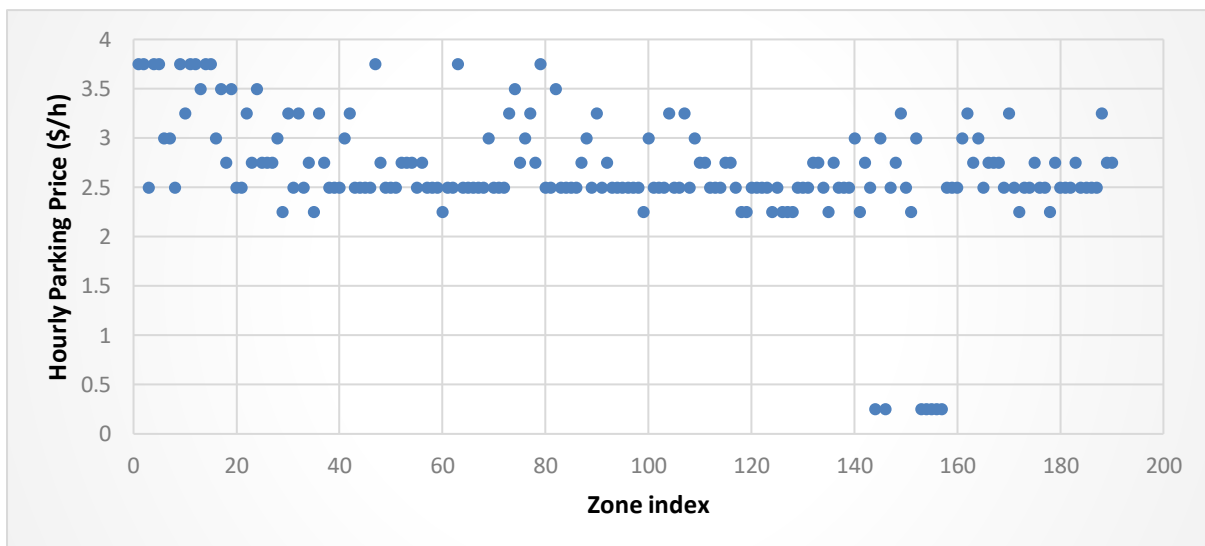


Graph 5.3- Parking prices for the San Francisco county case study (with no additional constraints)

The parking prices fall mainly in the interval between 2.25 and 3.75 dollars per hour, except for a few zones, between zone 144 and zone 157, where the price is 0.25 dollars per hour. The reason is that in these zones, demand is null, no drivers' attraction occurs, and, therefore, the parking prices are set to their lowest possible values.

133

Among the other parking prices, we can observe a variation of 1.5 dollars. This variation depends on the demand model, on the willingness to pay, and on the objective of the optimization model.

For instance, in zone 63, the one with the highest demand, the model proposes a price of 3.75 dollars per hour, which is the highest price. At the same time, there are other zones with lower demands (such as zones 2, 9, or 79) which have the same high parking price. In fact, zones are different in terms of demand, current parking places, and land value. In this example zone 63 has the highest demand from those three zones, but at the same time it has more parking places and the same land value. It is, in fact, the combination of these different factors that leads the model to set the same (highest) price. Graph 5.4 shows the number of *off-street* parking places to be built in each zone.
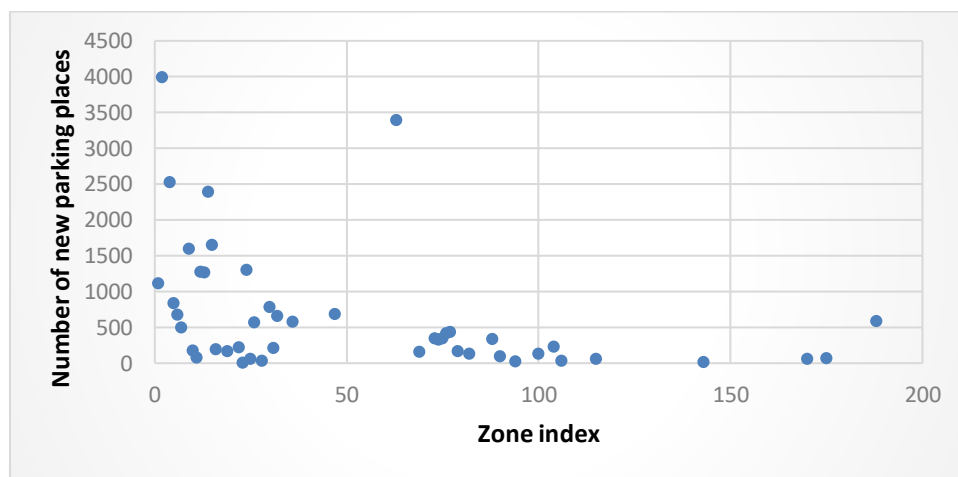


Graph 5.4. Number of new parking places for each zone (in the first scenario)

The two highest numbers are for zones 2 and 63. These two zones have the highest demand (see graph 5.2) and, based on our model, they also need the majority of the new parking places. The total number of new parking places is 30,754, with an objective function value of 950 million dollars.

One interesting feature of this solution is the distribution of the new parking places. Zones 1 to 45 are very crowded zones and mostly in the CBD area of San Francisco, with the model proposing for those zones, many of the new parking places. And naturally, the less crowded areas, such as zones 100 to 170, do not need so many new parks.

