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Microsimulation at the urban scale for the analysis of parking regulation policies

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Microsimulation at the urban scale for the analysis of parking regulation policies

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Resumen

Título: Microsimulación a escala urbana para el análisis de políticas de regulación de estacionamiento

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Convocatoria: Febrero 2021

Palabras clave: estacionamiento, transporte, políticas, Aimsun, microsimulación, aplicaciones de estacionamiento, tarifa dinámicas, etc.

Planteamiento, desarrollo y conclusiones:

El presente estudio consiste en la evaluación de diferentes políticas de estacionamiento regulado en áreas urbanas. El estudio combina el análisis de condiciones ambientales y de tráfico para cada una de las políticas analizadas. El modelo para realizar la microsimulación, DYNAPARK, ha sido implementado a través del software Aimsun.

Este modelo permite simular políticas de limitación temporal de permanencia y diferentes tipos de tarifas de estacionamiento, tanto estáticas como dinámicas. El modelo DYNAPARK es un modelo de comportamiento de estacionamiento basado en agentes y espacialmente explícito.

La simulación de las diferentes políticas de estacionamiento tiene como resultado una serie de datos que permiten cuantificar la influencia de estas políticas a partir de diferentes indicadores tales como: el tiempo de búsqueda de estacionamiento, el número de vehículos que buscan estacionamiento, la generación de emisiones y la tasa de ocupación de estacionamiento. El proyecto se aplica a un caso real en una zona del aparcamiento regulado en superficie de la ciudad de Santander.

Adicionalmente, el estudio realiza un análisis de sensibilidad de diferentes parámetros ambientales y de tráfico en función del porcentaje de usuarios informados en el sistema. De esta forma, los usuarios son clasificados en función de su conocimiento en tiempo real sobre las tarifas y la ubicación de las plazas de aparcamiento disponibles. Este análisis expone el posible impacto que tendría el fomento del uso de aplicaciones de estacionamiento para la búsqueda y pago de aparcamiento.

Los resultados obtenidos en el estudio demuestran que un sistema tarifario dinámico con restricción de tiempo de estacionamiento sería capaz de generar un menor impacto en el tráfico, así como reducir la generación de emisiones contaminantes al medio ambiente. A su vez, este trabajo revela algunos de los posibles beneficios del uso de aplicaciones de estacionamiento.

Résumé

Titre : Microsimulation à l'échelle urbaine pour l'analyse des politiques de régulation du stationnement

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Directeurs : Borja Alonso, Andrés Rodríguez Gutiérrez, Fabien Leurent

Appel : Février 2021

Mots-clés : parking, transports, politiques, Aimsun, microsimulation, applications de stationnement, tarifs dynamiques, etc.

Approche, développement et conclusions :

Le présent projet étudie l'analyse de différentes mesures de restriction de stationnement en surface dans les zones urbaines. Le projet combine l'étude des conditions environnementales et de circulation pour chacune des mesures de restriction analysées. Un modèle de micro-simulation est mis en œuvre pour évaluer les politiques de limitation temporaire des stationnements permanents et leurs taux de variations statiques et dynamiques. Cette étude est appliquée à un cas réel qui règlemente le stationnement de surface dans la ville de Santander, en Espagne.

Les données obtenues sont utilisées pour quantifier l'incidence de ces politiques sur le temps de recherche passé par les conducteurs pour trouver une place de parking, le nombre de véhicules, la génération d'émissions de gaz, la consommation de carburant et le taux d'occupation des parkings. On s'attend à ce que la mise en place d'une limitation dans le temps et d'un système de tarification dynamique améliore les conditions de circulation (nombre de véhicules cherchant une place de parking et temps de recherche) et réduire les émissions de polluants et la consommation de carburant.

En outre, l'étude actuelle effectue une analyse de sensibilité basée sur le degré des utilisateurs informés. L'utilisation des applications de téléphonie de stationnement pour la recherche de stationnement et le paiement seront discutés ainsi que leur impact. Ainsi, les utilisateurs sont classés par catégorie selon qu'ils disposent d'informations en temps réel sur la disponibilité, les tarifs et les emplacements de places de parking. On s'attend à ce que l'utilisation des applications de stationnement améliore les conditions de circulation, réduise la pollution de l'air et diminue les temps de trajet pour rechercher une place de parking et la distance parcourue.

Abstract

Title: Microsimulation at the urban scale for the analysis of parking regulation policies

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Submission: February 2021

Keywords: parking, transportation, policies, Aimsun, microsimulation, parking applications, dynamic rates, etc.

Approach, development and conclusions:

The study of the impact of parking pricing and time limitation is currently a substantial need to implement the most favourable parking policies that contribute to more efficient and cleaner transport systems.

The current study explores and evaluates different parking measures for on-street parking in urban areas. It combines the analysis of environmental and traffic conditions for each of the measures analysed. A microsimulation model, DYNAPARK, is implemented to simulate policies for temporary limitation of parking permanence and both static and dynamic rate variations. DYNAPARK model is a spatially explicit agent-based parking behavioural model. The software used for the microsimulation is Aimsun.

Through the simulation of different parking policies, data is obtained to quantify the influence of these policies on users' parking search time, number of vehicles searching for parking, generation of emissions and parking occupancy rate. The project is applied to a real case in the regulated surface parking in the city of Santander.

Furthermore, a sensitivity analysis of different traffic and environmental parameters is performed based on the degree of informed users in the system. Users are classified depending on whether they have real-time information about the availability, rates and

location of parking spaces. This analysis thereby exposes the impact of promoting the use of parking phone applications for parking search and payment.

The results obtained proof that the dynamic rate system with parking time restriction policy is able to generate a lower impact on traffic and the environment when compared to other policies. It also reveals some positive impacts of promoting the use of parking phone applications for parking search and payment.

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1. Introduction

Due to the extensive use of private vehicles, the supply of parking is a key component in the generation of traffic congestion and high levels of air pollution in urban areas. In the past, parking planning and policy development aimed to supply as many parking slots as possible to facilitate the use of private vehicles. However, looking for parking vacancies has become a difficulty for most private vehicle users and a major issue affecting transportation systems in cities. Transport planning and management has been facing several challenges in the last few decades.

The urban population has increased in most urban areas during this period. This resulted in an increase in the demand for private vehicle transportation and parking in cities. However, currently, other mobility means are prioritised over private vehicles. The promotion of more efficient, sustainable, accessible, and safer transportation systems is an essential goal for high-density urban areas. Parking planning and policies are now mainly focused on the reduction of traffic and congestion in urban areas.

Most cities aim to discourage the usage of private vehicles and promote non-motorised transport modes for mobility within urban areas. Public administrations seek to create pedestrian and green areas that may lead to more sustainable, lively and safer cities. The number of parking slots available in cities is being reduced, with the land used for current parking spaces being used for other purposes to promote alternative modes of mobility and liveable public spaces. Therefore, parking slot management has become an essential factor to achieve efficient transport systems.

1.1 Problems of on-street parking in urban areas

The supply of on-street parking in urban areas entails various negative consequences. According to a study carried out by Donald Shoup (2006), the process of searching for parking spaces represents approximately 30% of the total traffic in urban areas. This research concluded that cruising for parking takes about 3.3 to 14 minutes in American cities. Thus, cruising for parking leads to a considerable increase in the total travel time of all users, not only cruising users, and an increase in traffic and congestion.

Moreover, cruising for parking contributes to the generation of greenhouse gas emissions. The transportation sector generates 20% of the total CO_2 emissions in the world (The World Bank). For this reason, transportation policies, including parking policies, are crucial for the reduction of greenhouse gas emissions and the achievement of the Sustainable Development Goals (SDGs) of the United Nations (United Nations Sustainable Development Goals).

In addition, according to the RAC Foundation (2004), private vehicles are parked 80% of the time. This means that there is a highly inefficient and underutilised occupancy of land, especially in city centres, which could otherwise be used for more efficient purposes, such as additional lanes for public transportation.

1.2 Benefits of parking regulation

Public administrations use parking policies as a major tool to manage demand and solve parking problems. Through the implementation of parking regulation policies, such as parking tolling and parking stay-length restrictions, public administrations can impact users' choices concerning transport modes, car-sharing, parking zones, and so on (Vickrey, 1963).

As an example, parking tolling has multiple benefits. First, parking tolling decreases cruising for parking time for users looking for parking due to the decrease in parking demand.

Secondly, due to the decrease in the number of vehicles looking for parking, parking rating improves the efficiency of the transportation system. Thus, it reduces traffic congestion, pollution, and all users' travel time, including transit (not cruising for parking) and public transportation users.

Third, parking tolling increases parking turnover rate. This may improve the economy of businesses in the area of influence because of the increase in parking accessibility for potential clients.

Fourth, it improves spatial distribution of parking among users. It provides the option to users to reduce the payment rate or time. Those users whose time value is higher (short-term parking users, disabled people, etc.) will prefer to pay higher rates for parking in areas closer to their destination; while those users who prefer free-parking, or lower rates, will park in further areas, thus, walking a longer distance.

Fifth, public administrations can benefit and allocate the revenues of the parking pricing system for the improvement of public transportation and other public services. Last, parking rating improves social equity. Low-income users are usually prone to use public transportation instead of private vehicles. Hence, they will not contribute to parking costs. While higher-income users will contribute to subsidise public transport services through parking taxes.

1.3 Aim of the study

As explained above, cruising for parking contributes to the generation of traffic and congestion in urban areas. This leads to a considerable increase in the total travel time of all transport users and the generation of greenhouse gas emissions. The implementation of parking policies may help manage demand and reduce problems derived from parking.

This study aims to explore and compare various parking policies, especially regarding parking pricing and parking stay length limitation, to conclude which parking restriction measures are most favourable to reduce the impact on traffic and the environment. The project combines the study of environmental and traffic indicators for each of the parking policies selected. Additionally, the current study seeks to acknowledge other potential solutions to increase the efficiency of parking, such as the use of parking management technologies. Accordingly, the study performs a sensitivity analysis based on the degree of informed users in the system to expose the impact of promoting the use of parking applications for parking search and payment on various parking conditions and environmental indicators.

To this end, the study comprises various sections. Firstly, the study starts by introducing the state the art. This section provides a description of some parking policy examples and an overview of parking simulation models and various existing parking management technologies. Secondly, the study provides a description of the model and the criteria used for the simulation and evaluation of parking policies. The model used is a parking behavioural model called Dynapark. The simulations have been performed using a microscopic modelling software called Aimsun. Thirdly, the study provides a description of the area of analysis in the regulated surface parking of Santander and the different policy alternatives and scenarios generated, especially regarding the model input variables for each scenario. Fourthly, the study shows and analyses the results obtained for each policy alternative of each modelling simulation scenario. Fifthly, the study conducts a sensitivity analysis on the degree of informed users to analyse the impact of promoting the use of parking phone applications on various parking conditions and environmental indicators. Finally, the study is concluded by explaining the relevance, scope and limitations of the simulation of parking policies performed as part of this project, as well as the main conclusions of the study.

1.4 Research Mission

During the conduction of the final degree project, I have worked closely with the research project team, which is comprised by Borja Alonso, project principal researcher; and Andrés Rodríguez, researcher in charge of the project. The project team created the Dynapark model, which is based on two different sub-models: parking space selection and parking space search. The model was implemented in the Aimsun simulation software, building a custom API programmed in Python 3.7. The team has recently been involved in the analysis of the impact that different parking management policies could have on public roads, as well as the analysis of different parking paying rate and user information scenarios. Through this final degree project, I supported the team in the analysis of the impact of different parking management policies and the conduction of the sensitivity analysis based on the degree of informed users in the system. The team has guided and supervised my work along the development of the project.

It must be acknowledged the important contribution of Ángel Ibeas and Gonzalo Antolín to the project. Before handing over to Borja Alonso and Andrés Gutierrez, both started the project as principal researcher and in charge researcher of the project respectively. In addition, Luigi dell'Olio and Rubén Cordera helped the team model user's behaviour and set the traffic demand.

2 Objective

The current final degree project is based on the analysis of different restrictions for surface parking in urban areas. The project combines the study of environmental and traffic conditions for each of the restrictions analysed. A microsimulation model is implemented to evaluate policies for the temporary limitation of parking permanence and both static and dynamic rate variations. This study is applied to a real case in regulated surface parking in the city of Santander.

The data obtained will be used to quantify the influence of these policies on users' parking search time, number of vehicles searching for parking, generation of emissions, fuel consumption and parking occupancy rate. The implementation of a time limit restriction and a dynamic rate system is expected to improve traffic conditions (number of vehicles searching for parking and the search time) and reduce the emission of pollutants and fuel consumption.

Additionally, the current study will perform a sensitivity analysis based on the degree of informed users in the system. This analysis will therefore expose the impact of promoting the use of parking applications for parking search and payment. To this end, users will be classified depending on whether they have real-time information about the availability, rates, and location of parking spaces. The use of parking applications is expected to improve traffic conditions, reduce air pollution, and diminish parking travel times and the distance travelled.

3 State of the art

This chapter provides a description of examples of parking policies, especially regarding parking pricing policies. This will facilitate the selection of parking policies for the comparison of their effect on various traffic and pollution indicators. Subsequently, this chapter provides an overview of parking simulation models as a parking behavioural model will be used to simulate the effect of the aforementioned policies. Finally, the current chapter will present some existing parking management technologies. This will provide the context for the sensitivity analysis that will be conducted as part of this study. This analysis will be based on the impact of the implementation of parking phone applications on various traffic and pollution indicators.

3.1 Examples of existing parking policies

Most parking policies are based on strategies that aim to discourage the use of private vehicles (Buehler et al., 2017; Nurdden et al., 2007). As mentioned above, public administrations use parking strategies and policies to regulate and manage parking demand and supply.

First, one of the most common strategies to reduce parking demand in large cities is tolling for driving within the city. Although it is not a direct parking policy, it has a great impact on parking demand. Tolling prices can be rather fixed; schedule-based, thus, they vary depending on the time of the day, being considerably higher during peak periods; or dynamic. For example, in 2003, the city of London introduced a £5 daily congestion charge for driving in the Inner Ring Road (Blow et al., 2003). This strategy aimed to reduce traffic within the area by 15%.

Second, another common parking strategy is called Park and Ride, which seeks to decongest city centres by implementing parking facilities in the outskirts of cities. These parking facilities are connected to public transportation, which transports users to the city centre. For example, the city of Barcelona implemented a Park and Ride strategy to decongest and reduce emissions in the city (Vila Serrano, 2019). There are currently approximately 1500 parking slots in three Park and Ride areas in the outskirts of the city, in the neighbourhoods of Besòs, Sarrià and La Ciudad de la Justicia, which are located close to train stations.

Third, parking time limitation is another strategy that constrains parking time to discourage long-term parking and promote parking turnover. Shorter periods restraint users' activities, while longer periods encourage parking accessibility for inhabitants in the area of influence. Investigations recommend commercial zones to establish short-term limited parking in 10-30% of parking spaces to increase businesses activity (Victoria Transport Policy Institute, 2020). By improving parking turnover, administrators may favour businesses in the area by increasing clients' transit and accessibility. Although time limitation is an effective strategy, it is difficult to implement due to the fact that users tend to move their vehicles to other parking slots once the time limitation is reached (Simićević et al., 2013).

Fourth, other common parking regulation strategies are (Litman, 2016): (i) limitation of parking access in certain areas for residents only or other allowed users (public services vehicles, short-term users, etc.), (ii) restriction of parking in arterial lanes during high demand periods in order to facilitate traffic, (iii) time period limitation to certain times of the day depending on the desired use of parking during each time period, etc.

Finally, paying for parking is another common parking strategy, where a user pays to occupy a parking slot. This strategy can be defined as parking pricing (Shoup, 2005). Parking tolling may produce multiple changes in the transportation system, such as the reduction of private car ownership, shift to active modes of transport, modification of parking location, changes in transport schedule, modification of parking stay-length, reduction of users' travel time (Litman, 2010). It is also generally implemented to achieve one or multiple of the following goals: reduce traffic congestion, diminish parking search times, achieve the desired parking availability rate, increase revenues derived from parking taxes, etc.

3.2 Overview of pricing policies

3.2.1 Static rate

One of the most common parking payment practices is fixed paying rate parking. Static rate systems charge a fixed parking fees, thus, it does not vary over time. Static rates are frequently implemented only during an established period of time during the day, when the parking demand is higher. However, this type of parking strategy cannot control real-time parking demand and supply. As shown by Arnott and Inci (2006), underrated paying fees produce considerable welfare losses. Static rates do not adjust to the optimal parking fee that maximizes benefices and minimizes costs.

3.2.2 Dynamic rate

Dynamic rating has recently become a major solution for parking problems. Although policies based on variable parking paying rates are more difficult to implement, as they require the collection and analysis of parking data, they allow to manage parking demand and supply in a real-time basis. In addition to demand and supply management, dynamic rating is also useful in achieving other objectives, such as encouraging parking turnover, reducing environmental impact, maximising monetary benefits, optimizing the spatial distribution of parking, etc. One of the first researchers to evidence the need for variable parking tolling was William Vickrey (1954). He highlighted the importance of setting the appropriate paying rate to increase parking accessibility for those users willing to pay for it. The lower the parking fee is, the higher the on-street parking demand (Calthrop and Proost, 2005).

