ERASMUS UNIVERSITY ROTTERDAM

Erasmus School of Economics

Master Thesis Urban, Port and Transport Economics

# An introductory estimation of the marginal external cost of on-street parking:

## The case for welfare optimising parking fees in Amsterdam

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Date final version: 21-01-2022

### Abstract

Within travel management systems, the role of parking management is becoming increasingly more important. In the Netherlands, parking policy is decentralized and often lacks empirical or theoretical rationale. This thesis aims to construct a model which expands on previous literature concerning welfare optimising parking fees by internalizing externality costs arising from cruising for parking. The model is then applied in a case study for the city of Amsterdam. The results show that the majority of socially optimised parking fees are lower than the current actual parking fees. The largest welfare losses are endured in the city centre, as social cost transcend parking fees.

# List of Abbreviations

| | |
|---|---|
| ANWB | Algemene Nederlandse Wielrijdersbond |
| CBD | Central Business District |
| CBS | Centraal Bureau voor de Statistiek |
| CO | Carbon monoxide |
| CO2 | Carbon dioxide |
| DALY | Disability Adjusted Life Years |
| dB | Decibel |
| EU | European Union |
| EU28 | European Union (all 28 member states) |
| HGV | Heavy Goods Vehicle |
| KiM | Kennisinstituut voor Mobiliteitsbeleid |
| KpVV | Kennisplatform Verkeer en Vervoer |
| LCV | Light Commercial Vehicle |
| MECP | Marginal External Cost of Parking |
| NE | North-east |
| NMHC | Nonmethane hydrocarbons |
| NPR | Nationaal Parkeer Register |
| NW | North-west |
| OECD | Organisation for Economic Co-operation and Development |
| PBD | Parking Benefits Districts |
| PDN | Platform Detailhandel Nederland |
| Pkm | Person-kilometre |
| PMs | Particulate matter |
| RWS | Rijkswaterstaat |
| SE | South-east |
| SW | South-west |
| UNEP | United Nations Environmental Programme |
| Vkm | Vehicle-kilometre |
| VTT | Valuation of Travel Time |
| WHO | World Health Organization |

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# 1. Introduction

In 1908, car manufacturer Ford launched the first model T-Ford at a price of 850 US dollars. Some 12 years later, after numerous and consistent price drops, consumers were able to buy a T-Ford for 300 US dollars. This affordability enabled most consumers to buy and own their first car, causing car-ownership to skyrocket. Since then, the car has become the most dominant mode of transportation. So much so that nowadays cities, policies, economies and even societies are all to some extend influenced by- and dependent on- cars. In 2019, around 80% of all kilometres travelled in the Netherlands came from car usage. Furthermore, the total distance travelled by passenger cars has increased by almost 35% over the last three decades, following the seemingly ever-increasing trend in car usage (CBS, 2020).

Although cars have globally boosted efficiency and accessibility, the rise of car usage has also brought life to a variety of negative externalities like emissions of greenhouse gasses and air pollutants, congestion, and noise, which are increasingly scrutinised by policy makers (Glaeser and Kahn, 2004). Less attention however has been reserved for the externalities that arise when cars are not used. According to Button (2006), cars are parked around 95% of their lifespan. Especially in densely populated areas, where land is scarce and populations are growing, this has caused parking demand to often outgrow parking supply. This excess demand translates into cars "cruising for parking" while waiting for a parking place to free up. Cruising for parking is shown to be a substantial contributor to negative externalities and time costs. For example, Schaller Consulting (2006) found that 28% of all traffic in the SoHo district in New York consisted of drivers who were searching for parking, while Hampshire and Shoup (2018) analysed 22 international cruising studies and found an average of 34% of traffic cruising for parking with an average search time of 8 minutes. For the Netherlands in particular, lower average numbers were found by Van Ommeren et al. (2012). This can be partly explained by the relatively small differences between on-street and off-street parking fees in the Netherlands compared to other regions of the world. For example, in the United States, where on-street parking is often free or cheap compared to off-street parking, drivers are willing to cruise for parking longer to find a cheap, on-street parking place.

As stated by Pigou (1954), an externality can be explained as private costs being diverged into social costs because of a failing price mechanism. On its own, the price mechanism fails to internalize all cost aspects, thereby indicating the need for interference. There are multiple ways for policy makers to intervene on a market. First, policy makers could influence supply and demand of parking to obtain an improved social equilibrium. From a supply side however, simply paving more parking places seems undesirable from different perspectives. First, in many western societies, a trend of decreasing vehicle attractiveness can be observed. Long-term urban planning and policy goals in cities across these countries are designed to promote alternative mobility. So, creating and/or reserving land for parking places does not seem to be in line with these strategies. Second, although parking places may be scares in some areas, they compete with other utilities over an even more scares good: public land. An average sized parking place in the Netherlands takes up between 12-17m$^2$ of valuable public land that can no longer be used for other purposes. In densely populated urban areas in the Netherlands like the Randstad, these parking places are using up space that could otherwise be used in other land-dependant markets like the one for residential housing (Trouw, 2020).

A better tool to mend supply and demand to a more socially optimal equilibrium therefore seems to be the pricing mechanism, as increasing parking prices would lead to an increasing vacancy rate and therefore less cruising for parking. In an ideal case where perfect information on parking places and optimal pricing of parking are present, cruising time would be (almost) zero (Arnott and Inci, 2006). In the Netherlands, parking is usually priced using hourly parking fees. Although parking fees are employed throughout the entire country, a lack of central pricing regulations and guidelines causes the formation of parking fees to be ambiguous (KpVV, 2012). Parking is a key element in policy making in different topics like transport, environment, land-use, economic and social development, and finance (Mingardo, 2016) and therefore the underlying determinants and reasoning for local parking fees can vary widely between local governments. Little to no municipalities however currently base their parking fee structures on welfare analysis, which could lead to sub-optimal social equilibria where welfare losses are endured under the current parking fee structure.

This thesis will expand on previous research concerning welfare-based parking fees to estimate socially optimised parking fees for the city of Amsterdam. To do so, a model will be constructed to estimate Marginal External Cost of Parking (MECP), combined with newly added components to account for externalities. This model will act as an introductory methodology for future research, as it is likely that not all social costs are accounted for and assumption-based estimates are used due to data limitations.

In the MECP model by Van Ommeren et al. (2021), the additional search time for an arriving driver caused by an additional unit of parking time by an already parked driver is estimated, thereby accounting the endured time losses as social cost. However, externalities created by these cruising drivers are not accounted for. Although time costs are a large component in external traffic costs, it is important to estimate all other external costs in road pricing systems (Macharis et al., 2010). The information on the MECP, combined with literature and data on externality costs, will therefor lead to a more extensive model and a closer approach to welfare optimising parking fees.

Following from this, the central research question in this thesis can be formulated as follows:

*What are the optimal parking fees for the different parking zones within the city of Amsterdam, seen from a social welfare perspective?*

To answer the research question, a literature review will be conducted to gain a clear understanding on the current parking infrastructure, (price) management and environment. In addition, literature concerning externalities will be reviewed to identify different externalities that will be used as social cost determinants in the model. Afterwards, the original model of Van Ommeren et al. (2021) will be explained and reviewed. Once this is done, the additions and changes to the original model will be stated and data concerning the pricing of the additional externalities will be analysed to incorporate them into the model. Once the model is constructed, data on the average occupancy rates and a dataset containing mobile parking transactions in Amsterdam will be used to estimate relevant input factors for the model. The results from the model with these different input values will then be compared relative to each other and to the current parking fee structure in Amsterdam. Lastly, the extended model will analyse the data used by Van Ommeren et al. (2021) from Melbourne to evaluate the impact of the additional expressions to the model.

# 2. Literature review

## 2.1 Parking management in general

Parking management in general consists of three main activities, namely the creation, exploitation, and maintenance of parking places (KiM, 2018). Within the creation of parking places, there are two key elements for policy makers to consider: the number of parking places and the location of the parking places. The number of parking places is often dictated by local guidelines on the minimum and maximum number of parking places for different land-use destinations (Shoup, 2011). The location for assigning parking places differs across regions. For example, in many European and Northern-American cities, on-street parking in widely available in most city centres, while in many of Asia's biggest cities (e.g., Seoul, Tokyou, Singapore) on-street parking in restricted in most parts of the city centre (Asian Development Bank, 2011). The decisions on both elements impact local safety, accessibility and quality of life and should therefore be part of local spatial and transport planning processes (Marsden and May, 2005). For example, Balcombe and York (1993) indicated that many heavily parked urban areas in the UK no longer had safe informal crossing points for children.

The choices that the supplier of parking places make in the different management activities are often aimed at reaching a certain goal. According to Mingardo et al. (2015), the four main goals of parking policy in the Netherlands can be formulated as; contributing to the accessibility and mobility of cities; contributing to an improved living environment; generating income and supporting the local economy. In general, however, many parking management measures are implemented on the spot while lacking the theoretical or empirical evidence to support these measures (Ibeas et al., 2018) and being based mostly on emotions and sentiment (Bates, 2014). A survey from 1996 (Wilson) showed that the two most frequently cited methods by urban planners to the question "how do you set parking requirements?" were "surveying nearby cities" and "consulting parking handbooks". Shoup (1999) explained the danger in both these methods; the first may simply result in repeating someone else's mistake while the handbook used in the second method simply holds information on observed maximum parking demand at different land-use sites. Adding to the latter, Shoup (2005) stated that policy makers are often neglecting both the price and cost of parking when setting regulations, and as a result the maximum observed parking demand is often simply set as the minimum required parking supply.

Nowadays, the view on parking management has shifted, as it is increasingly seen as a vital tool in traffic management and urban planning. Litman (2006) was one of the first to recognize and describe this change in attitude after his meta-analysis of parking policy literature. He stated that parking management is shifting from an "old paradigm" to a new one. The old paradigm focussed on supplying parking to maximize car usage. This meant overshooting parking supply to limit demand problems and keeping parking fees as low as possible, resulting in parking being largely financed by general taxes. In the new paradigm, instead of focusing on the supply side of parking, policy makers try to make more efficient use of existing parking infrastructure.

In line with this theory, Mingardo et al. (2015) indicate that parking management strategies in urban areas often follow a three-phase pattern (see fig. 1). In phase one, car ownership and car usage is relatively low and there is sufficient parking supply. In this phase, there is no real need for parking policy. In phase two, demand for parking is higher due to increased car usage and therefor parking fees are implemented to manage parking. In phase one and two, parking management is still "reactive management", meaning it evolves and reacts to rising parking problems. In phase three, parking supply can no longer be increased, and more attention is given to externalities caused by parking. In this phase, reactive management is no longer efficient, and the focus is shifted to balancing demand and supply and using parking places more efficiently to increase usage, which can be compared to the new paradigm stated by Litman (2006).

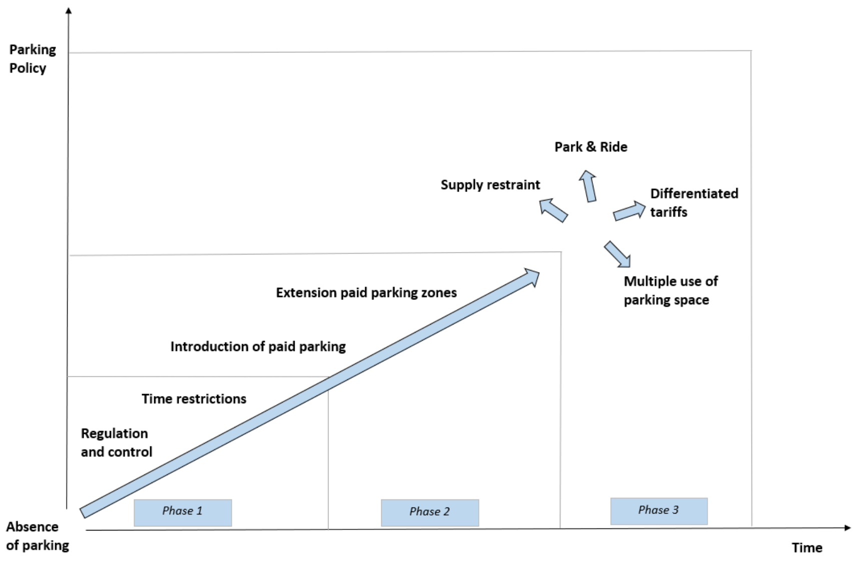


*Figure 1.* Three stages of parking policies *(Mingardo et al., 2015)*

## 2.2 Parking management in the Netherlands

Like mentioned above, parking management consists of three main activities: creating, exploiting, and maintaining parking places. In the Netherlands, all three activities are carried out by the municipalities (KiM, 2018). The Dutch House of Representatives (1992) stated that regulatory parking policies are an "indispensable part of integral transport policy". Despite this view, a lack of centralized parking management has led to an intricate web of rules and regulations concerning paid parking in the Netherlands (CROW, 2012).

There are an estimated 14 to 18 million parking places in the Netherlands. These parking places consist of private property, on-street, off-street and Park & Ride parking places, making the supply of parking places public, private or a combination of the two. About 10 million parking places are publicly supplied, of which the vast majority are on-street parking places, and around 4 million parking places are privately owned, either by businesses or residentials (KiM, 2018). To assure sufficient parking supply, municipalities follow the so-called "CROW-kengetallen". These key figures indicate a minimum and maximum number of parking places that vary for different land-use destinations (e.g., work, leisure, residential). Municipalities can deviate from these figures when argued. In practice however, most municipalities take the figures as given and overlook the varying figures for different destinations. Especially in densely populated areas where car-ownership is relatively low (e.g., the Randstad), upholding the minimum figures can result in an oversupply of on-street parking places in some areas, while undersupplying in others (Shoup, 2011). Such an oversupply of on-street parking places is undesirable as it can ruin urban planning and promote car dependency (Cuttera & Franco, 2012).

In creating on-street parking places, the costs for municipalities consist of i) investment cost ii) exploitative cost and iii) land costs. However, many municipalities fail to consider the latter, as ground is seen as part of the public space, costs are already perceived to be endured in creating and maintaining roads or they assume there is no alternative use of parking places possible (KiM, 2018). As a result, the costs of parking place creation are being underestimated, which leads to a mismatch in parking fees that are aimed to offset the costs (CROW, 2006). This can be seen in the percentage of private costs covered by parking revenues, which is only around 80% (CROW, 2003). These costs do not account for social costs, so the mismatch between total (social) costs and parking revenues might be even larger.

Although every driver indirectly pays for the creation and maintaining of parking places through taxes, there are no direct costs of parking for most parking places, as around 94% of all parking places in the Netherlands are unpaid (CROW, 2014). Paid parking zones are mostly found in crowded places. For example, the 20% most densely populated municipalities all have paid parking in place, while in the next two quantiles, respectively 75% and 55% of municipalities make use of paid parking schemes (Van Ommeren et al., 2012).

The revenues generated by exploiting parking places are part of the general taxes in the Netherlands. This means that municipalities oversee collecting, allocating and spending parking revenues. In most cases, the budget created by parking revenues is used as general income and divided over the different expenses of the municipality. There are however different methods of allocating the revenues. One of these methods is using Parking Benefit Districts (PBD). When PBD policy is in place, profits of parking are invested back into the area where these profits were made. The main idea behind this is to lower political barriers that are often the biggest obstacle in raising parking fees (Shoup, 2005). Another advantage is that profits proceeding from parking revenues are made public, and residents can see tangible benefits from parking regulations (Johansson et al., 2017). In the city of Amsterdam, although there is no formal PBD policy in place, 23% of revenues collected from parking are allocated to the mobility budget, which invests in public transport and improving active mobility (KiM, 2018).

Within the Netherlands, CROW (2017) indicates that most municipalities follow a “demand-following” parking policy approach as opposed to a “supply-focussed” approach. For large urban areas however, there is a pattern of more “alternative use” and “efficiency improvement” strategies, which is in line with the previously mentioned three-staged development of parking policies theory stated by Mingardo et al. (2015).

## 2.3 Types of parking management

Within literature concerning parking management, studies can generally be divided into three categories: modelling, demand-supply management, and pricing mechanism (Najmi et al., 2021). In this chapter, different policy measures that can be implemented in parking management strategies will be analysed.

### 2.3.1 Pricing mechanism

Within pricing-mechanism literature, most studies focus on the use of parking fees (CROW, 2017), and correspondingly on price elasticity of demand. In the Netherlands, the first form of paid parking was introduced at Schiphol Airport in 1961 (CROW, 2012). Since then, the use of paid parking has spread rapidly. In 2014, all cities with over 100.000 inhabitants and over a third of cities with 20.000-50.000 inhabitants had paid parking schemes in place, of which the vast majority make use of time regulations. Most studies concerning the pricing mechanism in parking literature are focusing on measures that can be placed in either the first or second stage of parking management (see chapter 2.2.1), with an exception for differentiated and/or flexible parking fee measures.

It is important to notice that parking fees are predominantly used as a tool to manage parking demand instead of being used as a cost-offsetting tool. Early advocates for the introduction of parking fees, like Vickery (1954) and Roth (1965), build on the idea that parking is a public good. This meant that the benefits derived from parking for a driver were not affected by the number of other drivers who wanted to park. As a result, these authors claimed that standard marginal cost pricing should be applied to parking, meaning that the parking fee was to be set equal to the marginal cost of providing the parking place. Glazer and Niskanen (1992) however pointed out that, although parking might have some characteristics of being a public good, it is in fact not. Parking is excludable and therefore a certain number of drivers can cause external costs to other drivers in the form of congestion, indicating the role of parking fees in city planning instead of it purely being used as a cost-offsetting tool.

Contrary to what economic theory suggest, parking fees often fail to reflect to true cost of supplying and maintaining parking places (Van Ommeren et al., 2011). From an economic point of view, this is surprising as on-street parking is a monopoly good controlled by local governments. Economic theory suggests that monopolists will limit supply and let prices rise, causing the price of parking places to offset the general willingness-to-pay, thereby causing a shortage of affordable parking places and limiting social welfare. However, in reality, the contrary happens: a lacking supply of parking places is often created by prices being too low instead of too high (Manville and Pinski, 2021). This can in part be explained by a reluctancy of policy makers to increase parking fees, as drivers often see a parking fee as an additional form of taxation, next to general taxation already in place (Manville, 2014).

When assessing the effectiveness of parking fees, the general belief is that pricing for parking is an effective way of managing parking. The exact influence is however not undisputed. The general consent is that parking fees either reduce demand for parking all together (e.g., Arnott and Inci, 2006), and thereby the total travel time and cruising time (Chatman and Manville, 2014) or shifts the demand to other surrounding parking areas (Qian et al., 2012). Adding to the discussion, literature suggests varying price elasticities of demand. One of the factors complicating price elasticity estimations, is the fact that demand for parking, like transportation, is a derived demand. This means that the demand for parking stems from demand for a different, often related good or service like shopping, working or leisure activities. Parking in itself holds little to no added value in fulfilling these activities at the destination, and differs in duration, location and time of day, which is reflected in the varying price elasticity of demand for parking for drivers with different destinations (Gillen, 1978). Even more so, in studying price elasticities, most literature does not account for cruising for parking, leading to biased elasticity estimates (e.g., Madsen et al., 2013, Inci, 2015).

For example, drivers with parking demand for business trips are less sensitive to parking fees as drivers who enter parking zones for shopping purposes (Simicevic et al., 2012). This leads to widely varying price elasticities of demand found in literature. For example, Jeihani et al. (2015) found a price elasticity of demand of -2.26 (indicating price elasticity), while Schroten and Blom (2011) found a price elasticity ranging between -0.1 and -0.3 (indicating price inelasticity). More in particular for the city of Amsterdam, research suggests a residential parking price elasticity of car ownership of -0.8, which means a 10% increase of residential parking prices in the city would be associated with a 8% reduction in car-ownership (De Groote et al., 2016). A meta-analysis on price elasticity for demand studies was conducted by Lehner and Peer (2019), showing the varying outcomes (see fig. 2).