### 5.3.2 Second scenario (with a budget constraint)

Without additional constraints (see previous section), the required number of extra places is 30,754. Here, we are going to include a budget constraint and assume the decision maker can just afford to invest on 15,000 extra *off-street* parking places for the entire city (basically, half of the necessary number of places). This is expressed in the model by constraint 46, limiting the budget to 15,000. This constraint also makes the model more coherent (for the different zones), with no separate computations

for each zone. The results for this second scenario are shown on graph 5.5, with the hourly parking prices for all the 190 zones.
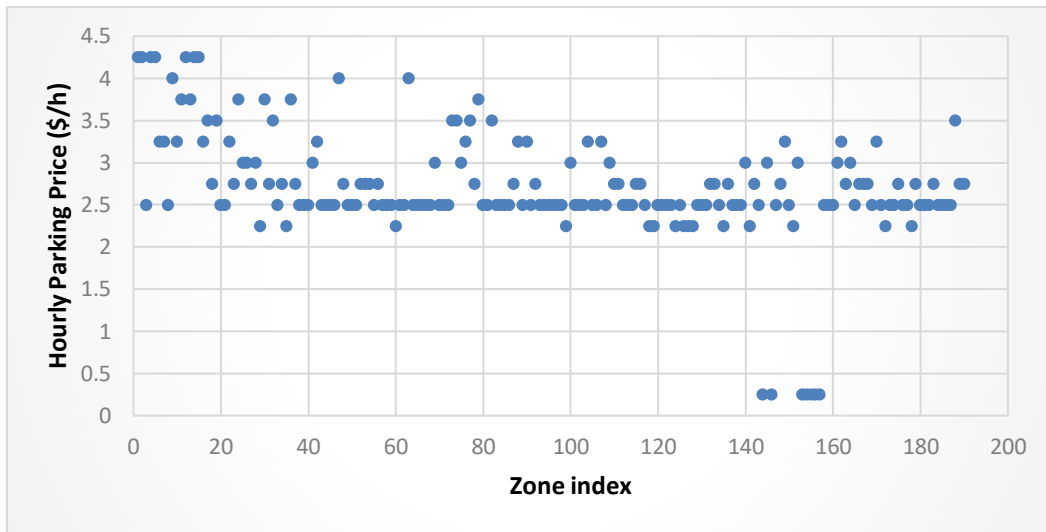


Graph 5.5- Parking prices for all zones (with a budget of 15,000 new places)

By limiting the budget and making the model more coherent, we can notice that the range of the parking prices became wider (with values from 2.25 to 4.25 dollars per hour). Graph 5.3 shows the differences between the parking prices in the first scenario (brown dots) and in the second scenario (blue dots).
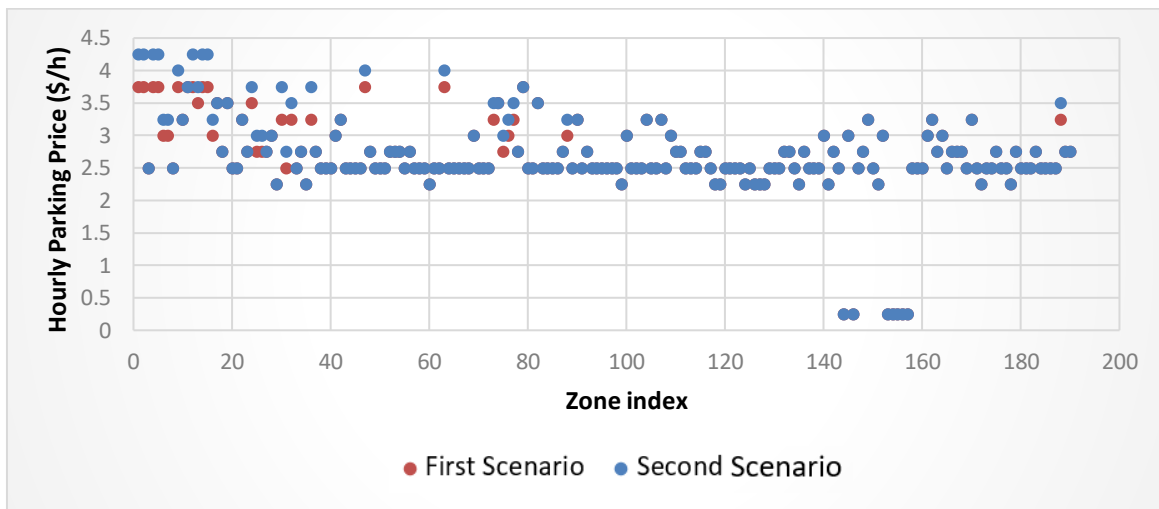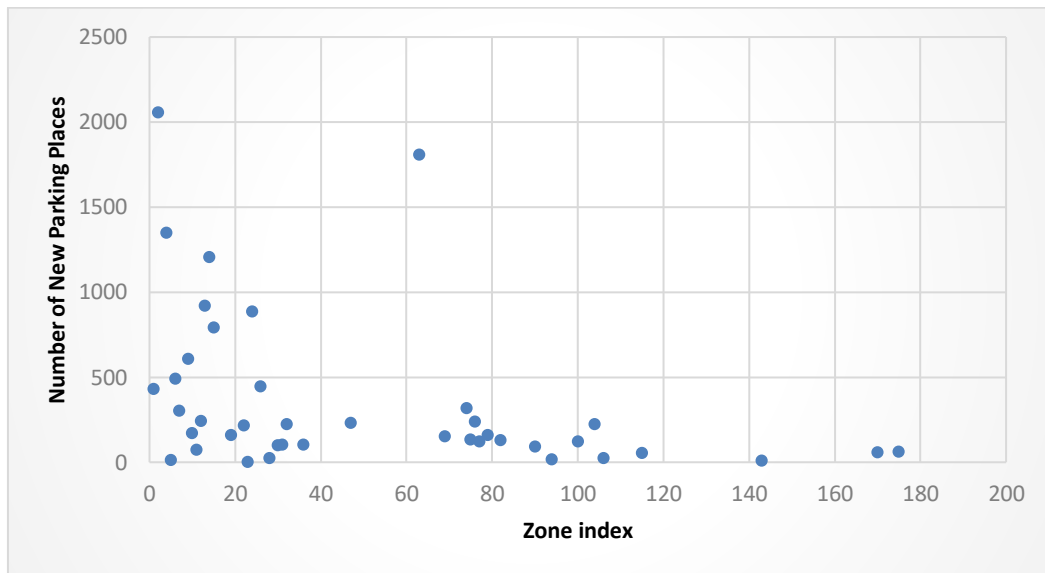


Graph 5.6. Comparing the parking prices between the first scenario (brown dots) and the second scenario (blue dots)

We can observe that there are some zones where the parking prices increase, due to the budget limitation. In fact, by increasing the parking price in these zones (expression 71), the model increases

135

the travel costs, and consequently there is a decrease in the demand in those zones, in such a way that the total number of new parking places is less than 15,000.