Dynamic rating can be implemented in different ways, as follows:

(i) Fixed schedule: rate varies with the time of the day. This practice aims to manage demand depending on the time of the day as it varies considerably from peak to off-peak hours.

(ii) Escalating prices: rate increases with users’ parking time (Federal Highway Administration, 2013). This method aims to reduce long-stay parking times and promote parking turnover. This policy is mainly used in airport parking areas.

(iii) Performance-based dynamic rating. This strategy seeks to set the optimal pricing rate based on parking demand and supply through the use of real-time occupancy data. It requires the implementation of parking sensors to monitor the occupancy status of parking slots. Research shows that the optimal occupancy rate is approximately 85% in order to reduce cruising for parking time and failure to find a vacant parking slot (Shoup, 2005). When occupancy rate increases over 85%, the probability of finding a vacant spot rapidly approaches zero (Millard et al., 2014). Pierce and Shoup, 2013, highlighted the benefits of implementing a performance-based dynamic rate system. Performance-based rating reduces parking search time for cruising users and travel time for transit and public transport users. In addition, performance-based rating increases parking turnover that allow more cruiser to park in the area.

Only some airports and a few cities, such as San Francisco and Madrid, have implemented a performance-based dynamic tolling system. On the one hand, in 2011 the city of San Francisco implemented a pilot parking program called SFpark. This program aimed to control and allocate demand across the city by setting dynamic paying rates. The occupancy status of parking spaces is controlled by parking sensors. The SFpark intends to modify the parking fee to attain one to two available parking slots per block. As of 2014, the program was implemented in 7000 parking slots in San Francisco and since its initiation, the program has attained the objective occupancy and reduced cruising by 50% (Millard et al., 2014). On the other hand, the dynamic rate system in Madrid implements parking policies based on environmental and traffic criteria. This program also uses automated vehicle plate recognition for the monitoring of parking accessibility and turnover.

3.3 Parking simulation models

Parking policy development requires the forecast and analysis of users' behaviour and their reaction to policies. Parking models allow cities to test the behaviour of users towards the implementation of new policies and their effect on traffic and emissions. For this reason, parking modelling is an essential tool for the development of parking policies that aim to solve parking problems.

The use of parking simulation models and data are key to represent users' decisions and behaviour in relation to parking, including their responses to the implementation of new parking policies.

Parking simulation models have been extensively studied in the last few decades. Martens et al. (2008) classified existing parking models into two groups: spatially implicit and spatially explicit models. Spatially implicit models comprise the initial parking models that focus on the economic point of view of parking and users' preferences based on their destination decisions. In some research parking costs are considered to study the impact of parking on the choice of transport from an economic point of view (Willson and Shoup, 1990). However, this approach only illustrates users' commuting patterns without considering other parking decisions. More specific parking models have been developed in the last few decades to represent parking behaviour. In contrast, spatially explicit models are more sophisticated models that provide a representation of parking dynamics and users' behaviour and decisions in parking processes.

Young et al. (2008) also provided a classification of models depending on the scale of analysis: (i) parking spot, (ii) parking zone, (iii) parking sub-region, (iv) parking urban area, etc.

There currently exist various types of parking models. One of the most common type of models are behavioural models, which focus on users' behavioural schemes regarding discrete parking choices. Most parking choice models are mainly based on the random utility theory and, thus, users' intention to maximise utility among different alternatives. These models are widely used to analyse the influence of parking policies on users' behaviour. There are several variables of parking cost, such as walking time to destination, age, gender, parking type and occupancy, which can influence parking decisions on a macroscopic level (parking area, mode of transport) and a microscopic level (parking slot choice). As previously mentioned, initial choice models simulated cruising for parking as per the individual behaviour of users by focusing on different macroscopic decisions such as parking destination or mode choice (Coppola, 2004; Hess and Polak, 2004; Polak et al., 1991).

Young et al. (1986) presented a parking model called PARKSIM, which simulated the movements of vehicles within a parking facility that allowed to analyse the efficiency of the parking layout design. Thompson and Richardson (1998) proposed a parking model in which each user decided whether or not to park in a certain parking slot based on a utility function that in turn depends on travel time, waiting time and paying rate. Later, agent-based models were introduced and Benenson et al. (2008) developed PARKAGENT, which is a spatially explicit agent-based model that represents the dynamics of users' spatial behaviour when cruising for parking. This model incorporates different distributions of search time, walking distance and parking costs for different types of users. This model does not take into consideration the parking paying rate. Dieussaert et al. (2009) developed SUSTAPARK, an agent-based model that uses cellular automation, vehicles navigating from cell to cell, to simulate the process of cruising for parking while interacting with other users with different purposes and destinations on the network. This model considers different variables such as the type of parking, paying rate and occupancy.

In addition, other models have been developed in the basis of the allocation of traffic in the parking network by combining parking decisions and route choices. Lam et al. (2006) proposed a network equilibrium model that couples supply simulations, based on a stochastic and time-dependent supply network, and demand variations, including departure time, route, parking location and parking duration. Gallo et al. (2011) presented a parking simulation model that uses three different layers to simulate parking dynamics: the walking layer, parking searching layer and trip layer. Leurent and Boujnah (2014) proposed a traffic equilibrium model that represents the network flows based on the users' search path and parking choices coupled to a stochastic observation of parking occupancies.

3.4 Parking management technologies for on-street parking

Given the parking problems discussed above, cities aim to optimise parking management and search for solutions through the use of technologies. The following are some of the objectives of current parking management technologies widely used:

- Unoccupied parking slots information. The information about the availability of parking slots may be provided by variable message signals. These signals inform in a real-time basis about the availability of parking slots in on-street parking.

Figure 1. Variable message signal. Source: Transportxtra

In addition, users are also able to know the location of available parking slots through the use of parking applications or GPS. This technology is normally used in off-street parking. It saves time and reduces parking search time for drivers. This is especially useful in highly transited areas, where a reduction in the search time of users may considerably improve traffic in the area. These technologies use real-time occupancy data based on the detection of the occupancy status of parking slots. There are various types of vehicle detection technologies (Idris et al., 2009): infrared sensors, inductive loop detectors, magnetometers, pneumatic road tubes, microwave radars, acoustic sensors, ultrasonic sensors, etc.

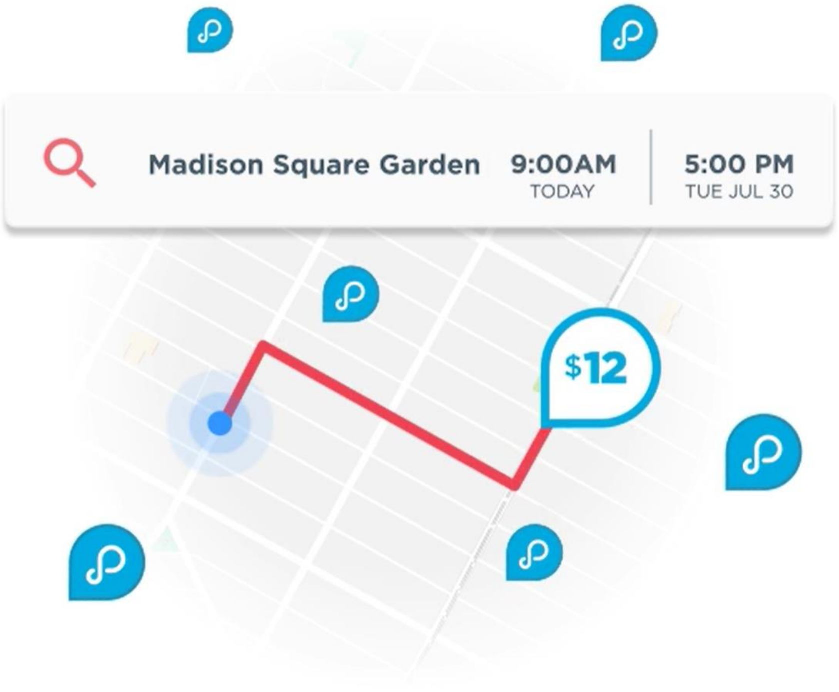

Figure 2. Parking application. Source: Best Parking. (Available at: https://www.bestparking.com/)

- Smart parking payment. Parking meters are the most common tool for parking payment in on-street parking.

Figure 3. Parking meter. Source: Parking OKC. (Available at: http://parkingokc.com/new-meters)

As an alternative to conventional parking meters, there are several technological advances that optimise the parking payment process, such as smart cards, phone applications, automated vehicle recognition devices, etc.

- Smart parking reservation (Oke et al., 2016). Parking reservations may require the use of a sensor installed in the parking area to detect the occupancy status of each slot and smart phone applications to show each user the location and pricing of the vacant slots. The application may also incorporate parking payment choice. In addition, parking slots can also be booked through SMS, where the driver books a parking slot and receives an SMS with the password to access the parking zone and the parking slot number. The parking slot has a sensor that recognizes the presence of the vehicle. In case the user does not occupy the parking in a limited period of time, the parking reservation is cancelled.
- Automated parking. This system uses a machine that stores the vehicles with no need for human intervention. The main objective of this type of parking is to save parking space, as there is no need for conventional cruising routes. Vehicles may also be stored vertically to save parking space.
- Parking control. Parking monitoring is usually carried out through human supervision. However, new technologies are becoming more and more popular for the detection of parking violations. Sensors at the entrance and exit of parking regulated with barriers may be used to detect time limitation violations. In addition, scanners can be used for vehicle plate recognition to identify vehicles parked in paying on-street areas without permission.

4 Methodology

From the analysis of the state of the art, it has been noted that there is a paucity of studies in the international literature on the analysis of the impact of the implementation of different parking policies on public roads. Also, the study of recent parking management technologies for parking search and payment encouraged this study to conduct a sensitivity analysis based on the degree of informed users in the system.

This study aims to respond to various questions related to the impact of parking solutions on the efficiency of the system, such as: What is the impact of some parking measures on traffic and parking conditions? What is the impact of some parking measures on the environment? Can the degree of informed users in the system improve traffic and parking conditions, and reduce air pollution?

This chapter describes the methodology used to answer these questions. The microsimulation model, Dynapark, implemented for the evaluation of different parking policies is described below.

4.1 Dynapark model

The model used for the simulation and analysis of different parking policies, named DYNAPARK, was developed in the framework of the project referenced as TRA2017-85853-C2-1-R. This project is financed by the Spanish Ministerio de Ciencia e Innovación. In this chapter, the main characteristics of this model will be described.

The microscopic simulations for the analysis of the impact of different parking policies have been performed using Aimsun (Transport Simulation Systems, Barcelona), a popular microscopic modelling software used worldwide. The Dynapark model was coded in Python 3.7 and 2.7, required by Aimsun API, and integrated into Aimsun through the API provided by this software. Aimsun allows for the modelling of the individual behaviour of users within a traffic network based on different microscopic behavioural theories, such as (i) car following, (ii) lane changing and (iii) gap acceptance. The model helps establish and analyse the effect of different pricing policies, mainly static and dynamic policies.

Based on the classification described in the previous chapter, the DYNAPARK model is a spatially explicit agent-based parking behavioural model. The parameters of the model were estimated through the use of data obtained in the area of analysis (Santander, Spain) and a parking users' declared preferences survey. The model allows to simulate the behaviour of users when cruising for a vacant parking slot in different situations, parking pricing policies, percentage of informed users, occupancy rates, etc. Although there are other types of parking spaces for other modes of transport in the area of analysis, such as motorcycle, bicycle and temporary delivery parking; in this case the model is only applied to car parking simulation.

For the execution of the model, the introduction of the traffic demand data is required. The demand data includes the transit traffic and seeking-for-parking traffic data in the area of analysis. The demand is monomodal, introduced as an Origin-Destination matrix. This matrix has been extracted and rearranged from a multimodal Origin-Destination matrix of the whole city of Santander, which was obtained from a household survey conducted in 2015. Also, the model requires the introduction of the parking supply. The area is divided into different sections. Each Origin/Destination is defined as a different section in the area. There are a total of 11 origin sections from which users can access the area and travel to their destinations. In addition, the number of parking spaces and businesses in each section is introduced in the model. Seeking-for-parking vehicles are distributed across sections based on the number of shops and businesses. To this end, sections are clustered in different centroids of the parking areas and the total number of vehicles is distributed proportionally to the number of businesses in each of them.

The different simulations are executed using the Aimsun application, which provides the necessary basis to simulate the behavior of vehicles that are heading from an origin centroid to a destination centroid through the network defined in the software. To establish each vehicle stopping point at each section, it is assumed that the parking lots are located along the entire section and the stopping point along it is randomized for each vehicle.

It must be noted that Dynapark uses two different submodels: (i) parking selection submodel and (ii) parking search submodel. Hereafter, the process, and methodology of the model are explained.

4.1.1 Differentiation between types of users

Before entering the network, users are assigned a user typology identification. There are three types of users in this regard:

- Transit users: These users do not search for a parking slot but are considered in the model.
- Inhabitant users with private parking: These users have private parking and do not use the public parking system.
- Non-inhabitant users: These users seek off-street or on-street parking slots in the area of analysis. They are further divided into two groups:
  - Users with information: These users know the paying rate and available parking slots in the streets.
  - Users without information: These users do not know availability of parking slots and the paying rate; accordingly, a standard parking rate of the city is assumed in this case.

4.1.2 Parking selection submodel

Once the user has a user typology assigned, they are introduced into the network. The model estimates the destination centroid to which the user heads (see next section). Then, the model calculates the utilities for each parking alternative in relation to the type of parking and parking section.

Regarding the type of parking, three types are considered: (i) on-street paying parking; (ii) off-street paying parking and (iii) free on-street parking. On-street parking includes those parking slots on the street, while off-street parking refers to those parking slots and underground parking with controlled access. The utility of each alternative is estimated by a multinomial logit model given by the following formulas provided by SUMLAB:

$$\text{V (free)} = \beta_0 + \beta_{TD} TD_{Libre} + \beta_{TB} TB_{Libre} + \beta_{OCU} OCU_{Libre} \qquad (1)$$

$$\text{V (on-street)} = \beta_0 + \beta_{TD}TD_{Calle} + \beta_{TB}TB_{Calle} + \beta_{OCU}OCU_{Calle} + \beta_{TAR}TAR_{Calle} + \beta_{TMAX}TMAX_{Calle} \quad (2)$$

$$\text{V (off-street)} = \beta_0 + \beta_{TD}TD_{Sub} + \beta_{TB}TB_{Sub} + \beta_{OCU}OCU_{Sub} + \beta_{TAR}TAR_{Sub} \quad (3)$$

The variables for each formula are explained in the following table:

Multinomial Logit model variables	
Rate	TAR
Time to destination	TD
Searching time	TB
Occupancy	OCU
Max. parking time	TMAX

Table 1. Multinomial Logit model variables

Concerning the selection of the parking section, the multinomial logit model is also used to estimate the utility of each section. In this case, additional variables are introduced. The parameter of $\gamma_{usuario}$ sets a searching time of 0 whenever there is an informed user, as the user knows that there is an available parking slot in that section. $TB_{acumulado}$ takes into consideration the accumulated searching time whenever users do not find a vacant parking spot. Regarding the parking fee ($TAR_{seccion}$), in the case of informed users, the actual parking fee is introduced. On the contrary, a standard parking rate of the city is assumed in the case of non-informed users. Additionally, in this case, $TAR_{seccion}$ and $OCU_{seccion}$ are updated every 15 minutes. Thus, the formula is expressed as follows (Rodríguez Gutierrez, 2020):

$$\text{V (section)} = \beta_{TD}TD_{seccion} + \beta_{TB}(\gamma_{usuario}\, TB_{seccion} + TB_{acumulado}) + \beta_{OCU}OCU_{seccion} + \beta_{TAR}TAR_{seccion} + \beta_{TMAX}TMAX_{seccion} \quad (4)$$

For the joint selection of parking type and section, the model uses a hierarchical logit model. It calculates the utility of parking in paying on-street parking based on the maximum utility of sections in the on-street network. This selection is given by the following formula where the parameter i represents the set of section alternatives for paying on-street parking:

$$V\ (\text{on-street}) = \frac{1}{\lambda} EMU = \frac{1}{\lambda} ln \left\{ \sum_i e\ [\lambda V(seccion_i)] \right\} \quad (5)$$

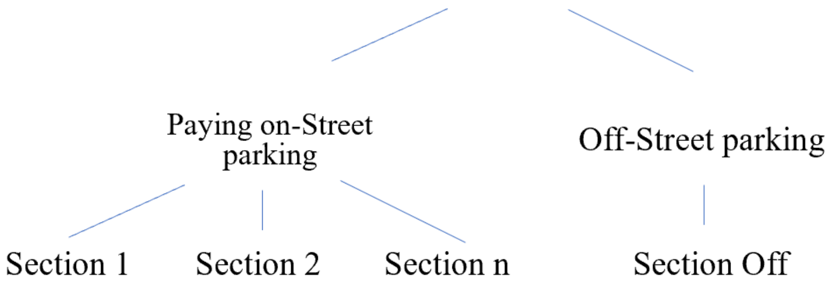

Figure 3. User parking type and section choice

4.1.3 Parking search submodel

Once the parking selection is performed, the parking searching process occurs. As mentioned above, the model estimates the destination centroid to which the user heads by calculating the demand based on the methodology proposed by Gillen (1978). The demand of each section is estimated based on the proportion of businesses located next to the section in relation to the total number of businesses in the area. The model estimates the parking section with the highest utility for each user in an iterative manner.

