THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Using digitalisation for data-driven freight curbside management

A perspective from urban transport planning

JUAN PABLO CASTRELLON

Department of Technology Management and Economics
Division of Service Management and Logistics
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2023

Using digitalisation for data-driven freight curbside management
A perspective from urban transport planning

JUAN PABLO CASTRELLON

Technical report no L2023:150

Division of Service Management and Logistics
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone + 46 (0)70-148 7231

Printed by Chalmers Digital Print
Gothenburg, Sweden 2023

Using digitalisation for data-driven freight curbside management
A perspective from urban transport planning

Juan Pablo Castrellon
Division of Service Management and Logistics
Department of Technology Management and Economics
Chalmers University of Technology

Abstract

Given trends in urbanisation, e-commerce, active mobility and modal shifts, streets have sprung up as scenes of conflict where competing demands for curbside space have increased. Because public space is limited, urban transport planners are called to solve public space conflicts by defining how much space is allocated to specific users as a means to achieve sustainable cities. In the allocation of curbside space, freight parking operations are sometimes overlooked compared to other curbside uses such as private vehicles parking. However, limited space for freight deliveries generates negative impacts on urban traffic (e.g. due to double parking), as well as on emissions and companies' efficiency (e.g. due to the need to cruise for parking). This thesis aims to contribute to current understandings of the need for and uses of data to inform curbside management decision-making for freight parking from the perspective of urban transport planning. To that end, a case study was conducted to collect and analyse data about freight curbside operations using quantitative and qualitative methods, and a cross-sectional research design facilitated the exploration of the impacts of curbside interventions on cities' sustainability worldwide.

This study revealed four major factors for implementing flexible curbside management: (1) data sharing, (2) an understanding of parking durations, (3) dynamic regulations of curbside use and (4) enforcement capabilities. Machine learning tools supported prescriptive and predictive models aimed at supplying curbside space for freight operations following time-varying regulations based on the stochastic behaviour of parking demand. The variability of parking demand was modelled using big data representing parking operations in loading zones from the case study. Regarding freight parking demand, the research involved reviewing the significant variables and modelling methods used when establishments data are available. Probed data about parking operations, when inputted into explanatory assessments of parking durations, showed that the type of commodity, vehicle size and the hour of the day are significant factors in estimating parking durations. Context-related variables were also assessed (e.g. location, feels like temperature and precipitations), that are fundamental for flexible curbside management. Reflections on managerial implications of curbside digitalisation revealed challenges such as the need for data analytics, collaboration among stakeholders and interoperable parking systems. Last, a systematic literature review showed the extent to which curbside interventions positively support the achievement of the United Nations' Sustainable Development Goals.

The contribution of this thesis is twofold. First, it proposes a conceptual approach to studying freight curbside management from the perspective of urban transport planning. The approach is built on factors that determine curbside supply and demand for freight parking operations. Second, it identifies data-intensive needs and explores the use of data via data analytics to inform freight curbside management and its potential impacts on certain Sustainable Development Goals. Outcomes from the research stand to support urban transport planners in de-conflicting the curb via data-driven regulations, flexible curbside management and enhanced strategic, tactical and operational decisions.

Keywords: curbside management, urban freight transport, loading zone, digitalisation, freight parking, urban transport planning, data analytics, last-mile delivery

List of appended papers

Paper I

Castrellon, J.P., Sanchez-Diaz, I. and Gil, J. (2023), 'Smart loading zones. A data analytics approach for infrastructure network design in freight curbside management'.

The paper has been submitted for publication to an international journal. An earlier version of the paper was peer-reviewed and presented in a lectern session of the 101st Transportation Research Board Annual Meeting, 9–13 January 2022, Washington, DC, USA.

Paper II

Castrellon, J.P., Sanchez-Diaz, I. and Kalahasthi, L. (2022) 'Enabling factors and durations data analytics for dynamic freight parking limits'. *Transportation Research Record*. https://doi.org/10.1177/03611981221115086

An earlier version of the paper was peer-reviewed and presented in a poster session of the 102nd Transportation Research Board Annual Meeting, 8–12 January 2023, Washington, DC, USA.

Paper III

Sanchez-Diaz, I. and Castrellon, J.P. (2023) 'Freight trip generation models: using establishments data to understand the origin of urban freight traffic'. Book chapter in Marcucci, E., Gatta, V., Le Pira, M., *Handbook on City Logistics and Urban Freight*. Edward Elgar (in production).

Paper IV

Castrellon, J.P. and Sanchez-Diaz, I. (2022) 'Uncovering freight curbside management effects on cities' sustainable development goals: A systematic literature review'.

The paper has been submitted for publication to an international journal. An earlier version of the paper was peer-reviewed and presented at the Transport Research Arena Conference, 14–17 November 2022, Lisbon, Portugal.

To my godsons Juan Nicolás,
Juan Pablo and Juan Felipe.

Acknowledgements

Si el tiempo no brinda las condiciones (...), la vida abraza todas las limitaciones
y se abre paso triunfante para albergar un destino en sus entrañas
Pablo I. Galvis D.
in "Atizando el fuego de la paz. Diarios de un bibliotecario en el Caguán"

I have gone through half of my doctoral studies journey. Looking back to the moment I was admitted to the Department of Technology Management and Economics, my idea of conducting PhD studies was not as exciting as what I have experienced during the past 2.5 years. Despite being far from my family and friends, and the unnormal conditions imposed by a pandemic, the process has left only positive outcomes in a journey full of new learnings, friends, and deep self-knowledge. Nonetheless, I am aware also of how some limitations have hampered my process and that without the help of people who supported me, I would not have been able to get to the stage I am now.

I am grateful to all the organisations that have made this research possible. Thanks to the Chalmers University of Technology, Vinnova, and the Volvo Research and Educational Foundations (VREF) through the Urban Freight Platform (UFP) for funding my studies. I want to acknowledge the UFP team conducting the project titled "Using Data Analytics for Smart Loading Zones Management in Cities", the interviewees, and the case study participants, especially Joana Rodríguez from the City of Vic (Spain) and Carles Sentís and Simon Hayes from Parkunload, who were always open to sharing data and having fruitful discussions about curbside management.

I am also grateful to all my colleagues from the Division of Service Management and Logistics who, even before my arrival, have not skimped on resources and support for a smooth landing on my new life and the provision of proper conditions for my development. I would especially like to thank Ivan Sanchez-Diaz, my main supervisor, for his guidance and friendship. His knowledge, experience, and extraordinary human qualities are assets he has offered with generosity, which I very much appreciate. Thanks to Michael Browne and Lokesh Kalahasthi, who have been part of my supervision team, and whose advice and mentorship have been enlightening at the different stages of my process. I want to thank Violeta Roso, Ceren Altuntas-Vural, and our colleagues from SSPA, Sara and Vendela, for being great research mates and involving me in a project whose results have been enhanced by synergies with industry, complementary research perspectives and coordinated teamwork.

My family and friends have also made possible a pleasant stay in Sweden and, with it, the steady progress of my studies. Thank you to Ivan, Nico, Diana, Angie, and Vane for keeping me emotionally healthy and connected to Colombia through the traditional food we share and the fantastic nights of *vallenato chévere, vallenato del alma*. Thanks to the wonderful visitors who have cheered me up and given me lots of energy, and of course, have been the perfect company during my vacation trips. I keep in my heart great memories from the visit of my grandmother Amparo, my parents María and Vladimir, my uncle Leo, Wuendy, and some of my life friends: Rafa, Nataly, Laurita, Alvarito, Daniela, the Adarme-Mejía family, Cifu, Ivan, Edna, Cata and Dayron, who have also been enchanted by the Nordic nature and the beauty of the European cities. Thank you all for coming and motivating me every day to keep going.

I want to mention the vital support of people I have met during my stay in Sweden, who have provided the perfect complement to student life. Thanks to my officemate Daniel for his always fine sense of humour and great company, to Caro for showing me that PhDs can be fun, to Tarun for our Fika talks and reflections about academic life and to all the colleagues and friends who have been part of this process: the Luengo-Hurtado family, Ara, Travis, Tess, Hannes, and many more. Thank you all for your friendship and fun moments.

Finally, I extend my gratitude to all my family, friends, and former students who have been permanently in contact with me from Colombia, always sending positive energy and irradiating my days with optimism and hope. All my gratitude to the Universidad Nacional de Colombia for being the door to this and previous opportunities.

I am very excited about the way ahead, the experiences to come, the research to be done, and the people to thank. For these reasons, I am looking forward to the next step in these doctoral studies.

Juan Pablo Castrellon,
Gothenburg, January 2023.

Table of contents

List of figures

List of tables

Abbreviations

CR	Critical realism
FTG	Freight trip generation
GPS	Global Positioning System
ICT	Information and communications technology
KPI	Key performance indicator
LZ	Loading zone
ML	Machine learning
OECD	Organisation for Economic Co-operation and Development
ROW	Right-of-way
RQ	Research question
SDG	Sustainable Development Goal
SLZ	Smart loading zone
UFT	Urban freight transport
UN	United Nations

1. Introduction

This introductory chapter presents challenges in managing public space for freight operations in urban areas. It addresses the background and problematisation that inspired the aim, scope and research questions (RQs) of the research conducted for this thesis. The chapter concludes by describing the thesis's structure and its intended audience.

1.1. Background

Urban public space is a valuable and scarce resource with proven impacts on citizens' quality of life (Beck, 2009). Urban public space takes the form of green parks where people walk and children play; it provides transport corridors that people use to move from one place to another; it attracts people to commercial areas via pedestrianised alleyways; it serves as a parking facility for private vehicles; and it acts as a platform for loading, unloading and delivering goods/services. Because all that urban public space provides has environmental, social and economic value for cities, its management is a cornerstone of cities' sustainable development (Emanuel, Schipper and Oldenziel, 2020).

The densification of cities and modal choices excessively biased towards the use of private cars have made public space scarce and its management a contentious matter when deciding its uses. Competition for space has compelled urban planners to define priorities among different users so that the supply of space satisfies demands with the greatest priority. Such provision of public space is physical evidence of an urban dialogue among citizens, businesses and urban planners that, however, sometimes is selective or even disregarded (Smith, 2020). To prevent those outcomes, urban planners need to ensure that their prioritisation of public space does not depend on how loud a user shouts for space but on carefully designed plans based on an understanding of the demand for different users and the impacts of specific uses on social, economic and environmental aspects (Central London Freight Quality Partnership, 2021).

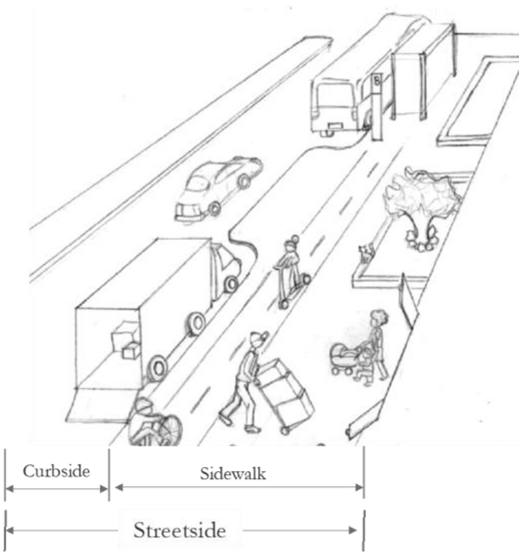

Figure 1. Curbside and sidewalk public space
(Artwork by Diana Aguilar)

At the centre of that discussion are streets, which not only account for more than 80% of cities' public space—that is, approximately 25% of their surface area (Rodriguez-Valencia, 2014)—but are also the scene of hostile interactions among users, at least somewhat due to the unfair distribution of space. Streets have indeed sprung up as "scenes of conflict" (Sanders, Zuidgeest and Geurs, 2015) where competing demands for both curbside and sidewalk space—hereafter, "streetside space" (see Figure

1)—coexist in time and place. Because streetside space is limited, cities are called to solve public space conflicts by defining how much streetside space is supplied at any given location and when it can be used by specific users, all in an effort to achieve urban sustainability (Thayne and Andersen, 2017).

Despite its local scope, equilibrating the supply of and demand for public space is a matter of international relevance. The United Nations (UN) has included explicit reference to public space actions in one of the 17 Sustainable Development Goals (SDGs), i.e. SDG11, which envisions "Sustainable cities and communities, to promote policies and actions that leverage universal access to safe, inclusive, and green public spaces" (UN, 2017). SDG11 measures the effectiveness of managing competing demands for public space for uses that respond to human needs for social interaction, mobility, access to supplies, activation activities and a healthy environment. Emanuel, Schipper and Oldenziel (2020) have paraphrased the UN's definition of *sustainable development* as involving the fair allocation of urban space, whereby "one person's mobility does not come at the expense of another's mobility in the present or future generations".

Citizens' needs for streetside space can be either direct or derived. *Direct needs* refer to the occupation of space by activities that citizens perform, including forms of mobility (e.g. walking and cycling), parking private vehicles, using stations for public transport and enjoying open spaces. *Derived needs* refer to freight transport operations that occupy public space on behalf of citizens who demand the goods that freight vehicles deliver.