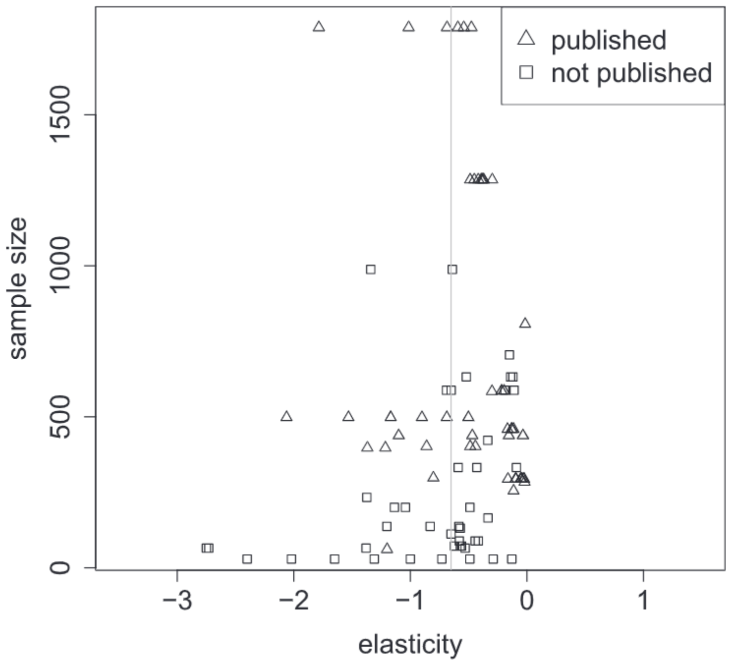


*Figure 2. Funnel plot showing price elasticities found in parking literature. The vertical line indicates the average (Lehner & Peer, 2019)*

As the price elasticity varies across time and space, a more effective way of using the pricing mechanism to manage parking demand might be to make use of varying parking fees. An example can be found in San Francisco, where policy makers implemented the SFpark program to battle the city's growing parking problems. In this program, parking fees are based on occupancy rate, with the goal to always keep 1 or 2 parking places per block vacant. Although the varying fee structure can still be improved by communicating with drivers (Pierce and Shoup, 2013) or increasing the flexibility of the fee (Chatman and Manville, 2014), the program seems to lower occupancy rates and therefore seems to be an effective tool in battling cruising for parking.

In the Netherlands, varying parking fees are rarely being used. In the SFpark example, parking fees are determined and evaluated by live information, while in the Netherlands, parking fees in large cities are mostly only differentiated based on the average occupancy rate at different day(part)s (KiM, 2018). For example, in Amsterdam, the highest parking fees are set in the most crowded area (historic city centre), while the lowest parking fees are set in predominantly residential areas that are relatively far away from the centre. However, even if there are no cars parked at all in the city centre, the first car to park there will still have to pay the unadjusted, high parking fee. There are multiple reasons why varying fees based on live information are hard to implement in the Netherlands (Van den Akker, 2014). First, only the largest few cities have sufficient parking demand to effectively make use of varying fees. Second, for varying fees to be effective, an extensive infrastructural network consisting of occupancy sensors and information systems is required, which is currently not present in the largest cities in the Netherlands. Cities are however getting more and more interested in exploiting parking based on vehicle type, time, emissions, and location (KiM, 2018).

### 2.3.2 Demand and supply management

Price is however not the only factor influencing parking demand. In earlier studies, drivers indicated that choosing where to park is mostly dependent on the location of the parking place (60%) followed by accessibility (25%), quality (10%) and lastly the parking fees (5%) (Stienstra, 2015). Similar results were presented by the ANWB (2013). From their interviewed clients, 78% stated that they never search for local parking fees before travelling somewhere. Furthermore, studies suggest that car ownership, which is clearly linked to parking demand, is more dependent on parking supply than on other factors like income and household characteristics (Guo, 2013). Therefore, general management of the demand and supply of parking places might be more effective in limiting cruising for parking. The measures within demand and supply management mostly fall into the previously discussed phase three of parking management (Mingardo, 2015) and the new paradigm stated by Litman (2006) (see chapter 2.1).

A growing number of studies are looking into the feasibility of estimating parking demand, either by machine learning (e.g., Yang et al. (2019), Zhang et al. (2020)) or by modelling (e.g., Xiao et. al (2018), Schuster & Volz (2019)). The complexity of a driver's decision (where) to park is hard to truly capture in a model, especially when the authors are aiming to construct a generally applicable model. Adding to the complexity, is again the fact that parking demand is derived from the demand for underlying goods and services. This is reflected in the large number of different modelling approaches that can be found in parking literature, like direct-demand models, flow models, network analysis models, discrete-choice model and more (Turner et al., 2017). This complexity in predicting demand also indicates the difficulty of supplying parking based on demand predictions by government institutions like CROW in the Netherlands; the demand predictions simply vary too much.

Another example of managing demand and supply can be found not in quantity but in location of parking places. For example, over 400 Park & Ride zones have been introduced in the Netherlands (KpVV, 2013). These zones allow drivers to park relatively cheap outside the city centre and use public transport to get to their final destinations, aiming to lower downtown traffic, emissions and parking pressure while also promoting public transport (Hamer, 2010). The extent to which Park & Ride zones are effective in reaching the goals however is not undisputed, as academics have provided evidence for a re-distribution of traffic, rather than a reduction (e.g., Parkhurst, 2000). This form of management is mostly aimed at drivers who want to park for longer durations of time, as parking fees are shown to have a larger influence on drivers that want to park for longer durations of time (Kobus et al., 2013) and the extra travel time generated by parking at a Park & Ride zone is inefficient for short-term parkers.

Furthermore, alternative use of parking places is being used as a parking management tool. In Germany, researchers found that respondents were least supportive towards financial policy parking measures, but more supportive than expected by policy makers towards "reuse of parking places" (Kirschner and Lanzendorf, 2020). Especially in urban areas where there is an abundance of parking places, finding different use for these places seems vital. For example, Hoehne et al., (2019) found that for each car in Phoenix, Arizona, there are around 4 parking places available, clearly indicating an extreme oversupply of parking places which makes policy measurements using the pricing mechanism useless. Reuse of parking places, or even destroying and re-developing the land, in these cases can help restore a balance between supply and demand. An example of alternative land use is indicated by Mora (2019), who indicates the potential added value created by transforming off-street parking garages into affordable housing.

## 2.4 Externalities in parking

Externalities were first described by Marshall (1919), and later expanded on by Pigou (1920). Pigou spoke about "divergences between marginal social net product and marginal trade net product" or "uncompensated services" when analysing economic behaviour, which was later shortened to the term "externalities". The definition according to the OECD is formulated as; "externalities refer to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided". Pigou explained how market failures are caused by externalities, and empirically argued that policy makers should interfere on these markets by using taxation to ensure the intended working of the market mechanism. Many current taxes and road pricing schemes are in fact based on the concepts first rolled out in the early 1920's by academics like Pigou and Knight (1924). Their work led, amongst other things, to the Pigou-Knight model, which was an influential tool within congestion analysis and shows how social cost can be endured in a market equilibrium within transport markets (see fig. 3). Vickrey (1954 & 1969) later added to this social cost theorem by explaining that road users should be charged a price equal to the delay cost they impose on others when choosing to drive or park, which led the way for traffic and parking related fee structures imposed by governments. In his 1998 work, Button explains that there are two basic types of externalities. The first implies that some people (ab)use resources and thereby impose damages on others (e.g., noise from car usage) while the second implies that users degrade the service quality of a good, thereby affecting all users of the good (e.g., congestion).

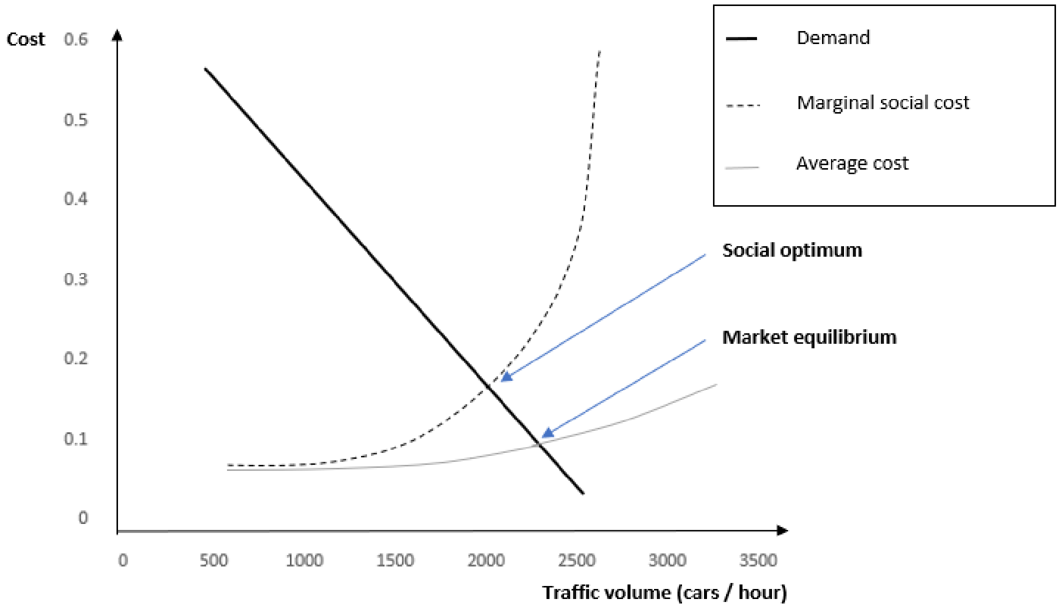


*Figure 3. Basic depiction of the Pigou-Knight model (Pigou and Knight, 1924)*

Externalities in parking almost exclusively arise from cruising for parking (De Groote et al., 2016). The first studies on cruising for parking date back to 1927, although over the years increasingly more focus has been reserved for the externalities linked to cruising for parking and how to effectively manage the congestion causing these external costs (e.g., Roth (1965), Verhoef et al. (1995), Arnott and Rowse (1999)). Although cruising for parking is a form of congestion, it is different to "regular" congestion as within the cruising for parking queue, there are also drivers that might not be looking for a parking place but are going somewhere else. These drivers are being both hindered by- and contributing to - the cruising for parking. This "invisibility" of cruising for parking, or in other words; the inability to separate cruising from congestion, could according to Shoup (2006) be one of the reasons that many researchers and economists have ignored it as a source of congestion for a long time, even though cruising for parking accounts for as much as 30% of downtown congestion in some cities across North America. Since it is a form of congestion, it also disproportionately impacts linked external costs, like emissions and noise (Russo et al., 2019). Adding to this, research suggests that transport policy aimed at limiting external costs should focus on limiting cruising for parking as opposed to regular congestion, as external cost of (cruising for) parking are often higher than external cost of congestion (Inci et al., 2015).

Studies examining the impact of cruising for parking are generally either of theoretical or empirical nature. The first method mainly uses economic literature to describe the impact of cruising for parking on negative externalities like congestion, emissions, and noise in general, while the latter makes use of methods like surveys, videotaping or controlled experiments to try to estimate the levels of cruising for parking for specific case studies. Within theoretical work on cruising for parking, the very existence of cruising for parking is explained as a driver's willingness to pay exceeding the price of parking (Inci, 2015). Arnott and Inci (2006) illustrate this in their work (see fig. 4). In the left plane of figure 4, the authors show the welfare loss in case of a capacity constraint and under-priced parking fees. In case there was no capacity constraint, the equilibrium price would be set at the point where demand matches the user cost. However, as most cities do have a parking capacity constraint, the user cost, and therefore the demand, is too high compared to the number of parking places available. As a result, drivers will be cruising for parking. The right plane in figure 4 shows that in case policy makers increase the parking fee to the optimal parking fee to increase the user costs, the equilibrium price can be matched at the capacity constraint.

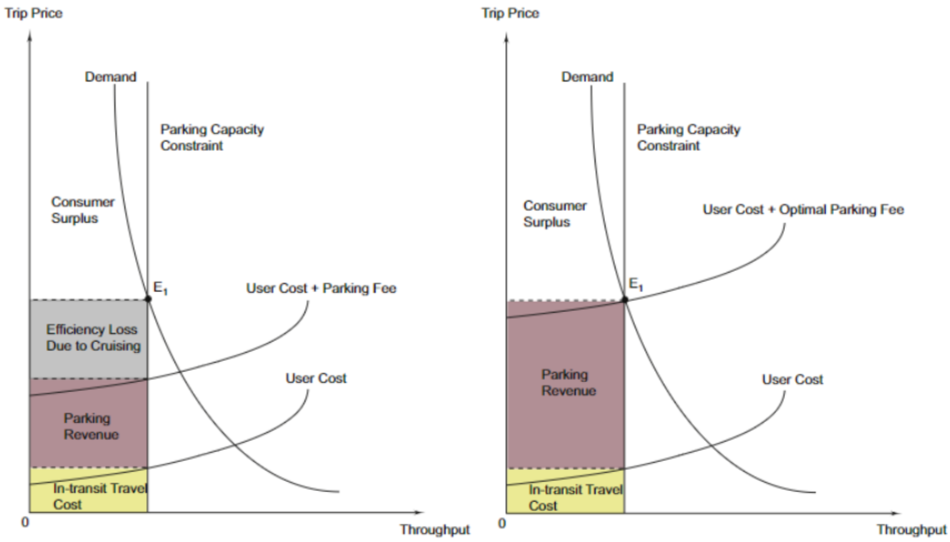


*Figure 4. Efficiency loss due to cruising for parking and the optimal parking fee. (Arnott and Inci, 2006)*

Another extensively researched topic within cruising for parking studies is the relationship between on-street and off-street parking. Within these studies, the general belief is that when off-street parking prices are set too high, cruising for parking will be more attractive for drivers (e.g., Inci and Lindsey (2015), Calthrop and Proost (2006)). For the Netherlands however, this problem does not arise; the difference between the average on- and off-street parking fees is neglectable (PDN, 2009).

Contrary to many earlier works focusing exclusively on arriving drivers in the formation of congestion, Shoup (2005) was one of the first to recognize the importance of already-parked drivers; by reducing the duration of parking, the total numbers of parkers might increase. This meant that an occupancy rate of 100% was too high, and a 85% occupancy rate was more desirable. In his work, he estimates that in one small area of Los Angeles alone, parking-based congestion accounted for 3600 miles of excess travel each day. Later, Shoup (2006) described the congestion caused by parking as "cruising for parking", which he defined as follows: cruising for parking creates a mobile queue of cars that are waiting for parking place vacancies.

In empirical work on cruising for parking, there are two main types of methodologies: measuring and estimating. Measuring can be done either manually or automatically. Examples of automatically counting can be found in using movement sensors on parking places, videotaping techniques, or parking zone entry registration. However, measuring seems undesirable as it is often labour and capital intensive and is hard to expand. Therefore, the second way of mapping cruising for parking is by estimating. This method often designs methodology in the form of a model, and then uses administrative parking data to estimate the level of cruising for parking. This method is easier to expand to other regions and the required data is often already available.

Although most studies show that cruising for parking is a substantial contributor to congestion, the overall findings on the percentage of traffic cruising for parking varies a lot across cities. Van Ommeren (2012) estimated that in the Netherlands, there are no searching time for parking for about 70% of all trips. In 24% of trips, search time exceeds 1 minute and in only 1% of trips it exceeds 3 minutes. However, when focusing in on urban areas, the number of drivers searching for parking is between 5-20% higher.  Although urban levels of cruising are higher in the Netherlands compared to rural areas, they are still a lot lower than the average of 30% of traffic cruising for parking found by Shoup (2006) in 16 international studies (see table 1). One cause for this could be the fact that, on average, parking garages are more expensive in the United States compared to on-street parking, whereas this is the opposite in the Netherlands (Kobus, 2015). For the Netherlands in particular, Van Ommeren et al. (2011) estimate a cost of cruising for parking for residents in the city centre of Amsterdam of around € 1 a day.

*Table 1. Share of traffic cruising for parking and average search time found in 16 international studies (Shoup, 2006).*

| Year | City | Share of traffic cruising for parking (%) | Average search time (min) |
|---|---|---|---|
| 1927 | Detroit (1) | 19% | |
| 1927 | Detroit (2) | 34% | |
| 1933 | Washington | | 8.0 |
| 1960 | New Haven | 17% | |
| 1965 | London (1) | | 6.1 |
| 1965 | London (2) | | 3.5 |
| 1965 | London (3) | | 3.6 |
| 1977 | Freiburg | 74% | 6.0 |
| 1984 | Jerusalem | | 9.0 |
| 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 |

In literature concerning cruising for parking, there are some externalities that are predominantly mentioned to arise from cruising: noise emissions and pollution (e.g., Russo et al. (2019), Van Ommeren et al. (2012)), safety hazards caused by manoeuvring in and out of parking places (Axhausen and Polak, 1989), time delays for all other road users due to slower travelling speeds when searching for a free parking place (Anderson and De Palma, 2004) and increased network traffic flow and congestion (Arnott and Inci, 2006). The relevant externalities for this thesis will be analysed in more detail below.

### 2.4.1. Noise

The first externality arising from traffic is noise pollution. Noise pollution has been identified by the World Health Organization as a “serious public health problem” and the effects on human wellbeing have been studied extensively (e.g., Fuks et al., 2011, Jakovljevic et al., 2009). Effects from noise pollution vary wildly from deterring (sleep) activities and performances, to causing concentration problems, annoyance, and stress, to increasing the risk of cardiovascular diseases and psychiatric disorders (CE Delft, 2007). Although thresholds above which noise is considered a nuisance vary, the general range is between 50-60 decibel (dB) (CE Delft, 2019). Next to human wellbeing, noise pollution is also shown to (negatively) impact other factors, like land value (Kim et al., (2007) and real estate values (Viano, 2001).

There are different ways to evaluate the external costs caused by noise pollution, as measurements are always to some extend subjective and no direct monetary losses can be allocated to noise pollution. One of the more common ways the costs of noise pollution are estimated, is by using willingness to pay; the amount people are willing to pay to avoid traffic noise. Using this method, it is estimated that road transportation causes around € 38 billion in social costs a year, of which 90% is caused by passenger cars and trucks (both € 18 billion) (CE Delft, 2007). This total noise cost equals around one third of total traffic accidents related costs. Comparable results are found when using a different method; evaluation of number of disability-adjusted life years (DALY). This method evaluates life years lost due to premature death and serious health condition related to noise pollution (Jacyna et al., 2017).