Three different situations may be simulated as part of the parking search process:

- The user finds a vacant slot on their way to the selected parking section. The model calculates the utility of the new parking slot and verifies whether it is acceptable or not compared to the previously selected parking section, based on a pre-defined relative utility value.
- The user finds a vacant slot at the selected parking section.

- The user does not find a vacant slot at the selected parking section. The model re-calculates utilities for the selection of parking type (free parking, paying off-street parking, paying on-street parking) and the new destination.

  Once the parking manoeuvre time is over, the vehicle is eliminated from the network.

4.1.4 Input data

In addition to the parking demand and supply data, the model requires the introduction of various model parameters and restriction variables related to the parking policies, which are aimed to be analysed in the current study. These model input parameters are listed in Table 2.

Model input variables
Parking maneuvre time (s)
Minimum parking time (s)
Maximum parkin time (s)
Initial occupancy (%)
Rate ranges (€)
Occupancy ranges (%)
Standard on-street rate (€)
Standard off-street rate (€)
Searching for parking time: mean and deviation (s)
Maximum relative utility
Rate update time (s)
Percentage of informed users (%)

Table 2. Model input variables

4.2 Dynamic pricing ranges based on occupancy

While for the static rate scenarios, the paying rate is fixed at 0.75 euros per hour. For the dynamic rate scenarios, the model incorporates various paying rates based on real-time dynamic rating. As performed in SFpark program carried out in San Francisco, the current model establishes a variation of the parking rate based on the real-time occupancy rate. The obtention of the demand elasticities in relation to pricing may provide the optimum pricing levels to reduce the occupancy rate. The following table includes the three paying rates that are considered for each occupancy rate.

Rate per hour (euros)	Occupancy rate (%)
0.5	Less than 60%
1	60% to 80%
1.75	80% to 100%

Table 3. Pricing and occupancy rating

4.3 Establishment of the methodology and criteria for parking policy evaluation

Most cities urge the implementation of new parking policies to reduce parking cruisers and search times, increase parking vacancy, etc. The introduction of a new parking policy can have a great impact on the dynamics of cities. For this reason, administrators must perform a broad analysis of the effects of new parking policies on the environment, traffic, revenues, etc. In order to compare parking policy alternatives, different methodologies can be used to quantify their effects. Based on existing literature, parking policies can be evaluated based on different factors, which mainly depend on the goal that each administration seeks. The most common criteria for parking evaluation can be classified as follows:

- Impact on traffic: Cars searching for parking can have a great impact on traffic. As mentioned above, studies reveal that about 30% of vehicles in traffic in cities are cruising for parking. Parking policies can vary the parking demand, thus, alter the number of vehicles searching for parking, the occupancy rate, the searching times, etc. Consequently, prior to the implementation of new parking policies, administrators must forecast and analyse their repercussion on traffic. The impact on traffic is commonly measured through various indicators, such as, users' travel velocity, number of vehicles cruising for parking, traffic density, etc. In this study, quantitative data regarding number of vehicles searching for parking and parking search time will be obtained to compare the effect of each parking policy alternative. The most favourable parking policy would be one that reduces each of these indicators as much as possible.

- Environmental impact. As a result of the impact on traffic, parking policies also affect the generation of emissions and fuel consumption. For this reason, in addition to the impact on traffic, administrators may also considerate this aspect for the evaluation of parking policies. Hence, the current study will analyse the effects of each policy on the consumption of fuel and generation of emissions. The desirable parking policy will be the one that generates less emissions and fuel consumption, thus, the most environmentally friendly one.

- Profit maximisation: A common tool for parking policy analysis is profit generation. Not only does parking pricing reduce emissions and congestion, it also creates monetary revenue. Parking profits can be defined as the financial gains resulting from the difference between revenue obtained through parking pricing and the operational and maintenance costs of the parking service. Cities can allocate these profits to various public services, such as the creation of green areas, improvement of sidewalks and public transport services and the reduction of current transportation taxes. Profit maximisation can be attained through the increase in parking charged areas and the establishment of higher prices and longer operational periods. Through the implementation of dynamic rating, administrators can balance parking price and demand to maximum revenues in real time. Although this is a common methodology for parking policy analysis, the comparison of profits generated by different policies will not be considered in this study.

- Occupancy rate: Another typical parking policy evaluation criterion is the parking occupancy rate. This can be defined as the ratio of occupied parking slots to the total number of parking slots. Research demonstrates that the optimal parking occupancy rate is 85% (Shoup, 2005). Parking administrators can thus set an 85% occupancy rate as an objective criterion for parking regulation. The current study is based on the adjustment of parking prices and length of stay in order to balance demand and supply based on real-time occupancy rates. Different parking policies will be evaluated based on their capacity to achieve and maintain an occupancy rate of 85%.

- Parking turnover: Lastly, parking turnover can be defined as the number of parking spaces over the number of vehicles parked in those parking spaces in a given period of time. Administrators can achieve higher turnover levels by establishing higher rates for long-term parking and/or by limiting parking length of stay. This improves access to parking for short-term parking users, which can significantly benefit businesses in the area of influence. Besides, this will promote long-term parking users to shift to other parking types or areas. Although parking turnover is a useful measure, it requires the control of license plates to properly examine parking length of stay. This is usually an expensive practice. In the current study, parking turnover will not be considered.

The current study proposes to analyse different parking policies based on some of the parking policy evaluation methodologies mentioned above. Quantitative data will be obtained through the simulation of different scenarios to analyse the effect of different parking policies. The comparison of policies will be performed on the basis of: (i) the minimisation of parking search times and number of vehicles searching for parking, (ii) the capacity to the occupancy rate, and (iii) the reduction of the generation of emissions and fuel consumption.

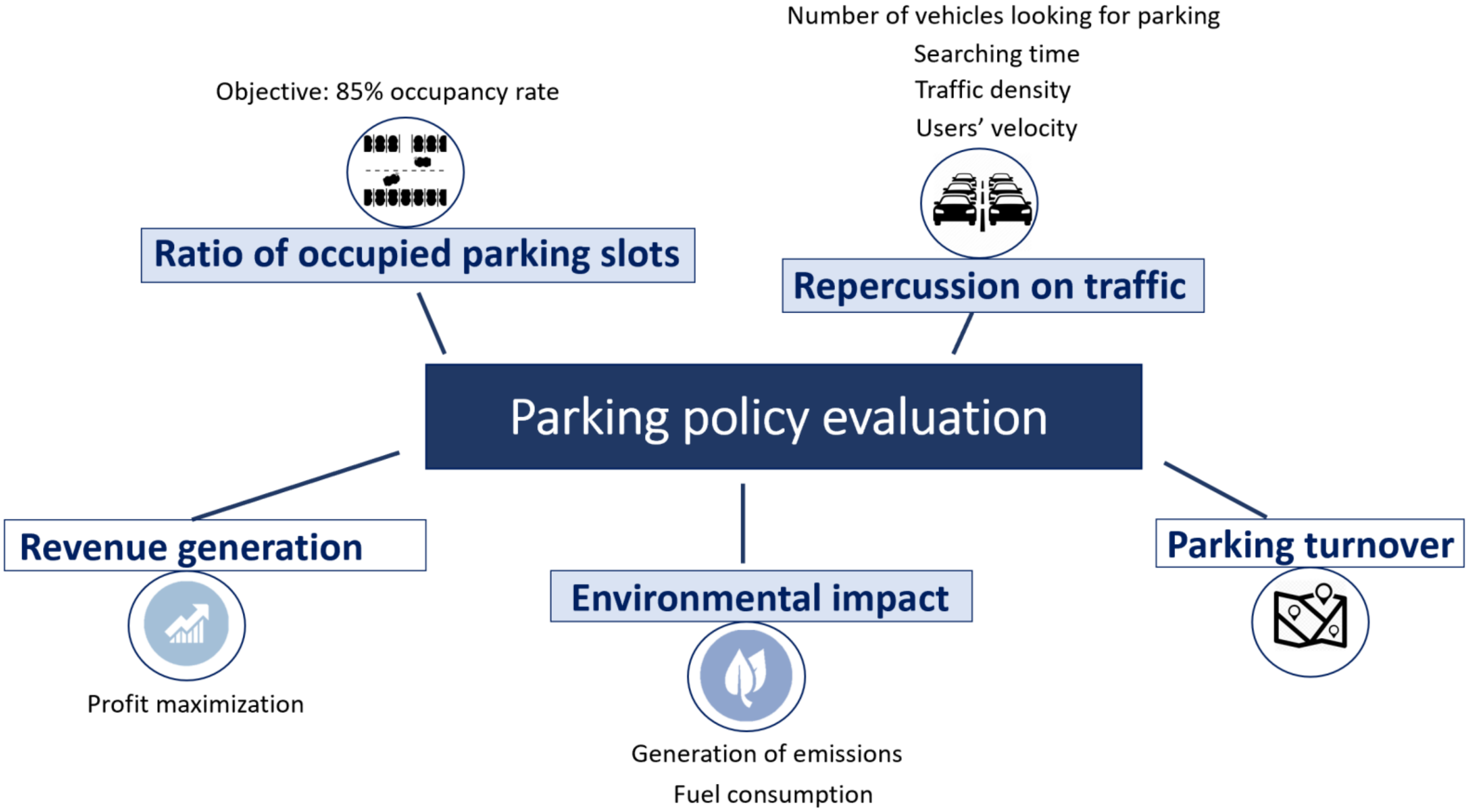

Figure 4. Parking policy evaluation types

5 Case study presentation

5.1 Area of analysis

The model described above is applied to the regulated surface parking area in the city of Santander, Spain. Santander is the capital of Cantabria, a region located in northern Spain, and has a population of 172,000 (2017). A majority of the population, economic activities and parking demand are located in the city centre. There were 102,069 employed workers in Santander in 2019 (Instituto Cántabro de Éstadística - ICANE). There was a vehicle fleet of 112.267 vehicles in 2019 (ICANE).

There are currently three types of public parking facilities in the city (Antolín et al., 2019): (i) free on-street parking, (ii) paying on-street parking and (iii) paying off-street parking (underground parking).

Free on-street parking

Free on-street parking does not follow any type of parking regulation (time limitation, parking cost, and so on). Most free on-street parking areas are located where parking demand is lower, such as the outskirts of the city and residential areas in the city centre. This type of parking increases cruising for parking time and congestion when located close to paying off-street parking areas in the city centre.

Paying on-street parking

Paying on-street parking is located in the areas with the most economic activity and is mostly found in the city centre of Santander. There are approximately 7,000 paying on-street parking slots in the city. The current paying rate is static and there is a time limitation of two hours. Parking regulations are only applied from Monday to Friday, from 10 AM to 2 PM and from 4 PM to 8 PM, and on Saturday, from 10 AM to 2 PM.

The current study is located in the regulated parking area, which is highlighted in the following map.

Figure 5. Paying on-street areas in Santander. Source: Antolín (2019)

The area of study is comprised of various local roads and two of the arterial roads of the city (Paseo de Pereda and Calle Casimiro Sainz), which bound the area to the south and to the east. Calle Casimiro Sainz is a dual carriageway with two lanes in each direction. Paseo de Pereda is a dual carriageway with three lanes in each direction. One of the lanes in each direction is segregated for the use of buses, taxis and motorcycles. Also, this road has a wide pedestrian refuge in the middle. There are regulated on-street parking on both sides of the pedestrian refuge. Regarding the local roads within the area of study, these are single or dual carriageway roads with one lane in each direction. Some of them include regulated on-street car parking and/or motorcycle parking on one side or both sides of the road.

Figure 6 shows the location of bus stops and public bikes parking near to the area of analysis. The bus stops serve various bus routes which link the city centre of Santander to the rest of the city.

Figure 6. Area of analysis

Paying off-street parking

The paying off-street parking is also located in the most commercial areas in the city centre of Santander, where most of the parking demand is concentrated. There are 11 underground parking facilities with 4,500 parking slots in the city. The paying rate is static, and the cost is approximately 1.5 € per hour. In this case, there is no time limitation imposed.

In the following map, the location of the off-street parking facilities close to the area of analysis are shown. The consideration of these parking facilities is key in the modelling of users' behaviour when cruising for parking. The capacity of each underground parking is: approximately 900 parking spaces in Parking 1; 438 parking spaces in Parking 2; and 350 parking spaces in Parking 3.

Figure 7. Location of off-street parking

The model is applied to the regulated surface parking area in Santander highlighted in orange in Figure 7. This area has been chosen for the analysis due to its central location in the city centre of Santander. It is one of the most commercial areas in the city, where most of the parking demand is concentrated. In addition, this area has been selected due to the availability of parking sensors located in several parking slots. The information provided by the project Smart Santander about the occupancy status of parking slots in this area has been utilised for this study. The area of study has been limited and defined according to the following constraints found in the surrounding area: to the north of the site, there are several free on-street parking (as explained below, this type of parking is not considered in this analysis); to the west of the site, there are almost no regulated on-street parking; to the east of the site, the characteristics and dynamic of this area are considerably different to the area of analysis; and, finally, the site is bounded by the sea to the south.

In the area of study there are approximately 600 parking slots. Among these parking spaces, 36% belong to the regulated surface parking, paying on-street parking, and the remaining 64% belongs to underground parking.

In addition, for the creation of the model, Aimsun requires the introduction of the characteristics and traffic of the area of analysis. On one hand, Aimsun requires the introduction of the physical characteristics of the network: road geometry, centroids, junctions, turning points, and so on. On the other hand, the software requires the introduction of traffic management dynamics such as velocity limits, turnings permitted at junctions and turning points, public transportation, traffic signals such as give ways and stops, and phases and timing of traffic lights. The following figure shows the area of analysis as represented by the software:

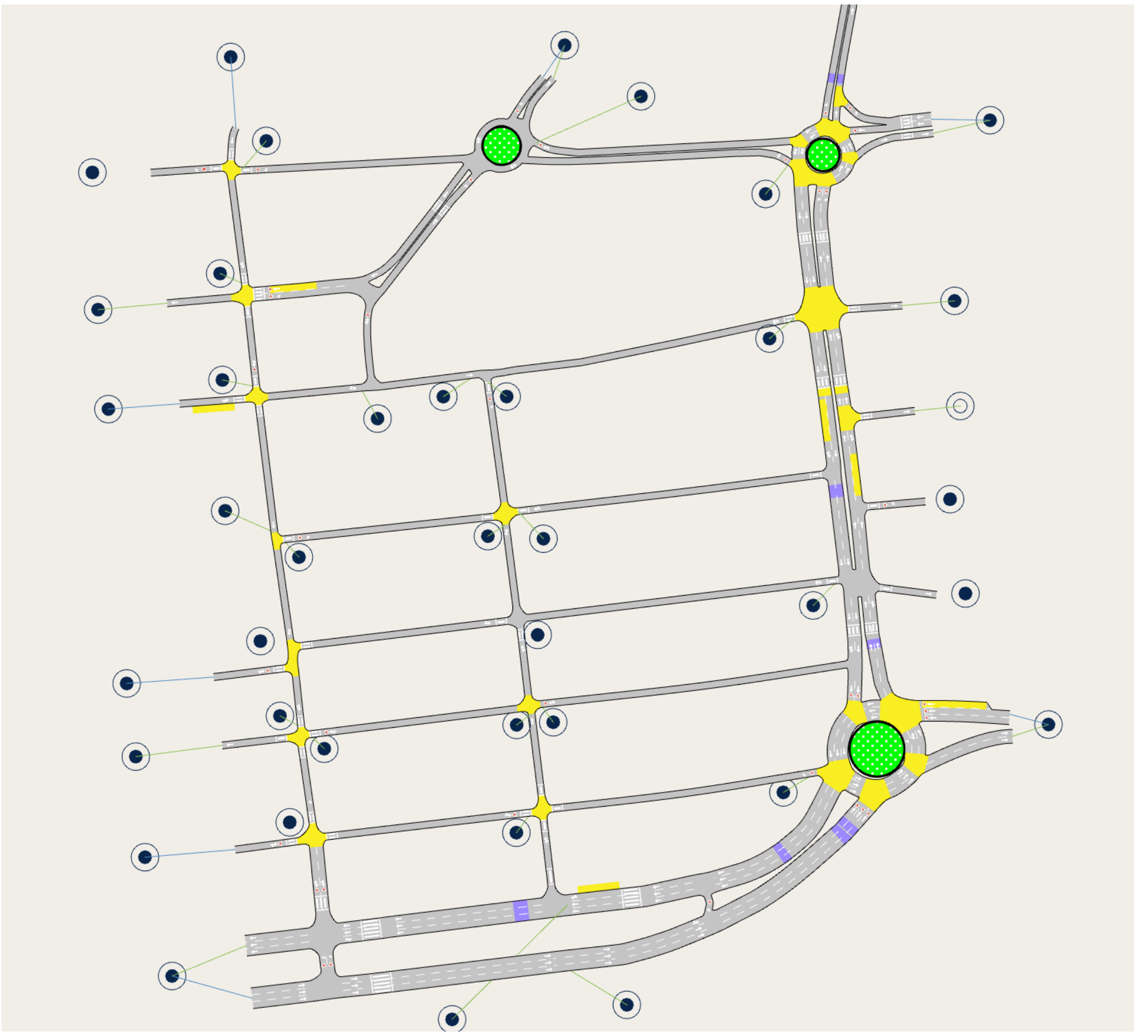

Figure 8. Area of analysis in AIMSUN

In the area of analysis, there are two parking types: (i) paying on-street parking and (ii) private parking. Additionally, as shown above, there are many underground parking facilities near this area. Parking sensors are distributed among the area of study, as shown in the following figure. This data was provided by the town council ("Ayuntamiento de Santander"). These sensors provide information on the occupancy status of parking slots in the area, with red representing an occupied space and green representing a free space. This information could be used to implement a dynamic paying rate system based on parking occupancy.