In supplying space to satisfy those demands, urban planners define priorities in the use of streetside space that are more beneficial to citizens' direct needs and thus ignore or deprioritise their derived uses of public space. For instance, though commercial establishments are part of streets' activation strategies, little attention has been paid to their demands for public space for freight parking and last-mile deliveries (Al-Turjman and Malekloo, 2019). Likewise, though home deliveries are part of consumer trends accelerated by the COVID-19 pandemic and have enabled fair access to goods and services (Sanchez-Diaz, Altuntas Vural and Halldórsson, 2021), the scope of policies has been limited in addressing the requirements of freight parking infrastructure to avoid traffic conflicts in neighbourhoods (Baudel *et al.*, 2016; Macário, 2021).

Although derived uses are nearly invisible in the prioritisation of the supply of space, their negative externalities are quite visible in terms of emissions, congestion, accidentality, and obstructions. For instance, freight transportation represents 20% to 30% of the total traffic in cities yet accounts for up to 60% of transport-related CO_2 and particulate matter (PM) emissions (Dablanc, 2007). Cruising (i.e. searching for parking) is one of the most common practices when the allocating curbside space for freight is scarce. Shoup (2011) has estimated that cruising contributes to more than 30% of traffic in central business districts, while Lopez *et al.* (2016) found that cruising occurs in 70% to 80% of the last-mile deliveries in European cities. The lack of curbside space for freight operations also precipitates the illegal use of public space (e.g. double parking or parking in banned zones). Kawamura *et al.* (2014) found that double parking is the third-most important cause of non-recurrent traffic congestion, namely after construction projects and crashes. Besides emissions and traffic, the unsustainable effects of freight operations also include noise and the intimidation of users of public space due to the size of freight vehicles and risks to their personal safety.

Providing curbside space for freight parking is becoming critical, majorly, because the demand for goods in urban areas has intensified amid trends such as e-commerce and because freight vehicles typically try to park as close as possible to the delivery location. The time that a freight vehicle is parked on urban streets represents more than 40% of the time that it spends in last-mile operations (Sanchez-Diaz *et al.*,

2020) and even up to 80% in some contexts (Fransoo, Cedillo-Campos and Gámez-Pérez, 2022). Given that freight vehicles need to meet citizens' demands for goods and services, limited or non-existent space for freight parking negatively affects urban traffic and emissions due to unintended practices such as cruising and double parking. By extension, Mingardo, van Wee and Rye (2015) have stressed that limited space for freight parking and its misuse (e.g. double-parking) are among the chief threats to the sustainability of cities.

Several cities worldwide have implemented policies to reduce the negative impacts of freight transport. Comi, Moura and Ezquerro (2022) have argued that the provision of curbside space for freight parking operations, ideally with loading zones (LZs), ranks among the most promising tools for reducing the negative impacts of last-mile deliveries in urban areas. Manzano Dos Santos E, and Sanchez-Díaz I. (2016) found that parking is the main obstacle for efficient urban freight transport from the carriers' perspective. In a survey conducted by Holguín-Veras *et al.* (2020), 17 of the 56 cities surveyed had implemented LZ-related initiatives as part of their mobility plans. In the same survey, practitioners, freight companies and society at large praised the initiative as an effective solution for problems with urban mobility. In Europe in particular, de Marco, Mangano and Zenezini (2017) found that 24 of the 70 European cities considered in their study had implemented LZ-oriented initiatives. Nonetheless, their implementation has been challenged by limitations in the knowledge and tools available for achieving equilibration between the supply of and demand for LZs—that is, freight curbside management.

1.2. Problem analysis

Freight curbside management is an emerging but promising field of research given current challenges in the distribution of space and the need to manage interactions between users of current and future forms of mobility (e.g. autonomous vehicles, delivery robots and electric trucks). Freight curbside management is also relevant for companies that urge the design of more efficient last-mile deliveries, which represent up to 75% of total logistics costs (Gevaers, van de Voorde and Vanelslander, 2011). For that reason, in transport research, the perspective of private companies has dominated, with contributions that quantify savings in terms of the cost and delivery time of curbside interventions. By contrast, little research has been conducted from the perspective of city planning that could nevertheless provide tools and insights for urban planners that inform better decision-making regarding freight curbside management.

In architecture and urban planning, studies have promoted frameworks aimed at improving decisions about the distribution of space that have driven the shift from vehicle-centred to human-centred urban development (Rosenblum, Hudson and Ben-Joseph, 2020). In turn, such contributions (e.g. healthy streets, complete streets and flex zones) have influenced curbside management policies in several cities in Europe. In Paris, up to half of all on-street parking will be removed by 2025, and Amsterdam is currently removing 10,000 parking stalls in its city centre. Among others, Berlin is evaluating a car-free zone for the city centre with an area larger than Manhattan, while Stockholm is implementing a plan for dynamic curbside parking spaces.

Those mobility-oriented plans clearly focus on increasing space for human interactions, promoting modes of active transportation and mass transportation and, in turn, reducing congestion and pollution. Nonetheless, opposite outcomes occur when such policies overlook the distinct nature of the demands and modal choices of freight delivery compared with private car parking (Malik *et al.*, 2017), which can prompt the implementation of solutions that fail to meet freight delivery's demands and thus effect *curbside supply–demand imbalance*.

From a practical perspective, Ionita *et al.* (2018) have identified five sources of curbside supply–demand imbalance in freight parking operations: insufficient knowledge about parking demand, weak enforcement that spurs the incorrect use of LZs, the lack of monitoring of freight parking occupancy levels, the lack of differentiation between regulations for freight parking and private car parking and, last, the so-called *big-no data paradox*, meaning the non-existence of analytical practices after investments in parking technology that collects vast amounts of data. Thayne and Andersen (2017) have also reflected on the implications for sustainability of having curbside space with singular fixed purposes and, as a result, admitted that those practices have unwanted side effects because they ignore street dynamics over time.

From a theoretical perspective, and in line with the problem of limited knowledge about the demand for freight parking, Jaller *et al.* (2021) have highlighted that understanding and modelling freight transport's demand for curbside space is one of the most common challenges in freight curbside management for two major reasons: data scarcity and limitations in modelling techniques. On the one hand, demand for freight parking is usually estimated based on data representing stated preferences from surveys instead of probed data about parking operations (Allen, Browne and Cherrett, 2012; Muñuzuri *et al.*, 2017). However, the static nature of the data collected, mismatches between data representing stated preferences in surveys versus real-world behaviours, and aggregation and generalisation errors hinder the estimation of such demand (Sánchez-Díaz, 2017). On the other hand, modelling the demand has involved attempts to adapt approaches from private car parking without considering that freight parking is influenced by different factors, including economic activity, city zone and vehicle type (Schmid, Wang and Conway, 2018). Ignoring the stochastic behaviour of parking demand has also been underscored as a limitation of methods in past research (Jaller *et al.*, 2021).

Research has shown that theoretical and practical problems are at the root of the supply–demand imbalance in freight curbside management. Figure 2 presents the elements of the research problem in focus in this thesis—that is, the allocation of space and parking duration limits (i.e. supply)—as well as the data and methods used to estimate parking demand and perform the SDG impacts assessment when supply–demand equilibration is intended.

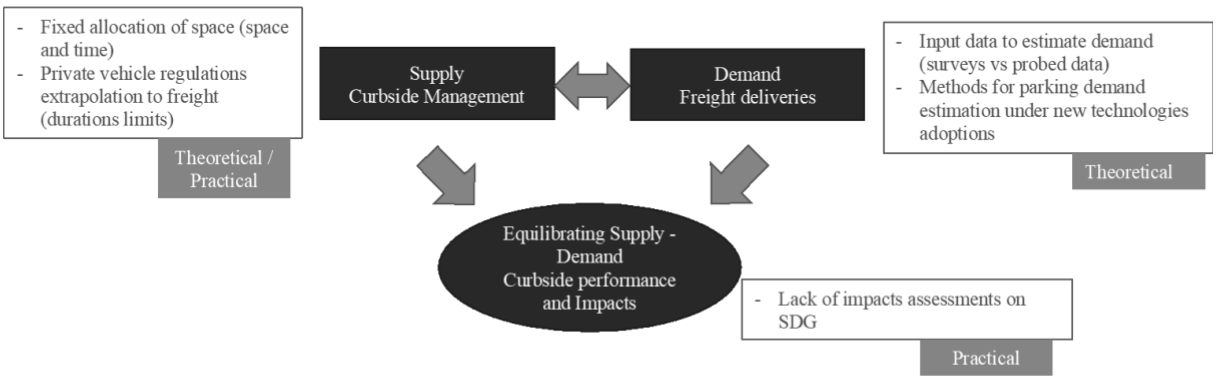

Figure 2. Practical and theoretical aspects of the research problem examined in the thesis

Regarding the allocation of space, research has focused on developing tools to improve the location of LZs, definitions of sizes, and service coverage (Aiura and Taniguchi, 2005; Dezi, Dondi and Sangiorgi, 2010; Alho *et al.*, 2018; Tamayo *et al.*, 2018; Letnik *et al.*, 2019; Muñuzuri, Alho and de Abreu e Silva, 2019; Pinto, Lagorio and Golini, 2019; Comi, Moura and Ezquerro, 2022). Such contributions have revealed how urban planners face dilemmas in choosing between various options for curbside use and allocating scarce space to satisfy the demands of freight delivery. The benefits of the space allocation for freight parking have been quantified in terms of time spent cruising for parking, traffic, delivery time and cost. However, few of those contributions have addressed the need for the flexible use of space so that excess infrastructure supply at specific time windows can be allocated to other users. Singular, static uses of the curbside allocated for freight may lead to overcapacity of infrastructure at specific times of the day or week at the expense of other users' needs for space.

Regarding parking durations, freight-focused studies have contributed to current understandings of the factors that influence such durations and LZ occupancy (Schmid, Wang and Conway, 2018; Low, Duygu Tekler and Cheah, 2020; Regal-Ludowieg, Sanchez-Diaz and Kalahasthi, 2022). The data sources for their causation analyses have mostly been surveys or censored data about the number of freight vehicles and their time spent on the curbside. However, data limitations in terms of the types of commodities delivered and types of vehicles from observations beyond specific pilot projects and reference companies continue to present a challenge to unlocking generalisable estimations of parking durations and, thus, designing improved regulations for freight parking operations.

In relation to estimating demand, econometric models are the prevailing method for modelling parking demand (Jaller, Holguín-Veras and Hodge, 2013; Gardrat and Serouge, 2016; Campbell *et al.*, 2018; Dalla Chiara and Goodchild, 2020). However, as pointed out by (Jaller *et al.*, 2021), such models present a major problem: the assumption of either static or deterministic demand. For that reason, it remains necessary to improve modelling for estimation parking demand by considering its stochastic nature.

Input data for estimating freight parking demand has also been the focus of several studies that have produced frameworks for data sharing and digital solutions in parking operations (McLeod and Cherrett, 2011; Patier *et al.*, 2014; Comi *et al.*, 2017; Mor, Speranza and Viegas, 2020). Most of these data sharing frameworks are based on booking systems that present problems with implementation due to drivers' unwillingness to use them and legal frameworks circumscribing the possibility of booking public space. Moreover, such implementations have been represented by pilot projects with specific companies and zones of cities, which has limited the generalisability of the results and data representativeness issues.

Last, although some studies have quantified the impacts of specific curbside management initiatives on metrics implicitly related to SDG11, there is a lack of comprehensive studies that have assessed the impact of different curbside interventions on the metrics for SDG11—that is, the average global share of urban space allocated to streets and open public spaces, the participation of civil society in urban planning and management, mean levels of fine Particulate Matter (PM) emissions and the development of urban public policies. That lack stems from the tendency of such studies to take the perspective of private operators, meaning that the public sector's perspective has not been widely considered in the study of curbside management.

Table 1 summarises the research problems, previous contributions and gaps in research regarding each component of freight curbside management. Given that curbside management is among the most promising initiatives for improving last-mile operations while lessening the negative impacts of freight transport on urban sustainability (Comi, Moura and Ezquerro, 2022), this thesis seeks to provide an understanding of the gaps in research shown in Table 1 and to contribute approaches for addressing them from the perspective of urban transport planning.

These approaches have curbside digitalisation as the backbone. The use of data provided by connected infrastructure and mobile devices afford the possibility of accessing variables not typically available to urban planners, including parking arrival and departure times by location, type of commodity and delivery vehicle. Such technology also enables access to probed data about freight parking operations, data which are expected to have more accurate estimates of demand than survey data, given the availability of population-based data instead of data from random samples. Although research has examined implementations of freight parking systems using such technology in several cities (Letnik, Mencinger and Peruš, 2020), data analytics and insights into data-driven decision-making in freight curbside management remain in an early stage of development (Comi *et al.*, 2017).