These actions decrease the attraction of those zones (for car users), leading to a decrease of cars traveling to those zones, thus respecting the total budget. This computation is done in a cohesive way, maximizing the objective function, and setting the total number of new off-street parking places to 14,943 (see graph 5.7).



Graph 5.7. Number of new parking places in each zone (second scenario)

We can see, for instance, that in zone 2, by increasing the parking price from 3.75 to 4.25 dollars per hour, the number of necessary parking places decreased from 3,986 to 2,058. These changes are such that the necessary new parking places are below 15,000, and the objective function is maximized.

Graph 5.8 shows the differences between the number of new parking places in the first scenario – no budget constraint (brown dots) and in the second scenario, considering a budget (blue dots).
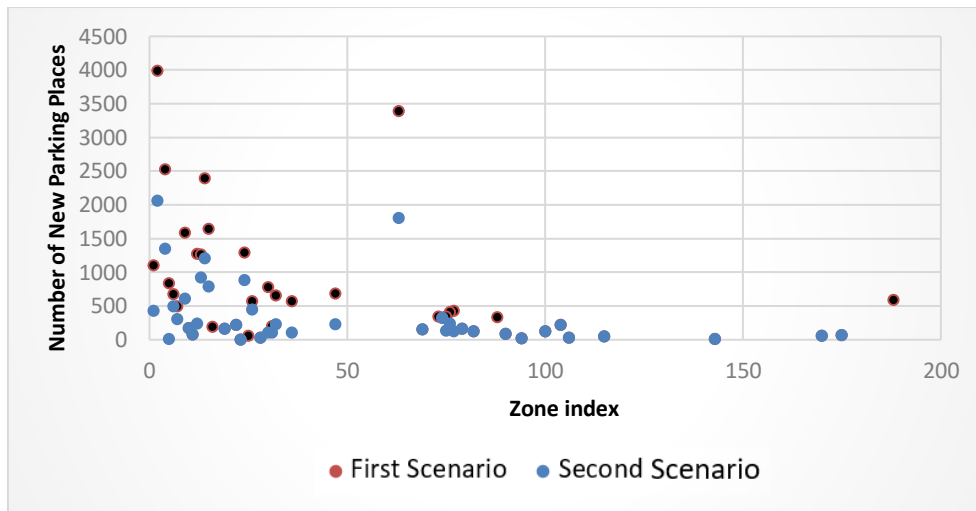
Graph 5.8. Comparing the number of new parking places between the first scenario (brown dots) and the second scenario (blue dots)

In the second scenario, with the budget constraint, the yearly amount of revenues will be 943 million dollars, lower than that of the previous scenario. This means that, when the budget is not enough, the yearly parking revenues will be lower. So, up to a certain level, higher investments will mean higher profits.

### 5.3.3 Third scenario (with budget and environmental constraints)

In the final scenario, the model is extended to include an environmental constraint, designed to decrease the hazardous effects of air pollution – this is achieved by imposing a limit to the total number of car drivers. In the first and in the second scenarios, the total number of car drivers in the peak hours was 252,215 and 235,820, respectively. Here we assume the maximum number of drivers is 200,000, and that there is  a budget limit for building extra *off-street* parking places. See the results on graph 5.9.
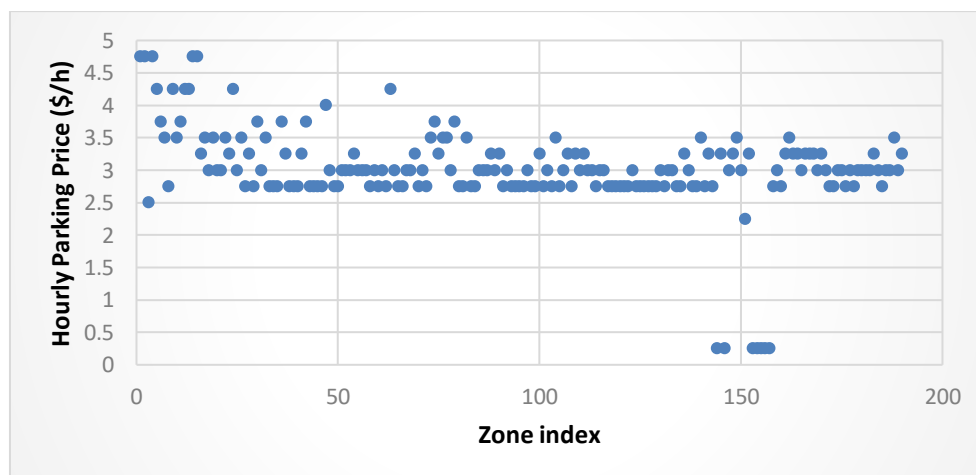


Graph 5.9. Parking prices, with a budget of 15,000 new places, and a maximum of 200,000 travels by car for peak hours