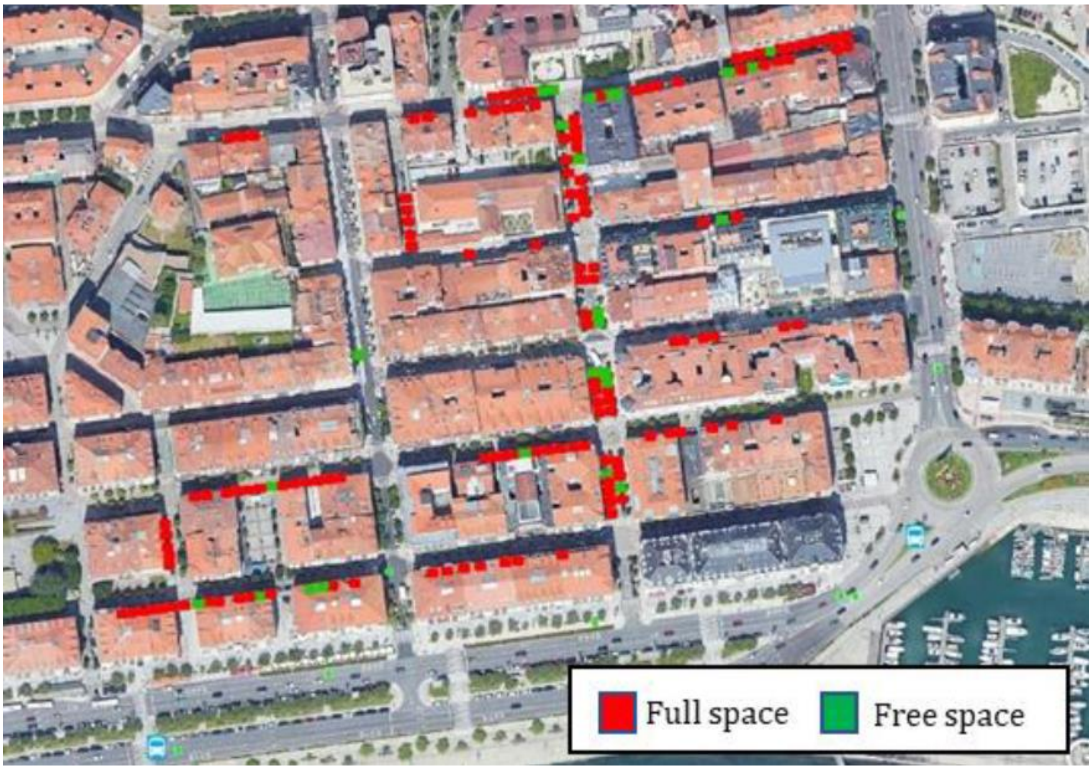

Figure 9. Parking sensors in the area. Source: Rodríguez Gutierrez

5.1.1 Declared preference survey

SUMLAB had obtained the parameters of the parking choice model in the area of analysis using a declared preference survey. Particularly, the survey provided the parking type and section choice parameters. The questionnaire was developed from experimental design, establishing different choice situations that each participant would have to face to choose a parking alternative.

Given the configuration of the area of analysis, the survey provided participants with three choice alternatives in each scenario: two hypothetical on-street parking sections, plus the underground off-street parking alternative. Each of the alternatives was defined based on the following attributes:

- Fee (€ / h)
- Search time (min)
- Time to destination from parking section (min)
- Probability of finding a vacant parking slot: High (occupancy <40%), Medium (occupancy 40% - 80%) and Low (occupancy >80%)
- Maximum stay time in the section (hours)

The questionnaire was conducted online. A total of 150 observations were registered. Answers from users who had travelled and parked in the area before were collected, as well as from users who were parking on site. Figure 10 shows an example of a survey scenario for users using the interface of the LimeSurvey online survey software.

* Scenario 1

Please, choose the best parking alternative as you were travelling as usual in the area outlined above

Attributes	On- street parking 1	On- street parking 2	Underground parking
Rate (euros/hour)	3 euros/hr	1 euro/hr	1 euro/hr
Search time (minutes)	10 minutes	5 minutes	3 minutes
Time to destiny (minutes)	1 minute	3 minutes	2 minutes
Probability to find a slot	High	Low	Medium
Maximum parking stay-length allowed (hours)	4 hours	2 hours	-
Example image			

Select one of the following options

Option 1 Option 2 Option 3

Figure 10. Example of survey scenario

5.1.2 Model parameters

The parameters of the model were obtained through the maximum likelihood method, using the responses of the declared preference survey conducted with usual and unusual users in the area of analysis. The model parameters obtained as part of the project mentioned above are included in the following table:

Variable	Parameter	Z
Rate (€/h)	-0.95057	-4.88
Parking search time (min)	-0.07261	-0.68
Time to destination (min)	-0.07761	-1.15
Occupancy (%)	0.00707	0.71
Maximum parking time (h)	0.52876	2.9
Underground constant	2.59822	4.58
Nido Street	0.68133	2.79
Log-Likelihood	-69.515	
Log-Likelihood (Null)	-138.629	
Log-Likelihood	-136.591	
McFadden Pseudo (R-squared)	0.4985	

Table 4. Model parameters

The parameters obtained for the variables of the model show the great influence of the following parameters on parking selection: paying rate in the on-street parking (negative), the fee in the underground parking (positive) and the maximum length of stay in the on-street parking (positive). In addition, the searching time and the time to destination do not have a significant influence on the parking selection. Even though the searching time and the time to destination increase, the preference of users to park in the on-street parking remains high. Lastly, the parameter of occupancy has not been introduced in the model as its sign is not correct. The occupancy rate should have a negative influence on the user's preference to park on the on-street parking.

5.2 Alternatives and restrictions: Scenario generation

Four simulation scenarios are executed: (i) static pricing with no time limitation, (ii) dynamic pricing with time limitation, (iii) static pricing with time limitation and (iv) dynamic pricing with time limitation. The simulations are executed for: (i) a first simulation of one-hour time length during the parking peak turnover hour, from 11 AM to 12; and (ii) a second simulation of four-hour time length during the morning peak period, from 9 AM to 1 PM. There is a preheating time of 300 seconds, which allows the arrival of initial users into the network.

The parameters of the different scenarios are shown in the following table.

Model input variables				
Scenario	**Scenario 0: Static rate + time limitation**	**Scenario 1: Dynamic rate + time limitation**	**Scenario 2: Static rate**	**Scenario 3: Dynamic rate**
Parking maneuvre time (s)	22.3	22.3	22.3	22.3
Minimum parking time (s)	300	300	300	300
Maximum parking time (s)	7200	7200	-	-
Initial occupancy (%)	95	95	95	95
Rate ranges (€)	-	0.5, 1, 1.75	-	0.5, 1, 1.75
Occupancy ranges (%)	-	60%, 80%, 100%	-	60%, 80%, 100%
Standard on-street rate (€ per hour)	0.75	0.75	0.75	0.75
Standard off-street rate (€ per hour)	1.6	1.6	1.6	1.6
Mean searching for parking time (min)	6.58	6.58	6.58	6.58
Standard deviation of searching for parking time (min)	1.54	1.54	1.54	1.54
Mean parking length of stay (min)	60	60	80	80
Standard deviation of parking length of stay (min)	60	60	60	60
Minimum relative utility	90	90	90	90
Rate update time (minutes)	15	15	15	15
Percentage of informed users (%)	50	50	50	50

Table 5. Parameters of model scenarios

The dynamic rate update time is 15 minutes. The values of the parameters "parking manoeuvre time", "searching for parking time" and "parking stay length" have been obtained from the declared preference survey described by Antolín et al. in 2019. A total of 801 households were surveyed (1,655 people).

The data collected in the survey included information regarding the characterization of each member of the household; existing vehicles and their characteristics; and parking spaces. Also, the survey registered information about the parking spaces, number of occupants in each vehicle, type of parking (free on-street, paying on-street or underground payment), trip start time, trip arrival time at destination, parking length of stay and parking search time. Likewise, information was collected about the place of origin, destination, reason for the trip, mode of transport, modes of transport available for the trip and frequency of the trip.

On the one hand, concerning the searching for parking time parameter, the results of the survey showed that the searching time is higher for regulated surface parking users than underground parking users. Regarding regulated surface parking, the most probable searching time for free on-street parking is from 14 to 29 minutes, while the most probable paying on-street parking searching time is less than 9 minutes. For paying on-street parking, the mean parking searching time is 6.58 minutes, with a standard deviation of 1.54 minutes.

Figure 11. Searching for parking time distribution. Source: Antolín et al. (2019)

On the other hand, regarding the parking length of stay, the survey showed that for the paying on-street parking the mean parking length of stay value is between 60 and 80 minutes with a standard deviation of 60 minutes. Plus, the underground parking and the free on-street parking had a higher probability of obtaining a higher value of parking length of stay with regard to the paying on-street surface parking (see Figure 12). This is due to the fact that the regulated surface parking has currently a limitation of maximum 2-hour length of stay. Accordingly, for the scenarios 2 (static rate with no time limitation) and 3 (dynamic rate with no time limitation), the length of stay value distribution would be similar to the ones obtained for the underground and free on-street parking, where there is no time limitation. In those scenarios, the mean length of stay value introduced is 80, with a standard deviation of 60.

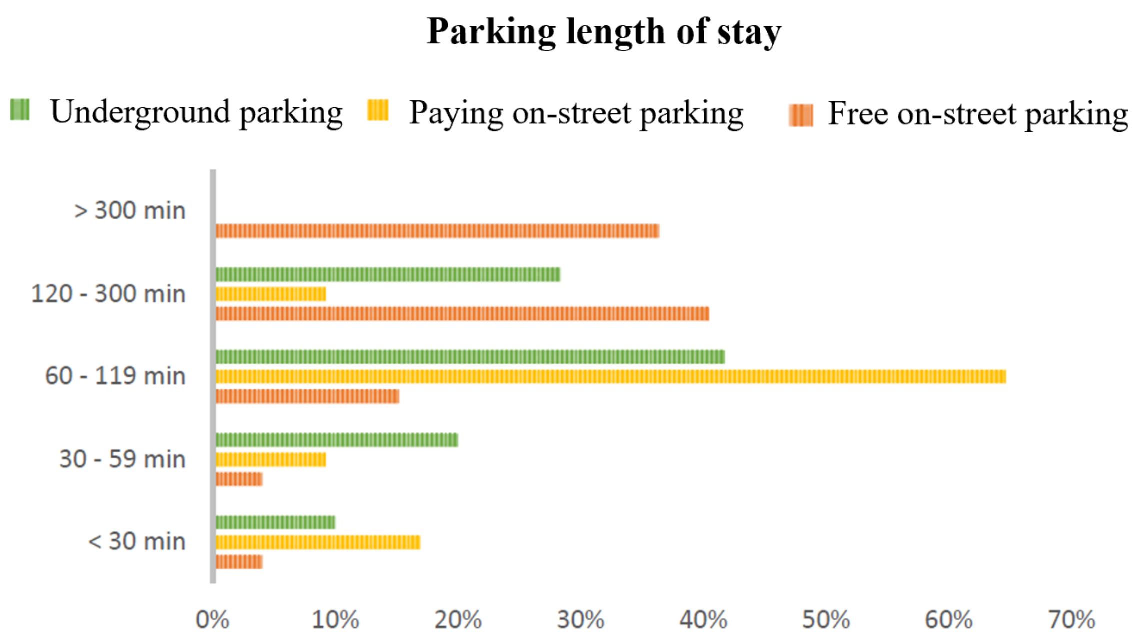

Figure 12. Parking length of stay. Source: Antolín et al. (2019)

The following figures show a representation of the itinerary that a given vehicle that aims to park follows in the area of analysis. Figure 13 shows the itinerary of a vehicle in a static rate scenario, while

Figure 14 shows the itinerary in a dynamic rate scenario. Each street is highlighted with a colour that represents the utility of parking in that area for the vehicle. The colour ranges from yellow to red, being red the one with the maximum utility.

Figure 13. Itinerary of a vehicle in a static scenario (user not informed)

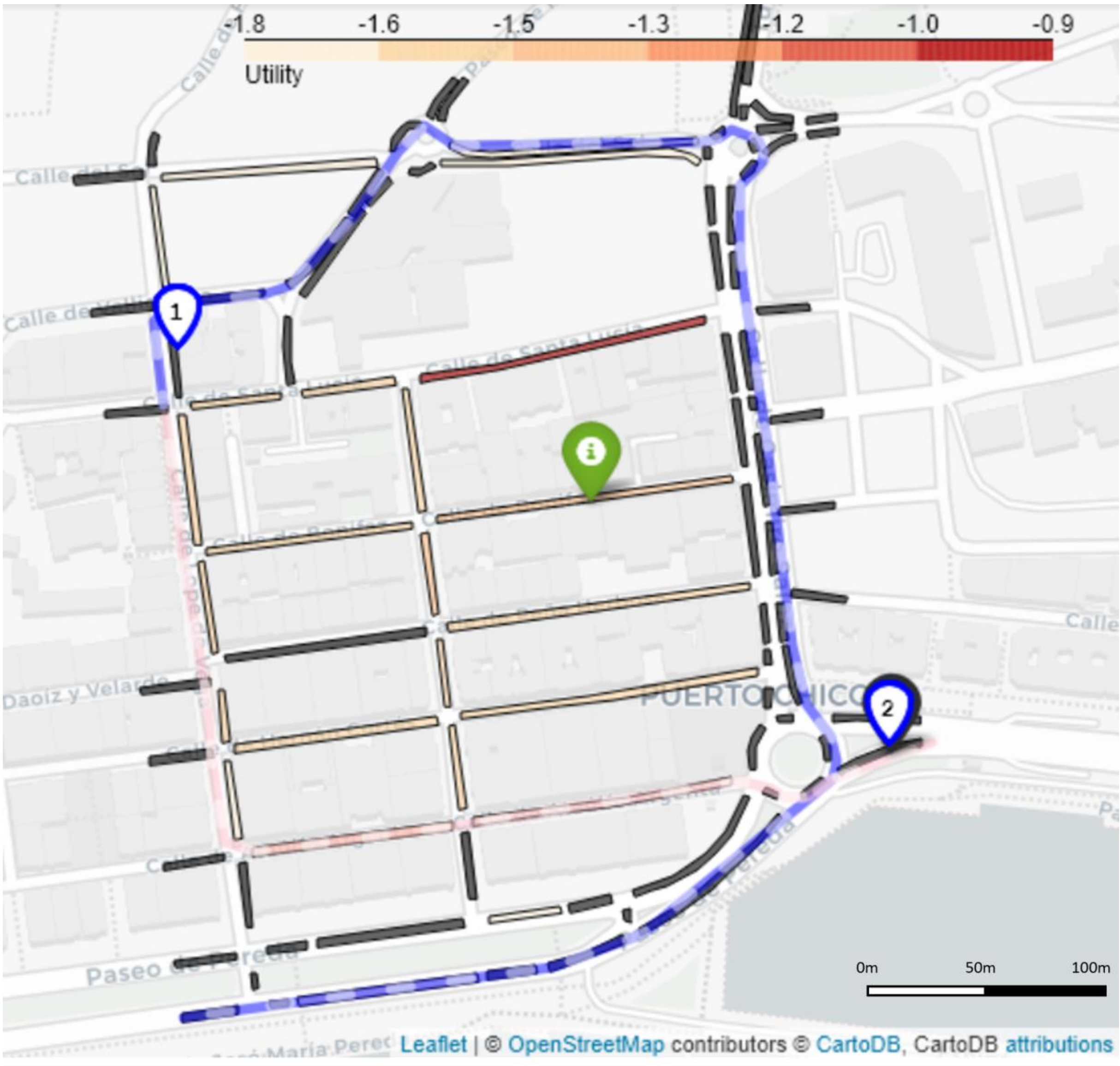

Figure 14. Itinerary of a vehicle in a dynamic scenario (user informed)

6 Analysis of results: Comparison of parking policies

To ensure the quality of results, each of the scenarios explained above was executed through 15 different simulations. The mean value of the results obtained with the 15 simulations was calculated. The following sections provide an analysis of the results obtained through the execution of two different simulations: one-hour simulation and four-hour simulation.