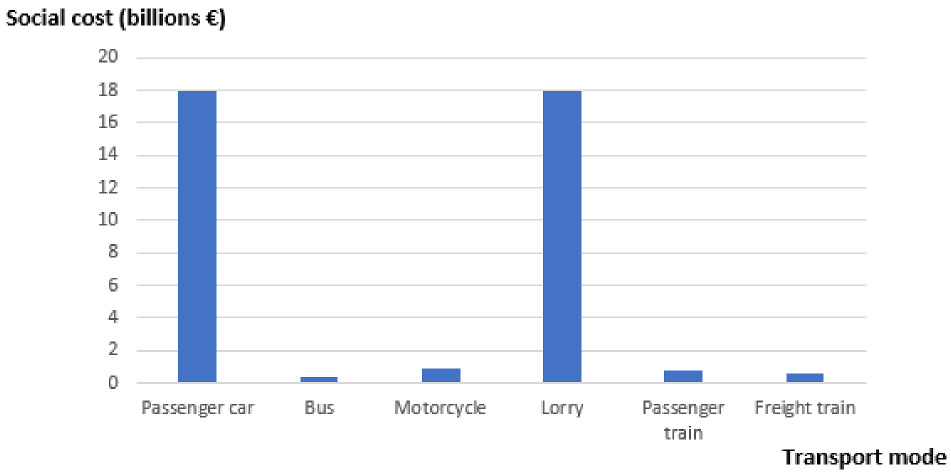


*Figure 5. Total yearly noise pollution costs in Europe (2006) in billions of euros (Jacyna et al., 2017).*

When examining noise cost, velocity is a crucial determinant (e.g., CE Delft, 2007). Vehicles at lower speed naturally create less noise than fast travelling vehicles (see fig. 6). Although speeds when cruising for parking are relatively low, decibel levels in dense traffic situations are higher than on calm streets (Danish Road Institute, 2004). Furthermore, in many urban areas like Amsterdam, houses are located close to the streets, causing noise levels measured at the standard measuring distance of 7.5 meters from the source used in research to be exceeded.

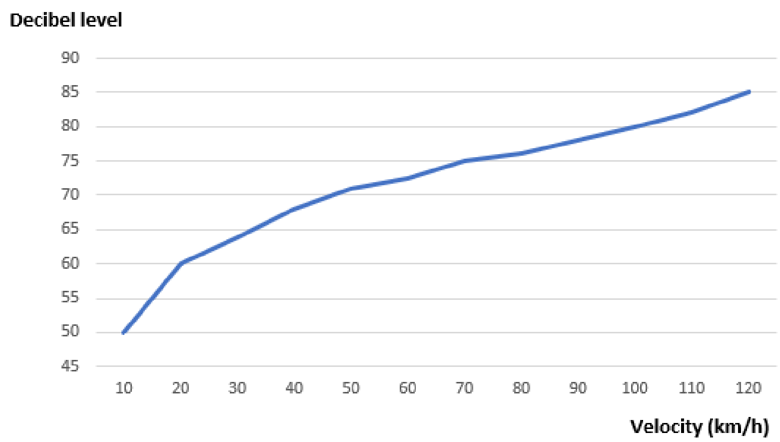


*Figure 6. Noise levels produced by passenger car at different travelling speeds (CE Delft, 2007).*

### 2.4.2. Congestion

The second externality arising from cruising for parking is congestion. Early literature like the previously mentioned works by Pigou (1920) and Knight (1924) identified the externalities caused by congestion and proposed "road pricing" to internalize and limit external congestion costs. Over time, this road pricing principle was translated into literature on congestion pricing. In congestion pricing, road-users are taxed based on their respective road usage by length, time, or route, which allows for differentiated taxation and therefore induces (socially) optimum behaviour (Nijkamp et al., 1995). In practice however, these congestion pricing schemes have long been a topic of debate. Although economic theory suggests the effectiveness of congestion pricing, public acceptance is generally low (Brinkman, 2015). Amongst policy makers the measure is also often heavily debated, as congestion is worse in areas with high levels of employment density, where positive agglomeration externalities occur. By taxing car-users for congestion, policy makers fear reduced employment density and therefore reduced agglomeration externalities. This is in line with literature, which suggests that positive agglomeration externalities are highly dependent on the proximity of working places, and externalities diminish quickly as proximity decreases, even with as little as a few miles (Rosenthal and Strange, 2003). So, as first-best solutions in practice are hard to implement, many countries currently have implemented second-best solutions in the form of undifferentiated fees (e.g., tolls, general road tax). Although both types of solutions aim to limit externalities, the effectiveness of second-best solutions is significantly lower, which is reflected by the growing congestion miles in countries where these solutions are in place (Nijkamp et al., 1995).

Congestion cost consists of four components (Qingyu et al., 2015): extra travel time; environmental pollution; traffic accidents and fuel consumption. In total, these costs add up to between € 3.3 and € 4.3 billion annually in the Netherlands and follow an increasing trend (KiM, 2018) (see fig. 7). As a comparison, traffic accidents account for total social cost around € 17 billion and environmental damage from traffic for around € 11 billion (KiM, 2019). As there are no current first-best solutions for the externalities created by congestion in place in the Netherlands (i.e., no differentiated congestion pricing scheme is in place), internalizing the congestion costs in, for example, the market for parking seems relevant.

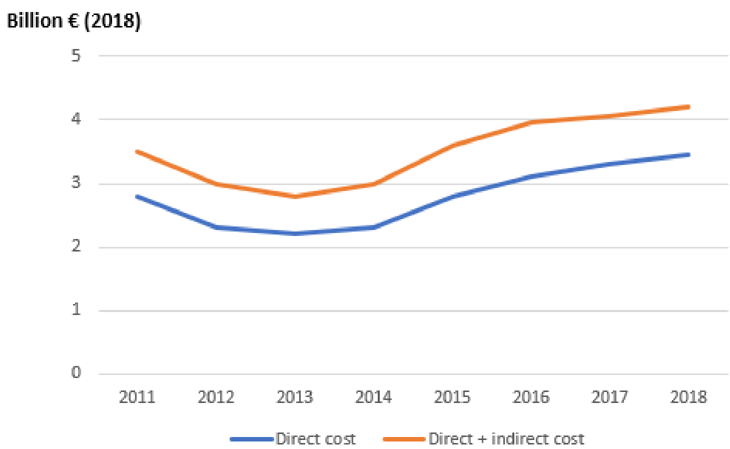


*Figure 7. Social costs related to congestion in the Netherlands between 2011-2018 (KiM, 2018).*

### 2.4.3. Greenhouse gas emission and air pollutants

It is important to recognize the difference between greenhouse gasses and air pollutants. Greenhouse gasses like carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) are all air pollutants, however they are classified different, as they impact our surroundings differently. Air pollutants in general directly affect human wellbeing and ground conditions (like soil and water) when emitted, while greenhouse gases are always present and do not directly impact human wellbeing, but rather impacts the entire atmosphere and contributes to climate change (UNEP, 2019).

The global emissions from traffic contribute significantly to the emissions of air pollutants and greenhouse gasses. These emissions account for 30% of all nitrogen oxides, 10 % of PMs, 54% of CO, 14% of CO2 and 47% of all NMHC (Sokhi, 2011). In total, the costs of these emissions add up to around € 11 billion annually in the Netherlands (KiM, 2019). In Amsterdam in particular, air pollution costs are estimated to be around €1,301 annually per inhabitant (CE Delft, 2020).

Like the calculations used to determine external noise costs, much of the literature concerning emission costs make use of Disability Adjusted Life Year (DALY) to estimate the total costs. Using this methodology, De Leeuw et al. (2018) found that policy measures implemented in the Netherlands to reduce emissions have been able to decrease health burdens created by air pollutants and greenhouse gasses equal to 1,150 – 3,378 healthy years of life. Furthermore, these measures have led to an average overall decrease in air pollutant emissions from traffic between 2010 – 2018 (see fig. 8).

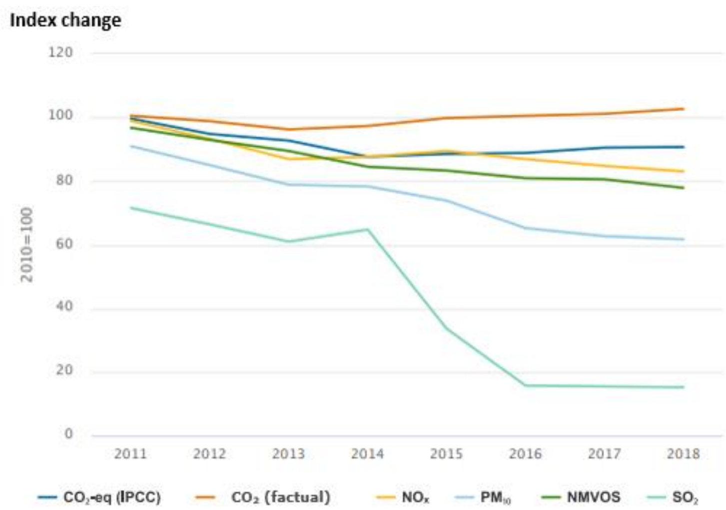


*Figure 8. Indexed change in different air pollutants emitted by traffic in the Netherlands between 2010-2018 (CBS, 2019).*

Again, the most efficient form of pricing external pollution costs from traffic would be to tax individuals based on their respective pollution output (i.e., a first-best solution). Although emerging technologies like mobile sensing might enable individual marginal cost pricing in the future (Ban, 2009), second-best solutions focussing on pricing certain links of transport networks (e.g., toll charging schemes on crowded roads) are currently deemed more feasible and therefor often preferred by policy makers (Lindsey and Verhoef, 2000).

## 2.5 Welfare based parking policy / literature

As mentioned previously, this thesis aims to construct a model that extends on the model created by Van Ommeren et al. (2021) to estimate socially optimizing parking fees. In this chapter, the model will be reviewed, whereafter the changes and additions to the model will be stated in chapter 4.2 and 4.3, respectively.

### 2.5.1. Van Ommeren et al. paper

As stated in chapter 2.4, there are two methods to analyse cruising for parking: measuring and estimating. The methodology constructed by Van Ommeren et al. (2021) uses the latter. The research extends on previous estimation methodology presented by Inci et al. (2017). In this paper, the authors use data on parking arrivals (i.e., when a parking transaction is started) and vacancies to (conservatively) estimate external cost created by a single additional driver searching for parking. Using fixed effects to eliminate all others factors potentially impacting the arrival rate, the authors show a relatively constant arrival rate at low occupancy levels, followed by a sharp decrease in arrival rate once the occupancy rate is approaching its maximum. From this, they estimate cruising for parking levels based on a marginal hour of parking by an already parked driver. The authors estimate that due to this marginal increase in demand, 3.6 cars will attempt to park in the parking zone but fail to find a spot, causing cruising for parking. The research lacks however in time and space variant explanatory power, as external cost could only be estimated when occupancy levels were high.

Although using the same train of thought, Van Ommeren et al. (2021) extend on the model by Inci et al. (2017) by using the theoretical framework presented by Zakharenko (2016) that can be used to estimate the marginal external cost of parking. This framework provides a more encompassing way of estimating costs, as it also considers search strategies and walking costs. Also, this extended model allows to estimate time-varying and location-specific marginal external costs, improving on the "snapshot" costs estimated by Inci et al. (2017).

### 2.5.2 Van Ommeren et al. Paper: The model

The model by Van Ommeren et al. (2021) is built on the notion that there is continuous time, which is denoted by $t$. Drivers who are parked choose to leave a parking place at time $t'$ after a duration of $\tau(t')$. Within this model, drivers search for a parking place in a parking zone at rate $I(t)A(t)$. Where $A(t)$ denotes the number of cars entering the given area and $I(t)$ is the probability that a person entering the zone is searching for a parking place. Space is assumed to be homogenous, as only on-street paid parking places are considered, and "special" parking places are filtered out. The number of parked drivers can then be denoted by $n(t) = \int_0^{\tau(t)} [\, I(t - \tau)\, A\,(t - \tau)\, ]\, d\tau$ and the total number of parking places per zone is $N$. The vacancy rate is therefore $v(t) = 1 - n(t)/N$. All drivers are assumed to have the same valuation of time, $c$. Furthermore, while searching for a parking place, the driver can sample parking places at rate $r$ (e.g., one parking place per second). The success of the parking search follows a Poisson distribution with a rate of $rv(t)$ (i.e., the sampling rate multiplied by the vacancy rate), meaning that space and time do not influence the search process. This leads to a total expected search time, consisting of both in-vehicle as well as walking time, for a driver arriving at time *t* of $Z(t)$:

$$Z(t) = \frac{\psi}{rv(t)} \tag{1}$$

In this equation, $\psi$ is a multiplier to estimate walking time based on in-vehicle search time. The authors base this walking time on previous research in combination with assumptions on the destination. The authors explain that a "circling search strategy", where a driver can circle around in a zone when looking for a place to park, as opposed to a "linear strategy" where drivers look along a certain road is more in line with the empirical findings of Inci (2015) and makes sure the walking multiplier is less overestimated. They show that $\psi$ depends on the ratio between the speed of driving, denoted by $s$ (while searching) and the speed of walking, stated as $w$. This ratio is denoted as $\theta$. For more information, see appendix A.

Following from equation 1, the total search cost of all drivers who arrive at a given time *t* can be described by $C(t)$:

$$C(t) = \frac{c\psi}{r}\frac{I(t)A(t)}{v(t)} \tag{2}$$

Equation 2 shows that the total search cost is dependent on the search time multiplied by the search cost (i.e., valuation of travel time) and the arrival rate at time $t$. This means that when arrival rates are high and vacancy rates are low, the cost significantly increase. Furthermore, this equation allows for analysis in the cruising times for each time and block, thereby improving on earlier studies in which models were unable to do so.

However, equation 2 only elaborates on the total costs of all drivers at time $t$, while we are interested in the effect of an already parked driver who decides to extend his parking duration, thereby marginally increasing the search time for arriving drivers. If all parked driver at time *t* would decide to increase their parking duration $\tau$ , the marginal effect would be equal to $[\, I(t - \tau)\, A\,(t - \tau)\,]$. The effect of an extended duration of parking for a single driver, $\tau^{i}$, however is of interest. This marginal effect of increase in duration (i.e., by one driver) on $n(t)$ is 1 . This leads to a formulation of the marginal external cost of parking (MECP), which is:

$$MECP = \frac{\partial \mathrm{C(t)}}{\partial \tau^i(t)} = \frac{\partial \mathrm{C(t)}}{\partial n(t)} = \frac{\partial \mathrm{C(t)}}{\partial v\big(n(t)\big)} \frac{\partial v(n(t))}{\partial n(t)} = \frac{\mathrm{c}\psi}{r} \frac{I(t)A(t)}{Nv(t)^2} \tag{3}$$

From this equation it follows that search time, and therefore the MECP, sharply increases when the vacancy rate is low. Also, search time is low when there are few drivers searching for parking, indicating the effectiveness of low parking fees. To illustrate the use of the equation, the authors provide a numerical example on how to calculate the MECP for each zone at each given time. In the example, there is a block with 20 parking places ($N$= 20). At a given time, there is a vacancy rate, $v$, of 0.10 (i.e., 10% of parking places is still free) and the hourly arrival rate, $I \times A$, is 30. Furthermore, drivers search for free parking places with sample rate $r$ = 3600 per hour, which means they are able to "scan" one parking place per second. Drivers have no expected walking cost, so $\psi$ = 1 and the hourly valuation of time $c$ is $25.

This would lead to an estimated MECP, and thus an optimal social parking fee, of $(((25 \times 1)\ /\ 3600) \times 30\ /\ (20 \times (0.1)^2) = \$1.04$ for that specific parking zone at a given time.

The authors explain how, when maximizing welfare with respect to duration, the optimal parking fee $p^*(t)$ is equal to $MECP$ as stated in equation 3.

A full list of the expressions used in the original model can be found below in table 2.

*Table 2. List of expressions and corresponding descriptions used in original model by Van Ommeren et al. (2021).*

| Expression | Description |
|---|---|
| $N$ | Total number of parking places in each area |
| $t$ | Point of time in a day |
| $A(t)$ | Rate of new vehicles entering a certain parking zone |
| $I(t)$ | Chances of newly entered vehicle wanting to park in this zone |
| $n(t)$ | Number of parked cars at a certain time |
| $q(t)$ | Occupancy rate indicating the percentage of occupied parking places, which follows from $q(t) = n(t)\ /\ N$ |
| $v(t)$ | Vacancy rate showing the percentage of free parking places. This is equal to $v(t) = 1 - q(t)$ |
| $c$ | Valuation of time. This is derived from literature and assumed to be equal for all drivers |
| $r$ | Sampling rate. This shows the rate at which drivers can "scan" parking places to find an open spot per hour. |
| $\theta$ | Ratio of driving speed to walking speed. $\theta$ is dependent on driving speed $s$ and walking speed $w$ and is assumed to be equal to 4 (i.e., a walking speed $w$ of 5 km/h and a driving speed $s$ of 20 km/h). |

| | |
|---|---|
| $\psi$ | Walking time multiplier which is dependent on $\theta$. This value can take on values between 1 and 5.8 when $\theta = 4$. |
| $w$ | Assumed walking speed of driver searching for parking |
| $s$ | Assumed driving speed of driver while cruising for parking |
| $Z(t)$ | Expected search time based on the in-vehicle and walking search time as follows $Z(t) = \psi \,/\, (rv(t))$ |
| $C(t)$ | Total search cost per unit of time $t$ considering the search cost, occupancy rate and sampling rate as follows $C(t) = (c \,/\, \psi r) \times (I(t)A(t))/v(t))$. |
| $MECP$ | Marginal external cost of parking. The MECP is the additional search time imposed on a searching driving by an already parked driver extending his parking duration, and is computed as follows $MECP = ((c\psi/r) \times (I(t)A(t))/(Nv(t)^2)$. When using the measures already computed, the MECP can be estimated as $C(t)/\,(Nv(t))$ |
| $P(t)$ | The hourly parking fee. Note that the socially optimal parking fee is $p^*(t) = MECP$ |

# 3. Case study

To apply the model, this thesis focusses on the city of Amsterdam in the Netherlands. Amsterdam has always had a complicated relationship with cars. Small canals, busy cycling lanes and many visitors in the city centre have historically made the city centre of Amsterdam relatively unattractive for cars compared to some other large cities in the Netherlands. The first parking policy measures in the city consisted of prohibiting parking in certain streets. However, as the municipality was already struggling with lacking parking supply as early as the 1950's, Amsterdam became the first Dutch city to implement paid parking by placing 500 parking meters in 1964 (CROW, 2012). Over the years, parking fees became a standardized tool for- and replacement of- road pricing in managing traffic in the city.

Compared to many other cities in Western societies, the mobility of inhabitants in Amsterdam is relatively active. Most trips undertaken in Amsterdam are travelled by car (27%), followed closely by cycling (26%), public transport (26%), walking (19%) and mopeds (2%) (Gemeente Amsterdam, 2019). Within the Netherlands, Amsterdam has the lowest number of cars per 1000 inhabitants, at 247 cars (KiM, 2016). Car ownership however varies across the different areas within Amsterdam (table 3), which can be in part explained by the presence of strict parking policy measures in some areas while more relaxed parking management is in place in others (Gemeente Amsterdam, 2017).

*Table 3. Car ownership and presence of parking places across different city areas (Gemeente Amsterdam, 2017).*

| City area | Average number of cars per 1-person household | Average number of cars per ≥ 2-person household | Registered cars (excluding lease cars) | on-street parking places (paid / unpaid) | off-street parking places (public / private) |
|---|---|---|---|---|---|
| Nieuw-West | 0,43 | 0,82 | 40.800 | 59.000 | 37.000 |
| Zuid | 0,48 | 0,65 | 41.600 | 53.000 | 23.000 |
| Zuidoost | 0,30 | 0,59 | 29.400 | 26.000 | 38.000 |
| Oost | 0,39 | 0,71 | 33.400 | 33.000 | 28.000 |
| Noord | 0,33 | 0,81 | 28.500 | 44.000 | 12.000 |
| West | 0,18 | 0,55 | 32.800 | 31.000 | 10.000 |
| Centrum | 0,21 | 0,55 | 24.300 | 15.000 | 13.000 |
| Westpoort | - | - | - | 4.000 | 5.000 |
| *Average* | 0,32 | 0,68 | | | |
| **Total** | | | 230.700 | 266.000 | 167.000 |

On April 14th, 2019, the municipality implemented the first major change in parking fees in years. The city council presented a renewed plan to discourage car-ownership and prioritize active mobility like cycling and walking. As part of this strategy, the city decided to increase the on-street parking fees. This move turned out to be effective, as the increase in parking fees accounted for a drop in on-street parking demand of 2-3%, which was not offset by higher off-street parking demand (Ostermeijer et al., 2021). This effect is in line with previous results: according to the municipality, the number of bicycle trips in the city of Amsterdam increased by 44% at the expense of car usage between 1990 and 2008. They contribute this shift in modality to their relatively strict car-ownership and parking policies in combination with a large influx of highly educated people, who are less likely to make use of the car (Gemeente Amsterdam, 2012). The higher parking fees have also acted as a budgetary tool for the city council, as Amsterdam is the only municipality in the Netherlands making a profit from the creation and exploitation of parking places. From the revenues, around 23% is allocated to the mobility budget, which is mostly used to invest in active mobility infrastructure and to reduce externalities caused by road traffic (Gemeente Amsterdam, 2020). On a short-term, the city is investing in infrastructure aimed to improve the walkability of the city centre, as rating from visitors and residentials on the walkability plummeted over the last few years (see fig. 9).