Table 1. Summary of gaps in research on freight curbside management

Component	Problem addressed	Scope of previous contributions	Gaps in research
Supply	Allocation of space	Location of LZs, definition of sizes, and service coverage (e.g. Comi, Moura and Ezquerro, 2022)	Lack of analytical tools for supporting flexible curbside management based on variabilities in the demand for space
	Freight parking regulations on parking durations	Models of private vehicle parking durations and analysis of factors influencing parking durations (e.g. Low, Duygu Tekler and Cheah, 2020)	Lack of tools for flexible regulations about parking durations that enable the dynamic use of space
Demand	Input data for estimating demand	Curbside digitalisation for freight parking—for example, booking or check-in systems and sensors (e.g. Yang *et al.*, 2019)	Limited understanding of factors that influence the demand for freight parking Lack of empirical knowledge about digitalisation's potential to improve freight parking operations
	Methods of estimating demand	Quantitative methods of modelling parking demand (e.g. Gardrat and Serouge, 2016)	Need for improved modelling for estimating parking demand that considers its stochastic nature based on automated data collection and analytics
Equilibrating supply and demand	SDG impacts assessment	Impact assessment of curbside interventions on emissions, cost, delivery time and parking violations, primarily from the private sector's perspective (e.g. Butrina *et al.*, 2017)	Limited quantification of the impact of curbside management initiatives on the achievement of SDGs Lack of contributions from the public sector perspective.

1.3. Aim and scope

This thesis aims to explore the different factors that determine curbside supply and demand for freight parking operations, as well as to contribute to current understandings of the need for and uses of data to inform curbside management decisions and their impacts on the achievement of relevant SDGs. Because the research conducted for this thesis focused on understanding that supply–demand dynamic, transport activities before parking and freight deliveries during parking (i.e. delivery on foot) were not considered. Although their study pertains to public space management (Kim, Goodchild and Boyle, 2021), data about those operations were limited during the research conducted for the licentiate phase of the author's doctoral study.

That said, the contribution of this thesis is twofold. First, it proposes a conceptual approach to studying freight curbside management from the perspective of urban transport planning. The approach is based on factors that determine curbside supply and demand for freight parking operations. Second, it identifies data-intensive needs and explores uses of data via data analytics to inform freight curbside management and identify its potential impacts on the achievement of SDGs. The results of the research stand to support public policies on curbside management to better accommodate the demands of freight delivery and make fairer decisions in allocating public space.

In curbside management, digitalisation is the vehicle that allows access to freight parking data (Comi, Schiraldi and Buttarazzi, 2018). Nonetheless, it is beyond this thesis's scope to assess available technology or business models that have sprung up around digitalisation. It is also beyond the thesis's scope to analyse curbside supply and demand from users other than freight vehicles. However, because the assessment of conflicts between curbside users and the integral perspective of urban planning that includes all stakeholders are fundamental to reaching sustainability goals, they would be considered in the research conducted later in the author's doctoral study.

1.4. Research questions (RQs)

The following three RQs guided this thesis in achieving its aim:

RQ1: What are the main factors that determine curbside supply and demand for freight parking?

As shown in the literature, curbside supply–demand imbalance is a problem in public space management. Identifying and analysing the factors that influence the supply of and demand for space for freight parking operations can contribute to understanding and reconciling such imbalance. From the supply side, urban planners are the primary source of information because they are responsible for public space provision. From the demand side, probed data on freight parking operations are critical to conducting exploratory assessments of factors influencing curbside occupancy.

RQ2: How does digitalisation in freight parking operations enable data-driven curbside management?

The upsurge of new technologies has opened the door for more robust data about curbside operations and, in turn, more accurate methods of supporting decision-making about the curbside. RQ2 guided the identification of management enhancements under evidence-based assessments using probed data about parking and their analytics, for the overall outcome of data-driven curbside management. Answering the question required diving deep into the study of decisions made in curbside management related to freight activities and how data-driven approaches (e.g. estimating the demand for parking using machine learning [ML] or curbside supply following optimisation assessments) enhance them.

RQ3: What are the potential impacts of data-driven curbside management on sustainability metrics for public spaces?

RQ3 connected decisions about freight curbside parking with the UN's SDGs. Because RQ3 implied a quantitative assessment of impacts, metrics for SDG11 were used to identify the contribution of data-driven curbside management to sustainable public spaces. In other words, the impacts were assessed regarding the average global share of the urban area allocated to streets and open public spaces, civil society's participation in urban planning and management, mean levels of fine PM emissions and the development of urban public policies.

1.5. Document navigation and intended audience

This thesis describes the research conducted halfway through the author's doctoral study. Its target audience includes but is not limited to researchers and practitioners interested in urban freight management and urban planning. The thesis's scope may also be of interest to users and developers of data analytics applications in urban contexts. The outcomes of the research are expected to inform public authorities, who should be the main users of the thesis. However, the results are also relevant to private actors because they provide insights into the impacts of decisions about the curbside on the efficiency of last-mile deliveries.

In what follows, Chapter 2 describes the frame of reference used as a lens to study the research problem, after which Chapter 3 presents the research process, design and strategy implemented to meet the thesis's aim. The outputs of the research conducted for the thesis thus far—a book chapter, journal papers and a conference paper—and which contain the results used to answer the RQs are summarised in Chapter 4. Next, Chapter 5 discusses the results, their contributions to research on the topic and their limitations. Last, Chapter 6 articulates the conclusions of the research and avenues for future research that may inspire the next half of the author's doctoral study.

2. Frame of reference

This chapter presents the definition of the concept that framed the research process for this thesis—that is, urban transport planning. The subsequent sections describe the approach followed in studying its two principal elements: transport supply, with a focus on curbside management, and transport demand, focusing on urban freight parking operations. The chapter concludes with the expected implications on sustainability of equilibrating the supply of and demand for public space for freight parking operations in urban areas, based on the UN's SDG11 (i.e. sustainable cities and communities).

2.1. Urban transport planning

Transport planning refers to the provision and management of public transportation assets to satisfy the demand for transport. Because its scope is context-dependent, transport planning has typically dealt with specific problems at local levels, including the state, county, and municipality (Rodrigue, 2020). By extension, *urban transport planning* refers to the analysis and identification of appropriate solutions to the problems associated with the demand for the movement of people and goods in cities—that is, *transport demand* (Victor and Ponnuswamy, 2012). Transport demand is not an end in itself but derived from the satisfaction of travel-intensive needs to work, study, procure and deliver goods and provide health services, among others (Ortúzar and Willumsen, 2011). The continued growth of urban populations and economic growth have augmented the gap between transport demand and the capacity of transport facilities to satisfy it—that is, *transport supply*. Consequently, urban transport planning has focused on equilibrating supply and demand to achieve and maintain sustainable transport systems in cities (Huang, 2003).

Although the private sector operates a significant portion of transport assets, urban transport planning is defined from the public sector's perspective (Rodrigue, 2020). Meyer (2016) has distinguished two courses of action taken by urban planners when facing problems with transport planning: supply-driven interventions (i.e. solutions centred on facilities and services needed to handle transport demand) and demand-driven interventions (i.e. solutions aimed at influencing travel behaviour to achieve sustainability-oriented objectives). The appropriateness of the solutions is subject to their efficacy in maximising the economic, social and environmental benefits of transport (Huang, 2003).

The emphasis on sustainability in urban transport planning is a relatively recent development, one that has gained consensus about not only the aim itself but also the actions taken to achieve that aim in both supply- and demand-driven interventions. For instance, reducing the need to travel, promoting the fair distribution and use of public space, reducing travelling distances, incentivising modal shifts to cleaner modes of transport and improving the energy efficiency of existing modes are just some of recently popular transport planning interventions aimed at realising sustainable development (Bertolini, Clercq and Straatemeier, 2008).

Victor and Ponnuswamy (2012) have developed a process-based view on urban transport planning (see Figure 3) that involves a set of interlinked steps, starting with the problem definition and ending with the corresponding solution. The second step, goal setting, involves identifying sustainability targets, evaluation criteria and metrics, such that an understanding of transport supply and demand provides the baseline case scenario as a reference for further comparisons in the third and fourth steps—that is, alternative plans and evaluation. Fifth, solution selection is the result of technical assessments from evaluation and the participation of stakeholders who contribute to urban planners' decision-making. Although Victor et al. proposed a linear process (i.e. continuous arrows in Figure 3), Meyer (2016) has suggested feedback loops (i.e. dashed arrows in Figure 3) that readjust choices based on the results of the subsequent steps and thereby make the planning process more adaptable to the dynamic nature of the specific transport system.

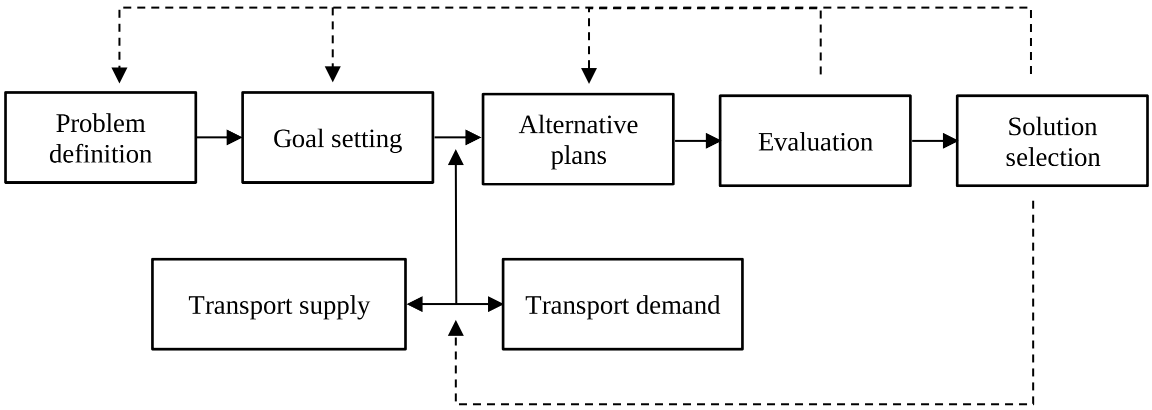

Figure 3. The process of urban transport planning
Adapted from Victor and Ponnuswamy (2012)

Analysing transport supply and demand is the cornerstone of the planning process (Meyer, 2016). In the definition of *transport system* presented by Browne, Dubois and Hulthén (2022), transport supply corresponds to the infrastructural layer and the transport layer that offers transport services. Aside from the combination of fixed assets (i.e. infrastructure) with mobile units (e.g. vehicles), Ortúzar and Willumsen (2011) have added the set of rules that frame transport operations (e.g. traffic regulations). Because transport demand occurs across space, it corresponds to the supply chain layer of the system proposed by Browne, Dubois and Hulthén (2022) and the traffic interface.

Data collection and modelling are commonly employed in analyses of transport demand and supply to understand the current status and performance of the transport system in question such that problematic situations and their sources emerge. Data collected and modelling developed at those steps are also critical to predicting patterns and anticipating transport problems in the future. Recent technological advances have improved the accuracy of assessments of transport supply and demand and consequently afforded more robust problem-solving capabilities in transport planning (Yang *et al.*, 2022). Nonetheless, the predominant focus on passenger transport has overshadowed the pending progress in freight transport in terms of understanding supply and demand and the development of potential solutions in response. As stated by Rodrigue (2020), “Planning for freight movements remains in its infancy”.

Taking the process-based view on urban transport planning, this thesis focuses on analysing supply and demand to contribute to an understanding of the freight curbside imbalance. From the supply side, curbside infrastructure and decisions about the curbside are considered, whereas the demand side considers freight parking operations on the curbside. The metrics of SDG11 are considered to be goals of the urban transport planning process.

2.2. Curbside management: Supply

The *curb* is the physical boundary between the sidewalk and the roadway. By extension, the *curbside* is a public transport asset traditionally used as the interface zone between vehicular movement and pedestrian activity, such that vehicles stop to allow the modal transition to and from walking (Marsden, Docherty and Dowling, 2020). Current needs for space have expanded such traditional use into a broader range of uses, including for on-street parking zones, loading and unloading goods, seating for restaurants and cafés and playgrounds for children. Given such diversified demand, curbside management consists of all decisions regarding the allocation, use and monitoring of curbside space to satisfy citizens' needs for accessibility, mobility, and the enjoyment of public space. DeBow and Drow (2019) have thus defined *curbside management* as the collection of concepts, techniques and practices that effectively allocate the use of the curbside.

Curbside management has gained relevance in the public realm, given the intensification and diversification of the demand for using the curb under an almost static capacity (Marsden, Docherty and Dowling, 2020). The chief goal of curbside management is to guarantee a fluent interface between the movement-related function of streets and their place-related and environmental functions (OECD, 2018). The place-related function of streets makes them a social, economic and/or recreational destination, whereas their environmental function gives them a role in capturing and reducing vehicle emissions, processing air pollution and thereby providing clean air and spaces to citizens (Hui *et al.*, 2017). Conceptual approaches that have guided the design of policies towards that goal include:

- *Liveable streets*, meaning policies and actions aimed at transforming streets into public spaces that promote social interactions in safe, healthy, inclusive and welcoming environments (Appleyard, 1980);
- *Complete streets*, meaning policies oriented towards providing street space to all users under safe conditions to satisfy social and environmental objectives (Hui *et al.*, 2017);
- *Healthy streets*, meaning the system of policies to incentivise the use of public transport and active mobility (e.g. walking and cycling) instead of private car use as a means to improve physical and mental health (Plowden, 2020); and
- *Flex zones* (see Figure 4), meaning policies about allocating curbside space that vary according to changing demands in time and space (OECD, 2018).