6.1 Analysis of modelling results: One-hour simulation

6.1.1 Parking occupancy rate

The following graphs show the evolution of the occupancy rate over time.

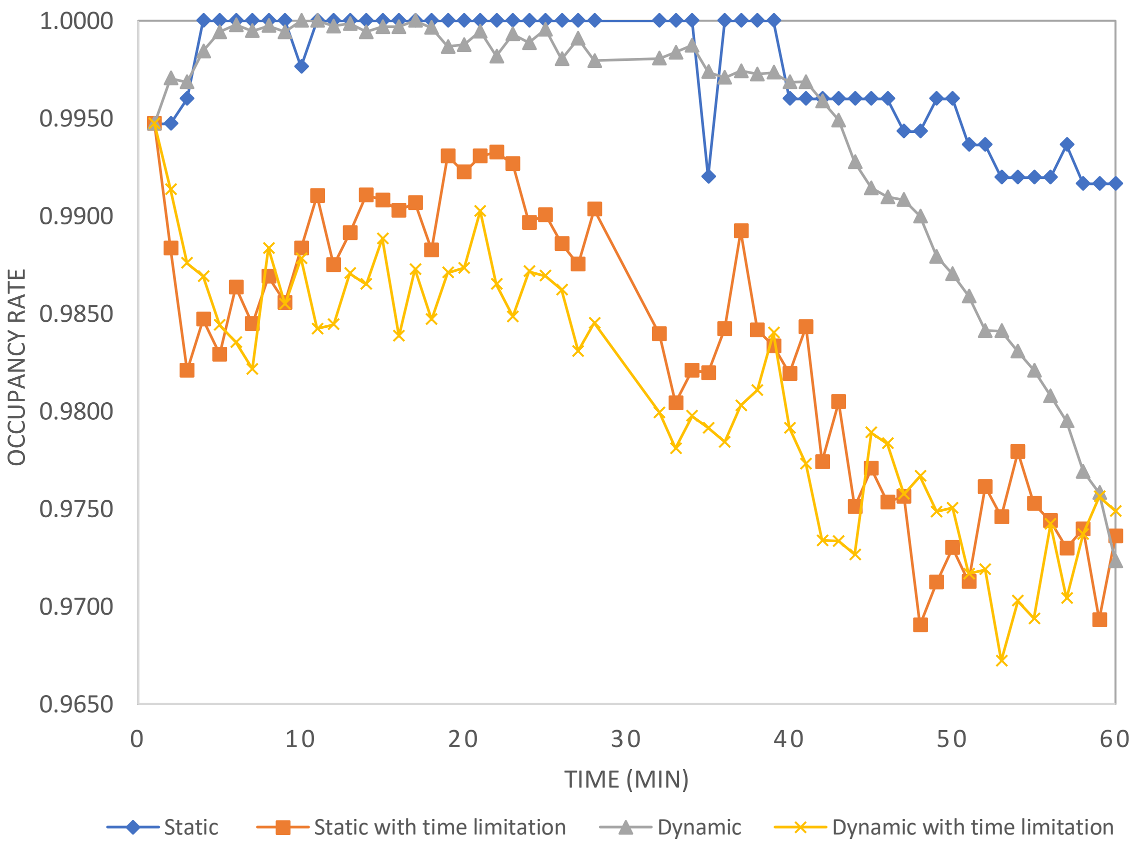

Figure 15. Evolution of occupancy rate

The occupancy rate value is maintained at a high level during the entire period of analysis in all situations analysed. This might be due to the fact that a one-hour simulation does not provide enough time to obtain an occupancy rate value close to 85%. For this reason, the current study also performs a four-hour simulation, which will be explained in the following section. Moreover, in all different situations, the evolution of the occupancy rates suggests a decrease with time, especially with the two policies that implement a dynamic rate system. The graph shows that the parking time limit restriction diminishes the initial occupancy rate by 1.5%; the pre-established occupancy rate was 99.5%. On the contrary, the two policies with no time limitation increase the initial occupancy rate by 100%.

Finally, although the occupancy rate is maintained at a high level during the entire period of analysis, the dynamic rate system with the time limitation policy is the policy that provides occupancy rate values closer to the objective occupancy rate of 85%.

6.1.2 Impact on traffic and parking conditions

The impact of each policy on parking conditions in the area of analysis can be described through various parameters, such as the evolution in the number of vehicles searching for parking and the search time during the simulation. The following graph shows the evolution of the number of vehicles searching for parking during the one-hour simulation. With respect to the 'dynamic rate system with time limitation' policy, after 20 minutes of simulation, the maximum number of vehicles searching for parking is reached at 40. Afterwards, the number of vehicles is maintained over time. Regarding the rest of the policies, the maximum number of vehicles simultaneously searching for parking is over 50. Thus, the implementation of a dynamic rate system with a time limitation policy allows a decrease in the number of vehicles searching for parking by up to a maximum of 20%.

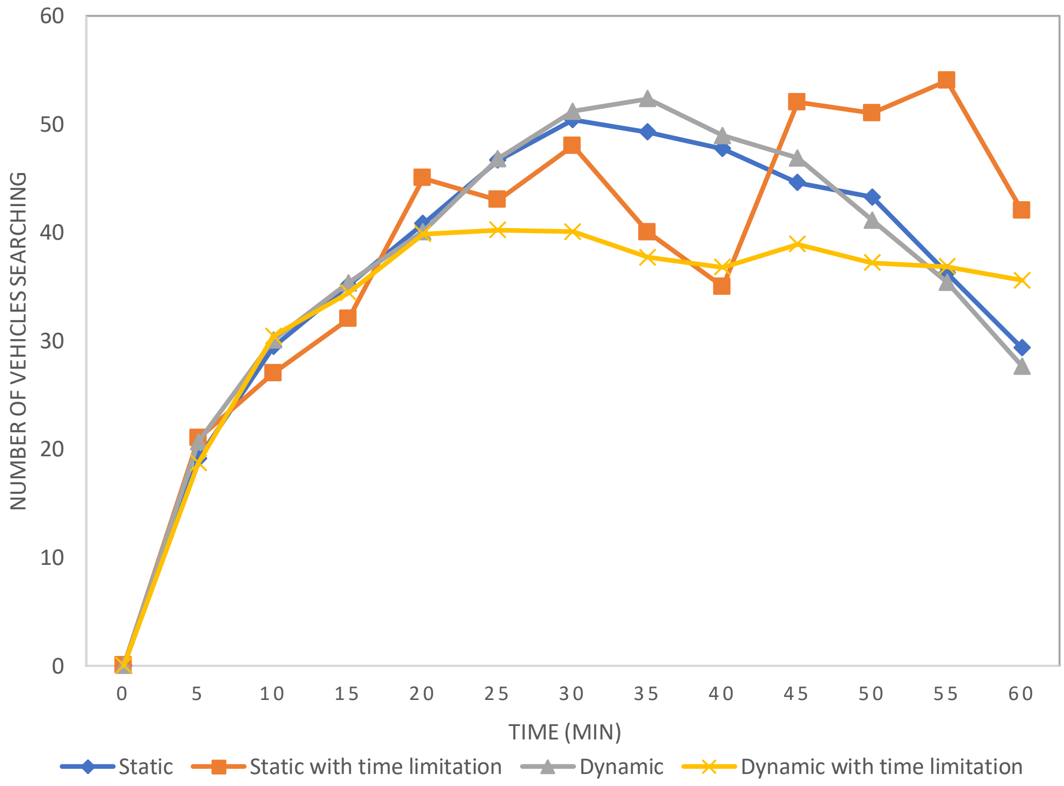

Figure 16. Evolution of number of vehicles searching for parking

This can also be noticed in the evolution of the search time (see Figure 17), which varies considerably between the different policies. While the evolution of the search time is similar for the policies with no time limitation, it is different for the policies with time limitation. This may be due to the fact that there is an accumulation of vehicles in the system in the policies with no time limitation. Accordingly, the dynamic rate system has a higher impact when the parking duration is lower or limited. It is observed that the dynamic rate system with time limitation policy provides the lowest search time values. While the two policies with no time limitation provide a search time evolution that continues to grow during the entire period of analysis, the policies with time limitation provide a search time evolution that reaches a maximum and then stops increasing. With the dynamic rate system with the time limitation policy, the search time reaches its maximum value of 4 minutes after 20 minutes at the beginning of the simulation. On the contrary, the policies with no time limitation reach a maximum of almost 13 minutes of search time at the end of the simulation. Thus, the implementation of the dynamic rate system with a two-hour parking time restriction allows a decrease in the search time of vehicles in the system by up to a maximum of 75%. Accordingly, with respect to the effect on parking conditions, the dynamic rate system with the time limitation policy is able to generate a lower impact in the area of analysis.

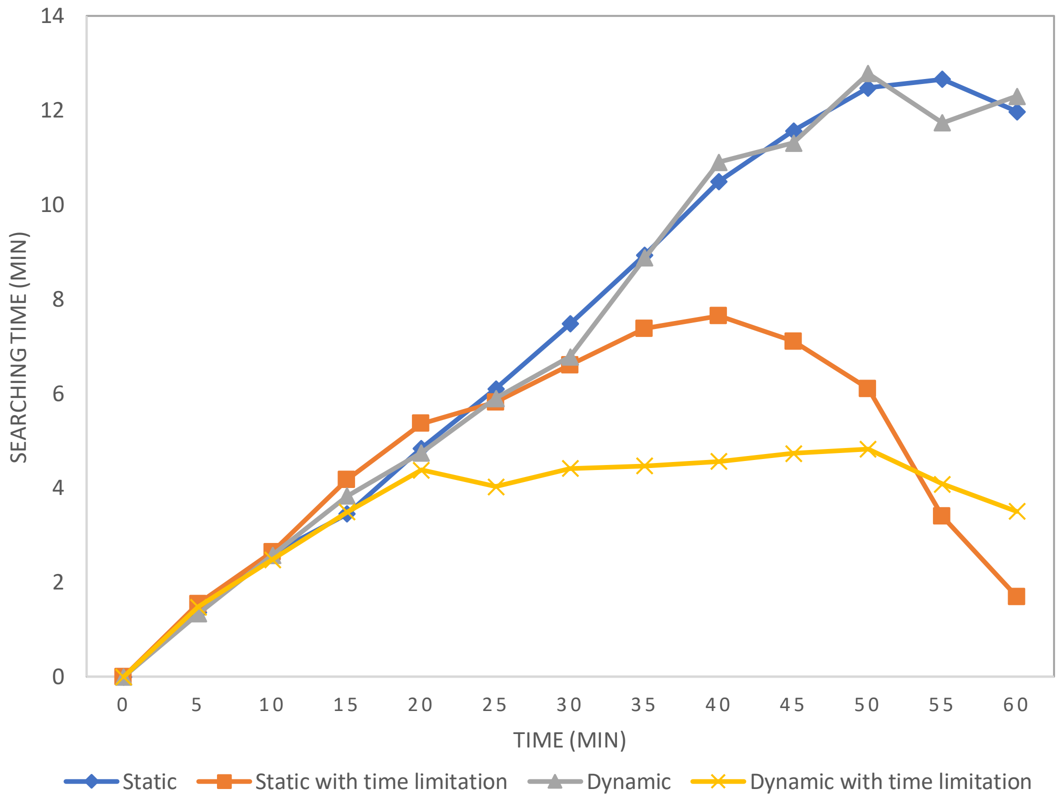

Figure 17. Evolution of parking searching time

Additional parameters related to the effect on traffic have been obtained to check the results shown above. These parameters, which are mentioned in the following table, are (i) speed, (ii) travel time, (iii) delay time and (iv) mean queue. All these parameters support the previously obtained results; the dynamic rate system with time limitation policy provides the most favourable values for each parameter.

Data description	Units	Static	Static with time limitation	Dynamic	Dynamic with time limitation
Speed	km/h	29.0	31.0	28.8	31.9
Travel Time	sec/km	169.5	142.5	174.1	133.5
Delay Time	sec/km	100.3	73.3	105.0	64.3
Mean Queue	veh	49.2	23.1	49.6	16.2

Table 5. Result of parameters relevant to the effect on traffic

6.1.3 Impact on generation of emissions

The following graphs show the evolution of the generation of four polluting gases through the implementation of the different parking policies. The four polluting gases are particulate matter (PM), carbon dioxide (CO_2), volatile organic compounds (VOC) and nitrogen oxides (NOX).

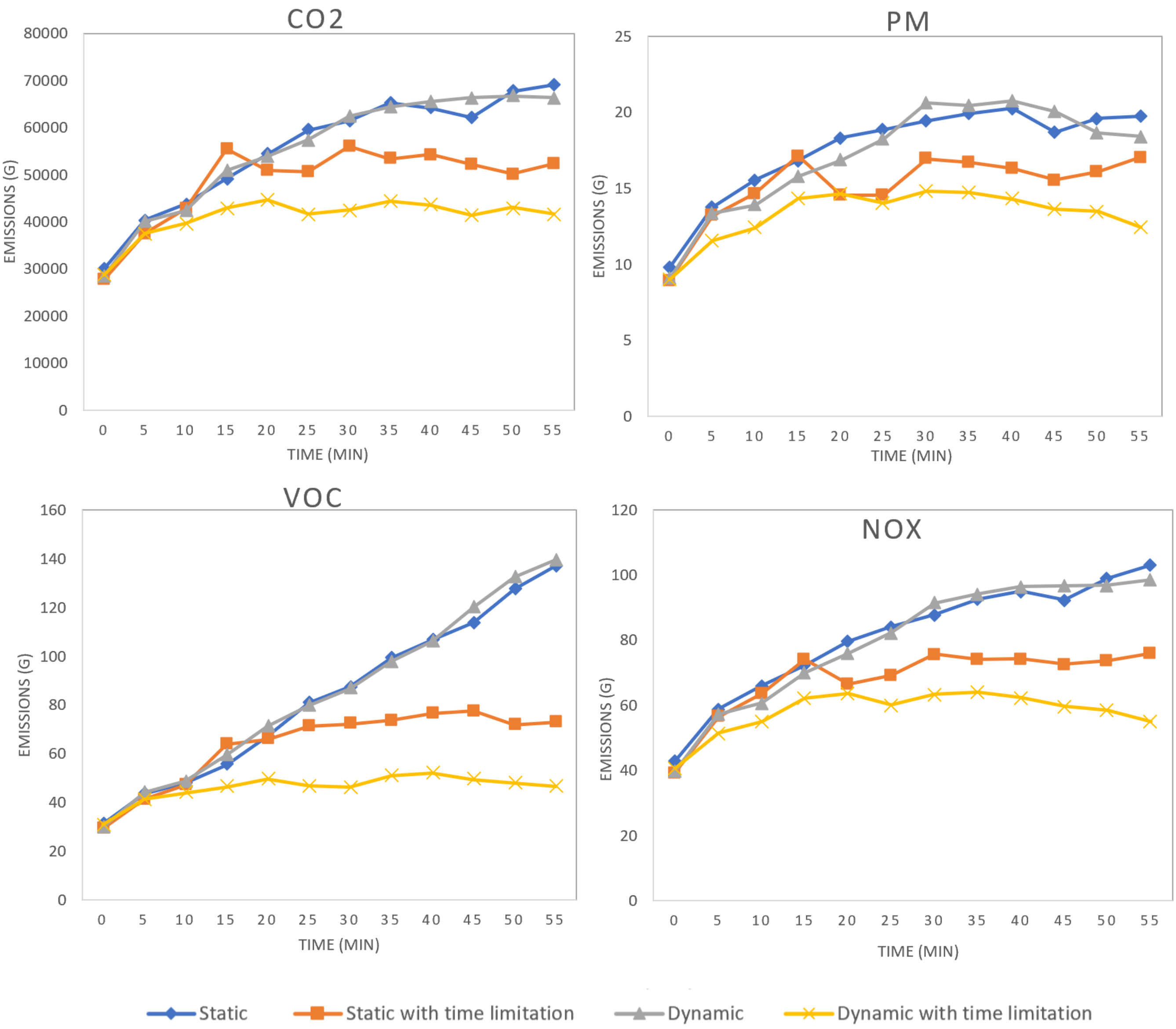

Figure 18. Evolution of generation of emissions

The generation of emissions in each parking policy follows the same pattern of evolution for each of the four gases analysed. In all situations, the tendency of the generation of emissions is to increase over time.

The static and dynamic with no time limitation policies follow almost the same evolution for the four gases. In those cases, the generation of emissions keeps growing during the one-hour simulation period. On the contrary, for the static with time limitation and the dynamic with time limitation policies, the evolution of generation of emissions differs from one another; the number of emissions is considerably lower for the dynamic with the time limitation policy. In both cases, the generation of emissions increases only for the first 20 minutes of the simulation. Afterwards, the generation of emissions remains approximately constant. After the first 20 minutes of simulation, the generation of emissions is about 30% lower for the dynamic with the time limitation policy.