As we can see on this graph, parking prices have a significant increase when compared to those of the previous scenario. Prices fall into a wide interval 2.25 - 4.75 dollars per hour. This increase in the prices leads to a significant decrease in the total amount of car drivers (less than 200,000). Graph 5.10 shows the changes in the parking prices from the previous to the current scenario.
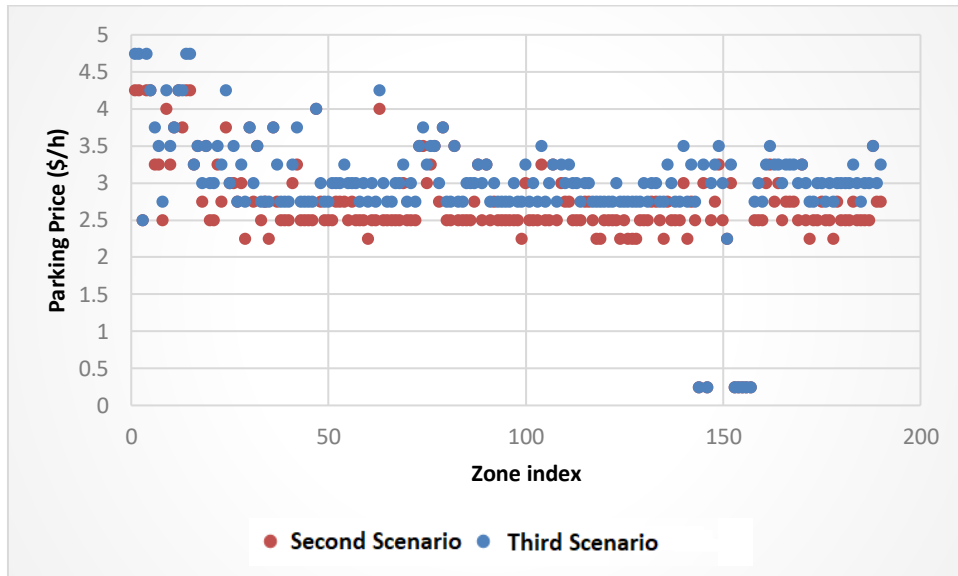


Graph 5.10. Comparing the parking prices between the second scenario (brown dots) and the third scenario (blue dots)
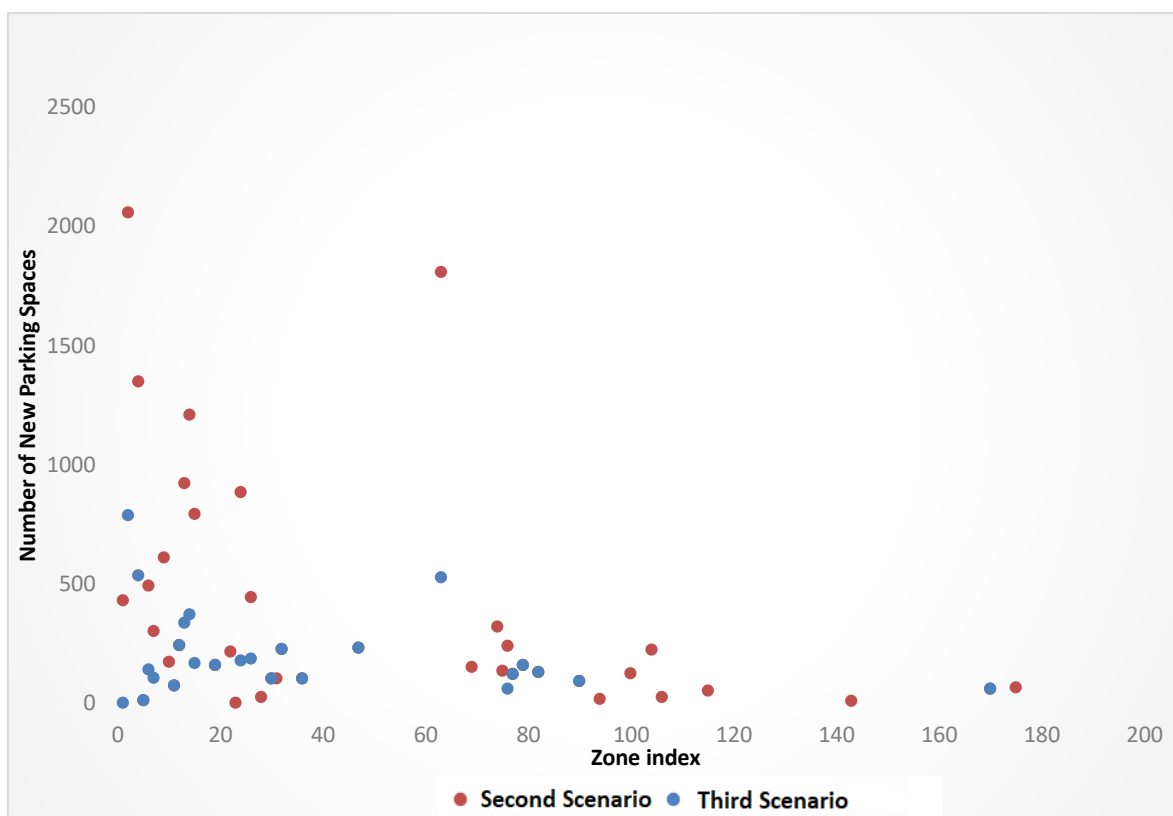
We can see (graph 5.10) that in the third scenario (considering the environmental constraint), we have a significant increase in the parking prices, for most of the zones. As referred above, these increases significantly depend on factors such as demand, capacity, willingness to pay, land use, etc.
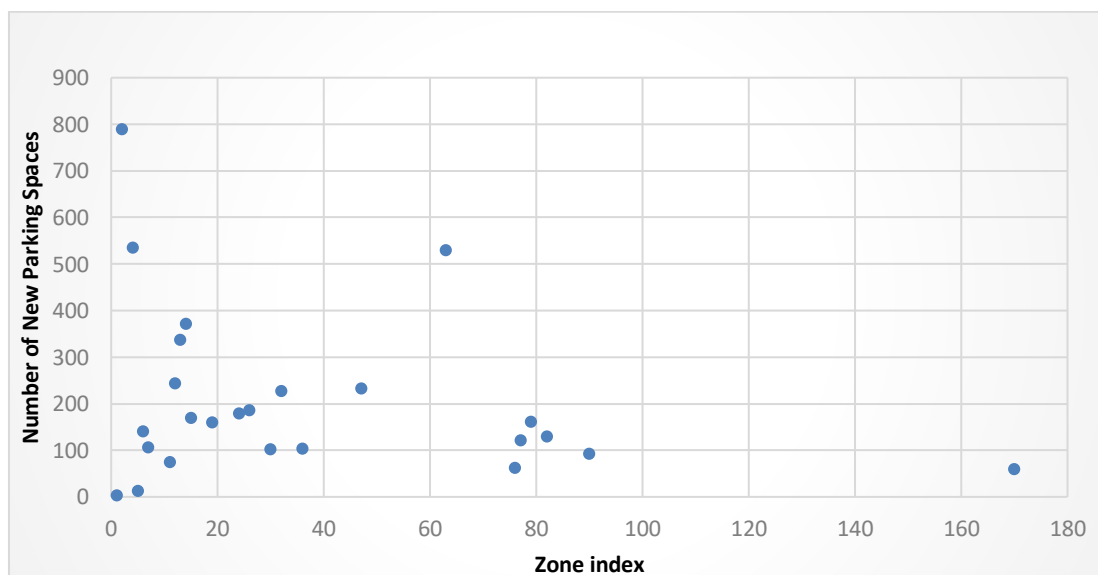