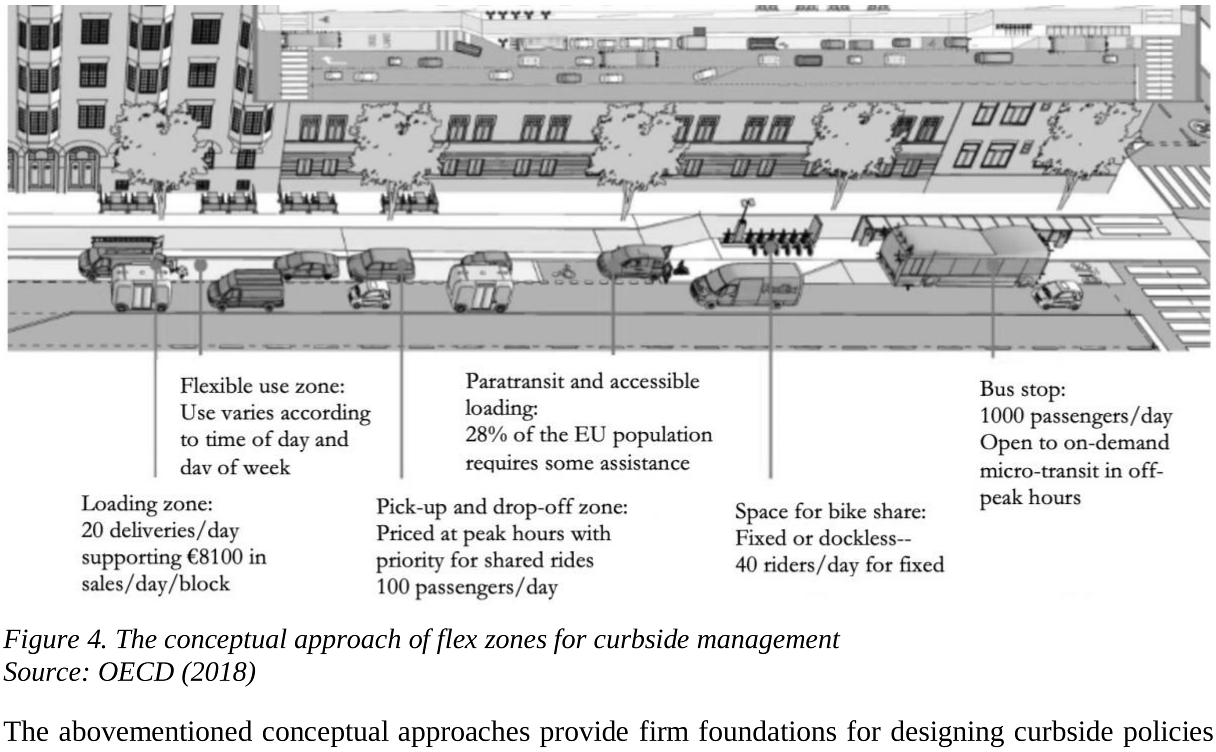

Figure 4. The conceptual approach of flex zones for curbside management
Source: OECD (2018)

The abovementioned conceptual approaches provide firm foundations for designing curbside policies and implementing actions to realise more sustainable streets. Nevertheless, local authorities have admitted lacking the technical tools to support decision-making about the curbside that generally relies on *ad hoc* processes or results from lobbying and political influence from specific groups in society (Wahid, 2020). For instance, Butrina *et al.* (2020) have reported results of interviews with curbside management staff within local authorities in the United States, some of them admitted that making decisions about allocating curbside space is “more of an art than a science”.

Apart from allocating curbside space, curbside management includes integrating fragmented data, monitoring the use of the curbside, communicating and enforcing rules about such use, and reporting the performance of the curbside (DeBow and Drow, 2019). The following sections define and highlight challenges in allocating curbside space, technology used to integrate data, monitor and enforce of curbside use and metrics to evaluate performance.

2.2.1. Conflicts in the allocation of curbside space

The lack of coordination due to the unclear allocation of curbside space or weak analyses of curbside users’ needs are the root causes of curbside supply–demand imbalance that leads to congestion (Hammami, 2020), safety risks (Dumbaugh and Li, 2010) and more polluted transport activities (Iwan *et al.*, 2018). Users’ claims to curbside space respond to fundamental human needs for freedom (e.g. freedom of movement), subsistence (e.g. access to goods and work and/or study) and leisure (e.g. walking or sitting in urban spaces). Therefore, decisions about allocating curbside space have been contentious because one user’s needs may be satisfied at the expense of another’s. Table 2 shows the competing demands for curbside space that increase every day as the curbside capacity remains the same.

Table 2. Competing demands for curbside space

Demand type	**Access to transport services**	**Movement of people**	**Storage**	**Access to goods**	**Enjoyment of public space**
Examples	• Public transport stops • Ride-sharing pick-up and drop-off • Taxi pick-up and drop-off	• Public transport (bus lanes) • Pedestrian alleyways • Bicycle lanes • Scooter riders	• Short- and long-term parking for private vehicles • Electric vehicle charging • Bicycle parking • Scooters parking • Garbage containers	• Loading zones for freight • Commerce delivery	• Trees • Planters • Tactical urbanism • Famers’ markets • Snow removal • Construction • Restaurant and café service areas • Parklets
Street functions	Movement		Place		Place or environmental

Adapted from Smart Cities Collaborative (2020)

Urban planners have adopted different strategies to de-conflict the curb based on the type of demands shown in Table 2 and the priorities defined in urban and transport policies. For instance, right-of-way (ROW) assessments have guided the allocation of space by optimising the distribution of the available space for the fulfilment of the movement-related, place-related and environmental functions of streets (Rodriguez-Valencia, 2014). Although ROW assessments guide decisions about the whole street with all its functions and users, there is a marked biased towards decision-making tools for movement functions, giving little scope to solutions on streets’ place- and environmental-related functions (Sheikh-Mohammad-Zadeh, Saunier and Waygood, 2022).

Given the need for more knowledge about streets’ place-related and environmental functions in the allocation of street space, Mitman *et al.* (2018) have proposed a decision-making framework for determining ROW that focuses on curbside management, one that is congruent with the urban transport planning process shown in Figure 3. After defining the desired outcomes (i.e. goals), the authors proposed six steps: (i) conducting an inventory and analysing it (i.e. supply), (ii) developing alternatives considering the need of each zone and priorities (i.e. demand), (iii) evaluating alternatives, (iv) choosing the preferred alternative, (v) implementing the solution, and (vi) evaluating it. The first two steps underscore the need to understand the supply of and demand for curbside space for each user, as discussed in the urban transport planning process. The National Academy of Sciences (2022) have elaborated on two additional concepts as being critical to include in that understanding. The first is *context*, defined by the land use and activities taking place in the area. Decisions about allocating curbside space should consider nuances according to residential, commercial, industrial, and mixed zones, because each land use has specific demands for space. The second concept is *time*, which reflects the need to consider the variation of the demand for curbside space from each user across time (e.g. variability in the frequency and duration of last-mile deliveries during the day, week, month or year).

Despite challenges in deploying those concepts for each curbside user, researchers and practitioners have devised solutions for allocating space that seek to satisfy the different types of demands. For freight transport, loading zones (*LZs*) have been defined as on-street areas reserved for vehicles needing to load and unload freight (Dezi, Dondi and Sangiorgi, 2010). LZs aim to satisfy the demand for accessing goods from residential, commercial and industrial establishments. The management of LZs (i.e. freight curbside management) considers decisions about location, size and usage (Alho *et al.*, 2018) and involves technological evaluations to select fixed and mobile devices that support the coordination, monitoring and enforcement of the use of LZs (Wahid, 2020). It also responds to regulations about accessing time, pricing strategies and enforcement (Nourinejad and Roorda, 2017). Although recent research has focused on managerial aspects of freight parking operations on the curbside, Muñuzuri *et al.* (2017) have highlighted the lack of robust planning tools based on sufficient data about demand that are needed to design and manage LZs. In overcoming that obstacle, digitalisation has been identified as a protagonist (Comi, Schiraldi and Buttarazzi, 2018).

2.2.2. Digitalisation in curbside management

The rise of sensors, computer vision technology, mobile apps, geolocation services and data analytics algorithms present an opportunity to amass and analyse large amounts of data about the use and availability of curbside space. Increasingly large amounts of data about adjacent space (e.g. offices, shops, and residential complexes), since becoming available, have also demonstrated value in estimating the demand for curbside space. Today, such new technology for digitalising the curb and monitoring its use is increasingly replacing costly traditional methods of data collection, including surveys, direct observation via space inventories and traffic counting (Jaller *et al.*, 2021).

Public investments in forms of static technology (e.g. cameras, in-ground sensors and Bluetooth and RFID readers) have additionally overcome the limitations of traditional observation-based estimations of curbside occupancy regarding the frequency and size of the samples observed and both the accuracy and representativeness of the data collected. Static technology also supports enforcement activities by providing data about the misuse of the curbside (e.g. illegal parking) and preparing cities for up-and-coming users, including autonomous vehicles, that will need to exchange data with the built environment in order to operate (Zhang and Wang, 2020).

In parallel, forms of mobile technology (e.g. app-based systems providing booking, payment, check-in and check-out services) have unlocked the possibility of gathering detailed data typically unavailable to local agencies, including the type of user, their purpose in occupying the curbside and when they arrived and departed. Such technology also benefits drivers by providing them with reliable information about the current and forecasted availability of parking spaces (Zhang and Thompson, 2019).

Apart from connectivity, using big data generated from the implemented technology and even sharing such data are powerful means of translating information into decisions that improve curbside management. Nonetheless, the linkages between those data and decision-making still need to be examined (Comi *et al.*, 2017; Butrina *et al.*, 2020). Aiming at overcoming that challenge, Lin, Rivano and le Mouel (2017) have proposed a construct for considering the digitalisation of the curbside, one with three macro-components:

- The *information collection*, which refers to decision-making and developments in the sensing and connectivity of parking information (e.g. parking meters, ground sensors and crowdsensing);
- The *system development*, which refers to software and data analytics used to predict unoccupied parking stalls and the scalability of digital curbside management; and
- The *service dissemination*, which refers to parking regulations, pricing, parking enforcement and drivers' behaviour.

According to the authors, by having those macro-components in place, urban planners can make data-driven decisions that are able to enhance curbside management.

2.2.3. Data-driven decision-making

Data-driven decision-making refers to the managerial practice of basing decisions on data analyses instead of intuition (Provost and Fawcett, 2013). Given the technological advances described in the previous section, research opportunities have arisen regarding the development of data-driven decision-making to improve curbside management based on probed data purporting the use and availability of the curbside. Huang (2003) has applied the data-driven decision-making framework for urban transport planning that incorporates supply- and demand-related data linked to the system's performance and impacts. Drawing on that framework, Figure 5 presents the corresponding data-driven decision-making framework for curbside management specifically for freight parking operations on the curbside.

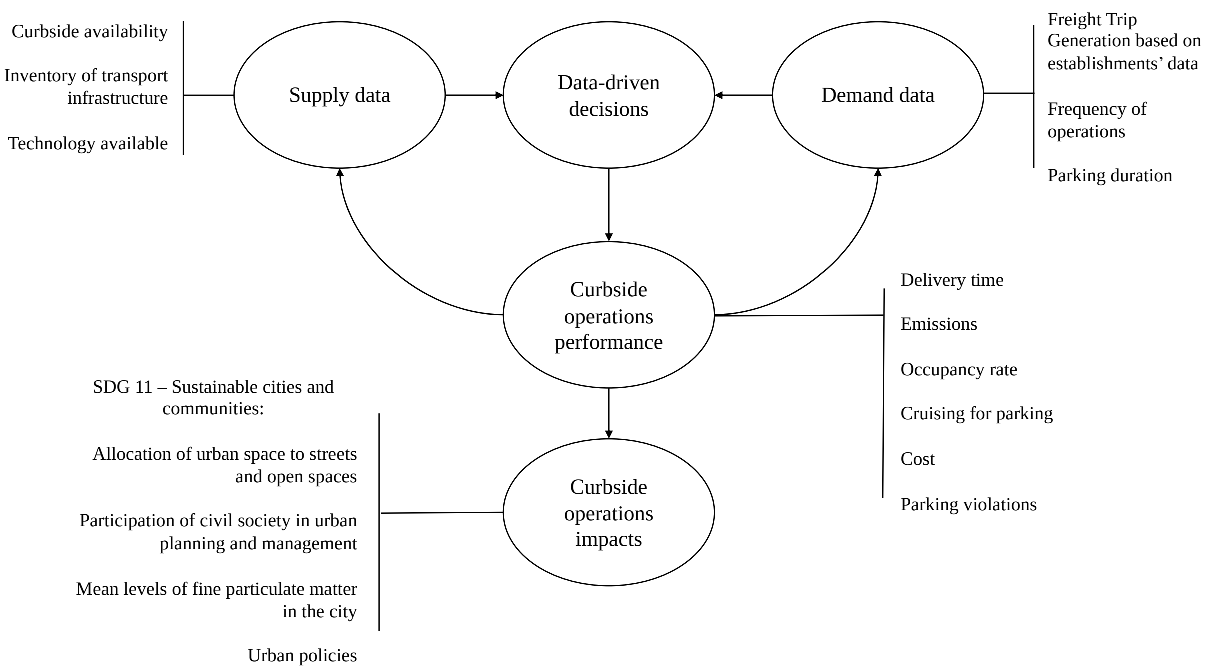

Figure 5. Data-driven framework for curbside management
Source: Adapted from Huang (2003)

Following the data-driven framework shown in Figure 5, interventions on the curbside aim to equilibrate supply and demand through data-based decisions—that is, decisions based on supply- and demand-related data and measured in terms of their effect on delivery time, emissions, occupancy rate, cruising, cost and parking violations (Meyer, 2016; Diehl, Ranjbari and Goodchild, 2021). Those performance indicators for curbside management are ultimately associated with the metrics of SDG11 and described in detail in Section 2.4. Identifying factors determining supply and demand and understanding decisions enabled by digitalisation and their impact on sustainability metrics correspond to the RQs that guided the research conducted for this thesis.