Data description	Units	Static	Static with time limitation	Dynamic	Dynamic with time limitation
Fuel Consumption	l	199.5	192.2	201.3	185.8
IEM Emission - CO2	kg	744	613	740.5	530.8
IEM Emission - NOx	g	1084.9	868.2	47.4	750.6
IEM Emission - PM	g	233.3	198.0	79869.3	172.3
IEM Emission - VOC	g	1137.4	733.0	109.3	585.2

Table 6. Total fuel consumption and emissions

Table 6 above shows the total number of emissions and fuel consumption for each of the four policies. From Table 6, it can be concluded that the generation of emissions can be diminished by approximately 30% by implementing the time limit restriction and the dynamic rate system. This may be a result of the decrease in parking search times, number of vehicles and generation of queues in the system through the implementation of these parking restriction policies, which has been shown above.

Regarding the fuel consumption, from the table above, it can be observed that the total amount of fuel consumed by the transit vehicles in one hour with the dynamic rate system with the time limitation parking policy is approximately 185.8 litres, while that with the static parking policy is 199.5 litres. Thus, there is a total reduction of 6.8% in fuel consumption. In addition, the following graph shows the evolution of fuel consumption over time, which is similar for the four different policies. It must be noted that the model only estimates the evolution of fuel consumed by transit vehicles in the system. Therefore, it can be concluded that the transit traffic is not considerably affected by the implementation of different parking policies.

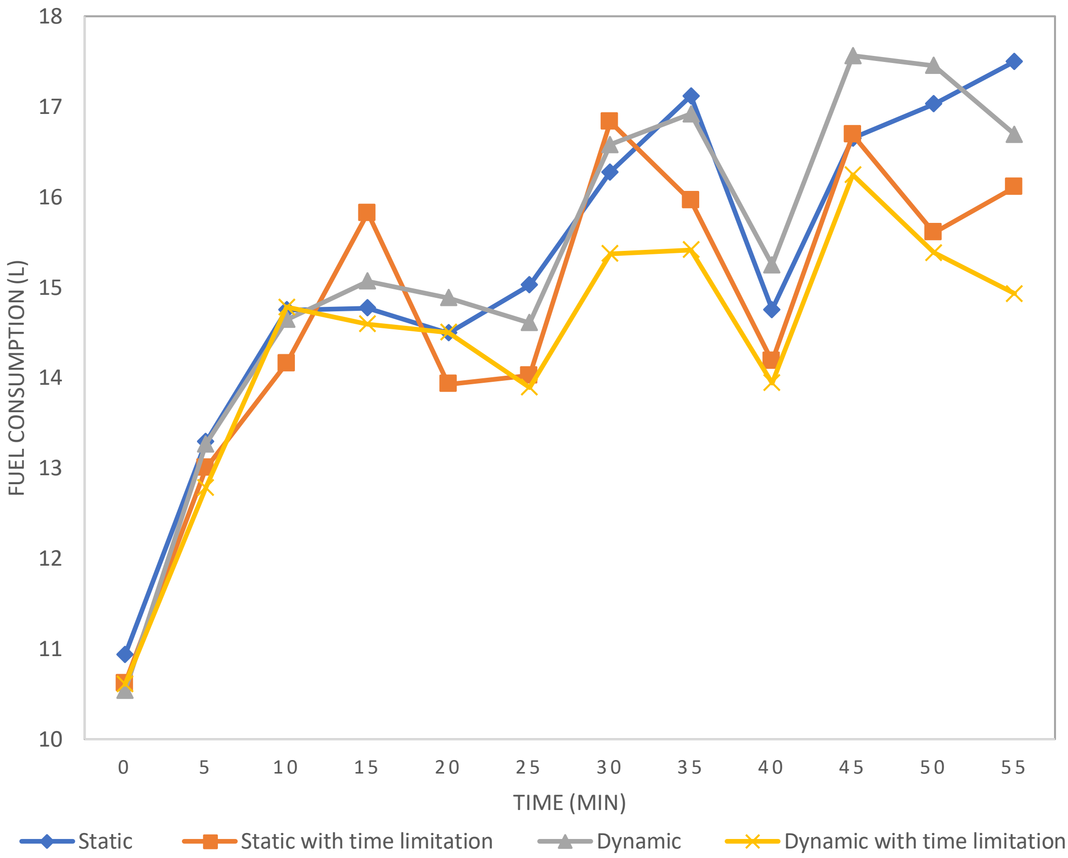

Figure 19. Evolution of fuel consumption

In conclusion, from the point of view of environmental sustainability, the policy that generates the lowest amount of emissions and fuel consumption, making it the most favourable, is the "dynamic rate system with a two-hour time limitation" policy.

6.2 Analysis of modelling results: Four-hour simulation

The current study also performs an analysis of a four-hour simulation to analyse the dynamics of the system in a longer period and compares its results with the ones obtained from the one-hour simulation. The four-hour simulation encounters only two policies: (i) the dynamic with no time limitation policy and (ii) the dynamic with time limitation policy. It considers only these two policies due to the fact that the dynamic rate system seems to be more favourable than the static rate system and, in addition, the results seem to vary considerably depending on whether a parking duration restriction measure is applied. It must be noted that in this case the demand varies considerably throughout the simulation period (from 9 AM to 1 PM), being the demand rate parameter: (i) 0.7 for the first hour; (ii) 1 for the second hour; (iii) 1.25 for the third hour; and (iv) 0.9 for the fourth hour. Thus, the demand from 11 AM to 12 PM (minute 120 to 180 of the second simulation) is the highest of the simulation. This fact is important to understand the results that will be shown below.

6.2.1 Parking occupancy rate

The following graph shows the evolution of the occupancy rate over time. It can be observed that approximately two hours from the beginning of the simulation, the objective occupancy rate of 85% is accomplished. It can be concluded that at that particular moment, the parking problem can be solved. However, after the first two hours, the occupancy rate starts to increase again due to the low parking fare that raises the on-street parking demand in the area of analysis. It should also be noted that at any time of the simulation, the parking policy with time limitation provides occupancy rate values lower than the one with no time limitation.

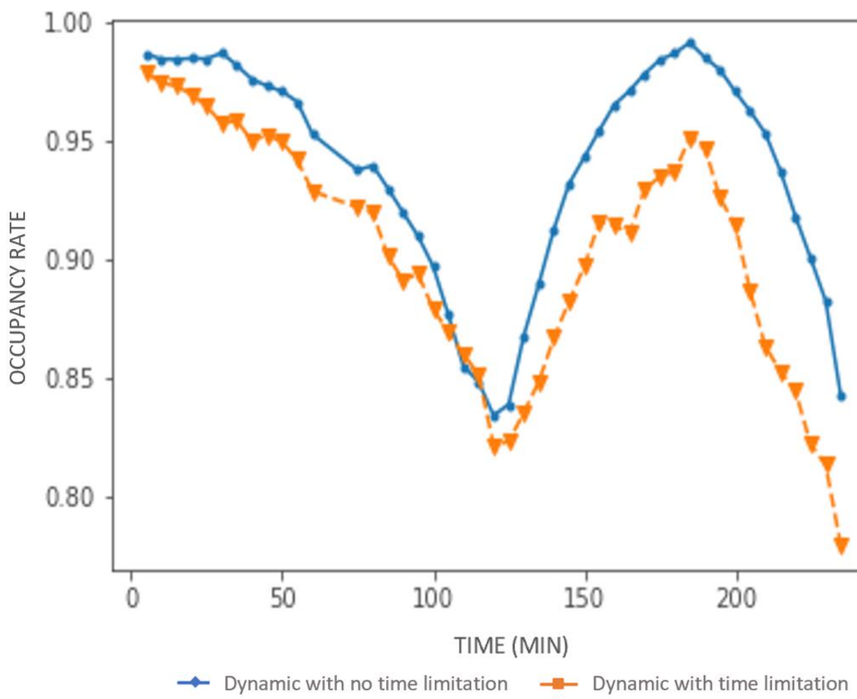

Figure 20. Evolution of occupancy rate

6.2.2 Effect on parking conditions

Figure 21 shows the evolution of the parking search time. It can be observed that the search time starts to greatly decrease after approximately the first hour of the simulation. This may be a result of the increase in demand during the first hour, which obtained a higher parking rate and search time than the second hour of the simulation. This resulted in a decrease in the utility of the on-street parking in comparison to other parking types during the second hour. Therefore, most users prefer other parking types, such as paying or free off-street parking.

Moreover, it can also be observed that the search time starts to steeply increase after the first two hours of simulation. This is because the dynamic rate system sets a lower parking rate as a result of the strong decrease in parking demand during the second hour of simulation. Consequently, the parking demand starts to increase again during the third hour of simulation. This effect is much more pronounced in the parking policy with no time limitation since vehicles are accumulated as a result of the lower parking turnover. Even though almost the same number of vehicles are searching for parking at each time in both policies (see Figure 22), the occupancy rate is higher in the case of the policy with no time limitation. This fact makes the parking search time higher for the policy with no time limitation; it is approximately up to a maximum of 60% higher than the time limitation policy in the third hour of the simulation.

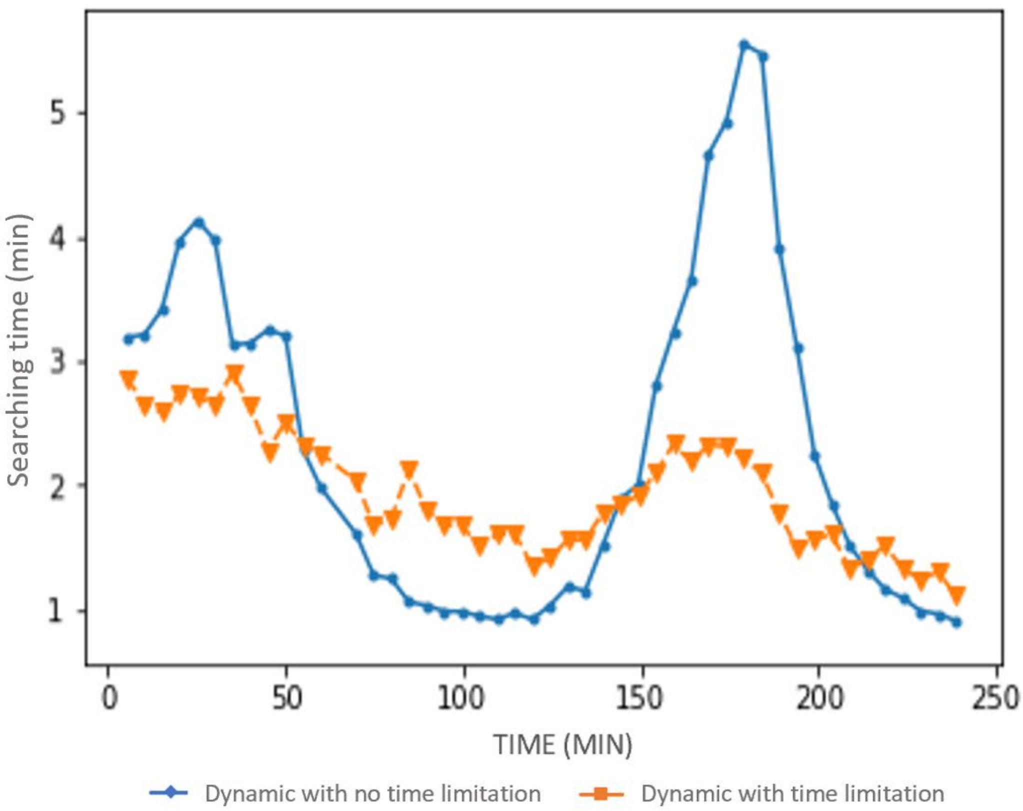

Figure 21. Evolution of searching time

Figure 22 shows the evolution of the number of vehicles searching for parking. In this case, the same effect described above can be observed; the search time starts to greatly decrease after approximately the first hour of the simulation and steeply increase after the second hour. This effect is much more pronounced in the parking policy with no time limitation due to the accumulation of vehicles in the system, which has been previously explained.

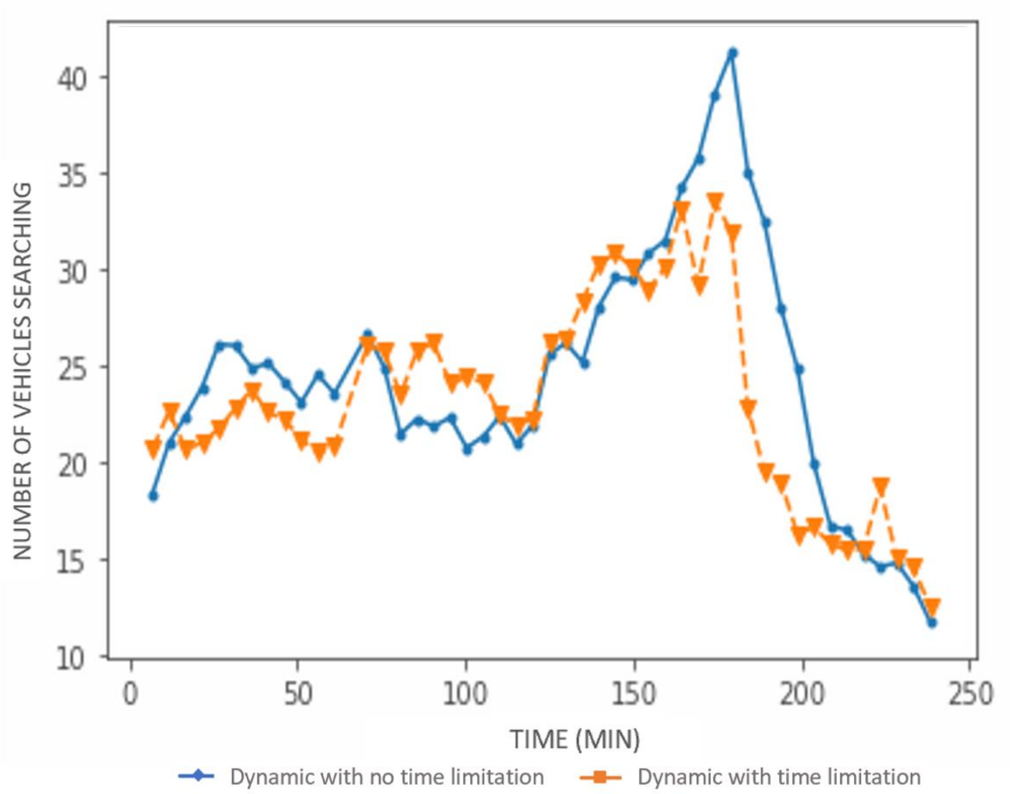

Figure 22. Evolution of number of vehicles searching for parking

Additionally, from the two graphs presented above, it can be observed that the results obtained in each simulation (one-hour simulation and four-hour simulation) differ considerably from one another. This is due to the fact that the demand varies from one simulation to the other since they are executed at different times of the day, so that the demand is different. As previously mentioned, the first simulation was executed from 11 AM to 12 PM (one hour), while the second simulation was executed from 9 AM to 1 PM (four hours). In both cases, the demand from 11 AM to 12 PM (minute 120 to 180 of the second simulation) remains the same. However, even though the demand is equal for both simulations in that time period, the results obtained from each of them are very different. As an example, on the one hand, in the one-hour simulation in the dynamic policy, the maximum search time is approximately 12 minutes; on the other hand, in the four-hour simulation, from minute 120 to 180, the maximum search time is approximately 5.5 minutes. Therefore, it can be concluded that the implementation of the discussed parking policies during a long period of time allows obtaining a more efficient system. In this case, it reduces the search time of users approximately by half.

6.2.3 Impact on the generation of emissions

The following graphs show the evolution of emissions for each parking policy. In accordance with the parking search time, the generation of emissions greatly decreases after approximately the first hour of the simulation and starts to steeply increase after the second hour. In general, the policy with the time limitation generates a lower number of emissions due to the lower search time, except from minute 60 to 120 (approximately) where this policy provides a higher number of vehicles searching for parking. To sum up, the policy with the time limitation provides less fluctuation over time due to a higher parking turnover that avoids the accumulation of vehicles, higher parking occupancy rates and higher search times in the system.