Graph 5.11. Number of new parking places in each zone (third scenario)

138

Graph 5.11 shows the new needed *off-street* parking places. In total, we need more 5,138 places, clearly below the 15,000 budget, and also below the value for the second scenario. In this third scenario, when the model satisfies the environmental constraint, it automatically satisfies the budget constraint, and set it lower than the budget. By increasing the parking price, the total amount of needed parking places will decrease, as well as the annual revenues ( 904 million dollars).

Graph 5.12 compares the number of new parking places between the second (brown dots) and the third scenario that includes an environmental constraint (blue dots).



Graph 5.12. Comparing the number of new parking places between the second (brown dots) and the third scenario (blue dots)

As we can see in most of the zones, the number of new *off-street* parking places has decreased in the third scenario, with few zones keeping the same number.

The decrease in revenues happens because in all zones we have an increase in the parking prices leading to a decrease in the demand for parking. This is also a result of considering the negative environmental effects of private cars. These options, meant to improve the environment, imply a decrease of around 20 million dollars yearly in the revenues. Improving environmental health and decreasing the air and

sound pollution is costly, and the model allows us, to some extent, to estimate these costs, and analyzing different *trade-off* solutions.

## 5.4 Conclusion

In this chapter, we applied our approach to a large, hopefully representative case study, based on data from the city of San Francisco, in California. Through a comprehensive research on different internet sources, we collected and estimated a coherent set of multiple data and parameters. We ran and assessed the model (base version and extensions) for three different scenarios, including budget and environmental constraints.

Our approach includes two main integrated components: a pre-processing stage and an optimization model. Binary variables (for selecting the parking prices) are used to connect these two components, and to linearize the model. These variables "move" on the demand curve, to help us find the optimum parking prices, for all the zones, maximizing total revenues. Decision variables are also used to define the number of new *off-street* parking places that should be built in each zone, based on the demand and the construction costs.

In the case study, parking prices vary between 2 and 5 dollars per hour, for different zones, and comparing these values to the current prices in San Francisco they are quite reasonable. Most of the new *off-street* parking places are in the CBD area, and this seems to be natural as the CBD area of the city absorbs most of the demand.

As it is natural, both the parking prices and the new extra *off-street* parking places vary if any element of the model, such as the coefficient of the demand model or the number of current parking places, changes. Different forms of sensitivity analysis have been performed in the previous chapter, in order to show and explore these changes, as a way to support the decision-making processes.

In conclusion, we believe that the proposed framework for modeling and supporting the design of parking policies is quite robust and flexible, as it was demonstrated with the San Francisco county case study. Nevertheless, our approach can easily be extended and improved by further including other decision makers' perspectives and travelers' concerns, in order to find more balanced and sustainable solutions for the parking problems of modern cities. There are, therefore, several opportunities for interesting future research in this area.

# 6 CONCLUSION

## 6.1 CONCLUSIONS AND MAIN CONTRIBUTIONS

Here we briefly present the key conclusions and results of this doctoral project, emphasizing our main contributions, both in terms of scientific results and practical applications:

- We have developed a comprehensive framework to model and analyze parking problems, and to help decision-makers selecting parking prices and investing in the construction of new *off-street* parks. This framework simultaneously includes the most important components of the parking problem and congestion issues. It is a flexible and robust approach, to support the design of more balanced and sustainable solutions for the parking problems of modern cities.

- This integrated framework allows a multi-perspective evaluation of different strategies, and can significantly impact on the parking design policies. Integration of the demand and the supply sides is guaranteed by the developed approach, by providing balanced solutions for these two problem components.

- A flexible design (as provided by our approach) can substantially optimize *off-street* parks. In big cities, the construction of new parks or the enlargement of existing ones, is strongly related to aspects such as the parking prices and congestion, and this needs to be taken into account in decision-making processes.

- If the traffic on roads and streets and the related congestion can be characterized correctly and in a meaningful way, we can price parking places reasonably well. A detailed analysis of the demand needs therefore to be performed in a first stage of the process.