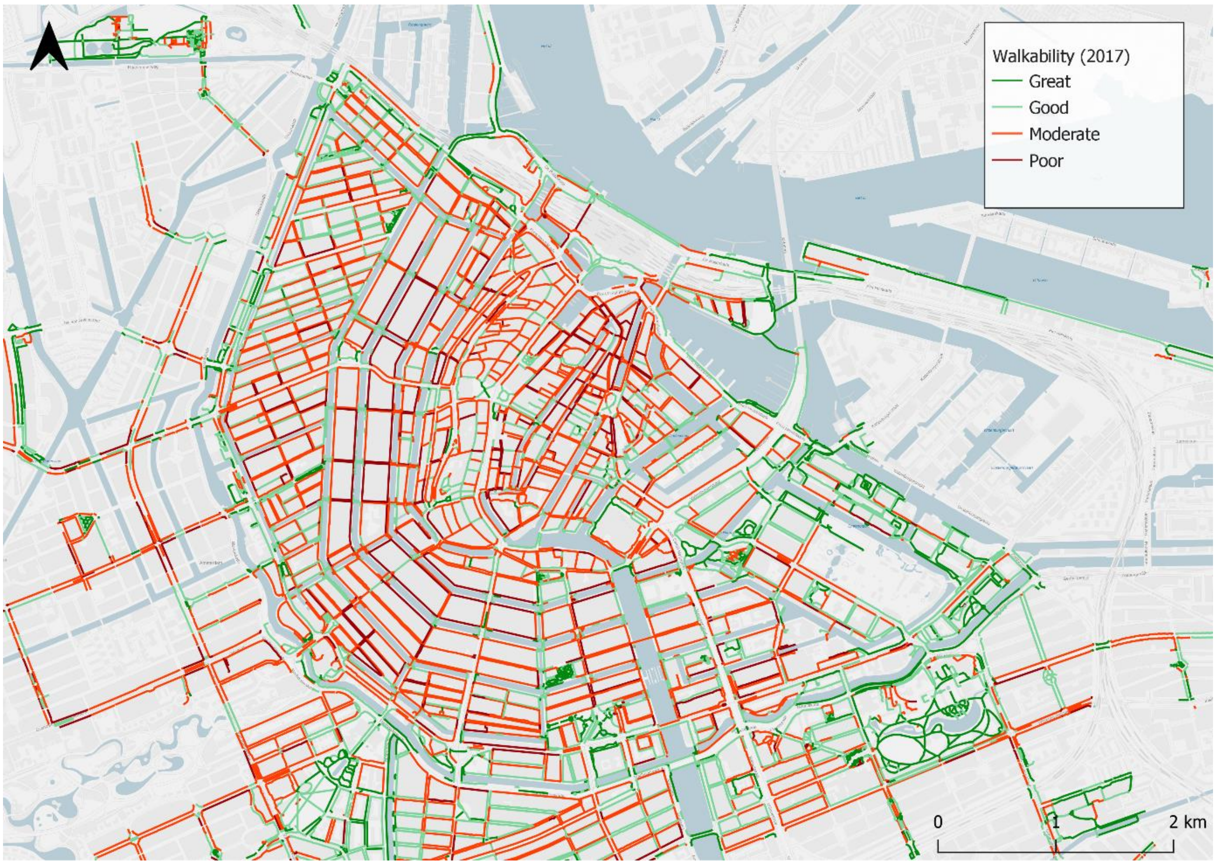


*Figure 9. Map showing walkability ratings from visitors and residents in the city centre (Gemeente Amsterdam, 2017).*

Even though the increase in parking fees seems to be a move in the right direction considering the goals from the municipality, parking demand is still high in many neighbourhoods across the city, leading to high occupancy levels. Partly based on these occupancy rates, the city has identified 7 different parking fee zones (fig. 10). In most zones, paid parking times stretch from 9:00 AM to 17:00 AM on weekdays. In the historical city centre however, paid parking durations can be significantly longer, stretching from 9:00 AM till 4:00 AM the next day.

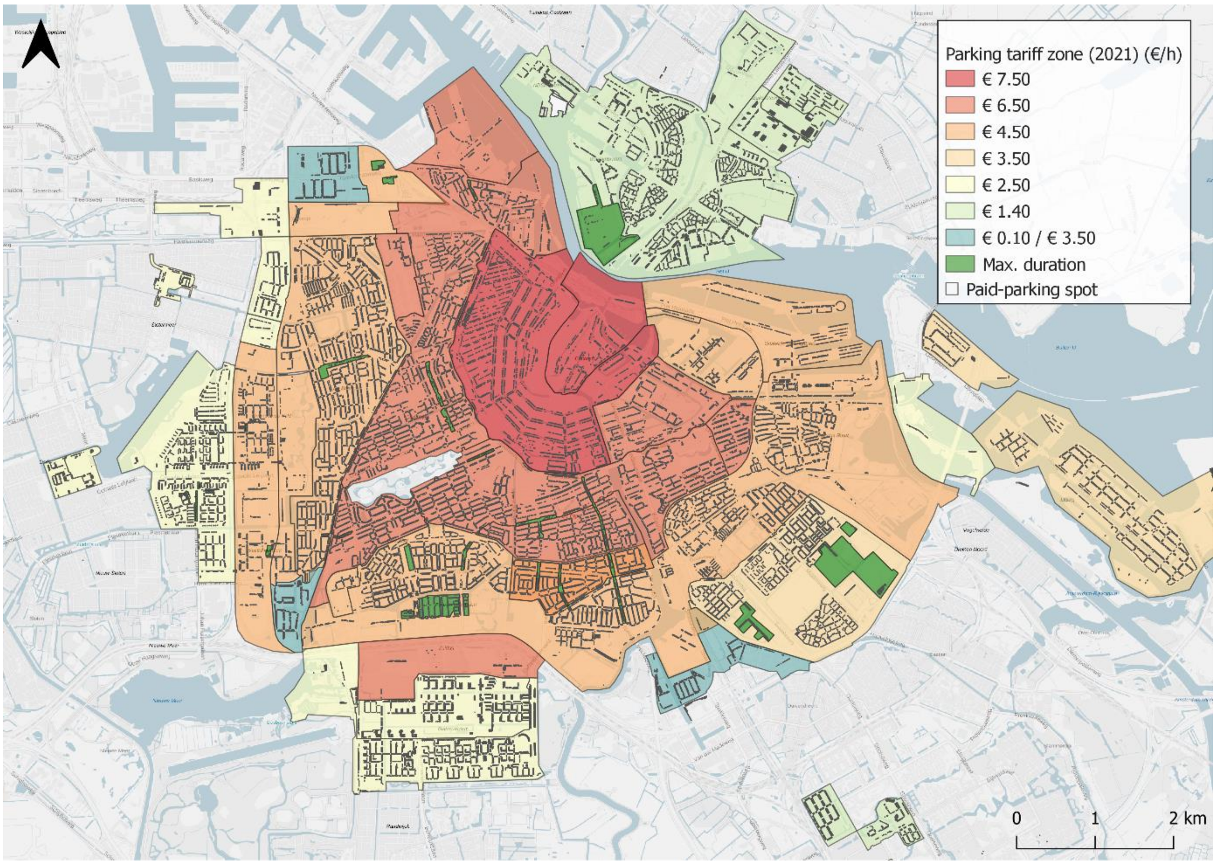


*Figure 10. Map showing the different tariff zones in Amsterdam. The dots represent paid off-street parking places (Gemeente Amsterdam, 2021).*

In these colour-coded zones, the parking fees vary from € 0.10 to € 7.50 per hour. In total, there are 151.003 paid on-street parking places in Amsterdam (table 4). This number is excluding "special" parking places like kiss & ride, taxi and disabled parking places. Next to the on-street parking places that are provided by the municipality, around 40% of all parking places in the city are off-street parking places (Het Parool, 2019). From these roughly 170.000 off-street parking places, around half are supplied by private companies.

*Table 4. Total number of on-street paid parking places for each (paid-)parking zone (Gemeente Amsterdam, 2021).*

| Tariff zone (€ / hour) | Total number of on-street paid parking places |
|---|---|
| 7.50 | 7.007 |
| 6.00 | 36.575 |
| 4.50 | 49.031 |
| 3.50 | 10.105 |
| 2.50 | 21.440 |
| 1.40 | 19.437 |
| 0.10 / 3.50 | 4.289 |
| Max. duration | 3.119 |
| *Total* | *151.003* |

In Amsterdam, over 165.000 residences are exposed daily to noise levels of >55 dB(A) (40% of total residences) that are passenger travel related. From this group, over 50.000 residences are experiencing severe noise nuisance, which accounts for about 6% of Amsterdam inhabitants (Gemeente Amsterdam, 2020). Especially in the city centre and along highways, noise levels rarely dip below the 55 dB(A) threshold for noise nuisance (see fig. 11).

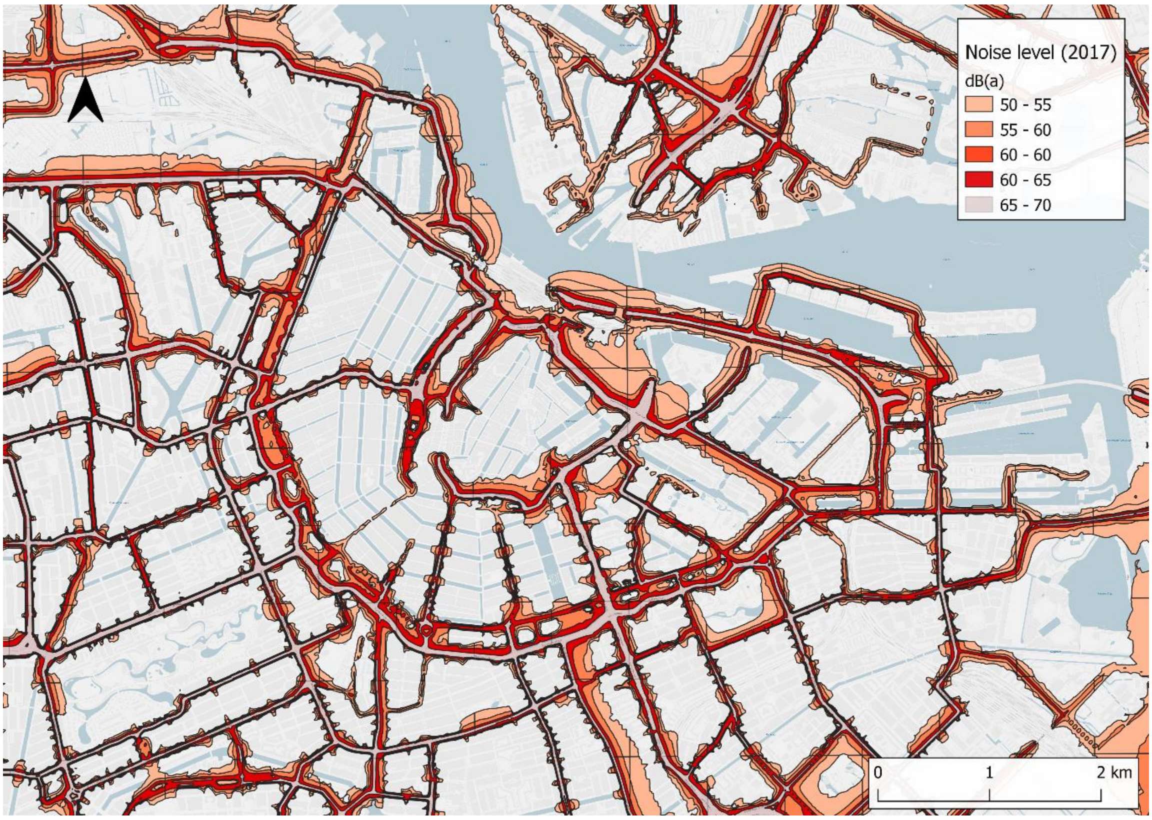


*Figure 11. Map showing noise levels in the city centre of Amsterdam (Gemeente Amsterdam, 2020).*

To battle this noise pollution, the city council has established the "Actieplan Geluid 2020-2030". In this plan, the city states a timeline for different measures that will decrease noise nuisance by an estimated 12% in 2030 (table 5).

*Table 5. Policy measures planned to reduce noise nuisance (Actieplan Geluid 2020-2030, Gemeente Amsterdam).*

| Year | Policy measure |
|---|---|
| 2020 | Implementation of environmental zone for passenger cars |
| 2022 | Implementation of emission-free zone for passenger and tourist busses within the city |
| 2025 | Implementation of emission-free zone for mopeds within the city |
| 2025 | Implementation of emission-free zone for freight transport, taxis, and public transport busses |
| 2025 | Implementation of emission-free zone for passenger boats and freight ships |
| 2030 | Implementation of emission-free zone for all vehicle modes in the entire city |

The measures stated to reduce noise are also partly in place to reduce greenhouse gasses and air pollutant emissions throughout the city. When looking at the levels of greenhouse gasses and air pollutants emitted, traffic contributes for around 17% of annual pollution emissions in the city. Combined with the estimated increase of traffic demand of 20% by 2040, this poses a serious challenge for the city. To decrease emissions and simultaneously improve connectivity and accessibility, the city uses the previously mentioned mobility budget (which is partly funded by the parking profits) to implement the policy measures proposed in the most recent climate plan (Gemeente Amsterdam, 2021). These policy measures include, amongst others, increasing space for pedestrians and cyclists, investing in electric charging infrastructure, and transforming city areas to emissions free zones.

# 4. Methodology

## 4.1 Additions or changes to the Van Ommeren et al. (2021) model

Although the methodology by Van Ommeren et al. (2021) explained in chapter 2.5 allows for welfare analysis of parking fees on some level, it is not an all-encompassing model. Like the authors themselves reflect, externality costs created by cruising for parking are not accounted for. As the model states that the MECP alone is equal to the socially optimized parking fee, the optimal parking fee $p^*(t)$ derived from the model underestimates the parking fee from a welfare perspective. This chapter will therefore explain the creation of additional expressions to the model that will be added to internalize (some of) the externality costs. Once internalized, the optimal parking fee will no longer be equal to the MECP, but rather to the MECP and the externality costs combined. Next to the additions made to the model, there will also be several changes in underlying assumptions due to data limitations that impact the estimations. In general, less detailed data is available for the case study in this thesis, thereby increasing the number of assumptions needed. This chapter will first briefly explain the changes to the methodology of the original model. Hereafter, the expressions that will be added to the model and their corresponding rationale will be explained.

## 4.2 Changes to the model

### 4.2.1. Arrival rate and time (continuity)

In the research by Van Ommeren et al. (2021), the authors make use of in-ground parking sensor data for the city of Melbourne. These sensors indicate on a 5-minute interval whether a parking place is occupied or vacant, which can be used to determine the arrival rate of drivers in the model. Ideally, this thesis would make use of similar data. In-ground parking sensors however are still scarcely employed worldwide, and the city of Amsterdam does not make use of these sensors yet.

As a result, the arrival rate $I(t)A(t)$ as stated in chapter 3.1 must be found in a different way. In the model by Van Ommeren et al. (2021), the authors estimate the MECP for three-hour intervals. In this thesis, the socially optimized parking fees will be estimated for the morning, afternoon and evening. Although smaller time periods or even fully flexible parking fees would have more impact on battling cruising for parking than three different parking fees (Chatman and Manville, 2014), the constructed model is able to compare the socially optimal parking fee to the current parking fee structure in Amsterdam (where there is one fixed parking fee per zone) and indicate the potential impact of parking fee differentiation throughout the day.

To estimate the arrival rate and address the issue of time continuity for the case study in this thesis, data on the average occupancy rate in the different parking zones within Amsterdam is used from the municipality. This data however is in some ways limited. First, it is only provided for the afternoon and evening, with data for the city area of Amsterdam Oost missing in the afternoon. Second, it provides data on the occupancy rate per neighbourhood or even per street, while the occupancy rate for the tariff zone in its entirety is of interest. The latter limitation is solved by taking the average of all occupancy rates of neighbourhoods in their respective tariff zone. To account for these limitations, a second method will be used to estimate the arrival rate. This is done by making use of a dataset containing mobile parking transactions. Data on the number of parking transactions started through this mobile parking provider, in combination with the total number of parking transactions as stated by the National Parking Registry (NPR) will be used. Furthermore, the number of parking permit holders per area will be accounted for to adjust the number of paid-parking places available to arriving drivers in each zone. As the mobile parking transaction dataset contains continuous time data for each tariff zone, this method allows us to estimate the occupancy rate, and therefore the socially optimised parking fee, in the morning, afternoon, and evening. After the estimations, the differences between the two methods and limitations of both will be described.

For more information on the data used in both methods, see chapter 5.

### 4.2.2. Value of travel time

An important difference between the case study analysed by Van Ommeren et al. (2021) versus the one analysed in this study is the use of valuation of travel time (VTT). Especially since this VTT has a large influence on the final social optimal parking fee. In the original model, a VTT of $ 33 stated by the Australian Transport Assessment and Planning Guidelines (2016) is used. In Australia, valuations of travel times are complex, and based on a lot of input factors, while the same VTT in Europe often relies on simply time-money trade-offs. In the latter, VTT is mostly derived from "stated choice" information from surveys about the valuation of time. However, these surveys over-simplify reality and fail to recognize and present all costs of time loss in the surveys, thereby often (substantially) underestimating the real valuation of time (e.g., Hensher et al. (2004), Hess et al. (2020)). As a result, the VTT found in studies outside of Europe are often substantially higher.

Furthermore, it is important to consider the different purposes of drivers when undertaking a trip. For example, in the Netherlands, a VTT of € 29,85 per hour was estimated for business trips, while commuting trips had a substantially lower VTT of € 9,53 per hour (price level 2010) (RWS, 2012). In this thesis, the assumption is made that 22% of all kilometers driven are driven for business purposes while the remaining 78% is driven with non-business purposes. These percentages are derived from the data on total kilometers driven annually by business-registered cars from the CBS (2019). This ratio of business/non-business trips is then multiplied with their respective VTT stated above and converted to 2020 price levels (+ 17,4 % compared to 2010) using CBS price level data (2021). This leads to an estimated average VTT (in 2020 price levels) of € 16,59 per hour. Please note that this VTT is still based on the Dutch VTT estimated by time-money trade-offs of respondents, which is likely to underestimate the real VTT.

## 4.3 Additions to the model

As mentioned in chapter 2.5.2., Van Ommeren et al. (2021) state that the optimal parking fee from a welfare perspective, $p^*(t)$ , is equal to the marginal increase of search time caused by an extended parking duration of a single driver, the MECP. However, next to the additional search time, other externalities arising from cruising for parking also influence welfare. The aim of this thesis therefore is to internalize relevant externality costs arising from cruising for parking and add this to the existing model to form a better approach to socially optimizing parking fees. To do so, this chapter will analyse existing literature on the pricing of these externalities to form the expressions that will be added to the model.