2.3. Urban freight management: Demand

Urban freight transport (UFT) is a complex, heterogeneous collection of interactions among shippers, carriers, recipients, terminal operators, public agencies and citizens (Holguín-Veras, Amaya Leal and Seruya, 2017). By definition, Ogden (1992) affirms that UFT, more than the movement of goods from origin to destination, looks to minimise, or at least reduce, the total social cost of the urban movement of goods. By and large, UFT-oriented practices have focused on solutions framed by the supply–demand approach and involving the extensive use of quantitative models (Ortúzar and Willumsen, 2011). By extension, *urban freight management* refers to the process of planning, implementing and evaluating initiatives in UFT from the perspectives of both the public and private sectors (Taniguichi *et al.*, 2012).

Figure 6 presents a proposed spectrum of the scope of urban freight management and decisions made at different levels therein, namely the macroscopic, mesoscopic and microscopic (Gonzalez-Feliu and Sánchez-Díaz, 2019). Level 1 (i.e. macroscopic) is a strategic level at which data and models estimate the current and future demand for goods and the resulting freight traffic. Data-based outcomes from those strategic models support the planning of infrastructure, including intermodal and regional corridors, logistics platforms and consolidation terminals. By contrast, zooming in on the geographical scope, estimations from macroscopic models feed decisions on Level 2 (i.e. mesoscopic), focused on corridor flows, to estimate the impacts of freight at the level of corridors and zones. Data about demand and traffic obtained from Levels 1 and 2 support decision-making regarding, for example, traffic restrictions, lane management and consolidation schemes. Last, Level 3 (i.e. microscopic), focused on individual vehicles, contains data about freight delivery operations used to support decision-making about access regulations and local space management, including curbside management.

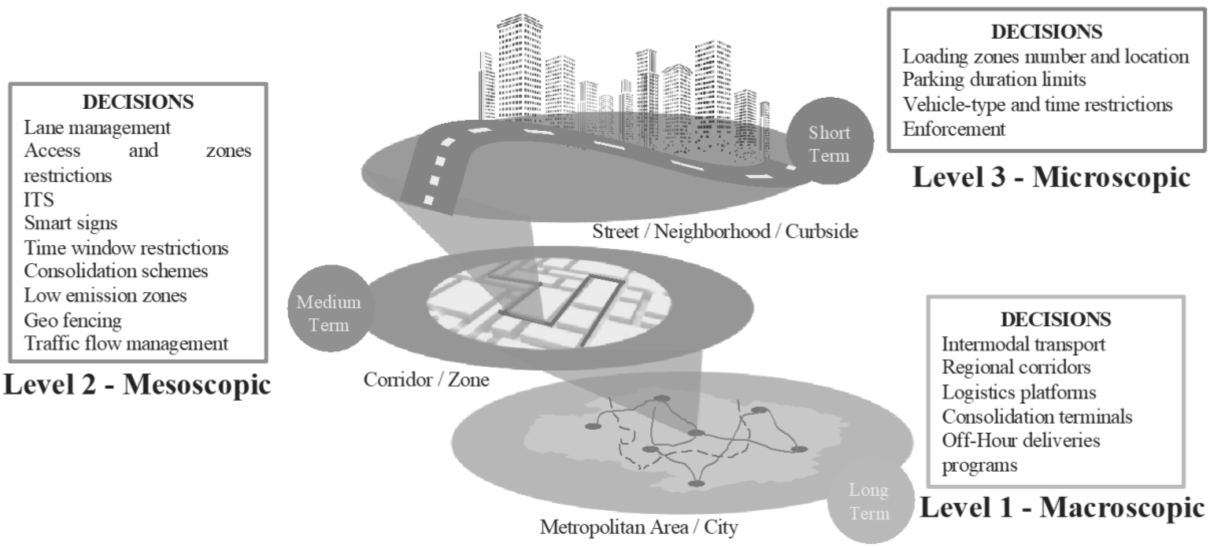

Figure 6. Urban freight management scopes

Each level of decision-making implies specific modelling approaches and, therefore, data-intensive needs. For instance, at the strategic macroscopic level, freight trip generation (FTG) and tour-based distribution models base their estimations on data purporting the demand of establishments and households, origin–destination matrices, traffic counts, data about decision-makers' preferences, infrastructure and network data. At the mesoscopic traffic management and control level, models also require vehicle emissions profiles and Global Positioning System (GPS) data. Last, at the local, microscopic planning level, data about parking occupancy and demand are required, including from establishments and households, as are emissions measurements, curbside and street profiles, urban form data, GPS data and delivery data. That last level is the focus of this thesis.

2.3.1. Curbside demand for freight deliveries

During last-mile deliveries, freight vehicles demand curbside space for parking (i.e. on-street parking) due to limited off-street parking infrastructure and the need to park as close to destinations as possible. Delivery operations using those vehicles are subject to programmed routes defined by companies to serve one or multiple customers in a city zone. Such routing is designed based on economic criteria (e.g. shortest path and urban conditions such as congestion), traffic regulations (e.g. time, zone, vehicle size and vehicle technology) and windows of time when customers are available. Once a vehicle is parked, its dwell time is affected by several factors depending on the size of the delivery, how it is packed and handled, the distance from the parking area to the destination building, the type of commodity and the paperwork needed during the delivery, among others. Once the delivery is completed, the vehicle leaves the parking area and continues its programmed route to the next customer.

However, literature on UFT and curbside operations mostly focuses on either estimating parking demand (Campbell *et al.*, 2018), estimating parking durations (Low, Duygu Tekler and Cheah, 2020) or impacts assessments through simulation models (Kladeftiras and Antoniou, 2013). Added to that, freight vehicles' routing plans for UFT seldom consider parking availability, primarily due to a lack of such information among shippers and carriers. The real-time monitoring of parking spaces and freight vehicles is also complicated due to the privacy and confidentiality necessitated by UFT. In view of those shortcomings and challenges, this thesis's scope includes clarifying freight deliveries' use of the curbside, which involves modelling parking demand and durations.

Modelling

Estimations of the demand for freight parking are predominantly modelled using econometric approaches. Campbell *et al.* (2018), for example, have proposed using FTG models to assess parking needs. The principal aim of such explanatory approaches is gaining knowledge about the impact of the features of establishments, operations and location on freight parking durations. For instance, Alho, Silva and Sousa (2014) have shown that employment and floor area are significant factors in estimating parking demand for retail establishments. Meanwhile, Butrina *et al.* (2017) have developed a framework for analysing the last 800 feet in freight delivery that describes the characteristics of the delivery and facilities (i.e. location) that influence the demand for and performance of freight curbside. By contrast, concerning models for estimating demand, Malik *et al.* (2017) have recommended including factors such as vehicle characteristics, vehicle ownership, freight drivers' (non-)payment of parking fees, type of commodity and duration of delivery. More recent approaches have adopted structural equation models and ML algorithms to explore the role of variables on variability in demand and in forecasting demand when available data allow such assessment (Kalahasthi *et al.*, 2022).

As for parking durations, several approaches have stressed the importance of considering economic activities in estimating dwell times and delivery behaviour. Schmid, Wang and Conway (2018), using survival models constructed to identify significant factors influencing parking durations, have shown that vehicle and delivery characteristics are the most important ones. In addition to those results, Low, Duygu Tekler and Cheah (2020) have found that parking location was also a significant factor in parking durations. Both groups of authors additionally highlighted the need for future research on parking duration patterns among freight vehicles using probed data from connected parking technology.

2.4. Sustainable cities and communities: Equilibrating supply and demand

In 1987, the Brundtland Report defined *sustainable development* as development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). That definition highlights three fundamental components of sustainable development: environmental protection, social equity, and economic growth. Because cities generate 70% of global emissions, host more than 50% of the global population and contribute to 85% of the global gross domestic product (GDP), they are in the spotlight of sustainability-focused actions. At that level, sustainable development implies overcoming the challenges that cities currently face regarding the air quality, modal shift, safer roads, decarbonisation, congestion, among others (Papachristou and Rosas-Casals, 2018).

Public space management plays a central role in facing the above challenges and building liveable cities. Policies encouraging a proper use of the public realm aim at reducing the negative impacts of transport activities by providing conditions of accessibility, equity, and safety. Moving towards that aim, the UN (2015) has defined among its 17 SDGs, one focusing on interventions in public space, mobility, health, energy, economic growth, infrastructure, and productivity: SDG11, titled “Sustainable cities and communities”. SDG11 promotes policies and actions that leverage universal access to safe, inclusive, green public spaces and, along those lines, guides policymakers in coping with one of the most critical sustainability-related issues in cities: the use of public space. In practice, it involves measuring the effectiveness of managing competing demands for public space for uses that fulfil human needs for social interaction, mobility, access to supplies, activation and a healthy environment.

SDG11 has four specific metrics that guide the implementation of actions in the public space: (i) the average global share of the urban area allocated to streets and open public spaces, (ii) the participation of civil society in urban planning and management, (iii) mean levels of fine particulate matter and (iv) the development of urban public policies. The research for this thesis involved investigating the role of interventions in freight curbside management in equilibrating supply and demand, the curbside performance and metrics for SDG11.

2.5. Overall conceptual approach of the research

The shaded area in Figure 7 shows the thesis’s scope delimited within the process of urban transport planning. In the research conducted for the thesis, the curbside conflicts related to the allocation of public space defined the problem in consideration, with a specific focus on the type of demand related to the access to goods—that is, freight delivery. Given that problem, the research involved a deep dive into the supply- and demand-related factors of the curbside space and their impact on the metrics for SDG11. Therein, the data-driven framework (see Section 2.2.3) guided the assessment of supply and demand and the connection with the goals of the urban transport process.

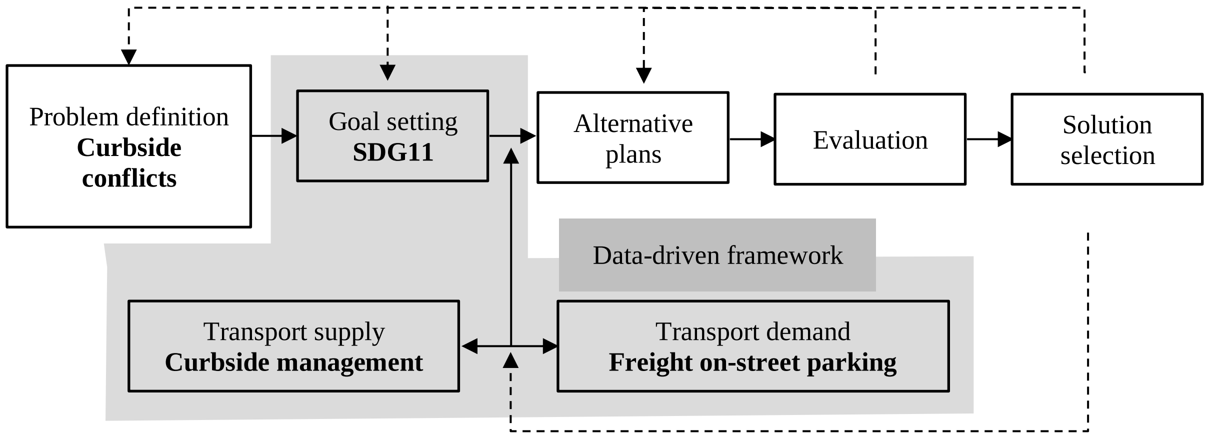

Figure 7. Conceptual research approach

3. Methodology

This chapter describes the methodological approach used to achieve the aim of the research conducted for this thesis. It begins with a general overview of the research process before presenting the research designs, strategies and methods used to address the RQs. Last, research quality considerations are discussed in terms of reliability, replicability, and validity.