- Our approach can be used to define the amount of land to be allocated to parking places, based simply on the parking prices (and on the resulting demand patterns).

- The optimum parking prices vary with different inter-related factors such as the demand, *on-street* and *off-street* parking capacity, land use, fuel cost, budget for new parks, and environmental concerns. Our approach analyzes these different factors in an integrated way.

- Demand is clearly an important factor in parking pricing – this aspect is well reflected in our models.

- Current *on-street* and *off-street* parking capacity has a significant effect on parking prices, and the areas of the city with a sufficient number of parking places have lower parking prices – this aspect is well reflected in our models.

- The land use and the price of the land are important factors in parking pricing. When demand exceeds supply, in more expensive areas, parking prices are naturally higher.

- The fuel cost has a negative effect on the parking prices. By increasing the fuel cost, the use of private vehicles decreases, and consequently parking prices become lower.

- The initial budget for building or enlarging new parks has a direct impact on the parking prices. If the budget is larger, we can cope with a higher demand on specific zones, and consequently parking prices become lower – this aspect is well reflected in our models.

- Environmental concerns have a strong impact in parking prices. In this thesis, we used the total number of car drivers in a city as a measure for air pollution, and we have shown that, if we want to increase the air quality and decrease the total amount of cars, parking prices should increase significantly. This increase in prices will help to attract less car drivers, and consequently we will have a better air quality.

## 6.2 FUTURE DEVELOPMENTS

A research project of this nature obviously raises opportunities for further work. In particular, concerning our framework and its models, we anticipate the following interesting extensions and improvements:

- The demand component of the framework could use a more detailed nested *logit* model, instead of the current binary *logit* one. The *on-street* and *off-street* parking decisions for car drivers can be more detailed, thus requiring a more comprehensive travel survey to find all the necessary coefficients.

- Short-term and long-term parking might be added to the model, in order to allow a more accurate analysis of the parking durations (behind the simple average times). This could be added by a simple linear model, with direct effects on the parking prices.

- The cruising time could be handled, by adding a new constraint to the model, or by considering it in the objective function. Apparently, the cruising time model proposed by Schoup could be easily adopted by our models and framework.

- Investment management on new parks can be significantly improved by more elaborate economic models.

- The environmental impacts of parking policies and systems can be grouped into subcategories, based on the specific requirements of the communities and the authorities. Moreover, the effects of different types of pollution related to parking (and to the associated policies) could surely be studied in more detail.

# 7 REFERENCES

Abidi, S., Krichen, S., Alba, E., Molina, J.M. (2015). 'A New Heuristic for Solving the Parking Assignment Problem'. Procedia Computer Science, Elsevier, Vol. 60, Pp.312-321.

Anderson, S.P. and De Palma, A. (2004). The Economics of Pricing Parking: Journal of Urban Economics 55 1–20.

Arnott, R. and Inci, E. (2005). An Integrated Model of Downtown Parking and Traffic Congestion.

Arnott, R. (2006). 'Spatial Competition Between Parking Garages and Downtown Parking Policy'. Transport Policy, Elsevier, Vol. 13, Pp. 458-469.

Arnott, R. and Rowse, J. (2008). 'Downtown Parking in Auto City'. Regional Science and Urban Economics, Vol. 39, Pp. 1-14

Arnott, R., Palma, A.D., Lindsey, R. (1990). 'A Temporal and Spatial Equilibrium Analysis of Commuter Parking'. Journal of Public Economics, Vol. 45, Pp. 301-335.

Arnott, R. (2014). 'On the Optimal Target Curbside Parking Occupancy Rate'. Cesifo Working Paper Series, No. 4416.

Arnott, R., Inci, E., Rowse, J. (2014). 'Downtown Curbside Parking Capacity'. Journal of Urban Economics, Elsevier, Vol. 86, Pp. 83-97.

Arnott, R. and Rowse, J. (1999). Modeling Parking: Journal of Urban Economics 45, 97-124.

Asgari, H. and Jin X. (2015). 'Towards a Comprehensive Telecommuting Analysis Framework; Setting the Conceptual Outline", Transportation Research Record, Journal of Transportation Research Board, No. 2496, Pp.1-9.

Asgari, H., Jin, X., Du, Y. (2016). 'Examining the Impacts of Telecommuting on the Time-Use of Non-Mandatory Activities', Transportation Research Record (Trr), Journal of Transportation Research Board, No. 2566, Doi: 10.3141/2566-09, In Press.

Asgari, H. (2015). "On the Impacts of Telecommuting Over Daily Activity/Travel Behavior: A Comprehensive Investigation through Different Telecommuting Patterns". Fiu Electronic Theses and Dissertations. Paper 2182.

Banister, D. (2005). Unsustainable Transport: City Transport in the New Century, Transport, Development and Sustainability. London; New York: Routledge.

Banister, D. (2008). The Sustainable Mobility Paradigm. Transport Policy, 15:73-80.

Ben-Akiva, M. And Lerman, S.R. (1985). Discrete Choice Analysis: Theory and Application to Travel Demand. Mit Press.

Barter, P.A. (2011). 'Off-Street Parking Policy Surprises in Asian Cities'. Cities, Vol. 29(1), Pp. 23-31.

Bendor, T., Westervelt, J., Song, Y., Sexton, J.O. (2012). 'Modeling Park Development through Regional Land Use Change Simulation'. Land Use Policy, Vol. 30, Pp. 1-12.

Bento, A., Cropper, M., Mobarak, A.M., Vinha, K. (2005). The Effects of Urban Spatial Structure on Travel Demand in the United States. The Review of Economics and Statistics 87 (3), 466-478.

Benenson, I., Martens, K., Birfir, S. (2008). Parkagent: An Agent-Based Model of Parking in the City: Computers, Environment and Urban Systems 32, 431–439.