### 4.3.1. Congestion cost

The first externality cost that will be internalized in the model is congestion. In the handbook on external costs created by traffic by CE Delft (2019), the authors calculate the "delay cost" (i.e., the total costs caused by congestion) by using the speed-flow function and information on, amongst others, transport demand and congestion indexes in the EU. This information is then used to calculate the congestion cost per vehicle and the total car congestion costs in EU cities. Adding these two costs leads to the average congestion cost per vehicle kilometre by country at urban level (see fig. 12).

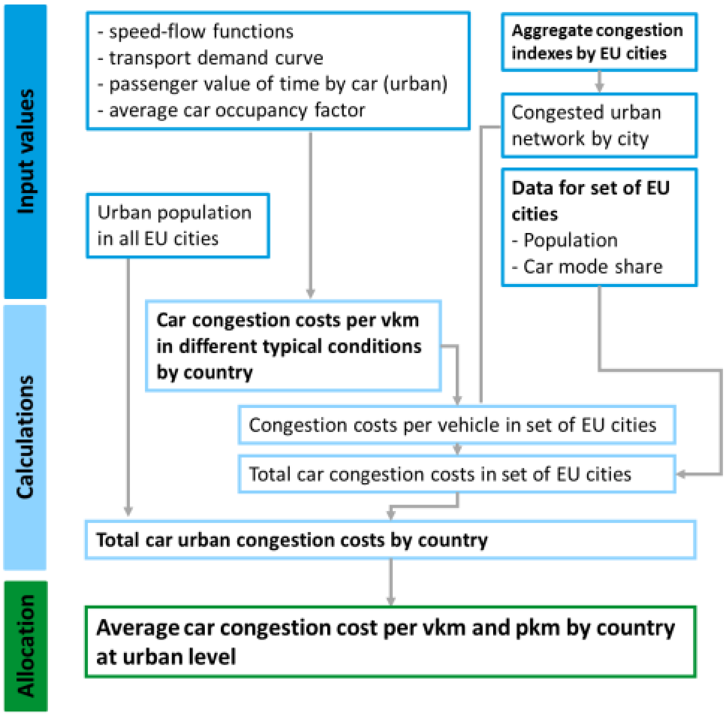


*Figure 12. Methodology used in estimating urban congestion costs (CE Delft, 2019).*

The results from this methodology can be found in table 6 below.

*Table 6. Total and average congestion cost by road vehicle in the EU28 (CE Delft, 2019).*

| *Vehicle category* | *Congestion costs* | | |
|---|---|---|---|
| | *Total EU28 (in billion €)* | *€-cent per passenger kilometre* | *€-cent per vehicle kilometre* |
| *Passenger car* | 206.2 | 4.37 | 7.03 |
| Passenger car – urban | 176.2 | 11.82 | 19.03 |
| Passenger car – inter-urban | 33.6 | 1.03 | 1.66 |
| *Coach* | | | |
| Coach – inter-urban | 2.1 | 0.74 | 14.49 |
| **Total passenger transport** | **208.3** | | |
| *Light Commercial Vehicle (LCV)* | 38.5 | 11.63 | 8.05 |
| LCV – urban | 32.6 | 27.75 | 19.21 |
| LCV – inter-urban | 5.9 | 2.78 | 1.92 |
| *Heavy Goods Vehicle (HGV)* | 23.8 | 1.30 | 17.72 |
| HGV – urban | 17.6 | 3.81 | 51.94 |
| HGV – inter-urban | 6.2 | 0.45 | 6.20 |
| **Total freight transport** | **62.3** | | |
| **Total road transport** | **270.6** | | |

In this thesis, the traffic cruising for parking is assumed to only exist from cars, as 99.98% of all mobile parking transaction started in the dataset were started by car-users. Therefore, the delay costs of 19.03 €-cent per vehicle kilometre for passenger cars in urban congestion will be used in the calculation of the externality costs arising from congestion in the model.

As the congestion cost per vehicle kilometre is known, the assumed average cruising speed (assumed for the MECP model) and the additional time spend cruising for parking (derived from the MECP calculations), will be used to calculate the total distance in kilometres travelled while cruising. This distance multiplied by the congestion cost per vehicle kilometre will provide the total congestion cost caused by one already-parked driver choosing to extend its stay as follows:

$$Congestion\ cost = Cc(t) = (additional\ cruising\ time * average\ cruising\ speed * congestion\ cost\ per\ vkm)$$

Which can be denoted as (see expression list in table 2):

$$Cc(t) = rv(t)\ \times s \times cc$$

$$Cc(t) = rsv(t)\ \times cc \tag{4}$$

### 4.3.2. Greenhouse gasses cost

Different to the calculation of the congestion costs, less input values are required to calculate the greenhouse gasses costs. The authors use cost factor equivalents combined with data on vehicle performance data per country provided by Eurostat and their respective greenhouse emissions to establish the average costs these emissions cause per vehicle kilometre. The complete methodology is visualized below:

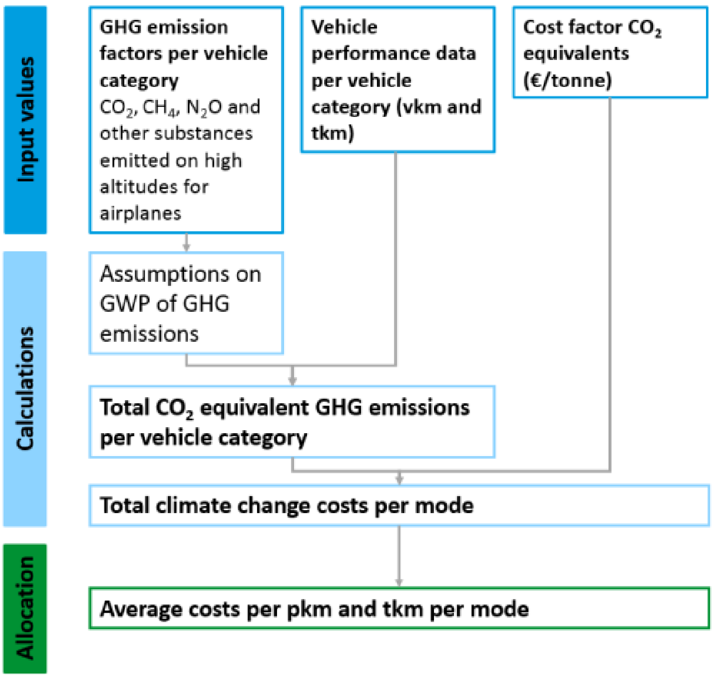


*Figure 13. Methodology used in determining the average and total costs of greenhouse gasses per vkm (CE Delft, 2019).*

Note that the costs associated with greenhouse gas emissions are calculated as an “avoidance” cost rather than a “damage” cost. The authors choose to do so by considering all greenhouse gas emissions above a certain threshold. This threshold is set in such a way that temperature increases due to global warming are limited to 2 degrees Celsius. Temperature rises above 2 degrees are stated to be “too risky for future generations” by the Paris Agreement, therefore it is easier to estimate the costs to avoid this maximum temperature rise as opposed to estimating the damages associated with temperature increases exceeding the maximum. Once all input values are collected, the authors find the following total and average cost for greenhouse gas emissions:

*Table 7. Total and average greenhouse gasses cost per vehicle in the EU28 (CE Delft, 2019).*

| *Vehicle category* | *Greenhouse gasses cost* | | |
|---|---|---|---|
| | *Total EU28 (in billion €)* | *€-cent per passenger kilometre* | *€-cent per vehicle kilometre* |
| *Passenger car* | 55.56 | 1.18 | 1.90 |
| Passenger car – petrol | 32.02 | 1.22 | 1.97 |
| Passenger car – diesel | 23.54 | 1.12 | 1.80 |
| Motorcycle | 1.47 | 0.89 | 0.94 |
| Bus | 0.84 | 0.47 | 8.83 |
| Coach | 1.61 | 0.44 | 8.66 |
| **Total passenger road** | **59.49** | | |
| Passenger train diesel | 0.22 | 0.34 | 20.1 |
| **Total passenger transport** | **59.71** | | |
| *Light Commercial Vehicle (LCV)* | 13.17 | 3.98 | 2.75 |
| LCV – petrol | 0.71 | 3.76 | 2.56 |
| LCV – diesel | 12.45 | 3.99 | 2.77 |
| HGV | 9.63 | 0.53 | 6.48 |
| **Total freight road** | **22.79** | | |
| Freight train diesel | 270.6 | 0.25 | 112.4 |
| Inland vessel | 0.40 | 0.27 | 383.1 |
| **Total freight transport** | **23.43** | | |
| **Total road, rail, inland waterway** | **83.14** | | |

For these externality costs the assumption again is made that cruising for parking only happens by passenger cars. From table 7 however, it can be derived that the type of passenger car impacts the costs per vehicle kilometre. To determine the final cost per vehicle kilometre, data on the composition of the parking car fleet is derived from the dataset containing data on the mobile parking transactions. The dataset shows that the ratio of petrol to diesel cars is almost equal to 3:1, with around 10% of cars parking being either hybrid (7.79%) or electric (2.78%).

It is assumed that all hybrid cars were driving electric as they were cruising for parking, and therefore 10% of cars parking do not contribute to greenhouse gas emissions, as electric vehicles do not emit these gasses. The remaining 90% is assumed to be a petrol or diesel cars according to their respective ratio of 3:1 (67.5% petrol versus 22.5% diesel cars) found in the dataset. These ratios and their respective cost per vehicle kilometre led to a final greenhouse cost per vehicle kilometre of 1.73 €-cent.

Again, by using the average speed while searching for parking combined with the additional minutes spend searching for parking from the MECP model, the externality costs associated with greenhouse gas emissions is internalized as follows:

$$Greenhouse\ gasses\ cost = Gc(t) = (additional\ cruising\ time * average\ cruising\ speed * greenhouse\ gasses\ cost\ per\ vkm)$$

Which can be denoted as (see expression list in table 2):

$$Gc(t) = rv(t)\ \times s \times gc$$

$$Gc(t) = rsv(t)\ \times gc \qquad (5)$$

### 4.3.3. Air pollutant costs

Where greenhouse gasses indirectly affect wellbeing by contributing to climate change, air pollutants emitted by traffic directly impact wellbeing and health when breathed in. The methodology used in the handbook by CE Delft (2019) to calculate the costs associated with air pollution is identical to the one used for the greenhouse gasses costs stated in chapter 4.3.2.

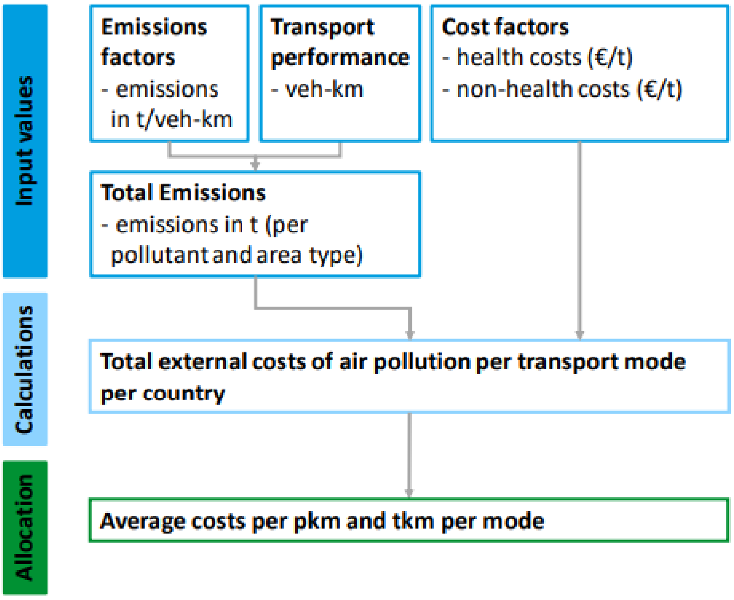


*Figure 14. Methodology used in determining average and total air pollutant cost per vkm (CE Delft, 2019).*

Contrary to the costs found for greenhouse gasses however, the costs associated with air pollution are "damage" costs. The authors consider, in monetary terms, the damage caused by air pollution on health, crop, materials, buildings and biodiversity. From the stated methodology, the following results are found:

*Table 8. Total and average air pollution costs for different vehicle modes in the EU28 (CE Delft, 2019).*

| *Vehicle category* | *Air pollutant cost* | | |
|---|---|---|---|
| | *Total EU28 (in billion €)* | *€-cent per passenger kilometre* | *€-cent per vehicle kilometre* |
| *Passenger car* | 33.36 | 0.71 | 1.14 |
| Passenger car – urban | 8.58 | 0.33 | 0.53 |
| Passenger car – inter-urban | 24.79 | 1.18 | 1.90 |
| | | | |
| Motorcycle | 1.84 | 1.12 | 1.17 |
| Bus | 1.35 | 0.76 | 14.19 |
| Coach | 2.67 | 0.73 | 14.34 |
| **Total passenger road** | **39.23** | | |
| Passenger train diesel | 0.22 | 0.34 | 20.1 |
| High speed passenger train | 0.002 | 0.002 | 0.66 |
| Passenger train electric | 0.03 | 0.01 | 1.14 |
| **Total passenger rail** | **0.55** | | |
| **Total passenger transport** | **39.78** | | |
| *Light Commercial Vehicle (LCV)* | 15.49 | 4.68 | 3.24 |
| LCV – petrol | 0.33 | 1.72 | 1.17 |
| LCV – diesel | 15.16 | 4.86 | 3.37 |
| | | | |
| HGV | 13.93 | 0.76 | 9.38 |

| | | | |
|---|---|---|---|
| **Total freight road** | **29.42** | | |
| Freight train diesel | 0.66 | 0.68 | 305.39 |
| Freight train electric | 0.01 | 0.004 | 2.14 |
| **Total freight train** | 0.67 | | |
| Inland vessel | 1.93 | 1.29 | 1869 |
| **Total freight transport** | **32.92** | | |
| **Total road, rail, inland waterway** | **71.80** | | |

Once again, the relevant cost and the average cost for passenger cars per vehicle kilometre, which is 1,14 €-cent, will be used in the final model. Multiplied by the average distance covered while cruising for parking (based on the speed and additional time spend cruising), the external costs caused by parking with respect to air pollution are internalized in the model as:

$$Air\ pollutant\ cost = Ac(t) = (additional\ cruising\ time * average\ cruising\ speed * air\ pollutant\ cost\ per\ vkm)$$

Which can be denoted as (see expression list in table 2):

$$Ac(t) = rv(t)\ \times s\ \times ac$$

$$Ac(t) = rsv(t)\ \times ac \qquad (6)$$

### 4.3.4. Noise cost

To estimate the costs associated with noise pollution from traffic, the authors make use of country specific data on noise levels or European noise maps to estimate the number of people affected by noise. Combined with data on the cost of annoyance and health arising from noise pollution, the handbook can estimate the average and total costs of noise pollution in the EU.

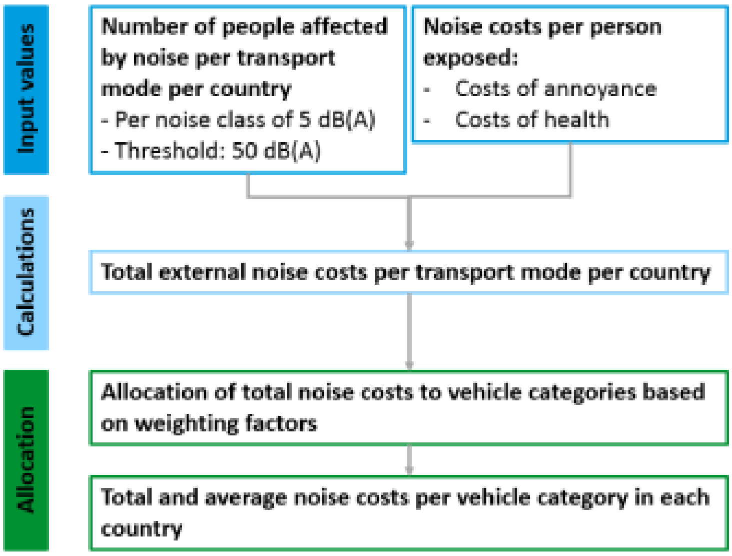


*Figure 15. Methodology used in determining the average and total noise cost per vkm (CE Delft, 2019).*

The costs consist of annoyance and health components for individuals who are exposed to noise above a 50 dB(A) threshold. Furthermore, the cost per vehicle kilometre is weighted by different multipliers found in literature to allocate the right amount of noise pollution to each vehicle type. For example, motorcycles have a weighting factor of 13 times that of passenger cars. The results can be found in table 9 below.

*Table 9. Total and average noise cost for different vehicle modes in the EU28 (CE Delft, 2019).*

| *Vehicle category* | *Noise cost* | | |
|---|---|---|---|
| | *Total EU28 (in billion €)* | *€-cent per passenger kilometre* | *€-cent per vehicle kilometre* |
| *Passenger car* | 26.2 | 0.6 | 0.9 |
| Passenger car – petrol | 13.8 | 0.5 | 0.8 |
| Passenger car – diesel | 12.4 | 0.6 | 0.9 |
| Motorcycle | 14.8 | 9.0 | 9.4 |
| Bus | 0.8 | 0.4 | 8.0 |
| Coach | 0.9 | 0.2 | 4.7 |
| **Total passenger road** | **42.6** | | |
| Passenger train diesel | 0.9 | 1.4 | 81 |
| High speed passenger train | 0.4 | 0.3 | 97 |
| Passenger train electric | 2.6 | 0.8 | 106 |
| **Total passenger rail** | **3.9** | | |
| **Total passenger transport** | **46.5** | | |
| *Light Commercial Vehicle (LCV)* | 5.4 | 1.6 | 1.1 |
| *Heave Good Vehicle (HGV)* | | | |
| HGV 3.5-7.5 t | 1.0 | 1.2 | 4.0 |
| HGV 7.5-16 t | 1.8 | 0.8 | 5.7 |
| HGV 16-32 t | 3.0 | 0.4 | 6.5 |

| | | | |
|---|---|---|---|
| HGV > 32 t | 3.2 | 0.4 | 7.2 |
| **Total freight road** | **14.5** | | |
| Freight train diesel | 0.4 | 0.4 | 201 |
| Freight train electric | 2.1 | 0.6 | 359 |
| **Total freight rail** | **2.5** | | |
| **Total freight transport** | **17.1** | | |
| **Total road, rail, inland waterway** | **63.6** | | |

As the cost are different for different passenger car types, the composition of the car fleet derived from the dataset containing mobile parking transaction is used again (see chapter 4.3.2.). Using this composition, an average cost of noise pollution per vehicle kilometre of 0.74 €-cent is found. These costs will be internalized in the model as follows:

$$Noise\ cost = Nc(t) = (additional\ cruising\ time * average\ cruising\ speed * noise\ cost\ per\ vkm)$$

Which can be denoted as (see expression list in table 2):

$$Nc(t) = rv(t)\ \times s\ \times nc$$

$$Nc(t) = rsv(t)\ \times nc \qquad (7)$$

## 4.4 Changes in coefficients and variables

In addition to the expressions stated in Table 2 in chapter 2.5, equations 4 to 7 are added to the MECP model constructed by Van Ommeren et al. (2021) to internalize relevant external costs arising from cruising for parking. Together, these equations can be denoted as the total external costs of cruising for parking at time $t$, $TEc(t)$:

$$TEc(t) = rsv(t)\ \times (nc(t) + gc(t) + ac(t) + cc(t)) \qquad (8)$$

These external costs are then added to the MECP model to estimate the optimal social parking fee $P^*(t)$ as follows:

$$P^*(t) = MECP + TEc(t)$$

$$P^*(t) = \frac{c\psi}{r}\frac{I(t)A(t)}{Nv(t)^2} + (rsv(t)\ \times (nc(t) + gc(t) + ac(t) + cc(t))) \qquad (9)$$

All expressions added to the original model can be found below in table 10. A complete list of all expressions used in the final model can be found in appendix C.