3.1. Research process

The research process employed for this thesis (see Figure 8) operationalised efforts to achieve the research aim and answer the RQs. In the process, the definition of two studies (i.e. Study 1 and Study 2) helped to decompose the general scope of the research into work packages with specific research designs, strategies, methods and outputs.

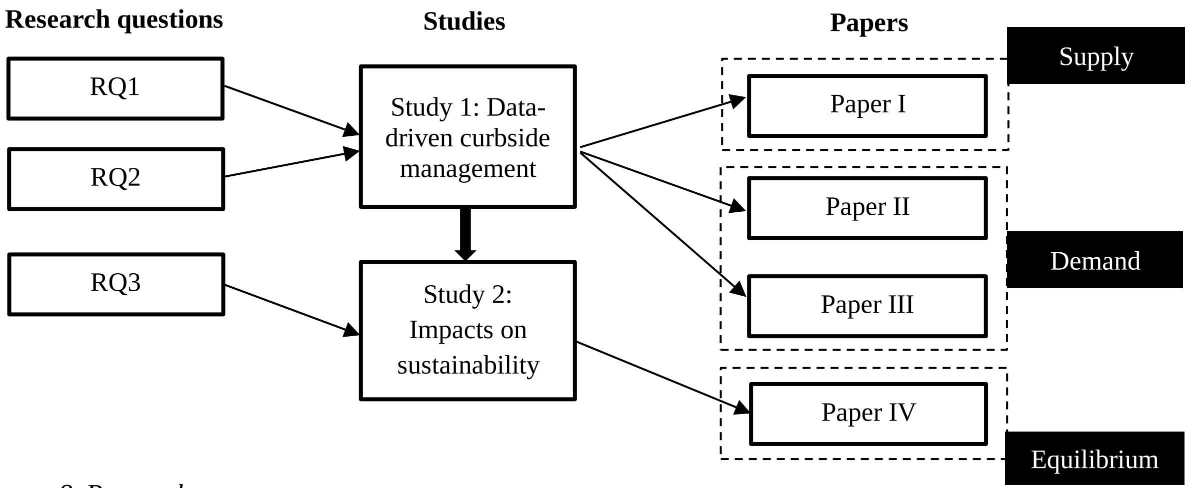

Figure 8. Research process

Study 1, "Data-driven curbside management", involved analysing curbside supply and demand for freight parking operations by using two research designs: a case study and a cross-sectional design. The results yielded quantitative and qualitative data used to answer RQ1 (i.e. regarding the identification of factors of supply and demand) and RQ2 (i.e. regarding the digitalisation of curbside management). The availability of probed parking data allowed implementing prescriptive and predictive methods to explain curbside supply and demand, whereas interviews and a literature review supported the exploratory approach to making data-driven decisions enabled by the digitalisation of curbside management. The outputs of Study 1 are three papers that present the results of curbside supply assessments (i.e. Paper I), of modelling and predicting freight parking durations (i.e. Paper II) and of modelling approaches for estimating freight demand (i.e. Paper III). The literature review was an iterative activity during the study that provided elements to answer the RQs and situate the results among past findings.

Study 2, "Impacts on sustainability", was based on findings from Study 1 regarding data-driven decisions aimed at equilibrating curbside supply and demand for freight parking. Focused on assessing the impacts of those decisions on metrics used for SDG11, the study employed a cross-sectional research design in order to answer RQ3 (i.e. regarding the impacts of data-driven curbside management on sustainability metrics for public spaces). The output of Study 2 is Paper IV, which presents the results of a meta-analysis that extracted impacts quantifications from a systematic review of literature in the field. Although the study was designed to be explanatory in nature, the scarcity of such impacts quantifications in the literature limited the possibility of having conclusive evidence, as discussed in Section 5.3, such that the study became exploratory instead.

Connections among the outputs of the studies are evident in Papers I and II, both of which are based on the same case study (see Section 3.2.1). They are also linked to the "Using Data Analytics for Smart Loading Zones Management in Cities" research project, led by the Chalmers University of Technology and funded by Vinnova, the Swedish agency for innovation. By comparison, Papers III and IV are based on research following a cross-sectional design and using a literature review as the primary method for collecting information and specifying each paper's scope.

Before describing the research designs, strategies and methods used in the research for this thesis, some ontological and epistemological considerations about the research merit discussion, for they supported methodological choices at each stage of the research process.

Ontological assumptions

Ontology refers to the essence of a phenomenon under investigation—in other words, the nature of reality (Bryman and Bell, 2015). Freight delivery, specifically on-street freight parking operations, is the phenomenon examined in this thesis. Such operations are embedded in an urban environment that is unique from place to place, given the distinct and variant nature of the factors influencing them at specific locations. For instance, the duration of parking operations may depend upon how shippers packed the freight upstream in the supply chain, how many recipients are served at a single stop (also influenced by urban density), the equipment for loading and/or unloading at destinations, the availability of on-street parking or even the need of other actors to use the streetside occupied by freight vehicles (i.e. conflicts of ROW). In all, freight parking operations result from economic and social interactions that shape a reality created by individuals. Understanding the causal mechanisms of that observable phenomenon is one of the chief concerns of the research conducted for this thesis.

Critical realism (CR) is an appropriate philosophy of science for this thesis. It acknowledges the existence of a reality independent of human knowledge of it and admits that that reality is subject to underlying structures that determine it, (i.e. realism). According to postulates of CR, explaining those structures and associated conditions is essential to understanding a phenomenon (Murtagh, Odeleye and Maidment, 2019). CR also suggests that such knowledge is both fallible and theory-laden, which makes it impossible to fully apprehend reality, for the available theoretical resources and the research interests pursued shape the perceptions of the researchers.

CR distinguishes three ontological domains (Bhaskar, 2008): the real (i.e. existing regardless of human knowledge of it), the actual (i.e. in which phenomena occur that humans may become aware of) and the empirical (i.e. in which phenomena can be experienced and data collected). As shown in Figure 9, data collection on freight parking operations and curbside supply occurs in the empirical domain. By contrast, data analytics contribute to the identification of events that caused them—that is, in the actual domain. Last, further analyses of explanatory models using, for instance, available constructs and references from multiple cases provide the elements necessary to understand the generative mechanisms and conditions of curbside supply and demand for freight—that is, in the real domain.

Epistemological assumptions

Epistemology refers to the study of how knowledge is formed (Bryman and Bell, 2015). Research on urban freight management and urban transport planning in general has provided tools for identifying regularities and causal relationships among elements of transport systems. Although the application of those tools can vary from researcher to researcher, generally accepted metrics are used to evaluate the accuracy and suitability of the various models. That approach is compatible with CR, whose ultimate goal is to develop more profound levels of explanation and understandings of reality instead of identify generalisable laws (i.e. positivism) or the lived experience of social actors (i.e. interpretivism).

As mentioned in CR's ontological assumptions, the understanding of reality is fallible and theory-laden. For that reason, using multiple sources of empirical evidence and contrasting them with existing constructs is necessary to getting a better bead on the observed reality and the mechanisms responsible for it (Trochim, 2002). That process has been termed *retroduction*. As the underpinning logic of CR, retroduction implies that events can be explained by postulating, if not also identifying, the mechanisms able to reproduce them by pinpointing ones with the greatest explanatory power (Næss and Jensen, 2010).

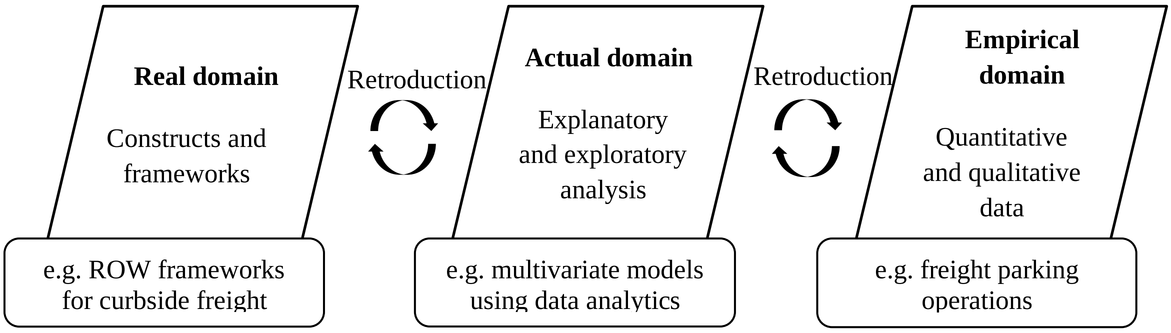

Figure 9. Ontological and epistemological domains of CR

Figure 9 presents the retroduction process between the ontological domains of CR with corresponding examples from the field. In the process, data collected from freight parking operations are fed into the explanatory models, which can reveal significant interactions among variables that are later input into ROW frameworks, all to examine the allocation of curbside space for freight activities. At each domain's interface, the data's suitability and the models' accuracy and explanatory power are iteratively evaluated so that the best explanation can be identified.

Methodological considerations for conducting the retroduction process in the research for this thesis depended on the implementation of the research designs that connected the empirical with the actual domain (e.g. case study) and the actual with the real domain (e.g. cross-sectional design).

3.2. Research design

Two research designs supported the processes of data collection and data analysis: a case study and a cross-sectional design. Freight parking on the curbside was the unit of analysis in both designs.

3.2.1. Case study

Case-study research, a powerful method of investigating social entities and situations, is used to frame data collection processes using multiple sources and develop a holistic description through an interactive research process (Easton, 2010). In the research conducted for this thesis, the case study was determined by the geographical area of the City of Vic, Spain, the capital city of the comarca of Osona in the province of Barcelona. The city has a population exceeding 47,000 inhabitants. The case was selected based on the city's pioneering experience with implementing digital devices to manage LZs in the city centre as part of the Z-DUMA initiative. The initiative consists of implementing a parking regulation that allocates dedicated space for freight parking operations on the curbside. With the implementation of mobile app technology provided by Parkunload®, the regulation aims to digitalise the management of the curb and making better decisions based on data analytics. Since the city was part of the research project funded by Vinnova, and the municipal authorities were willing to provide access to all of the freight parking data from the Z-DUMA initiative, the case study selection criteria corresponded to a convenience sampling (Flick, 2019).

Figure 10. Geographical scope of the case study
Source: Paper I

The City of Vic provided data about all freight parking operations that occurred between July 2018 and December 2019 at eight LZs defined *a priori* by the city's Office of Mobility (see Figure 10). The data contained accurate information from more than 103,000 operations regarding the duration of freight vehicle stays on the curbside, including features such as commodity type (i.e. commercial, construction, food, installation and maintenance, transport and parcels, local commerce and other), vehicle size (i.e. light vehicle [<3.5 T], van, truck ([≥3.5 T) and private car) and vehicle technology (i.e. high-emissions, medium-emissions, low-emissions, hybrid and electric). Data about those features were collected through a check-in, check-out app-based system run by Parkunload®. Freight vehicle drivers had to check in every time that they parked in an LZ and check out upon leaving. Aside from the mobile app, Bluetooth sensors were installed on parking signs to detect the presence of vehicles, which made the data provided about parking durations particularly reliable.

According to Easton (2010), multiple data sources are needed to complement the understanding of any case study. Thus, data about urban infrastructure (i.e. LZ dimensions and access to roads), establishments' locations and their economic activity complemented the parking data set provided by the City of Vic. More specifically, the data included geometric details about the LZs, including length and width in metres, distances between LZs and capacity in terms of parking stalls. Data on managerial aspects of the LZs were also collected via interviews with municipal public servants and representatives of the technology provider (see Section 3.3.1).

Meanwhile, regarding the establishments, data represented 348 establishments located within a maximum walking distance of 200 m from each LZ. All such establishments were in the city centre (i.e. black dots in Figure 10) and, by type, were retail stores, restaurants and hotels, among others. The walking distance between the establishments and the eight LZs was accessed using Google Maps API 4.4.5 in Python 3.7.10. The total area (m^2) of those establishments and the economic activity was collected from OpenStreetMap and manually augmented with data read from Google Maps. The area of each establishment was calculated by dividing the area of the building footprint from OpenStreetMap (i.e. where the establishment is located) by the number of establishments in the same building. The analysis of those data and parking operations are described in Section 3.3.2.

Taken together, the qualitative and quantitative data collected from the case study were the vehicle for accessing the empirical domain of the research, as well as fed data analytics processes to expand the understanding of relevant interactions among the variables. Such a research design contributed primarily to the scope of Study 1, which generated empirical evidence for assessing curbside supply and demand for freight parking operations and the role of digitalisation based on the experience of the City of Vic with the Parkunload® solution.