Bradley, S.P., Hax, A.C., Magnati, T.L. (1977). Applied Mathematical Programming. Addison-Wesley Pub.

Brown, S.A. And Lambe, T.A. (1971). 'Parking Prices in the Central Business District'. Pergamon Press, Pp. 133-144.

Caicedo, F., Blazquez, C., Miranda, P. (2012). 'Prediction of Parking Space Availability in Real Time'. Journal of Expert Systems with Applications: An International Journal, Vol. 39, Pp. 7281-7290.

Caicedo, F. (2011). 'Changing Parking By The Minute: What to Expect from this Parking Pricing Policy?'. Transport Policy, Vol.19, Pp. 63-68.

Calthrop, E. and Proost, S. (2006). Regulating On-Street Parking. Regional Science and Urban Economics 36 (1), 29-48.

Calthrop, E., Proost, S., Van Dender, K. (2000). Parking Policies and Road Pricing. Urban Studies 37 (1), 63-76.

Cohen, Y. (1987). 'Commuter Welfare under Peak-period Congestion Tolls: Who Gains and who Loses?'. International Journal of transport Economics 14, 289-266.

Donald, C.S. (1999). The Trouble with Minimum Parking Requirements. Transportation Research Part A, 33(7): 549–574.

D'acierno, L., Gallo, M., Montella, B. (2006). Optimization Models for the Urban Parking Pricing Problem: Transport Policy 13, 34–48.

Feng, S., Chen, Y., Li, H., Deng, L. (2009). 'Class of Comprehensive Optimization of Congested Road-Use Pricing and Parking Pricing'. Journal of Transportation Systems Engineering and Information Technology, Vol. 9, Pp. 74-79.

Ferilli, G. (2008). An Analysis of the City Centre Car Parking Market: the Supply Side Point of View, School of Engineering and the Built Environment Edinburgh Napier University.

Gallo, M., Montella, B., D'acierno, L. (2011). 'A Multilayer Model to Simulate Cruising for Parking in Urban Areas'. Transport Policy, Elsevier, Vol.18, Pp. 735-744.

Garcia, R. and Marin, A. (2002). Parking Capacity and Pricing in Park'n Ride Trips: A Continuous Equilibrium Network Design Problem: Annals of Operations Research 116, 153–178.

Gila, A. and Mahalel, D. (2006). Congestion Tolls and Parking Fees: A Comparison of the Potential Effect on Travel Behavior. Transport Policy 13 (6) 496-502.

Gillen, D.W. (1975). 'Estimation and Specification of the Effects of Parking Costs on Urban Transport Mode Choice'. Journal of Urban Economics, Elsevier, Vol. 4, Pp. 186-199.

Glazer, A. and Niskanen, E. (1992). 'Parking Fees and Congestion'. Regional Science and Urban Economics, Vol. 22, Pp. 123-132.

Glover, F. (1977). Heuristics for Integer Programming Using Surrogate Constraints. Decision Science, 156-166.

Goldberg, D.E. (1989). Genetic Algorithms in Search, Optimization, and Machine Learning. Kluwer Academic Publisher.

Van der Goot,.D. (1981). 'A Model to Describe the Choice of Parking Places'. Transportation Research Part A: General, Vol. 16, Pp. 109-115.

Handy, S. (2008). Regional Transportation Planning in the US: An Examination of Changes in Technical Aspects of the Planning Process in Response to Changing Goals. Transport Policy, 15:113-126.

Hensher, D.A. and King, J. (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.

Hollander, Y., Prashker, J.N., Mahalel, D. (2006). Determining the Desired Amount of Parking Using Game Theory: University of Leeds.

Hunt, J.D. and Teply, S. (1993). 'A Nested Logit Model of Parking Location Choice'. Transportation Research Part B: Methodological, Vol.27, Pp. 253-265.

Inci, E. and Lindsey, R. (2015). 'Garage and Curbside Parking Competition with Search Congestion'. Regional Science and Urban Economics, Elsevier, Vol. 54, Pp. 49-59.

Jansson, J.O. (2010). 'Road Pricing and Parking Policy'. Research in Transportation Economics, Elsevier, Vol. 29, Pp. 346-353.

Jin, X., Asgari, H., Hossan, M. (2014). 'Understanding Trip Misreporting in Household Travel Surveys by Comparing Gps-Assisted and Diary-Based Samples'. Cictp 2014: Pp. 3401-3412. Doi: 10.1061/9780784413623.326.

Jin, X., Mohseni, A., Asgari, H. (2014). 'Choice, Frequency, and Engagement – a Framework for Telecommuting Behavior Analysis and Modeling'. Transportation Research Record: Journal of the Transportation Research Board, No. 2413, Pp. 101-109.

Jin, X., Asgari, H., Hossan, S. (2014). 'Understanding Trip Misreporting Behavior Using Global Positioning System-Assisted Household Travel Survey'. In 'Mobile Technologies for Activity-Travel Data Collection and Analysis', Chapter 6, Igi Global, 2014. Doi: 10. 4018/ 978-1-4666-6170-7.

Jun, C. and Wei, W. (2003). The Planning Model for Locating Urban Parking Facilities and the Design of Genetic Algorithm: Proceedings of the Eastern Asia Society for Transportation Studies, Vol.4.

Kim, S.R., Dominici, F., Buckley, T.J. (2007). Concentrations of Vehicle-Related Air Pollutants in an Urban Parking Garage. Environmental Research 105 (3), 291-299.

King, D.A. (2009). Exploring the Localization of Transportation Planning: Essays on Research and Policy Implications from Shifting Goals in Transportation Planning, Dissertation, UC Berkeley, 2009.

Kolozsvari, D., Shoup, D. (2003). Turning Small Change to Big Changes. No. 23, Pp. 2-7.