*Table 10. Expressions that will be added to the model by Van Ommeren et al. (2021) to internalize external costs.*

| Expression | Description |
|---|---|
| $Cc(t)$ | Total congestion cost at time $t$ |
| $Gc(t)$ | Total greenhouse gasses cost at time $t$ |
| $Ac(t)$ | Total air pollutant emissions cost at time $t$ |
| $Nc(t)$ | Total noise cost at time $t$ |
| $cc$ | Congestion cost per vehicle kilometre |
| $gc$ | Greenhouse gasses cost per vehicle kilometre |
| $ac$ | Air pollutant cost per vehicle kilometre |
| $nc$ | Noise cost per vehicle kilometre |
| $TEc(t)$ | Total external cost at time $t$. The total consists of all externality costs per vehicle kilometre combined, multiplied by the total additional distance travelled cruising for parking. |

## 4.5 Assumptions overview

This chapter will briefly state the assumptions made in the previous chapters that impact the input values, and therefore outcomes, of the model.

First, an estimation of the socially optimised parking fee will be made for the different parking zones in Amsterdam for the morning, afternoon, and evening by using two different methods. The first method will make use of a dataset containing mobile parking transactions in combination with data on the composition of all parking transactions by the NPR and information on the number of parking permits per tariff zone from the municipality. The second method will rely on data on the average occupancy rate provided by the municipality, which is only available for the afternoon and evening dayparts.

Second, the purpose of the trip has a large influence on the VTT of drivers. Although precise data on the composition of traffic (based on purpose) is unavailable for Amsterdam, it is important to take this into account to some extent as VTT estimations in the Netherlands are already very limited (and therefore often underestimated) compared to other (often) non-European estimations (see chapter 4.2.2.). To account for the different purposes, the assumption is made that the composition of non-business / business related travel in Amsterdam is equal to that of the composition of total miles driven (based on purpose) in the Netherlands, which is 78% versus 22% respectively.

Third, cars are assumed to be the only vehicles searching for parking. This assumption is validated by the Parkmobile dataset, which shows that 99.98% of all parking transaction are started by car-users.

Fourth, the driving speed while searching for parking is unobserved but has a large impact on the externality cost. For the analysis, a driving speed of 20 km/h is assumed. This speed is derived from the same assumption made in the original model by Van Ommeren et al. (2021).

Fifth, the ratio of petrol to diesel cars used in determining the cost per vehicle kilometre is derived from the mobile parking transaction dataset. A relatively small percentage of drivers ride either hybrid (7.79%) or electric (2.78%) vehicles. It is therefore assumed that 10% of drivers do not contribute to greenhouse gas, air pollutant or noise externality costs, while the other 90% is assumed to be petrol or diesel cars according to their respective ratio of 3:1 (67.5% petrol versus 22.5% diesel cars).

Lastly, it is important to take into account the number of parking permits in each tariff zone, as these drivers do not show up within the parking transactions but make intensive use of parking facilities. Data on the maximum number of parking permits per parking zone is supplied by the municipality. As this is a maximum rather than the actual amount of parking permits in circulation, and cars are not always parked, the assumption is made that 50% of the total number of parking permits are actively used at any time, thereby decreasing the parking place supply in a tariff zone accordingly.

# 5. Data

To obtain the data necessary for the input values of the model, different data sources are used. For the first method, where the vacancy rate and arrival rate will be estimated, input values for the model are derived from a large dataset containing information on parking transactions in different cities in the Netherlands. The dataset is provided by a large mobile parking provider operating in the Netherlands. Information in the dataset includes, amongst others, start-date and time, end-date and time, parking durations, and total parking fee paid. More detailed information on, for example, the hometown of the driver was also included in the dataset. However, as this data is irrelevant in constructing or application of the model, these variables are dropped from the dataset.

The original dataset contains information on 49 different variables for over 20.5 million observations for the year 2019 in Amsterdam. Although similar data is available for 2020, the year 2019 was selected as there was no real influence from the COVID-19 pandemic on parking demand yet.

As the city of Amsterdam implemented significant increases in parking fees for the different tariff zones in April 2019, transactions before the 1$^{st}$ of May 2019 are dropped from the dataset. This lowers the number of observations to around 13.3 million. In table 11 below, the descriptive statistics are stated. It is noticeable that parking transactions in cheaper tariff zones are on average longer than in the more expensive zones. For the € 3.5/hour and € 1.4/hour zones in particular, this could be in part caused by the relatively low amount of parking permits that are available in these zones. This could cause more parking by residents, who tend to park longer than visitors, to increase the average parking durations.

*Table 11. Descriptive statistics: mobile parking transactions (Parkmobile, 2019).*

| | | | Vehicle type | | | Driver type | |
|---|---|---|---|---|---|---|---|
| **Tariff zone (€ / hour)** | *Transactions (% of total)* | *Average parking duration (min)* | *Gasoline* | *Diesel* | *Hybrid/electric* | *Visitor* | *Resident* |
| 7.5 | 797,012 (6%) | 88.94 | 48% | 41% | 11% | 59% | 41% |
| 6 | 3,031,366 (23%) | 95.44 | 52% | 38% | 10% | 54% | 46% |
| 4.5 | 3,455,242 (26%) | 92.91 | 54% | 37% | 9% | 48% | 52% |
| 3.5 | 858,583 (6%) | 178.38 | 54% | 37% | 9% | 51% | 49% |
| 2.5 | 1,325,691 (10%) | 126.11 | 58% | 33% | 9% | 47% | 53% |
| 1.4 | 1,946,555 (15%) | 209.91 | 62% | 29% | 9% | 47% | 53% |
| 0.1/3.5 | 1,890,303 (14%) | 147.44 | 64% | 26% | 9% | 51% | 49% |
| Total | 13,304,752 | 126.91 | 56% | 34% | 10% | 51% | 49% |

The dataset described above is used as one of the two methods to estimate the arrival rate, as stated in chapter 4. This dataset combined with data from the National Parking Registry (NPR) allows us to estimate the total number of parking transactions. The NPR dataset contains information on the annual number of parking transaction per city. This total number of transactions includes mobile and physical parking ticket sales. A total of 106,051,032 transactions were registered in 2018. Comparing this to the dataset from the mobile parking provider, it follows that around 45% of all parking transactions took place on the platform (i.e., ± 48 million from the total ± 106 million transactions).

*Table 12. Number of Parkmobile transactions and total number of transactions per year (NPR, 2019 & Parkmobile, 2019).*

| Year | Parkmobile transactions | Total transactions | % of transactions from Parkmobile |
|---|---|---|---|
| 2014 | 16,405,222 | 33,289,873 | 49.28% |
| 2015 | 23,866,313 | 41,531,471 | 57,47% |
| 2016 | 33,695,132 | 62,121,172 | 54,24% |
| 2017 | 44,123,638 | 88,757,520 | 49,71% |
| 2018 | 48,246,700 | 106,051,302 | 45,49% |

It is therefore assumed that the dataset containing parking transaction embodies 45% of all parking transactions, and a corresponding factor of 2.22 is used on, for example, the number of cars arriving using the mobile parking provider per day(part), to estimate the total number of cars arriving. The arrival rate is then estimated over the total number of parking places available minus half of the number of parking permit per area, as stated by the municipality.

The second method to estimate the occupancy rate is by using the data on average occupancy rate for different neighbourhood in Amsterdam provided by the municipality. The dataset contains the average occupancy rate for each parking zone in the city. The average occupancy rate of all parking zones in a certain tariff zone is calculated to form the final occupancy rate, as it is assumed that drivers are searching for parking in a certain tariff zone rather than in a smaller specific parking zone. The occupancy rates per parking zone are visualized in figures 16 and 17 in Appendix B.

A variable is created for all parking transaction per respective period of day (morning 9-12) afternoon (12-5) and evening (after 5). The descriptive statistics are stated in table 13 below.

*Table 13. Descriptive statistics per part of day (Parkmobile, 2019).*

| | | | Vehicle type | | | Driver type | |
|---|---|---|---|---|---|---|---|
| **Part of day** | *Transaction (% of total)* | *Average parking duration (min)* | *Gasoline* | *Diesel* | *Hybrid/electric* | *Visitor* | *Resident* |
| Morning | 4,540,694 (34%) | 163.97 | 50% | 41% | 9% | 56% | 44% |
| Afternoon | 5,683,161 (43%) | 89.10 | 58% | 32% | 10% | 48% | 52% |
| Evening | 3,036,019 (23%) | 134.96 | 61% | 28% | 11% | 47% | 53% |
| Total | 13,259,874 | 129.34 | 56% | 34% | 10% | 51% | 49% |

The input values for external costs are derived from CE Delft (2019) handbook on external costs in traffic management. This handbook is seen as thrustworthy source and is used in many external costs calculations throughout Europe. The final cost components of each externality is then composed by multiplying the relevant cost factors for each type of car (petrol / diesel / electric) with their respective assumed ratio (see chapter 4.5).

*Table 14. Overview of all relevant externality costs used in the model (CE Delft, 2019).*

| *Externality* | *Cost* | | |
|---|---|---|---|
| | *Total EU28 (in billion €)* | *€-cent per passenger kilometre* | *€-cent per vehicle kilometre* |
| *Congestion cost* | 206.2 | 4.37 | 7.03 |
| Passenger car – urban | 176.2 | 11.82 | 19.03 |
| Passenger car – non-urban | 33.6 | 1.03 | 1.66 |
| *Greenhouse gas cost* | 55.56 | 1.18 | 1.90 |
| Passenger car – petrol | 32.02 | 1.22 | 1.97 |
| Passenger car – diesel | 23.54 | 1.12 | 1.80 |
| *Air pollutant cost* | 33.36 | 0.71 | 1.14 |
| Passenger car – urban | 8.58 | 0.33 | 0.53 |
| Passenger car – non-urban | 24.79 | 1.18 | 1.90 |
| *Noise cost* | 26.2 | 0.6 | 0.9 |
| Passenger car – petrol | 13.8 | 0.5 | 0.8 |
| Passenger car – diesel | 12.4 | 0.6 | 0.9 |
| **Total petrol cars** | 45.82 | 1.72 | 2.77 |
| **Total diesel cars** | 35.94 | 1.72 | 2.70 |
| **Total urban traffic** | 184.78 | 12.15 | 19.56 |
| **Total non-urban traffic** | 58.39 | 2.21 | 3.56 |
| ***Total average cost*** | **321.32** | **6.86** | **10.97** |

Lastly, the constructed model will be using the publicly available dataset used by Van Ommeren et al. (2021) for the city of Melbourne to assess the impact of the additions to the model on the final approximation of the socially optimum parking fee. The MECP as calculated in the original paper is expanded by calculating the average search time for drivers in each zone for each day and multiplied by the externality costs per vehicle kilometre.

*Table 15. Average occupancy rate (%) across the different parking districts of Melbourne (Van Ommeren et al. 2019)*

| | **Weekdays** | | | | | **Saturday** | | | | | **Sunday** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 |
| CBD (NE) | 27 | 47 | 70 | 53 | 65 | 16 | 29 | 52 | 50 | 69 | 17 | 45 | 76 | 72 | 82 |
| CBD (NW) | 32 | 53 | 64 | 50 | 48 | 24 | 34 | 45 | 35 | 45 | 32 | 54 | 76 | 64 | 56 |
| CBD (SE) | 47 | 62 | 75 | 62 | 68 | 24 | 43 | 64 | 58 | 72 | 20 | 42 | 74 | 70 | 84 |
| CBD (SW) | 47 | 62 | 70 | 62 | 62 | 23 | 40 | 51 | 48 | 58 | 27 | 53 | 80 | 71 | 65 |
| East | 29 | 54 | 65 | 50 | 51 | 12 | 32 | 53 | 62 | 72 | 18 | 50 | 77 | 79 | 57 |
| North | 23 | 41 | 57 | 41 | 45 | 29 | 54 | 70 | 43 | 38 | 27 | 75 | 84 | 60 | 41 |
| Southbank | 18 | 36 | 44 | 35 | 47 | 18 | 27 | 38 | 45 | 66 | 4 | 14 | 61 | 60 | 45 |
| West | 18 | 37 | 48 | 33 | 30 | 25 | 42 | 46 | 20 | 25 | 7 | 53 | 85 | 44 | 22 |

*Table 16. MECP ($ / h) found for the different districts in Melbourne by Van Ommeren et al. (2021)*

| | **Weekdays** | | | | | **Saturday** | | | | | **Sunday** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CBD (NE) | 0.0 | 0.1 | 0.3 | 0.1 | 1.9 | 0 | 0 | 0.2 | 0.4 | 4.3 | 0 | 0.7 | 1.6 | 0.8 | 2.8 |
| CBD (NW) | 0.2 | 0.7 | 1.5 | 0.1 | 0.9 | 0.7 | 2.8 | 2.3 | 0.7 | 1.3 | 0.2 | 6.7 | 6.5 | 1.3 | 0.3 |
| CBD (SE) | 0.3 | 0.8 | 1.8 | 0.6 | 4.8 | 0 | 0.2 | 0.3 | 2 | 9.2 | 0 | 0.3 | 2.9 | 1.7 | 5.6 |
| CBD (SW) | 0.1 | 1 | 1.7 | 0.7 | 1.6 | 0 | 0.2 | 0.3 | 0.2 | 2.2 | 0.1 | 0.4 | 2.9 | 0.9 | 0.3 |
| East | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0 | 0 | 0.1 | 0.2 | 0.2 | 0 | 0.1 | 0.3 | 0.2 | 0.1 |
| North | 0 | 0.1 | 0.3 | 0.3 | 0.5 | 0.2 | 1.6 | 5.2 | 1.1 | 0.1 | 0.1 | 15.6 | 10.1 | 3.2 | 0.1 |
| Southbank | 0 | 0 | 0.1 | 0 | 0.9 | 0 | 0 | 0.1 | 0 | 0.5 | 0 | 0 | 0.2 | 0.1 | 0.5 |
| West | 0 | 0 | 0 | 0 | 0.3 | 0 | 0.6 | 0.1 | 0 | 0 | 0 | 0.1 | 0.3 | 0 | 0 |
| | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 |

# 6. Results

## 6.1 Main results

This chapter will elaborate on the results obtained from the previously mentioned methodology, data and assumptions that are used to determine an optimal parking fee, seen from a welfare perspective. The model expands on the model created by Van Ommeren et al. (2021) by accounting for externality costs created by drivers searching for parking.

First, the walking multiplier and vacancy rates were calculated. The walking multiplier $\psi$ is derived from the ratio of driving speed to walking speed $\theta$ and the number of parking places $N$ in combination with the vacancy rate $v$ (appendix A). As the parking zones are large, and vacancy rates are relatively low, the walking multiplier is the same for all tariff zones when $\theta = 4$ (i.e., driving speed is 20km/h and walking speed is 5 km/h) and is equal to 5.8.

In determining the arrival rate, the probability that an arriving driver is looking for a parking place $I(t)$ is set as 1, as the arrival rates are based on the Parkmobile dataset, and all drivers observed in the dataset are searching for a parking place. Afterwards, these input factors were used in combination with data on the number of parking places (after correction for parking permits), the valuation of time $c$ and the assumed sampling rate $r$ of 0.75 parking places per second to find the MECP. Once the MECP is calculated, the additional cruising time per day(part) and cruising speed were used and multiplied by the relevant externality costs per vehicle kilometre to find the estimate the (improved) socially optimum parking fees.

## 6.2 Marginal external cost of parking

### 6.2.1. Additional cruising time

Table 17 shows the calculated additional cruising time in minutes. The numbers indicate the time a driver needs when entering the tariff zone to find a parking place. Note that it is in this time that the drivers are contributing to the externalities caused by driving, as stated in chapter 4.3.

On average, the additional cruising time equals 2.65 minutes from the model using the estimated vacancy rates, and 5.02 minutes from the model using municipality stated vacancy rates. The difference can be explained by the significantly lower vacancy rates observed in the municipality data (on average about 25 percent points lower). Furthermore, the difference in average cruising time can be explained by the fact that the second method only finds the search time for the afternoon and evening dayparts, in which vacancy rates are generally lower than in the morning.

In line with the both the estimated vacancy rates as well of these supplied by the municipality, the cruising times are the highest in the € 7.50 /hour tariff zone. In this zone, there are relatively few parking places available, a high number of parking permits and a high number of arriving drivers. Outside this tariff zone, search times differ relatively little.

*Table 17. Additional cruising time (in minutes) for arriving drivers, for different day(part)s*

| **Zone** | | | | **Morning** | | | |
|---|---|---|---|---|---|---|---|
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 2.73 | 3.53 | 3.27 | 3.26 | 3.37 | 1.73 | 1.17 |
| *6* | 1.89 | 2.09 | 2.02 | 2.03 | 2.09 | 1.51 | 1.15 |
| *4.5* | 1.95 | 2.11 | 2.03 | 2.04 | 2.09 | 1.60 | 1.15 |
| *3.5* | 1.66 | 1.75 | 1.73 | 1.71 | 1.74 | 1.59 | 1.18 |
| *2.5* | 1.58 | 1.69 | 1.63 | 1.66 | 1.66 | 1.28 | 1.15 |
| *1.4* | 1.53 | 1.58 | 1.56 | 1.57 | 1.57 | 1.35 | 1.18 |
| *0.1 / 3.50* | 1.32 | 1.33 | 1.29 | 1.31 | 1.28 | 1.24 | 1.15 |
| | | | | **Afternoon** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 8.94 | 24.20 | 20.73 | 30.42 | 38.08 | 4.68 | 2.95 |
| *6* | 2.83 | 3.31 | 3.24 | 3.24 | 3.55 | 2.50 | 1.37 |
| *4.5* | 3.10 | 3.68 | 3.60 | 3.36 | 4.07 | 2.82 | 1.14 |
| *3.5* | 1.99 | 2.12 | 2.20 | 2.06 | 2.28 | 2.26 | 1.16 |
| *2.5* | 2.02 | 2.19 | 2.14 | 2.08 | 2.22 | 1.61 | 1.14 |
| *1.4* | 1.86 | 1.93 | 1.92 | 1.92 | 2.12 | 2.01 | 1.45 |
| *0.1 / 3.50* | 1.42 | 1.45 | 1.44 | 1.43 | 1.41 | 1.34 | 1.16 |
| | | | | **Evening** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 2.09 | 2.18 | 2.27 | 2.74 | 2.68 | 2.41 | 1.91 |
| *6* | 1.68 | 1.82 | 1.80 | 1.93 | 1.94 | 1.76 | 1.27 |
| *4.5* | 1.79 | 1.93 | 1.89 | 1.93 | 2.00 | 1.81 | 1.14 |
| *3.5* | 1.63 | 1.74 | 1.72 | 1.76 | 1.82 | 1.67 | 1.16 |
| *2.5* | 1.34 | 1.37 | 1.37 | 1.43 | 1.40 | 1.32 | 1.14 |
| *1.4* | 1.42 | 1.46 | 1.46 | 1.49 | 1.53 | 1.42 | 1.22 |
| *0.1 / 3.50* | 1.34 | 1.38 | 1.40 | 1.42 | 1.37 | 1.24 | 1.19 |

### 6.2.2. MECP

After all input values were calculated, the marginal external cost of parking was calculated. Like in the work by Van Ommeren et al. (2021), it can be observed that the calculated MECP is higher than the current parking fee in only 3% of cases. This indicates that parking fees, from a social welfare perspective, are too high for most parking zones and day(part)s. Most parking fees are close to zero, as vacancy rates on average are low and thus the time losses for arriving drivers are minimal. It should however be noted that the MECP is strongly convex in the vacancy rate, as the MECP rises rapidly as the vacancy rate approaches 0. This is reflected in the high MECP in the €7.5/hour tariff zone in the afternoon (where the vacancy rate is between 3-5% between Tuesday and Friday) compared to, for example, the relatively low MECP in the same tariff zone in the morning, where vacancy rates are also low at around 32-35%.