3.2.2. Cross-sectional design

Per Bryman and Bell (2015), a *cross-sectional design* refers to the collection of data at a single point in time but from more than one observation in order to examine patterns of association between a set of variables and the unit of analysis. Such a design was useful at different stages of the research to collect evidence from multiple cases regarding the RQs inspiring this thesis. In particular, the cross-sectional design supported the data collection and analysis of experiences with and approaches in freight curbside management worldwide via various methods, including interviews, a literature review and a meta-analysis (see Section 3.3), that contributed to both Studies 1 and 2.

In Study 1, the cross-sectional design guided the collection of data from primary sources about the use of digitalisation in freight parking operations on the curbside and the managerial implications considering distinct stakeholders' perspectives (see Section 3.3.1). Secondary sources were also consulted regarding documented cases of digitalisation in curbside management. At that point in the research, the collected data from both the primary and secondary sources were coded based on the three macro-components proposed by Lin, Rivano and le Mouel (2017) regarding digitalisation in parking management: (i) information collection (i.e. sensing technologies on parking space availability), (ii) system deployment (i.e. software behind devices and data analytics for predicting parking availability) and (iii) service dissemination (i.e. information exchange between users and system managers, including pricing systems and enforcement). The managerial implications of the use of such technology were also discussed and synthesised in a framework for smart loading zones (SLZs), as shown in Section 5.2.

In Study 2, the research design supported the collection of data from documented experiences around the world—55 cases in all—regarding the relationship between curbside management initiatives and metrics for SDG11. Quantified performance measures of freight curbside management (e.g. delivery time, emissions, occupancy rate, cruising, cost and parking violations) were linked to the metrics for SDG11 using a meta-analytical approach (see Section 3.3.2), and general associations among variables guided the discussion for answering RQ3 (see Section 5.3).

3.3. Research strategy

The research for this thesis involved using quantitative and qualitative methods to analyse the data collected via interviews, a literature review and the freight parking technology in the case study. Both types of methods contributed to the development of the research in a complementary way. The triangulation of the methods, as encouraged in CR-based research, aimed at deepening as well as expanding the understanding of factors influencing curbside supply and demand for freight operations given the available qualitative and quantitative data.

3.3.1. Qualitative methods

The qualitative approach of the research for this thesis consisted of two methods: interviews and a literature review. With an exploratory nature, it aimed at gaining insights from transport planners, private freight operators and researchers about managerial aspects of freight curbside operations. Whereas interviews explored participants' perceptions of curbside supply and the role of digital technologies to improve the performance of operations, the literature review centred on tools for estimating freight demand and their implications for data-intensive needs.

Interviews: Focus on supply

Ten semi-structured interviews were conducted with four types of stakeholders: six urban transport planners, a vehicle manufacturing company, a parking technology provider and two carriers. The selection of participants followed convenience sampling, which targeted all of the Vinnova's project members, and additional participants referred by the project's steering group. Project members had participated in seminars and a focus group about curbside management prior to the beginning of the research for this thesis and thus possessed concrete knowledge from the digitalisation-oriented initiatives for freight curbside operations in their cities. Given the method's focus on supply, the sample was primarily composed of urban transport planners working in mobility offices in Stockholm, Sweden; Vic, Spain; Bogotá, Colombia; Prague, Czech Republic; and Emilia-Romagna, Italy.

Interviews were conducted online and lasted between 45 and 80 minutes. The interview protocol varied according to the type of stakeholder that the interviewee represented, and the interview questions were accordingly guided by the topics as marked in Table 3. Interviews were recorded, and their transcriptions were assessed using NVivo® version 20.5.0. For the purpose of this thesis, codes were defined based on Lin's macro-components for digitalisation in parking management, and a master's student supported the coding of the interview protocol.

Table 3. Structure of the interview protocol by type of stakeholder

	Urban transport planners	**Carriers**	**Parking technology provider**	**Vehicle manufacturer**
Digitalisation Role in urban freight strategy	x	x	x	x
Parking supply - planning Planning process for LZs	x		x	
Parking supply - allocation Number and location of LZs	x	x		
Parking supply - regulation Regulations about parking durations	x	x		
Enforcement Technology used to monitor LZs	x	x	x	x
Enforcement Fines for the misuse of LZs	x	x	x	

Literature review: Focus on demand

A literature review formed part of the cross-sectional design pertaining to modelling the estimation of freight demand. The review focused on the FTG modelling approach because it has been widely used by researchers and practitioners as a feasible framework for estimating the total number of freight vehicles arriving at establishments (Ogden, 1992). FTG is a tool for characterising zones in an urban setting according to the frequency of deliveries. FTG considers the type of industrial, commercial or service activity, as well as the size of the establishment and the number of employees, among other business features (Ortúzar and Willumsen, 2011), to estimate the number of freight trips generated by the zone(s) being studied.

The assessment of literature on modelling freight demand estimations consisted of identifying FTG procedures and choices reported in secondary sources regarding the definition of dependent and independent variables, the level of aggregation, estimation techniques, data collection practices and validation processes. The review aimed to gain an initial impression of models for estimating demand, which were further examined using quantitative methods for the specific field of freight parking operations.

3.3.2. Quantitative methods

The quantitative approach of the research for this thesis had an explanatory nature aimed at identifying significant interactions among variables that explain the studied phenomenon. Under the case-study research design, two data analytics methods were implemented (i.e. prescriptive and predictive) using freight parking records from Parkunload® from the City of Vic. In the case study, prescriptive methods supported the analysis of supply concerning LZ locations in relation to freight demand requirements, whereas predictive methods helped to clarify the dynamics of parking durations and their most influential factors. Last, a meta-analysis was conducted to quantify the effects of freight curbside management interventions on SDG11 from the results of a systematic literature review.

Prescriptive methods: Supply

Prescriptive methods, defined as data analytics procedures that provide optimal solutions to a specific problem (Appelbaum *et al.*, 2017), supported the assessment of LZ supply conditions in the case study. The methods considered variables such as the area of establishments, their economic activity and location, estimated demand for freight parking demand, walking distances from the LZs to the establishments, the availability of parking infrastructure and the road network. A two-step procedure first captured the interactions between spatial and demand variables by way of a greenfield analysis. Second, LZ locations were optimised based on the available parking spaces. Paper I contains a detailed explanation of the proposed procedures and algorithms, which are summarised below.

The greenfield analysis involved applying an LZ location problem using a continuous and unrestricted space in the studied zone of the city. Clustering algorithms grouped establishments based on a weighted distance criterion (i.e. walking distance multiply by an establishment's freight demand) either from a central theoretical point in each cluster, that is, *k*-means, or from the surrounding neighbours—that is, DBSCAN. After several iterations, the algorithms converged to a set of establishment-inclusive clusters whose centroid represented a hypothetical location for an LZ. The walking distance between centroids and grouped establishments met a maximum length defined by a coverage constraint (e.g. a walking distance of 75 m). Table 4 summarises the greenfield analysis's data-intensive needs, models and outputs.

Table 4. Summary of the greenfield analysis

Input data	Model	Output
Location of establishments	Clustering models used to compare performance to identify the best algorithm (e.g. *k*-means or DBSCAN) based on urban morphologies	Number of potential LZs
Walking distance between establishments		Approximate location of LZs
Spatial information from the study area (e.g. maps and roads)		
Parking demand: - Vehicle arrival rates - Parking durations - Economic activity of establishments - Area of establishments		Establishments' allocation to potential LZs represented by the centroid of each cluster

Source: Paper I

Parking demand was computed following Equation 1, in which τ_{jt} is the number of parking stalls required by the establishment *j* at time *t*. Equation 1 was derived from Little's law of queueing systems applied to parking operations (Tavafoghi, Poolla and Varaiya, 2019). Therein, λ_{kt} represents the arrival rate calculated with parking data from the LZ, *k*, at time *t*; μ_c corresponds to the specific parking duration computed for the economic activity, c, that the establishment *j* belongs to; θ is the acceptable curbside service level that public authorities expect (i.e. 85% is the most widely used); and WA_j^k denotes the weighted factor for the proportion of the area that establishment j occupies among all establishments in the same cluster, k. That weighted factor is included to account for the number of establishments that a freight vehicle serves per stop.

$$\tau_{jt} = \frac{\lambda_{kt}\mu_c}{\theta} WA_j^k \qquad (1)$$

Because the pre-identified centroids of the clusters could be located at unfeasible locations, the second step adjusted the results of the greenfield analysis by determining the optimal number and size of LZs and feasible locations for them depending on curbside features and available infrastructure. Integer linear programming was used to determine the minimum number of LZs and the number of parking stalls needed to satisfy the demand for parking hourly throughout the day. The model was run using the extended educational license of Lingo® 18.0.56. Table 5 summarises the data-intensive needs, models and outputs of the assessment of location allocation.

Because the City of Vic had already defined the locations and dimensions of LZs needed to satisfy the demand for parking from more than 340 establishments in the city centre, the results from the optimum location-allocation analysis were contrasted with the current situation to identify conditions of the over- or undersupply of LZ infrastructure within different windows of time.

Table 5. Summary of the analysis of optimal location allocation of LZ

Input data	Model	Output
Number and location of LZs (i.e. from greenfield analysis) and a list of feasible locations close to the centroids of clusters	Integer linear programming for the LZ location- allocation problem	Optimum number of LZs
Walking distance between LZs and establishments		Optimum location of LZs
Parking demand (Equation 1)		Optimum number of parking stalls per LZ

Source: Paper I

Predictive methods and multivariate analysis: Demand

On the demand side, quantitative methods were applied to predict parking durations and LZ occupancy levels based on significant variables that explained variability in such durations. Two approaches guided comparisons in duration analytics and LZ occupancy predictions: queueing models and predictive ML algorithms. The former involved using the arrival and departure time of freight vehicles as input data to estimate probability distributions of birth–death processes, whereas the latter used parking duration as the response variable and attributes of parking operations as covariates (i.e. vehicle type, commodity, weather conditions and time of the day, week, month or year). Based on the predicted durations, an occupancy profile was constructed for the LZs in the case study, and error metrics were used to compare the models' accuracy based on a comparison of predictions and observations. Paper II contains a detailed explanation of the implemented procedures and algorithms, which are summarised below.

In the queueing modelling approach (see Figure 11), freight parking is understood as a stochastic process with probabilistic vehicle arrival and departure rates to and from parking stalls representing servers in a time-varying $M(t)/G(t)/n$ queue—that is, non-homogeneous Poisson processes. $M(t)$ represents the Poisson process defined as discrete events that happen at a random rate of λ. $G(t)$ is the time-varying cumulative probability distribution of parking durations. The model considers a multi-server system because n multiple parking stalls per LZ independently provide a parking space service in parallel on a first-come, first-served basis. The number of occupied stalls $N(t)$, is a Poisson random variable with a mean $\eta(t)$ that results from assessing the functions $M(t)$ and $G(t)$. For instance, in the stationary case, with λ and μ as constants, occupancy estimations follow $\eta = \lambda\mu$ by way of Little's law.

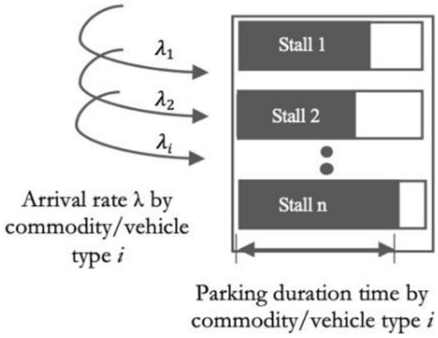

Figure 11. Queueing modelling approach for freight parking operations
Source: Kalahasthi et al. *(2022)*

In the ML approach, a set of algorithms for forecasting parking durations were tested. Generalised linear models were the baseline to compare regression trees, gradient-boosting machines and neural networks. The decision variable was parking duration based on the features vector $\mathbb{X}$, which contained 59 explanatory variables related to two numerical variables (i.e. feels-like temperature and precipitation) and dummy variables representing six categorical variables (i.e. vehicle type, vehicle emissions type, professional activity, LZ, hour of day [1-hour bins from 6–18 h], day of the week and month), all obtained after data pre-processing and dimensionality reduction. Aside from predicting durations, ML algorithms were also employed to evaluate the importance of the factors contained in $\mathbb{X}$ and ranked them according to the significance of their associations with the variability in parking durations.

Computed parking durations were the input for the arrival–departure timestamps needed to estimate occupancy rates per unit of time, *t*, as expressed in Equation 2, in which $n_p(t)$ is the number of active freight parking operations in the LZ p at time t, and the denominator $C_p(t)$ is the number of parking stalls available at the LZ p at time *t*.

$$Occupancy_p(t) = \frac{1}{C_p(t)} \sum_p n_p(t) \qquad (2)$$

The models' accuracy and explanatory power were assessed using metrics such as the coefficient of determination R^2, the mean absolute error, the root mean square error and the symmetric mean absolute percentage error. The data set was split into training (80%) and testing (20%) sets, of which the latter was the base for the evaluation of accuracy (i.e. forecasted vs. observed). The best ML algorithm was the one with the least error achieved.

Last, forecasted occupancy levels from queueing models and the best ML algorithm were compared using a validation data set composed of observed parking data not used during the training–testing process. The selected method was the one with the least mean absolute error in estimating occupied parking stalls per hour at each LZ.