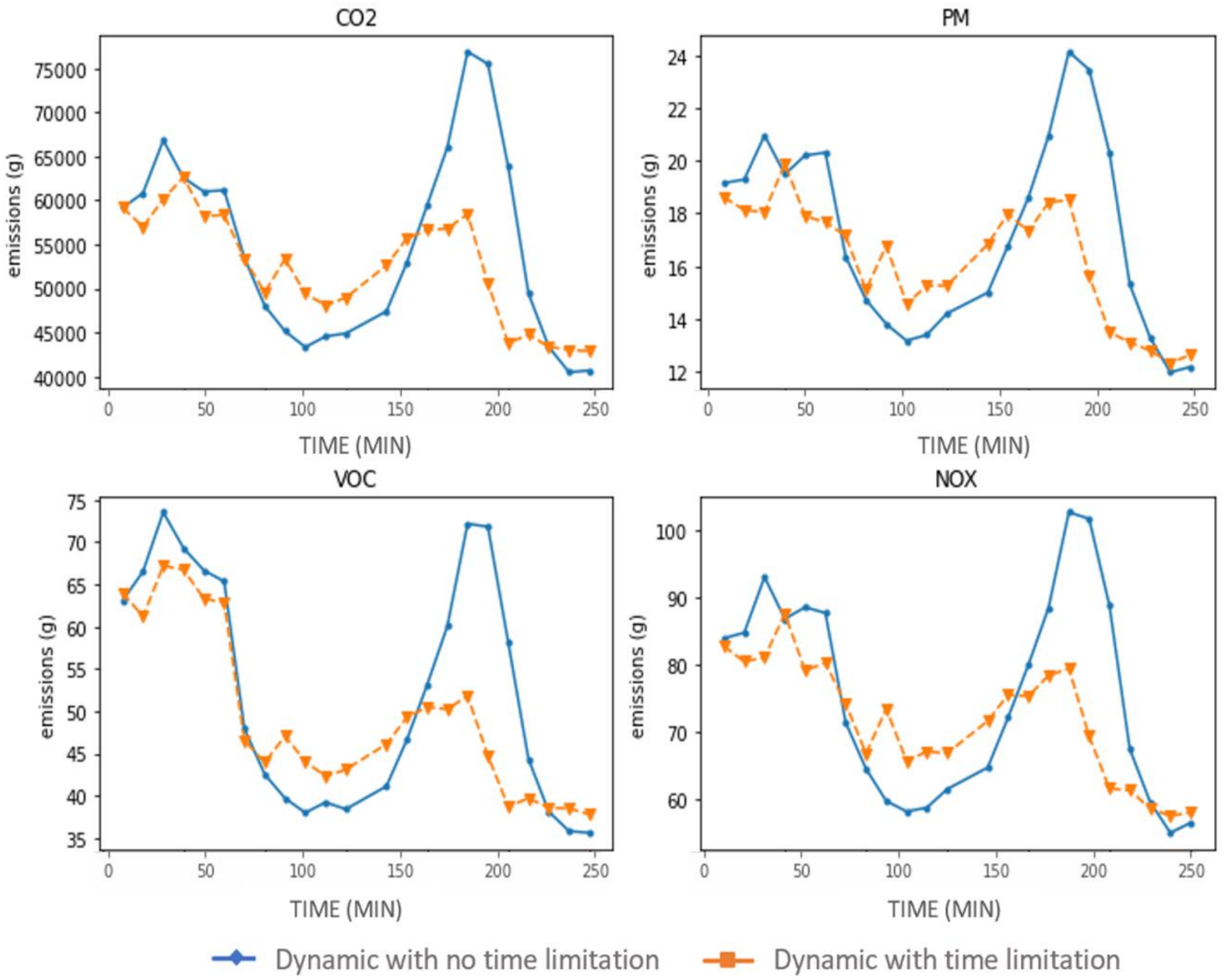

Figure 23. Evolution of generation of emissions

7 Sensitivity analysis based on the degree of informed users

The current section contains a sensitivity analysis based on the percentage of informed users in the system. The previous section demonstrated that the dynamic rate with a parking time limitation of two hours scenario provided the most favourable results in terms of impact on parking conditions, fuel consumption, generation of emissions and parking occupancy rate. For this reason, the sensitivity analysis will concentrate on this specific scenario. As mentioned above, informed users are those who use parking applications to pay and search for parking in the area and, consequently, have real-time information about the location of available parking slots and paying rates. Hence, informed users take into consideration the parking paying rate when selecting a parking slot. To conduct the sensitivity analysis, several indicators have been obtained and analysed: (i) mean queue generated, (ii) fuel consumption, (iii) vehicle density, (iv) distance travelled and (v) delay time. Each of these indicators has been estimated for all vehicles, transit vehicles and vehicles aiming to park in the area of analysis. As in the previous section, to ensure the quality of results, each scenario (degree of informed users) executed through 15 different simulations and the mean value of the results obtained with the 15 simulations was calculated.

All the indicators analysed below aim to represent the impact of promoting the use of parking applications to increase the percentage of informed users in the system.

Indicator	Units	Percentage of informed users				
		100%	80%	60%	40%	20%
Mean queue - all	veh	14.8	18.2	26.1	27.9	40.8
Mean queue - vehicle	veh	9.4	11	14.6	15	20.8
Mean queue - vehicle park	veh	5.4	7.1	11.6	12.9	20.1
Consumption - all	l	227.8	236.4	261.4	271.7	293.9
Consumption - vehicle	l	178	178.1	187.8	190.3	200.1
Consumption - vehicle park	l	49.8	58.3	73.6	81.4	93.8
Distance Travelled - all	km	1101.5	1081.2	1090.7	1084.9	1076.6
Distance Travelled - vehicle	km	934.5	919.8	932.6	935	934.4
Distance Travelled - vehicle park	km	167	161.4	158.1	150	142.2
Delay Time - all	sec / km	58.1	65.8	81.1	82.3	107.1
Delay Time - vehicle	sec / km	57.9	65.5	80.6	81.9	106.1

Delay Time - vehicle park	sec / km	97.5	117.9	154.1	154.5	245.9
Travel time - all	sec / km	33.6	35.5	40.4	41	48.7
Travel time - vehicle	sec / km	33	34.8	39.4	40.1	47.1
Travel time - vehicle park	sec / km	0.5	0.7	1.1	0.9	1.6
CO2 - all	kg	36	37.2	40.9	42.8	45.7
CO2 - vehicle	kg	26.3	26.3	27.6	28.1	29.3
CO2 - park vehicle	kg	9.6	10.9	13.2	14.7	16.4
PM - all	kg	11.3	11.7	12.7	13.3	13.8
PM - vehicle	g	8.2	7.9	8.4	8.6	8.7
PM - vehicle park	g	3.1	3.8	4.3	4.6	5.1

Table 7. Indicators based on percentage of informed users

First, the mean queue generated represents the mean number of vehicles that form a queue in the system. In this case, from Table 7, it can be concluded that the percentage of informed users considerably influences the generation of a queue; the lower the percentage of informed users, the higher the mean queue generated. The mean queue generated is 62% lower for the scenario of 20% informed users (40 vehicles) as compared to 100% informed users (15 vehicles).

Second, the distance travelled represents the distance transited by users in the network. The distance travelled increases with the percentage of informed users in the system. Regarding users searching for parking, the distance travelled is 15% lower for the lowest percentage of informed users as compared to 100% of informed users. In the case of 100% informed users, all users previously know the location of available parking slots. Then, as informed users have the advantage of being aware of the location of available parking slots, when there is a high percentage of informed users in the system, competition for a parking slot increases. To sum up, as it will be described later, informed users tend to park farther away from their destination node. On the contrary, uninformed users tend to spend more time searching for parking but they park closer to their final destination. For this reason, when the percentage of informed users is high, competition for a parking slot increases. This causes users to end up parking in areas farther away from their destination. Thus, the total distance travelled in the system increases.

In addition, the distance travelled does not vary for transit users as, even though their travel time may increase, their route and distance travelled remain constant. Regarding users who seek for parking, when they fail to find a vacant slot, the travel distance increases due to the need for route change and additional cruising for parking.

Third, the delay time represents the time that passes between the vehicle waiting at the end of the queue and it leaving the departure line. This value increases with the percentage of uninformed users. The delay time of 100% informed users, 58.1 sec/km, is almost half that of 20% informed users at 107.1 sec/km.

Fourth, contrary to the distance travelled, when the percentage of uninformed users is higher, travel time increases for both transit and parking users. Regarding those users searching for parking, the travel time is 65% lower for the highest percentage of informed users, at 0.55 sec/km, as compared to 20% of the informed users, at 1.6 sec/km. In addition, regarding transit users, their travel time is 30% higher for 20% of informed users compared to 100% of informed users. Thus, the degree of information of users can considerably impact transit traffic.

Finally, as in the previous, the model only estimates the evolution of fuel consumed by transit vehicles in the system. For this reason, the percentage change of each scenario in fuel consumption and generation of PM and CO_2 emissions are not proportional. Both parameters decrease with the percentage of informed users. These parameters are highly related to the delay time and the number of vehicles in the network, an aspect that will be explained further.

The following table contains several model results for each of the percentages of informed users previously analysed. Within these user information levels, the table also shows the results for informed and uninformed users. These results help in the analysis of the variations of parameters for the different types of users. The variables included in the table are the following: (i) the distance travelled by users before finding a vacant parking slot, (ii) the distance walked by users from the parking slot to their destination, (iii) the number of parking attempts, (iv) the parking slot search time and (v) the percentage of users who end up parking in an off-street parking slot.

% info	20		40	
User type	informed	not_informed	informed	not_informed
Distance travelled	628.2	1175.6	643.8	1293.2

Distance between nodes	190.6	130.4	186.4	125.7
Parking attempts	0.9	3.5	0.9	3.9
Search time	4.3	8.6	3.3	7
Off-street Parking	36.1	20.1	31.5	16.5

% info	60		80		100
User type	Informed	not_informed	informed	not_informed	informed
Distance traveled	656.5	1282.9	654.6	1297.1	696.9
Distance between nodes	180.3	123.4	170.6	123.7	166.9
Parking attempts	1	3.8	1.1	3.9	1.2
Search time	3.4	6.8	2.8	5.6	2.7
Off-street Parking	33.6	14.7	30.7	10.2	31

Table 8. Model results based on percentage of informed users

In relation to the distance travelled, on one hand, as mentioned above, the distance travelled increases with the percentage of informed users in the system. On the other hand, in each of the situations analysed, the distance travelled by informed users is lower than the distance travelled by uninformed users. This may be due to the fact that informed users have information about the location of available parking slots. As well, it may be related to the number of parking attemps while cruising for parking, which is higher for uninformed users. Thus, informed users travel a shorter distance than uninformed users while cruising for parking.

Concerning the distance between nodes, in all the scenarios this parameter is higher for informed users than uninformed users. It can be concluded that informed users are more prone to park in peripherical parking areas, farther away from their destination node. Hence, they walk a longer distance to their destination. Informed users are more influenced by the paying rate than the distance to their destination. On the contrary, the distance between nodes decreases with the increase in the percentage of informed users in the system. This can be a result of a better spatial distribution of parking slots among users when there is a higher percentage of informed users in the system.

Furthermore, concerning the number of parking attempts, this parameter is approximately triple for uninformed users compared to informed users in all the scenarios.

Informed users perform approximately one parking attempt, while uninformed users perform around four parking attempts. This indicator is highly related to the travel time indicator shown above, where the travel time for the lowest percentage of informed users is almost triple that of 100% informed users. On the contrary, it should also be noted that, the higher the percentage of informed users in the system, the higher the number of parking attempts. This may be due to the fact that, as explained above, informed users have information about the location of available parking slots. Thus, the competition increases when the percentage of informed users is higher. Accordingly, the number of parking attempts increases with the percentage of informed users.

In relation to the parking search time, this parameter decreases when the percentage of informed users increases. This may be a result of the improvement in traffic fluency and decrease in vehicle density when the percentage of informed users is higher. Also, in all situations, the search time is always higher for uninformed users than for informed users as informed users know about the location of vacant slots. In addition, these values are coherent with the results obtained for the number of parking attempts, which increase with the percentage of uninformed users as the searching time increases. This is due to additional cruising to look for parking when they fail to find a vacant slot.

Regarding off-street parking, on one hand, in the situations where there is a high percentage of informed users, the ratio of users that end up parking in an off-street parking is lower. On the other hand, informed users tend to end up parking in an off-street parking more than uninformed users. This is due to the fact that informed users tend to park further away from their final destination and thus tend to park in private and off-street parking slots.

7.1 Effect on parking conditions

Number of vehicles searching for parking

Another indicator obtained from the model is the number of vehicles seeking parking over a period of time in the area of analysis. From Figure 24 ,it can be observed that the number of vehicles increases over time in almost all cases. However, when the percentage of informed users is low, the number of vehicles in the system increases significantly at the beginning and peaks approximately 30 minutes into the simulation. Subsequently, the number of vehicles in the network begins to decrease. This is due to the fact that, as mentioned in the previous section, when the ratio of uninformed users is higher (20% of the informed users), the parking search time increases. Therefore, there is an accumulation of users in the system over time. However, due to the increase in the availability of parking in the area, after approximately 40 minutes, the curb time starts to decrease considerably. This will be explained later, in the explanation of the Figure 26. Searching time evolutionabout searching time evolution. For this reason, regarding the situation of 20% informed users, once the availability of parking slots starts to increase, the accumulation of vehicles in the systems decreases.

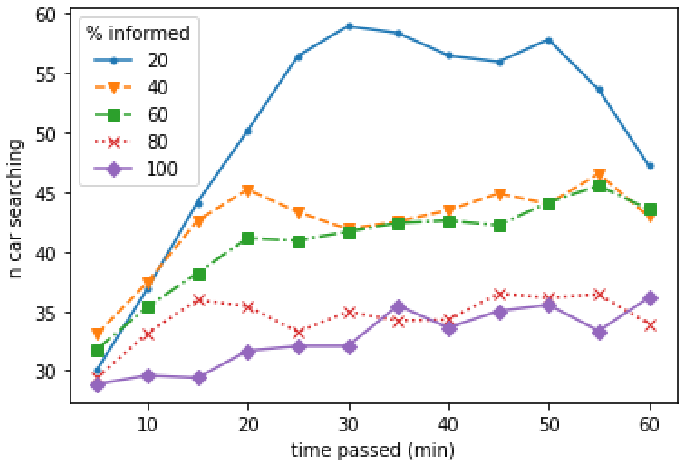

Figure 24. Evolution of number of vehicles searching for parking

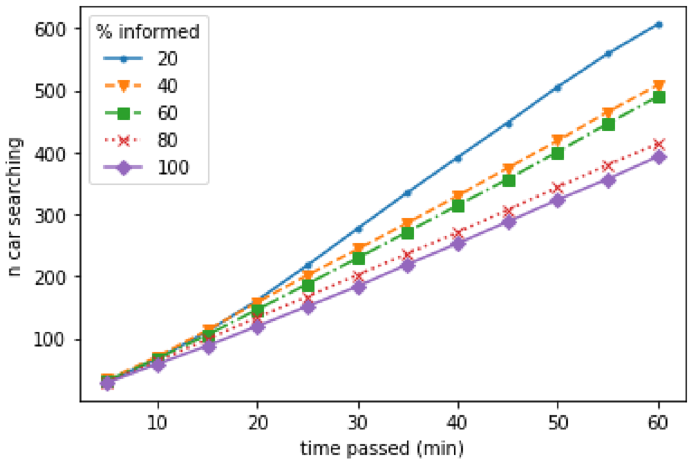

Figure 25. Cumulated evolution of number of vehicles searching for parking

Searching time evolution

As shown in the following graph, curb time varies considerably depending on the percentage of informed users. For example, at the 15-minute mark, the curb time for the scenario of 20% informed users is around 9.5 minutes, while curb time in the scenario of 100% informed users is 2.5. Thus, there is a reduction of up to a maximum of almost 75% in the search time for available parking slots. Additionally, in most cases, from approximately the 40-minute mark onwards, the curb time starts to decrease considerably due to the increase in the availability of parking in the area. For the situation of 20% informed users, the curb time reduces from 9 to 3.5 minutes (a 60% reduction) once the parking problem is solved.

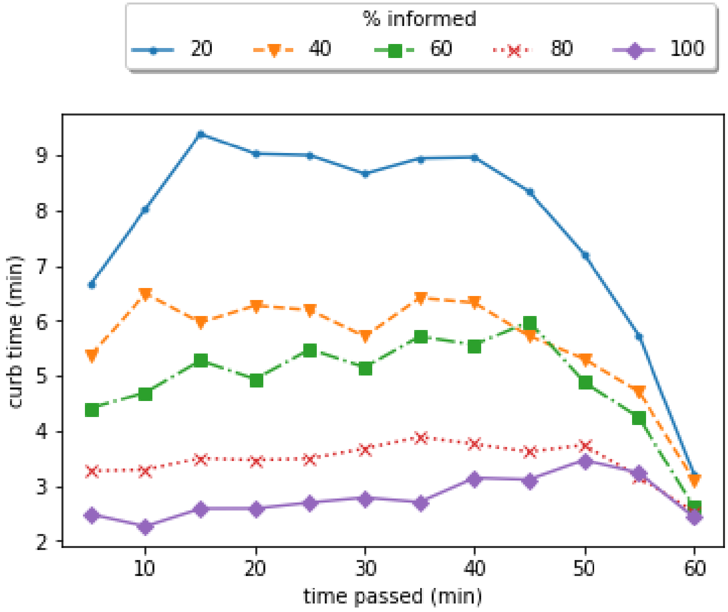

Figure 26. Searching time evolution

7.2 Evolution of generation of emissions

The following graphs show the evolution of the emissions of four vehicle pollutants over time: CO2, PM, VOC and NOX. From these graphs, it can be observed that the evolution of emissions is similar in all cases. The generation of emissions is proportional to the number of vehicles in the network. For this reason, the generation of emissions follows a similar evolution to that shown in the graphs above regarding the number of vehicles in the system. Regarding the scenario of 20% informed users, the generation of emissions increases to its maximum approximately at the 25-minute mark, when the number of vehicles is also maximum. Additionally, the graphs show the relation between the generation of emissions and the percentage of informed users in the network, i.e., the higher the percentage of informed users, the lower the generation of emissions. For example, the NOX emissions graph shows that for the scenario of 20% informed users, the maximum generation of emissions is approximately 73 g, while for the scenario of 100% informed users, the maximum generation of emissions is 55 g. Thus, the increase in the percentage of informed users results in a reduction in emissions by up to a maximum of 25%.