*Table 18. MECP (€/hour) for the different parking zones at different day(part)s estimated with Parkmobile data*

| **Zone** | | | | **Morning** | | | |
|---|---|---|---|---|---|---|---|
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.12 | 0.23 | 0.19 | 0.19 | 0.21 | 0.03 | 0.00 |
| *6* | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.02 | 0.00 |
| *4.5* | 0.04 | 0.06 | 0.05 | 0.05 | 0.05 | 0.02 | 0.00 |
| *3.5* | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.00 |
| *2.5* | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.01 | 0.00 |
| *1.4* | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.00 |
| *0.1 / 3.50* | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| | | | | **Afternoon** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 1.92 | 15.36 | 11.17 | 24.50 | 38.70 | 0.46 | 0.15 |
| *6* | 0.13 | 0.20 | 0.19 | 0.19 | 0.24 | 0.09 | 0.01 |
| *4.5* | 0.17 | 0.26 | 0.24 | 0.21 | 0.33 | 0.13 | 0.00 |
| *3.5* | 0.05 | 0.06 | 0.06 | 0.05 | 0.07 | 0.07 | 0.00 |
| *2.5* | 0.05 | 0.06 | 0.06 | 0.05 | 0.07 | 0.02 | 0.00 |
| *1.4* | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.05 | 0.01 |
| *0.1 / 3.50* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| | | | | **Evening** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.05 | 0.06 | 0.07 | 0.12 | 0.11 | 0.08 | 0.04 |
| *6* | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.03 | 0.00 |
| *4.5* | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.03 | 0.00 |
| *3.5* | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.00 |
| *2.5* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 |
| *1.4* | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 |
| *0.1 / 3.50* | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |

= Lower than current parking fee = Higher than current parking fee

*Table 19. MECP (€/hour) at different day(part)s estimated using municipality data on occupancy rates.*

| | | | | **Zone** | | | |
|---|---|---|---|---|---|---|---|
| | *7.5* | *6* | *4.5* | *3.5* | *2.5* | *1.4* | *0.1 / 3.50* |
| *Afternoon* | 2.83 | 0.33 | 0.14 | 0.03 | 0.11 | 0.09 | 0.38 |
| *Evening* | 11.71 | 1.02 | 0.33 | 0.07 | 0.12 | 0.09 | 0.05 |

= Lower than current parking fee = Higher than current parking fee

## 6.3 The socially optimized parking fee

From the MECP the respective search times were calculated. Multiplying the in-car search time with the average search speed of 20 km/h, the distance travelled while cruising for parking is found. This distance is then used to find the social cost per externality (Appendix D). The total external cost varies from € 0.09 when vacancy rates are high, to € 2.91 when vacancy rates are low and cruising is extensive. Overall, the largest part of these externality cost consists of congestion cost (approximately 84%). Once added to the earlier found MECP, the results as stated in table 20 and 21 are found. As can be derived from table 21, the optimal parking fee is higher than the actual current parking fee in 16% of the cases, compared to 3% when only analysing the MECP. This could indicate the importance of accounting for as many social cost components as possible.

*Table 20. The socially optimised parking fee (€ / hour) based on welfare analysis using Parkmobile data.*

| **Zone** | **Morning** | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.33 | 0.50 | 0.44 | 0.44 | 0.47 | 0.16 | 0.09 |
| *6* | 0.18 | 0.21 | 0.20 | 0.20 | 0.21 | 0.13 | 0.09 |
| *4.5* | 0.19 | 0.22 | 0.21 | 0.21 | 0.21 | 0.14 | 0.09 |
| *3.5* | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.14 | 0.09 |
| *2.5* | 0.14 | 0.15 | 0.15 | 0.15 | 0.15 | 0.10 | 0.09 |
| *1.4* | 0.13 | 0.14 | 0.14 | 0.14 | 0.14 | 0.11 | 0.09 |
| *0.1 / 3.50* | 0.11 | 0.11 | 0.10 | 0.11 | 0.10 | 0.10 | 0.09 |
| | **Afternoon** | | | | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 2.60 | 17.20 | 12.75 | 26.83 | 41.60 | 0.81 | 0.37 |
| *6* | 0.35 | 0.45 | 0.43 | 0.43 | 0.51 | 0.28 | 0.11 |
| *4.5* | 0.40 | 0.54 | 0.52 | 0.46 | 0.64 | 0.35 | 0.09 |
| *3.5* | 0.20 | 0.22 | 0.23 | 0.21 | 0.25 | 0.24 | 0.09 |
| *2.5* | 0.20 | 0.23 | 0.22 | 0.21 | 0.24 | 0.14 | 0.09 |
| *1.4* | 0.18 | 0.19 | 0.19 | 0.19 | 0.22 | 0.20 | 0.12 |
| *0.1 / 3.50* | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.11 | 0.09 |
| | **Evening** | | | | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.21 | 0.23 | 0.24 | 0.33 | 0.32 | 0.27 | 0.19 |
| *6* | 0.15 | 0.17 | 0.17 | 0.19 | 0.19 | 0.16 | 0.10 |
| *4.5* | 0.17 | 0.19 | 0.18 | 0.19 | 0.20 | 0.17 | 0.09 |
| *3.5* | 0.15 | 0.16 | 0.16 | 0.16 | 0.17 | 0.15 | 0.09 |
| *2.5* | 0.11 | 0.11 | 0.11 | 0.12 | 0.12 | 0.11 | 0.09 |
| *1.4* | 0.12 | 0.12 | 0.12 | 0.13 | 0.13 | 0.12 | 0.10 |
| *0.1 / 3.50* | 0.11 | 0.11 | 0.12 | 0.12 | 0.11 | 0.10 | 0.09 |

= Lower than current parking fee = Higher than current parking fee

*Table 21. The socially optimised parking fee (€ / hour) based on welfare analysis using municipality data.*

| | **Zone** | | | | | | |
|---|---|---|---|---|---|---|---|
| | *7.5* | *6* | *4.5* | *3.5* | *2.5* | *1.4* | *0.1 / 3.50* |
| *Afternoon* | 3.65 | 0.64 | 0.37 | 0.16 | 0.31 | 0.27 | 0.72 |
| *Evening* | 13.33 | 1.53 | 0.64 | 0.24 | 0.33 | 0.28 | 0.20 |

= Lower than current parking fee = Higher than current parking fee

The largest welfare losses are endured in the city centre, especially in the afternoon and evening. During these parts of the day, the socially optimised parking fee is between 170% to 554% higher than the actual parking fee. The city centre in Amsterdam houses most shopping areas, nightlife districts and cultural sights and is known to be crowded with visitors and residents. Combined with limited parking places and a relatively high number of parking permits, vacancy rates are low during the day.

Furthermore, in the tariff zone € 0.10 / € 3.50, where parking is cheap for the first three hours, the social optimised parking fee is higher than the current parking fee for most day(part)s. Even though vacancy rates are relatively high in this zone, the low parking costs fail to reflect the social cost encountered by the drivers looking for parking. Of course, this is not the case from the 4th hour of parking onwards, as parking fees then increase to € 3.50 per hour. However, as the average parking duration in this zone is less than three hours (147 minutes), the actual parking fee is often lower than the welfare cost.

Another difference to the results found using the expanded model compared to those found by Van Ommeren et al. (2021), is the fact that the socially optimised parking fee is never € 0/hour. Because externalities are accounted for rather than just the time-loss for drivers, there are always some social costs endured. Even if the vacancy rate is a 100% and the cruising distance is short, there are some social costs associated with driving in the tariff zone.

## 6.4 Melbourne

Lastly, the expanded model was used on data from the city of Melbourne to compare the results to those found by Van Ommeren et al. (2021). As it is impossible to make the exact same data cut-offs as Van Ommeren et al. (2021), the walking multiplier is assumed to be 4.3, which is stated to be the average walking multiplier found in the original research. Furthermore, the composition of the vehicle fleet searching for parking is assumed to be the same as that of Amsterdam in calculation the external costs.

As was to be expected, all optimal parking fees found by the constructed model are higher than the original parking fees (table 16). The parking fees are between 2% and 192% higher, with an average increase of 66% (see table 22). The lower percentual changes are found in the areas where vacancy rates are low and thus the MECP is high, as the externality costs are less convex in the vacancy rate and therefore the MECP grows substantially faster and higher as vacancy rates approach 0.

Furthermore, there are no more day(part)s where the socially optimal parking fee is equal to 0. Even with high vacancy rates, there is always some in-car search time as drivers try to park closer to their destinations rather than parking immediately when entering a tariff zone. Since the expanded model considers the externalities created by this cruising rather than limiting the social cost to time losses, the minimum parking fee found for Melbourne is $ 0.10 / hour compared to $ 0.00 / hour found in the original model. Although the socially optimal parking fees are still lower than the actual parking fee in most cases, the percentage of socially optimised parking fees outgrowing the actual parking fee rose from 3% to approximately 8 %. The results thereby indicate that an expansion of the parameters used to estimate the socially optimised parking fee could not only provide a more encompassing way of estimating social cost, it also puts existing parking fee structures under increased scrutiny.

*Table 22. Socially optimised parking fees ($/hour) for Melbourne composing of the MECP found by Van Ommeren et al. (2021) and the externality cost.*

| | **Weekdays** | | | | | **Saturday** | | | | | **Sunday** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CBD (NE) | 0.11 | 0.26 | 0.58 | 0.28 | 2.14 | 0.10 | 0.12 | 0.37 | 0.57 | 4.57 | 0.10 | 0.85 | 1.94 | 1.10 | 3.26 |
| CBD (NW) | 0.32 | 0.88 | 1.73 | 0.27 | 1.06 | 0.81 | 2.93 | 2.45 | 0.83 | 1.45 | 0.32 | 6.88 | 6.84 | 1.53 | 0.49 |
| CBD (SE) | 0.46 | 1.02 | 2.13 | 0.82 | 5.06 | 0.11 | 0.34 | 0.53 | 2.20 | 9.50 | 0.10 | 0.44 | 3.22 | 1.98 | 6.12 |
| CBD (SW) | 0.26 | 1.22 | 1.92 | 0.92 | 1.82 | 0.11 | 0.34 | 0.47 | 0.36 | 2.40 | 0.21 | 0.58 | 3.31 | 1.18 | 0.54 |
| East | 0.22 | 0.28 | 0.44 | 0.27 | 0.37 | 0.09 | 0.12 | 0.28 | 0.42 | 0.50 | 0.10 | 0.27 | 0.66 | 0.48 | 0.29 |
| North | 0.11 | 0.24 | 0.49 | 0.44 | 0.65 | 0.32 | 1.78 | 5.48 | 1.24 | 0.23 | 0.21 | 15.93 | 10.62 | 3.41 | 0.24 |
| South | 0.10 | 0.13 | 0.25 | 0.13 | 1.06 | 0.10 | 0.11 | 0.23 | 0.15 | 0.74 | 0.09 | 0.10 | 0.41 | 0.31 | 0.65 |
| West | 0.10 | 0.13 | 0.16 | 0.12 | 0.42 | 0.11 | 0.74 | 0.25 | 0.10 | 0.11 | 0.09 | 0.28 | 0.85 | 0.15 | 0.11 |
| | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 | Before 9:00 | 9:00 - 12:00 | 12:00 - 15:00 | 15:00 - 18:00 | After 18:00 |

# 7. Discussion, Conclusion and Future Research

## 7.1 Conclusion

As stated in chapter 6, the socially optimised parking fee is estimated to be relatively low (less than € 0.50/hour) for most tariff zones across time. This indicates that, from a social welfare point of view, parking fees in most tariff zones in Amsterdam are currently set to high and therefore welfare losses are endured. These welfare losses are highest in the city centre, where vacancy rates are relatively low and traffic intensity is high. The socially optimised parking fee is highest in the afternoon on weekdays (using estimated vacancy rates) and on evenings (using municipality data on vacancy rates).

Overall, most outcomes are in line with those found by Van Ommeren et al. (2021); vacancy rates are high, and the time losses caused by cruising for parking are often lower than the current parking fees. It is important to recognize however that comparing the socially optimised parking fee to the current parking fees asks for a nuance. Pricing parking according to social welfare is a vastly different approach compared to the current approach, in which the price mechanism is mostly used as a tool of mending supply and demand. This of course also means that the effects of implementing socially optimised parking fees is ambiguous; lowering parking fees leads to lower price points where demand could outrun supply.

Therefore, implementing a paid parking structure based on welfare estimations would be most convenient and effective by using perfectly flexible parking fees. Implementing flexible pricing could look something like the current Uber pricing model, in which taxi fares rise accordingly to multiple variables like traffic density, demand, time and distance of trip (in case of parking; time and length of stay). In case of parking, live data on the vacancy rates and arrival rates combined with expended knowledge on walking / driving speeds could be used to determine a fully flexible socially optimised parking fee that aims to minimize cruising for parking, as this is the main source for social costs. By doing so, the parking fees would be able to limit both time losses for drivers as well as externality costs. Also, such a paid parking structure would eliminate the need for complicated and ungrounded parking regulations that are now often in place; differences in parking zones, paid parking times, parking fees, duration limitations and other restrictions would become obsolete. Lastly, this infrastructure would also expand the possibilities to monitor location-specific social costs and thereby provide the municipality the opportunity to use the revenues generated by parking to improve welfare in those areas where the welfare losses are endured. Although current infrastructure does not yet allow for this way of pricing parking, it could prove a more efficient (but maybe less profitable) way of pricing parking.

Although this thesis presents an introductory expansion on the model by Van Ommeren et al. (2021), it indicates the importance of accounting for as many costs components as possible when trying to estimate desirable parking fees from a welfare perspective. Even with our “modest” introduction of four external costs components, the socially optimised parking fee have increased on average by 66% compared to the model only considering time losses due to cruising for parking. Furthermore, the “ease of use” of the original model is not impacted by introducing externality costs as data requirements only increase a little, thereby preserving its potential widespread usability.

## 7.2 Limitations

Next to assumptions stated in chapter 4.5, there are some simplifications that impact the results found in this thesis. First, it is assumed that every driver wants to park in the tariff zone he or she enters. Of course, there might be parking places in adjacent tariff zones that are more attractive that parking places in the same tariff zone but far away. By not taking this into account, in-car search time might be overestimated when vacancy rates are low.

Next, in estimating the vacancy rates, the assumption on the number of parking permits is very influential. In the current model 50% of parking permits are deducted from the parking supply, however more specific data or information on the parking habits of these permit holders could have a large impact on the estimations. For example, if 75% of parking permits were assumed to limit the parking supply, the socially optimised parking fee would already outrun the current parking fee in 35% of all cases, with the parking fee quadrupling in some areas.

Furthermore, average external costs for different combustion engine types are used. However, within the combustion types there could also be large differences in emission classes (and therefor external costs). Although the impact on the final socially optimal parking fee is limited in most cases, more detailed information on emission classes and vehicle types could improve the estimations for the external costs.

Also, the total amount of parking places per tariff zone is assumed to be fixed for all days, while there are parking places in each tariff zone subjected to special regulations like max. durations, or alternative paid parking times. This could also influence another potential limitation: the differences in vacancy rates found using the two different methods. Although the first estimation is based on some crucial assumptions and differs from the municipality data, it does provide a more time-varying approach as the municipality data is present for only 2 dayparts and provides an average over all seven days of the week. Therefore, information and expanded data on parking transactions could improve estimations on arrival rates, which have a large impact on the outcomes.

Although multiple social cost factors were introduced to the model, there are likely still multiple cost factors missing. For example, considering vehicle operating cost (per hour) while cruising for parking or estimating accident costs linked to cruising for parking might have a significant impact on the final estimations.

## 7.3 Recommendations for future research

As stated, this thesis aims to present an introductory methodology towards welfare-based paying for parking by building on expanding on existing literature. As the data available was limited, multiple assumptions can corrupt the explanatory value of the model. Data limitations will likely become less relevant in the future, as since 2017, EU-member states must register parking status data (EU directives 2010/40 and 2015/962) and live-tracking parking sensors are increasingly being utilized in parking infrastructure. As this infrastructure improves, the potential impact of a paid-parking fee structure using real-time, flexible, socially optimising parking fees (as described in chapter 7.1) should be explored.

Also, as data becomes more widely available, the model can be tuned, tested, and improved by implementing it in different (international) case studies and comparing the corresponding outcomes with outcomes from previously conducted research concerning welfare based paid parking structures. By doing so, the use of the model can be validated, and the general applicability of the model further be improved.

Furthermore, additional social cost factors should be added to the model for it to effectively estimate the socially optimising parking fees. A more extensive literature review in combination with the construction of new relevant cost-parameters would improve the potential of the model to limit welfare losses and improve its explanatory value. The model should therefore be seen more as a starting point for future welfare estimations of parking fees.

Adding to this, the cost of creating, maintaining, and exploiting parking places for municipalities should also be considered while estimating the parking fees, as new paid parking structure based on welfare analysis are unlikely to be implemented in case the costs for municipalities rises significantly, and vice versa.

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# 9. Appendices

## Appendix A

**Searching strategies**

In the paper by Van Ommeren et al. (2021), the authors explain the assumed search strategy of drivers searching for parking that is used to estimate the walking time multiplier.

First, a "naïve" linear search strategy is described in which a driver is searching for parking along a road and only starts looking for parking once arrived at the destination. In this case, the driver first drives through the distance between his destination and parking place and then needs to walk the same distance twice, right after parking and right before departing. This results in $\psi = 2\theta + 1$. When $\theta$ = 4 (recall; the driving speed while searching for parking is 4 times larger than the walking speed), $\psi = 9$. This naïve linear search strategy however is overestimating the walking time multiplier, as drivers can start searching for parking before arriving at their destination. Van Ommeren et al. (2021) show that this leads to

$$\psi = (2\theta + 1)\ln\left(\frac{4\theta}{2\theta - 1}\right) \tag{10}$$

Which gives a lower walking multiplier than the naïve search strategy ($\psi = 5.8$ in case $\theta = 4$ ). However, the authors explain that this rational linear search strategy still limited in reflecting observed parking behaviour. They therefore state a circling search strategy in which drivers can circle around the block to reduce walking time after reaching the destination. When assumed that drivers search only within a block and that the destination is at one end of that block, a driver is expected to walk half a block. If destinations are distributed uniformly along the block, then the expected walking distance will be a quarter of the block. Alternatively, if a driver drives in a square search pattern around four blocks with identical occupancy, spots, and spatial spot density, then the expected walking distance will be two blocks. This leads to

$$\psi = (2\theta + 1)\ln\left(\frac{4\theta - 2\theta e^{-0.5vN}}{2\theta - 1}\right) \tag{11}$$

In which $\psi$ is increasing in $vN$. When $vN$ is large (i.e., when the vacancy rate is substantial and the block is large), $\psi$ approaches equation 10 from below, as the driver is searching on a straight line. In the case study for Amsterdam conducted in this thesis, this is the case, and the walking multiplier is closer to the one estimated from the rational linear searching strategy ($\psi = 5.8$ when $\theta = 4$ ).