Kocur, G., Hendrickson, C. (1981). 'Design of Local Bus Service with demand equilibration'. Transportation Science. Vol 16, No 2.

Kuzmyak, J.R., Weinberger, R., Pratt, R.H., Levinson, H.S. (2003). Parking Management and Supply, Chapter 18, Report 95, Transit Cooperative Research Program; Transportation Research Board.

Lam, W.H.K., Tam, M.L., Yang, H., Wong, S.C. (1999). Balance of Demand and Supply Parking Spaces. Transportation Research Board, 707-731.

Larson, R.C. and Sasanuma, K. (2007). Congestion Pricing: A Parking Queue Model. Working Paper.

Litman, T. (2006). Parking Management Best Practices, Planners Press.

Mackowski, D., Bai, Y., Ouyang, Y. (2015). 'Parking Space Management via Dynamic Performance-Based Pricing'. Transportation Research Procedia, Elsevier, Vol. 7, Pp. 170-191.

March, A. (2007). Toward Strategic Planning for Car Parking. Working Paper.

Mardsen. G. (2006). The Evidence Base for Parking Policies- A Review. Transport Policy, 13(6), 447-457.

Michael, B. and Mokhtarian. P. (2002). The Impact of Residential Neighborhood Type on Travel Behavior: A Structural Equations Modeling Approach. The Annals of Regional Science 36, 279-297.

Nguyen V.M. (2010). Mathematical Modeling and Simulation. Phd Desertation.

Ortuzar, J.D. and Willumsen, L.G. (2001). Modeling Transport. Wiley and Sons, 3rd Edition.

Ommermen, J.V., Wentink, D., Dekkers, J. (2011). 'The Real Price of Parking Policy'. Journal of Urban Economics, Vol. 70, Pp. 25-31.

Ommeren, J.V. and Russo, G. (2014). 'Time-Varying Parking Prices'. Economics of Transportation, Vol. 3(2).

Pierce, G., Willson, H., Shoup, D. (2015). 'Optimizing the Use of Public Garages: Pricing Parking by Demand'. Transport Policy, Vol. 44, Pp. 89-95.

Qian, Z. And Rajagopal, R. (2014). 'Optimal Dynamic Parking Pricing For Morning Commute Considering Expected Cruising Time'. Transportation Research Part C: Emerging Technologies, Vol. 48, Pp. 468-490.

Roth, G.J. (1965). 'Paying For Parking'. London Institute Of Economic Affairs, Series Of Hobart Paper, 0073-2818.

Rye, T. (2010). Parking Management: A Contribution towards Livable Cities, Module 2c, Sustainable Transportation: A Sourcebook for Policy-Makers in Developing Countries, Sustainable Urban Transport Project.

Shoup, D. (2005). The High Cost of Free Parking. Chicago: Planners Press, American Planning Association.

Shoup, D. (1997). 'Evaluating the Effects of Cashing Out Employer-Paid Parking: Eight Case Studies'. Transport Policy, Elsevier, Vol. 4, Pp. 201-216.

Shoup, D. (2004). 'The Ideal Source of Local Public Revenue'. Regional Science and Urban Economics, Elsevier, Vol. 4, Pp. 753-784.

Shoup, D. (2006). 'Cruising for Parking'. Transport Policy, Vol. 13, Pp. 479-486.

Shoup, D. and Pickrell, D. (1978).'Problems with Parking Requirements with Zoning Ordinances'. Traffic Quarterly, Vol. 32, Pp. 545-563.

Sokolowski, J.A. and Banks, C.M. (2009). Principles of Modeling and Simulation. Hoboken, Nj: Wiley. P. 6.

Straatemeier, T. (2008). How to Plan for Regional Accessibility? Transport Policy, 15:127-137.

Su, Q. and Zhou, L. (2011). 'Parking Management, Financial Subsidies to Alternatives to Drive Alone and Commute Mode Choices in Seattle'. Regional Science and Urban Economics, Vol. 42, Pp. 88-97.

Talbi, E.G. (2009). Methaheuristics: From Design to Implementation. Wiley.

Thompson, R.G. and Richardson, A.J. (1996). 'A Parking Search Model'. Transportation Research Part A: Policy and Practice, Elsevier, Vol. 32(3), Pp. 159-170.

Vaziri, M., Dashtestaninejad, H., Asgari, H., Salimi, F. (2014). 'Rural Travel Behavior in Developing Countries: A Study of Farm-Based Villages in Iran'. The Journal of Sustainable Mobility, Vol.1, No.2, Pp. 25-45 (21).

Vernhoef, E., Nijkamp, P., Rietveld, P. (1995). The Economics of Regulatory Parking Policies: The (Im)Possibilities of Parking Policies in Traffic Regulation. Transpo, Res,-A. Vol. 29a, No 2, Pp. 141-156.

Vickrey, W. (1969). 'Congestion Theory and Transport Investment'. American Economic Review, vol. 59, issue 2, 251-60.

Weinberger, R. (2012). 'Death by A Thousand Curb-Cuts: Evidence on the Effects of Minimum Parking Requirements on the Choice to Drive'. Transport Policy, Elsevier, Vol. 20, Pp. 93-102.

Yan, H., Yang, X.G., Yan, B.J. (2005). Parking Choice Model Study for Special Events. China Journal of Highway and Transportation, 18(2): 90–93.

Young, W. (2000). Modeling Parking. In Handbook of Transport Modeling Edited by Hensher, D.A. and Button, K.J. Amsterdam; New York: Pergamon.

Zhenyu, M., Yiqiang, X., Jun, C., Wei, W. (2010). Optimizing Model of Curb Parking Pricing Based on Parking Choice Behavior. Journal of Transportation System Engineering and Information Technology, 10(1), 99-104.