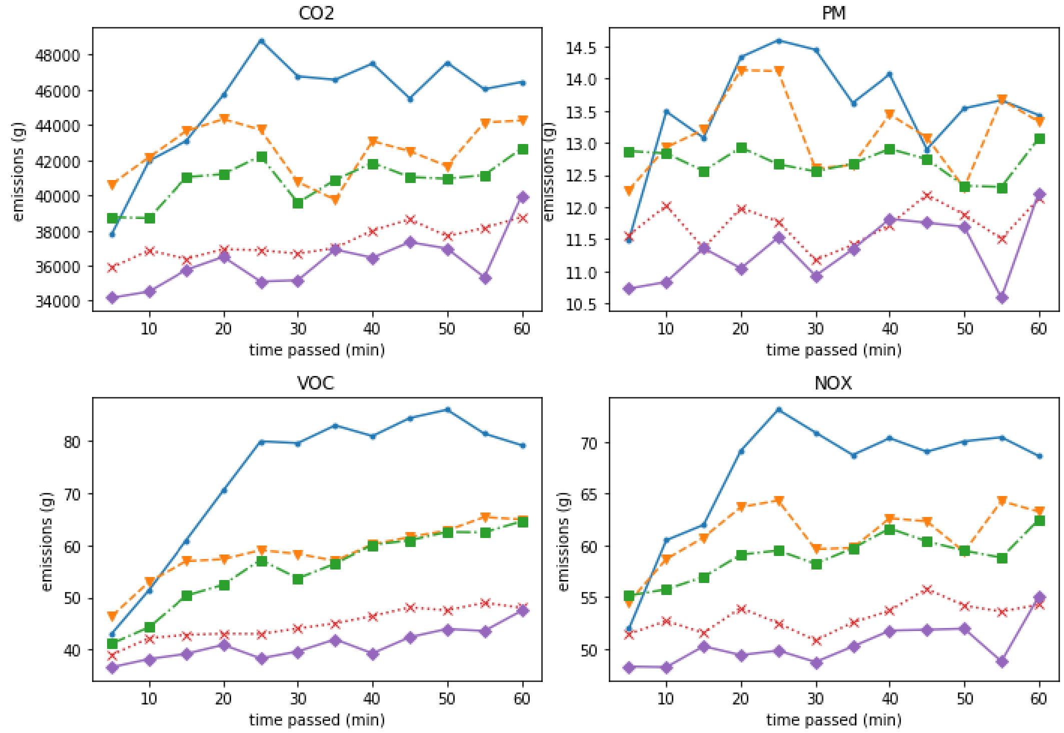

Figure 27. Evolution of generation of emissions

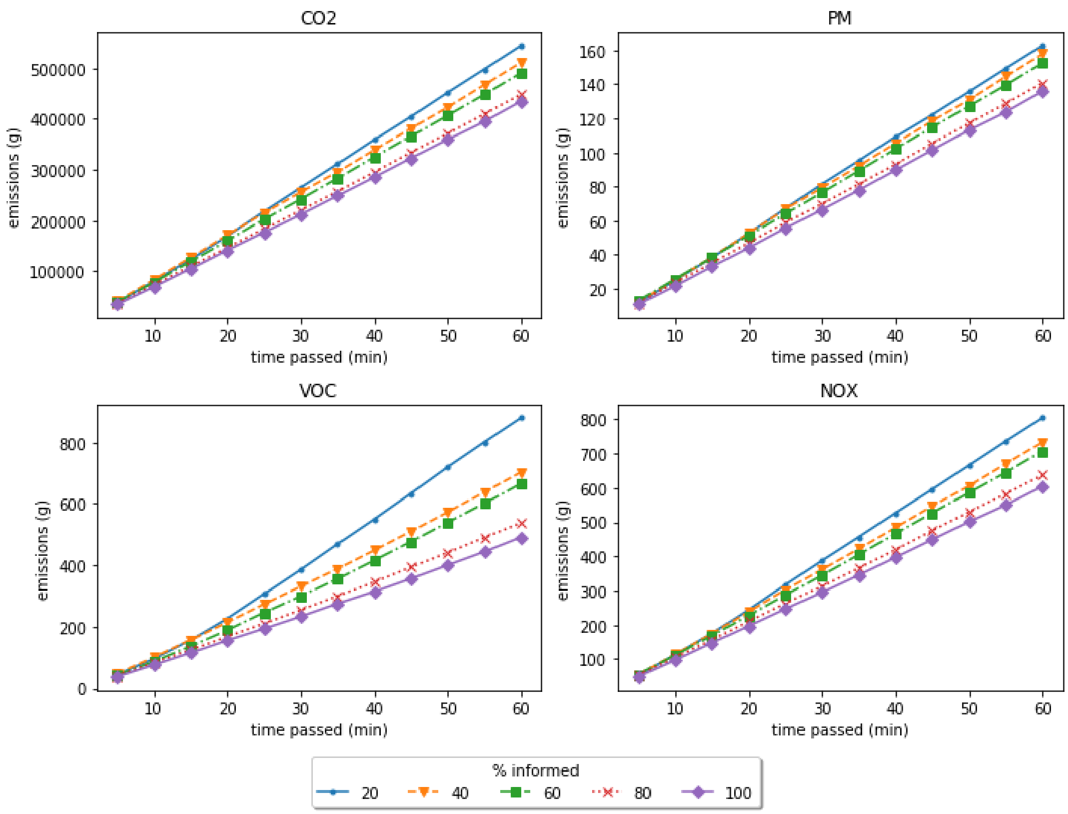

Figure 28. Cumulated evolution of generation of emissions

7.3 Parking occupancy rate

As shown in the following graph, the occupancy indicator is generally reduced over time. In all cases, the occupancy status is very close to 100% due to the short simulation period analysed. Thus, no evident relation between the parking occupancy and the percentage of informed users can be concluded from the graph.

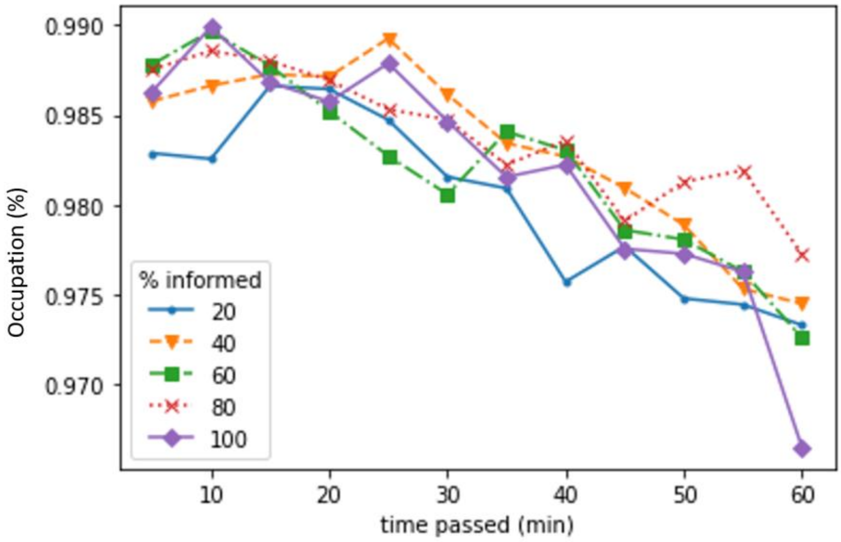

Figure 29. Evolution of occupancy rate

In conclusion, the parameters analysed above demonstrate the advantage of promoting the use of parking applications. Through the promotion of the use of applications by all users, search time may be reduced by up to a maximum of 75%. In addition, the generation of emissions can be reduced by up to a maximum of 25%. This can be possibly explained by an improvement in the efficiency of the system and a better spatial distribution of parking slots among users when the percentage of informed users is higher. However, it should also be noted that, as explained above, informed users park farther from their destinations than uninformed users. For this reason, travel costs must also take into consideration the increase in walking time from the parking location to the destination.

8 Relevance and scope of the simulation of parking policies

The aim of the current study was to explore and evaluate different parking measures for surface parking in urban areas. To this end, a microsimulation model was implemented using the software Aimsun to simulate different parking policies. An important contribution of this study is the analysis of the effect of implementing a restriction on the parking length of stay and the comparison between the impact of implementing a dynamic and a static paying rate system. This analysis demonstrates the advantages of implementing a parking time limit restriction, as well as those of a dynamic rate system in comparison to a static one.

As predicted in the initial hypothesis, the results obtained in this study concluded that the dynamic rate system with parking time restriction policy is the one that is able to generate a lower impact on traffic and the environment.

Regarding the impact on traffic and parking conditions, it has been observed that the dynamic rate system has a higher impact when the parking length of stay is limited. This may due to the fact that the time limitation policy avoids the accumulation of vehicles, which results in lower parking occupancy rates and search times for users. Contrary to the static rate policy, the implementation of the dynamic rate with a two-hour time limitation policy allows a decrease in the number of vehicles simultaneously searching for parking by up to a maximum of 20%. It also allows a decrease in the search time of vehicles by up to a maximum of 75%. In addition, it was concluded that the simulation of parking policies during a longer period of time provides a system that is more efficient in the long term.

Concerning the impact on the environment, the policy that generates the lowest amount of emissions and therefore the most favourable policy is the dynamic rate system with a two-hour time limitation policy. The implementation of this policy allows a reduction in the generation of emissions by up to a maximum of 30% and diminishes fuel consumption by 6.8%.

Another important contribution of the current study is the development of a sensitivity analysis based on the degree of informed users in the system. This analysis reveals the impact of promoting the use of parking applications for parking search and payment. On the one hand, as initially predicted, it was observed that the parking search time decreases when the percentage of informed users increases. It was concluded that the use of parking applications may reduce search time by up to a maximum of 75%. This might be a result of the improvement in traffic fluency and a decrease in vehicle density when the percentage of informed users is higher. In addition, fuel consumption and generation of emissions decrease when the percentage of informed users is higher. For 100% of informed users, there was a 25% reduction in emissions for the simulation period analysed compared to 20% of informed users.

On the other hand, contrary to the initial hypothesis, the distance travelled increases when the percentage of informed users is high. Regarding users searching for parking, the total distance travelled increased by 15% for the situation of 100% informed users compared to 20% informed users. The introduction of parking search and booking applications increases competition to find a vacant parking slot, as most users are aware of their location. Besides, informed users tend to park farther away from their destination node. This results in a higher distance travelled in the system when there is a high proportion of informed users. It can be concluded that the promotion of parking applications creates a more efficient system (as parking search time and emissions are reduced) with a better spatial distribution of parking slots among all users as the total distance travelled increases due to the fact that informed users tend to park farther from their destinations.

Other results obtained from the sensitivity analysis are as follows:

- Informed users are more influenced by the paying rate than the distance to their destination. The 'distance between nodes' parameter is higher for informed users than uninformed users in all the scenarios. Hence, it was concluded that informed users park in peripherical parking areas, farther away from their destination node. In addition, informed users tend to opt for off-street parking more than uninformed users.
- The travel time of transit users is 30% higher for the situation of 20% of informed users compared to 100% of informed users. Thus, the use of a parking application may not

only impact parking users, but it also may considerably reduce travel time for transit users.

- The number of parking attempts is approximately triple for uninformed users compared to informed users.
- However, the higher the percentage of informed users in the system, the higher is the number of parking attempts. When the percentage of informed users is higher, there is an increase in the competition in finding a vacant parking slot. This results in an increase in the number of parking attempts.

Although it has been demonstrated that the use of parking applications increases the efficiency of the system, as it promotes a better spatial distribution of parking slots among users, it should be noted that informed users park farther from their destinations than uninformed users. In order to better quantify the effect of the use of parking applications, the analysis of total travel costs should also take into consideration the increase in distance travelled and walking time from the parking location to the destination.

9 Conclusion

The current study was initiated by conducting a description of examples of existing parking policies, parking simulation models and parking management technologies. The state-of-the-art review, especially regarding the examples of existing parking policies, led the current study to focus on the effect of different parking policies on various traffic and pollution indicators. The analysis was particularly based on comparisons of the impact of the main parking policies discussed, which included the static and dynamic pricing and the limitation of parking length of stay. To sum up, the state-of-the-art study regarding recent parking management technologies for parking search and payment promoted this study to evaluate the impact of the use of phone applications for parking search and payment on various parking conditions and pollution indicators. The current study conducted a sensitivity analysis of the introduction at different levels of parking applications. In addition, the state-of-the-art analysis of parking simulation models motivated this study to implement a spatially explicit agent-based parking behavioural model, named 'DYNAPARK', to simulate different parking policies. In comparison to other models, DYNAPARK allowed simulating the behaviour of users based on different preference variables, such as (i) pricing rate, (ii) parking type, (iii) occupancy and (iv) user's degree of information. It also allowed to introduce various paying rates to simulate based on real-time occupancy data.

Nonetheless, this study encountered various limitations. The model used for the simulation of policies, DYNAPARK, simulated the behaviour of users when cruising for a vacant parking slot. The parameters of the model were estimated using parking users' declared preference surveys. For the obtention of model parameters, discrete choice models require the collection of a considerable amount of data. However, the number of declared preference surveys in the area of analysis was limited. In this regard, the capacity of the model to simulate the behaviour of users may be limited. This fact may be due to the potential low variability and correlation among the data obtained through the declared preference surveys.

Some factors in the area of study related to the interaction with other modes of transport are not taken into consideration. In August 2018, the City Council installed on-street escalators in the area of study. This promoted the mode shift of users to walking. Thus, reducing the demand for parking in the area. Also, a car-sharing program has been recently implemented in the area by the company Guppy. This has caused a slight reduction in parking demand and various car parking spaces have been allocated to electric vehicles. These factors are not considered in the current analysis and could alter the results obtained. These factors should be considered in future research. Furthermore, another phenomenon observed in the area is the illegal use of regulated car parking spaces by motorcycles. Although this phenomenon could also alter the results obtained in this study, in order to consider this phenomenon in the model, the use of the car parking spaces by motorcycles should be regulated.

Another limitation of the study is the fact that the model does not take into consideration the parking stay length for the calculation of the parking fee as part of the utility function. Although the parking type and section choice could vary depending on the desired parking stay length of each user, this factor has not been considered in this study as results from the declared preference survey in the area of analysis showed that its influence on parking choice was minimal. Also, the model does not take into consideration the capacity of other types of parking in the area of influence. Consequently, especially in four-hour simulation, the effect on parking conditions results show considerable fluctuations over time. As an example, the evolution of the parking search time in the four-hour simulation starts to greatly decrease after approximately the first hour, due to the decrease in the utility of the on-street parking alternative, and steeply increase after the second hour of simulation. It must be noted that this situation does not occur in a real-case scenario, as the model does not consider the limitation in the number of off-street parking slots and the influence of close free parking slots. Although this fact presents a limitation for the model, the underground parking in the area of influence is rarely fully occupied. For this reason, this limitation can be considered minor.

Regarding the sensitivity analysis, it was concluded that the use of parking applications increases the efficiency of the system. Informed users tend to park farther from their destinations, which results in a better spatial distribution of parking slots among all users.

However, it should also be noted that in order to better quantify the effect of the use of parking applications, the analysis of total travel costs should also take into consideration the increase in walking time from the parking location to the destination. This fact can be considered as a potential line of research.

Additionally, due to the limited simulation capacity, two short-period simulations, of one hour and four hours, were executed. This can be considered another limitation of the study, as longer simulation periods should better represent a real-case scenario. This fact can also be considered in future research.

Finally, the parking model is not able to simulate an elastic parking demand. Thus, the parking demand always remains static. Although the parking demand is allocated among the different types of parking, based on their utility, the origin-destination demand matrix that is introduced in the model does not vary. Hence, the demand is independent of the dynamic parking rate. Therefore, the model is focused on managing a specific demand, but not on performing comprehensive demand management. A potential research line can be the integration of the current model into a comprehensive demand management model through the consideration of macrosimulation and model variations.

Regarding the knowledge adquired during the double-degree diploma at the University of Cantabria and the École Nationale des Ponts et Chaussées, this study has allowed me to apply several of the learning to a real case study. Some of the knowledge applied in this study is outlined below.

Several of the aspects learnt at the Traffic Engineering I and Traffic Engineering II courses, related to the theoretical basis of traffic engineering, have been used for the microsimulation carried out in Aimsun.

Likewise, some of the courses taken during the degree have helped me understand and distinguish between the different levels of user movement simulation, mainly at macroscopic and microscopic level. As an example, the Méthodes d'analyse des systèmes territorial (MASYT) course project taught me to simulate the movement of users at a macroscopic level. In this study, I have used the simulation of users´ behavior at the microscopic level.

Also, general transport-related knowledge acquired during the diploma, such as demand and supply in terms of transport engineering, as well as its configuration (Origin-Destination matrix), have been useful for the analysis carried out in the present study and its introduction in Aimsun.

Additionally, statistics courses taken at both universities have allowed me understand and apply the methodology used by the Dynapark model for the estimation of the utility function of each parking type and section through the use of the multinomial logit model. As well as to obtain the input parameters of the model through the use of the maximum likelihood method.

Other courses, such as Transit Lab, have allowed me to understand and apply the different parts of the Dynapark model code introduced in the API of Aimsun.

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