# Appendix B

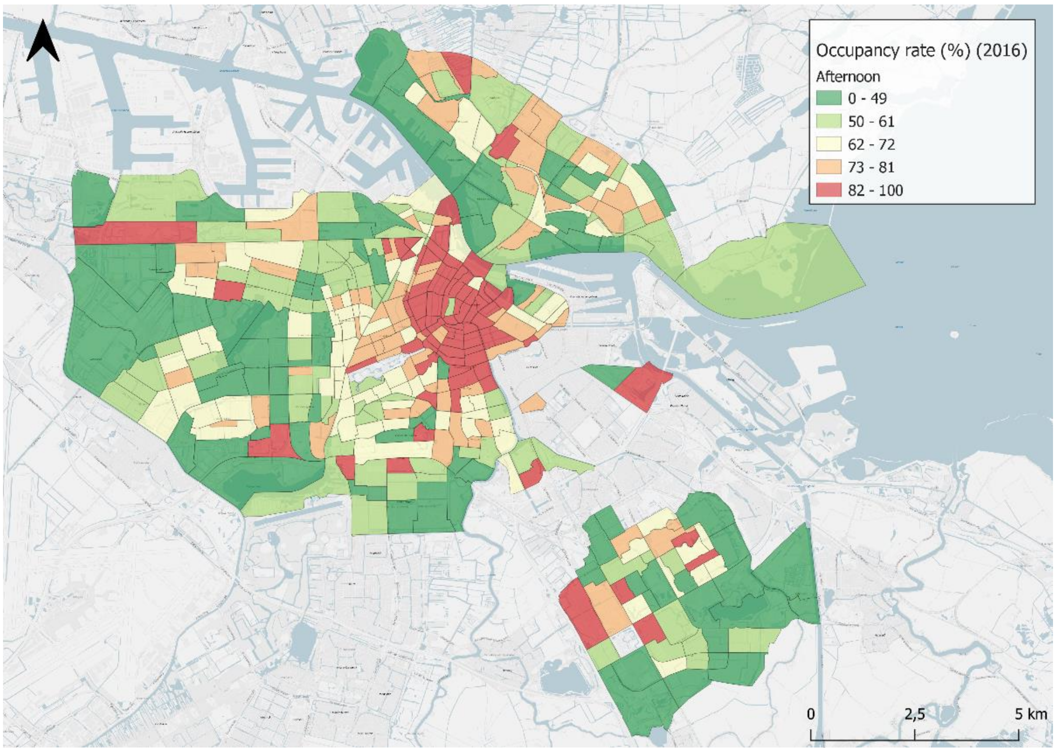


*Figure 16. Occupancy rates during the afternoon in Amsterdam (Gemeente Amsterdam, 2019)*

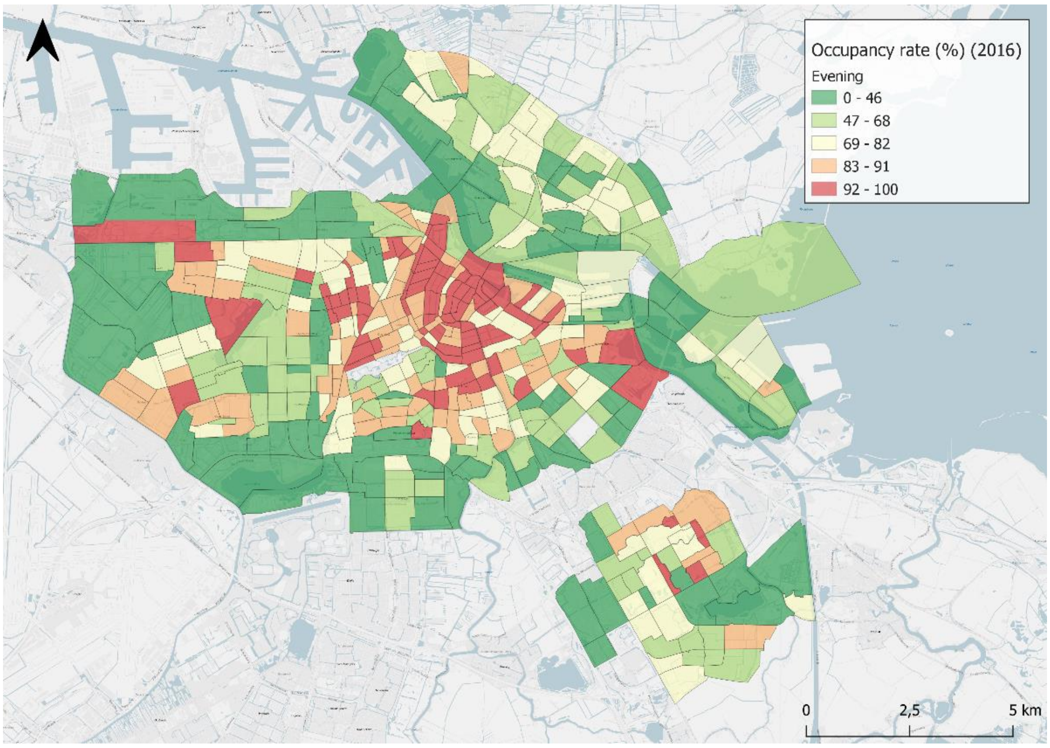


*Figure 17. Occupancy rates during the evening in Amsterdam (Gemeente Amsterdam, 2019)*

## Appendix C

*Table 23. List of expressions used in the final model.*

| Expression | Description |
|---|---|
| $N$ | Total number of parking places in each area |
| $t$ | Point of time in a day |
| $A(t)$ | Rate of new vehicles entering a certain parking zone |
| $I(t)$ | Chances of newly entered vehicle wanting to park in this zone |
| $n(t)$ | Number of parked cars at a certain time |
| $q(t)$ | Occupancy rate indicating the percentage of occupied parking places, which follows from *q(t) = n(t) / N* |
| $v(t)$ | Vacancy rate showing the percentage of free parking places. This is equal to *v(t) = 1 – q(t)* |
| $c$ | Valuation of time. This is derived from literature and assumed to be equal for all drivers |
| $r$ | Sampling rate. This shows the rate at which drivers can "scan" parking places to find an open spot per hour. |
| $w$ | Walking speed in kilometres per hour |
| $s$ | Driving speed while searching for parking in kilometres per hour |
| $\theta$ | Ratio of driving speed to walking speed. This ratio is assumed to be 4. |
| $\psi$ | Walking time multiplier which is dependent on $\theta$. This value can take on values between 1 and 5.8 when $\theta = 4$. See appendix A for more explanation. |
| $Z(t)$ | Expected search time based on the in-vehicle and walking search time as follows $Z(t) = \psi\ /\ (rv(t))$ |
| $C(t)$ | Total search cost per unit of time *t* taking into account the search cost, occupancy rate and sampling rate as follows $\mathrm{C}(t) = (c\ /\ \psi r)\ \times (I(t)A(t))/v(t))$. |
| *MECP* | Marginal external cost of parking. The MECP is the additional search time imposed on a searching driving by an already parked driver extending his parking duration, and is computed as follows $MECP = ((c\psi/r)\ \times (I(t)A(t))/(Nv(t)^2)$. Using the measures already computed, the MECP can be estimated as $C(t)/\ (Nv(t))$ |
| $P(t)$ | The hourly parking fees. Note that the socially optimal parking fee is $p^*(t) = MECP$ |
| $Cc(t)$ | Total congestion cost at time $t$ |
| $Gc(t)$ | Total greenhouse gasses cost at time $t$ |
| $Ac(t)$ | Total air pollutant emissions cost at time $t$ |
| $Nc(t)$ | Total noise cost at time $t$ |
| $cc$ | Congestion cost per vehicle kilometer |
| $gc$ | Greenhouse gasses cost per vehicle kilometer |
| $ac$ | Air pollutant cost per vehicle kilometer |
| $nc$ | Noise cost per vehicle kilometer |
| $TEc(t)$ | Total external cost at time $t$. The total consists of all externality costs per vehicle kilometer combined, multiplied by the total additional distance travelled cruising for parking. |

## Appendix D

*Table 24. Total external cost (€) for different parking zones at different day(part)s using Parkmobile data.*

| Zone | | | | Morning | | | |
|---|---|---|---|---|---|---|---|
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.21 | 0.27 | 0.25 | 0.25 | 0.26 | 0.13 | 0.09 |
| *6* | 0.14 | 0.16 | 0.15 | 0.15 | 0.16 | 0.12 | 0.09 |
| *4.5* | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.12 | 0.09 |
| *3.5* | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.12 | 0.09 |
| *2.5* | 0.12 | 0.13 | 0.12 | 0.13 | 0.13 | 0.10 | 0.09 |
| *1.4* | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.10 | 0.09 |
| *0.1 / 3.50* | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 |
| | | | | **Afternoon** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | *0.68* | *1.85* | *1.58* | *2.32* | *2.91* | *0.36* | *0.22* |
| *6* | *0.22* | *0.25* | *0.25* | *0.25* | *0.27* | *0.19* | *0.10* |
| *4.5* | *0.24* | *0.28* | *0.28* | *0.26* | *0.31* | *0.22* | *0.09* |
| *3.5* | *0.15* | *0.16* | *0.17* | *0.16* | *0.17* | *0.17* | *0.09* |
| *2.5* | *0.15* | *0.17* | *0.16* | *0.16* | *0.17* | *0.12* | *0.09* |
| *1.4* | *0.14* | *0.15* | *0.15* | *0.15* | *0.16* | *0.15* | *0.11* |
| *0.1 / 3.50* | *0.11* | *0.11* | *0.11* | *0.11* | *0.11* | *0.10* | *0.09* |
| | | | | **Evening** | | | |
| | *Monday* | *Tuesday* | *Wednesday* | *Thursday* | *Friday* | *Saturday* | *Sunday* |
| *7.5* | 0.16 | 0.17 | 0.17 | 0.21 | 0.20 | 0.18 | 0.15 |
| *6* | 0.13 | 0.14 | 0.14 | 0.15 | 0.15 | 0.13 | 0.10 |
| *4.5* | 0.14 | 0.15 | 0.14 | 0.15 | 0.15 | 0.14 | 0.09 |
| *3.5* | 0.12 | 0.13 | 0.13 | 0.13 | 0.14 | 0.13 | 0.09 |
| *2.5* | 0.10 | 0.10 | 0.10 | 0.11 | 0.11 | 0.10 | 0.09 |
| *1.4* | 0.11 | 0.11 | 0.11 | 0.11 | 0.12 | 0.11 | 0.09 |
| *0.1 / 3.50* | 0.10 | 0.11 | 0.11 | 0.11 | 0.10 | 0.09 | 0.09 |

*Table 25. Total external cost (€) for different parking zones at different day(part)s using municipality data.*

| | | | | Zone | | | |
|---|---|---|---|---|---|---|---|
| | *7.5* | *6* | *4.5* | *3.5* | *2.5* | *1.4* | *0.1 / 3.50* |
| *Afternoon* | 0.82 | 0.31 | 0.22 | 0.13 | 0.2 | 0.18 | 0.33 |
| *Evening* | 1.62 | 0.51 | 0.31 | 0.17 | 0.21 | 0.19 | 0.16 |

## Appendix E

**R script**

```
# Installing packages

        > install.packages("tidyverse")

        > install.packages("kableExtra")

        > install.packages("data.table")

        > install.packages("knitr")

        > install.packages("xtable")

        > install.packages("stargazer")

        > install.packages("olsrr")

# Opening packages

        > load("tidyverse")

        > load ("kableExtra")

        > load ("data.table")

        > load ("knitr")

        > load ("xtable")

        > load ("stargazer")

        > load ("olsrr")

# Loading data

        > df <- readRDS("~/Thesis/Data/R data/20211210_Niels_subset_Parkmobile_amsterdam_2019.Rds")

# Checking descriptive statistics on variables

        > summary(df[c("variable X")])

# Checking content of variables

        > table(df$variable)

# Dropping irrelevant columns from the dataset to transform to the right data frame

        > df[4] <- NULL

        > df[10:16] <- NULL

        > df[12:24] <- NULL

        > df[14:25] <- NULL

# Dropping parking data before 1st of May 2019

        > df1 <- df[!(df$stop_date_tk<20190502),]

# Adding variable to see the day of the week

        > df1$weekday <- weekdays(df1$start_date_tk)

#Adding 3 variables to check whether the parker arrived in the morning, afternoon or evening

        > df1$morning_start <-(df1$time_str > "06:00:00" & df1$time_str < "12:00:00")
```

```
> df1$afternoon_start <-(df1$time_str > "11:59:59" & df1$time_str < "17:00:00")

> df1$evening_start <-(df1$time_str > "16:59:59" & df1$time_str < "23:59:59")
```

# Assigning correct tariff zone to each parking transaction

```
> df1$tariff_zone_7.5 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 6.5)

> df1$tariff_zone_6 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 4.75 &
(df1$parking_amount / (df1$parking_duration_minutes / 60)) < 6.5)

> df1$tariff_zone_4.5 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 3.75 &
(df1$parking_amount / (df1$parking_duration_minutes / 60)) < 4.75)

> df1$tariff_zone_3.5 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 2.75 &
(df1$parking_amount / (df1$parking_duration_minutes / 60)) < 3.75)

> df1$tariff_zone_2.5 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 2 &
(df1$parking_amount / (df1$parking_duration_minutes / 60)) < 2.75)

> df1$tariff_zone_1.4 <- ((df1$parking_amount / (df1$parking_duration_minutes / 60))> 1 &
(df1$parking_amount / (df1$parking_duration_minutes / 60)) < 2)

> df1$tariff_zone_var0.1 <- ((df1$parking_duration_minutes > 180) & (df1$parking_amount < 1))
```

# Finding the average parking duration (in minutes) for the different tariff zones

```
> mean(df1[df1$tariff_zone_7.5 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_6 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_4.5 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_3.5 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_2.5 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_1.4 == "TRUE", 'parking_duration_minutes'])

> mean(df1[df1$tariff_zone_var0.1 == "TRUE", 'parking_duration_minutes'])
```

# Finding composition of fuel types per tariff zone

```
> table(df1[df1$tariff_zone_7.5 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_6 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_4.5 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_3.5 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_2.5 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_1.4 == "TRUE", 'fuel_type'])

> table(df1[df1$tariff_zone_var0.1 == "TRUE", 'fuel_type'])
```

# Finding descriptive statistics for each part of day

```
> table(df1$morning_start)

> table(df1$afternoon_start)

> table(df1$evening_start)
```

# Filtering for day, day part and tariff zone to manually fill in number of arrivals / parked cars

```
> view(df1)
```

```
# Creating separate data frames for each part of day
> df1_morning <- subset(df1, df1$morning_start !="FALSE")
> df1_afternoon <- subset(df1, df1$afternoon_start !="FALSE")
> df1_evening <- subset(df1, df1$evening_start !="FALSE")
# Creating table to see the ratio of different vehicle types that park in the afternoon
> table(df1_morning$vehicle)
> table(df1_afternoon$vehicle)
> table(df1_evening$vehicle)
# Creating separate data frames for only cars, per daypart
> df1_morning_cars <- subset(df1_morning, df1_morning$vehicle == "Personenauto")
> df1_afternoon_cars <- subset(df1_ afternoon, df1_ afternoon $vehicle == "Personenauto")
> df1_evening_cars <- subset(df1_ evening, df1_ evening $vehicle == "Personenauto")

# Creating tables to see the different emission codes per passenger car
> table(df1_morning_cars$emission_code)
> table(df1_afternoon_cars$emission_code)
> table(df1_evening_cars$emission_code)
```

## Appendix F

*Table 26. Average number of parking transactions started per day(part) (Parkmobile users only)*

| | Monday | | | Tuesday | | | Wednesday | | | Thursday | | | Friday | | | Saturday | | | Sunday | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *zone* | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** |
| ***7.5*** | 881 | 1317 | 688 | 1023 | 1438 | 720 | 985 | 1426 | 754 | 982 | 1452 | 882 | 1000 | 1464 | 870 | 514 | 1143 | 798 | 38 | 927 | 613 |
| ***6.5*** | 3418 | 5140 | 2792 | 3918 | 5645 | 3218 | 3768 | 5581 | 3176 | 3775 | 5581 | 3533 | 3913 | 5846 | 3571 | 2139 | 4684 | 3040 | 122 | 1444 | 887 |
| ***4.5*** | 4311 | 6553 | 3792 | 4757 | 7150 | 4256 | 4554 | 7079 | 4122 | 4590 | 6847 | 4258 | 4716 | 7450 | 4451 | 3010 | 6174 | 3853 | 120 | 39 | 35 |
| ***3.5*** | 812 | 1103 | 783 | 900 | 1196 | 891 | 888 | 1244 | 871 | 866 | 1154 | 910 | 894 | 1293 | 968 | 740 | 1281 | 827 | 96 | 49 | 45 |
| ***2.5*** | 1757 | 2765 | 971 | 2053 | 3028 | 1073 | 1908 | 2952 | 1062 | 1977 | 2866 | 1284 | 1977 | 3070 | 1186 | 720 | 1839 | 867 | 52 | 11 | 39 |
| ***1.4*** | 1508 | 2312 | 1172 | 1671 | 2438 | 1315 | 1594 | 2416 | 1312 | 1636 | 2422 | 1394 | 1631 | 2744 | 1508 | 934 | 2566 | 1183 | 213 | 1268 | 401 |
| ***0.1*** | 209 | 300 | 231 | 215 | 327 | 264 | 182 | 314 | 284 | 199 | 311 | 303 | 164 | 293 | 260 | 129 | 226 | 122 | 20 | 34 | 62 |

*Table 27. Estimation of average total number of parking transactions based on Parkmobile users and NPR data.*

| | Monday | | | Tuesday | | | Wednesday | | | Thursday | | | Friday | | | Saturday | | | Sunday | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *zone* | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** | **Morning** | **Afternoon** | **Evening** |
| ***7.5*** | 1958 | 2927 | 1530 | 2274 | 3195 | 1601 | 2188 | 3169 | 1675 | 2182 | 3228 | 1960 | 2223 | 3253 | 1933 | 1143 | 2539 | 1773 | 83 | 2059 | 1362 |
| ***6.5*** | 7596 | 11422 | 6206 | 8707 | 12545 | 7152 | 8373 | 12402 | 7058 | 8389 | 12403 | 7851 | 8696 | 12991 | 7935 | 4754 | 10409 | 6755 | 271 | 3209 | 1970 |
| ***4.5*** | 9579 | 14561 | 8426 | 10572 | 15889 | 9457 | 10119 | 15732 | 9161 | 10200 | 15217 | 9462 | 10480 | 16555 | 9892 | 6689 | 13721 | 8562 | 266 | 86 | 78 |
| ***3.5*** | 1805 | 2450 | 1739 | 2000 | 2657 | 1980 | 1974 | 2765 | 1935 | 1924 | 2564 | 2022 | 1987 | 2873 | 2150 | 1645 | 2847 | 1838 | 214 | 110 | 100 |
| ***2.5*** | 3904 | 6145 | 2158 | 4562 | 6729 | 2385 | 4239 | 6560 | 2361 | 4393 | 6368 | 2853 | 4394 | 6823 | 2637 | 1599 | 4087 | 1928 | 115 | 24 | 87 |
| ***1.4*** | 3352 | 5138 | 2605 | 3712 | 5418 | 2922 | 3543 | 5370 | 2915 | 3635 | 5381 | 3097 | 3624 | 6098 | 3352 | 2076 | 5702 | 2629 | 472 | 2817 | 891 |
| ***0.1*** | 465 | 667 | 512 | 477 | 728 | 587 | 404 | 698 | 630 | 442 | 691 | 674 | 364 | 650 | 578 | 287 | 502 | 272 | 45 | 76 | 139 |