Meta-analysis: Equilibrating supply and demand

Meta-analysis is a technique for extracting quantitative data necessary to conduct a statistical synthesis of multiple studies (Xiao and Watson, 2017). In the research for this thesis, the systematic literature review entailed searching for published work reporting performance measures for freight curbside interventions. Because effect measures vary from one study to another, the statistics of the reported studies were collected and transformed at comparable scales (e.g. elasticities or percentage of change). In essence, data extraction considered the percentage of change in performance measures of factors of freight curbside management and linked them to the metrics for SDG11.

The systematic literature review was built upon the search query ("freight parking" OR "loading zone" OR "loading bay") AND ("curbside" OR "curb side" OR "kerbside" OR "street") AND ("impact" OR "effect") AND ("sustainability" OR "sustainable development" OR "environment") AND ("urban" OR "city"). To avoid sources of sample bias (e.g. publication bias), the Google Scholar database was used to access grey literature, including unpublished reports, thesis, preprints and white papers. The first 980 results of the 2350 total results were available for inclusion in the sample, and publications from the Web of Science, ProQuest and Scopus databases were included as well. The search process was conducted in April 2022. The depuration of the first query results consisted of selecting published works based on information in the title and snippet, and only works that contained the keywords connected coherently in aspects related to the research conducted for this thesis were selected.

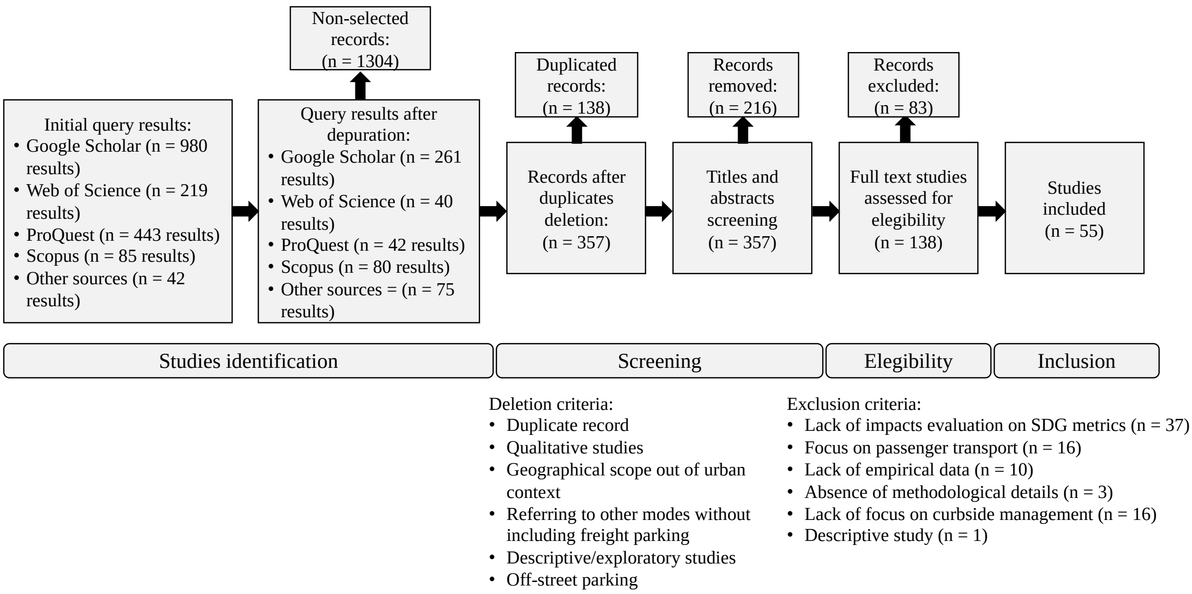

Figure 12. PRISMA diagram of the systematic literature review
Source: Paper IV

The screening process eliminated 138 duplicated results and filtered 357 records that matched the research interest. After the deletion and exclusion criteria shown in Figure 12 were applied, 55 records were included for data extraction. The list of references is available at https://dsw.chalmers.se/projects/d69106a2-6a4b-42d5-9a47-5185b9f7f621.

Published works were selected based on the possibility of accessing quantitative results about the measures of delivery time, cost, parking violations, emissions, curbside occupancy rate and cruising for parking as indicators of the performance of curbside management. Besides the summary statistics, the systematic literature review also collected information about the country, city and zone of study, as well as data collection methods and assessment tools (e.g. microsimulation and optimisation). Performance measures were assigned to the corresponding metrics for SDG11 based on each paper's aim and practical implications.

3.4. Research quality

Bryman and Bell (2015) have defined three criteria for evaluating research quality: reliability, replication and validity. *Reliability* refers to the consistency of the results across repetitions of the same study. Closely related to reliability, *replication* refers to the possibility of the research's replicability by other researchers using the same data and documented methods. Last, *validity* refers to the integrity of the conclusions of research and the transferability of the results.

As concerns reliability, the quantitative approach of the research conducted for this thesis involved using different algorithms and optimisation models that are subject to variation according to the modeller's view, the software's characteristics and/or data randomness. Detailed documentation of the implemented models' parameters and hyper-parameters coupled with technical specifications of the software used to run the models mitigated reliability risks. Randomness also needed to be considered because some variables were probabilistic in nature. Probability distributions of the assessed variables with the corresponding estimators of maximum likelihood and deviation metrics were also documented.

Meanwhile, ensuring reliability in the qualitative approach was possible by making sure that the interview protocols were consistent and followed the same template according to the actor's role as a stakeholder. Recording interviews also helped to reduce the risk that the researchers overlooked any information. Two researchers were present throughout the interviews, which facilitated discussions after each interview to avoid interpretation bias.

Regarding replicability, Bryman and Bell (2015) have suggested that procedures have to be documented in detail so that replication is possible. Aside from documenting the models in the papers, all of the algorithms, the optimisation model and the systematic literature review's process and results were uploaded to satisfy that quality criterion, namely to https://github.com/jpcastrellont/freight_curbside_operations.git, and to encourage transparency and replicability in the use of the quantitative tools. However, real data from the case study were not uploaded due to confidentiality agreements and compliance with the General Data Protection Regulation.

Last, validity can be assessed as internal and external validity. On the one hand, *internal validity* refers to whether a study provides enough elements to answer its RQ(s) to an adequate degree (Säfsten and Gustavsson, 2020). The mixed qualitative–quantitative approach followed to address the RQs in the research conducted for this thesis provided a complementary contribution to solving the research problem. It also motivated a triangulation process to assess the findings' suitability and validity based on perspectives from actors interviewed and results from reference studies in the literature. In the quantitative approach, the use of multiple data sources (e.g. weather conditions, parking operations and establishments' data), together with the comparison of methods (e.g. queueing models vs. ML algorithms), helped to secure robust internal validity rooted in objective performance evaluations. Beyond that, statistical measures for evaluating the models' explanatory power and the variables' significance were constantly assessed, such that decisions about model selection prioritised the best performance and conceptual validity. In the qualitative approach, by contrast, the triangulation of sources and respondents' validation of the data through the dissemination of the analysis of the interviews mitigated risks of poor internal validity.

On the other hand, *external validity* refers to the generalisability of results (Säfsten and Gustavsson, 2020). Throughout the four appended papers, transferability is a key topic of discussion. Given the variability of urban conditions, it is challenging to generalise results from quantitative models based on case data and qualitative studies based on actors' perspectives on specific contexts. Nonetheless, data attributes and analytics procedures implemented in the research for this thesis are subject to being transferred to other studies and contexts. Further comparisons of case studies (i.e. multiple-case studies) could also contribute to the generalisation of the findings and the theory building in the field of freight curbside management. Therefore, a multiple-case strategy represents an opportunity for future research, as discussed in Section 5.5.

3.5. Summary of the research methodology

Table 6 summarises the methodology of the research conducted for this thesis as described in this chapter and presents each study's research designs, research strategies, methods, papers and RQs that it helped to answer.

Table 6. Summary of the methodology of the research conducted for the thesis

<table>
<tr><th>Study</th><th>Research design</th><th>Research strategy</th><th>Method(s)</th><th>Paper(s)</th><th>Contribution to RQ(s)</th></tr>
<tr><td rowspan="3">Study 1: Data-driven curbside management</td><td rowspan="2">Case study</td><td>Quantitative</td><td>Prescriptive methods
Predictive methods</td><td rowspan="2">Paper I
Paper II</td><td rowspan="3">RQ1 and RQ2</td></tr>
<tr><td>Qualitative</td><td>Interviews</td></tr>
<tr><td rowspan="2">Cross-sectional</td><td colspan="2">Literature review</td><td>Paper III</td></tr>
<tr><td>Study 2: Sustainable impacts</td><td>Quantitative</td><td>Meta-analysis</td><td>Paper IV</td><td>RQ3</td></tr>
</table>

4. Summary of the appended papers

This chapter summarises the chief outputs of the research conducted for this thesis. It begins with reflections on the backbone of the thesis: digitalisation. The first section presents several stakeholders' perspectives on digitalisation's role in freight curbside management. Afterwards, a summary of the papers is presented with a description of their scope, the methodological approach taken, their major findings and their contributions to the research field.

4.1. The role of digitalisation in freight curbside management

Digitalisation is the backbone of the thesis's output presented in the following sections. Capturing data from freight parking operations enables using data analytics to support informed decision-making about managing LZs at different levels, as discussed in Section 5.2. However, implementing technology and having data available are not enough, for digitalisation also requires stakeholders' involvement and collaboration to translate the adoption of technology into concrete impacts on urban liveability. This section thus serves as an introduction to this chapter of the research's contributions by reflecting on the role of digitalisation in freight curbside management. The reflections are based on data collected via interviews with policymakers and private companies, whose views were classified using Lin's three macro-components for parking digitalisation: information collection, system deployment and service dissemination.

Information collection

Cities have institutions and technological means to control the use of the curbside, especially to monitor private cars that park there. Under those schemes, parking fines have been the sole source of data on freight parking operations. Public authorities used to get reports from enforcement agents or companies about the illegal conduct of freight drivers and/or the income that they generated for the city in the form of fines paid. As a result, knowledge of freight parking operations was limited to enforcement income statements and did not encompass their demand for curbside space or their impacts on urban liveability.

> Parking, in general, is a big deal in my organisation because it is the cash flow to my department due to the parking fees. Since drivers do not pay for the use of loading zones, there are some built-in interests in the city to minimise loading zones and maximise parking lots to increase income. (Respondent from the public sector)

More recently, technological developments have increased public authorities' expectations for controlling parking. They have also broadened the scope of parking monitoring by providing data about the use of the curbside, the types of users, activities performed and dwell time. For instance, parking surveillance using enforcement cars equipped with cameras (i.e. scan cars) has been found to be a convenient means of collecting data about curbside occupancy instead of only parking violations. Cameras and sensors installed on the curbside also provide real-time data about parking occupancy and, at times, types of users. Beyond that, mobile app systems furnish data on vehicles' arrival, departure and attributes regarding, for instance, type and technology, type of commodity and economic activity.

Public space managers have those and other forms of parking technology at their disposal to improve their planning and control capabilities. Selection criteria rely on cost–benefit assessments, privacy protocols (i.e. compliance with the General Data Protection Regulation), how easily users can interact with the technology (e.g. mobile app user interface) and the quality of parking data that can be collected. At the same time, public authorities have also observed the need to gain insight into freight vehicle operations on the curbside beyond traffic violations in order to improve decisions about allocating space.

> Having good information and real-time information of what happens on the curbside to support decisions regarding LZ is beneficial for the city. When you measure, you can control, but if you do not measure, you lack pieces of the big picture that are fundamental to making better decisions. I think technology plays an important role in efficiently managing the space. (Respondent from the public sector)

When cities have more than one technology for monitoring parking, space managers confront the challenge of realising their interoperability so that the cross-validation of data from multiple technologies can enrich decisions about curbside management. For instance, in-ground sensors and cameras that capture curbside occupancy need to be complemented with data from mobile apps to capture, among other things, types of users and activities performed. That information is also helpful for private companies seeking to improve their routing programmes based on the forecasted availability of LZs.

System deployment

In curbside management, investments in technology are worthwhile only if they facilitate the better management of space. Digitalisation-oriented efforts should go beyond the implementation of technology by building data analytics capabilities to support decisions about the curbside. Some of the cities that the interviewees represented face the big-no data paradox, which refers to limited knowledge about the use of the curbside despite being in possession of parking technology and big data. Although several conditions explain the paradox, two were mentioned most frequently during the interviews: limitations to data sharing and a lack of data analytics tools.

Data about the curbside can be scattered among various actors. Private companies possess GPS data about truck trajectories in cities, recipients' information and the attributes of packages delivered. Meanwhile, parking space managers have data about occupancy profiles and income from parking on the curbside, whereas urban planners have data about land use and claims to curb space from different actors. Data-sharing is a powerful solution for combining those pieces of the puzzle and enhancing space management. Nevertheless, a lack of incentives to share sensitive data, distrust, the weak involvement of stakeholders and privacy concerns are among what hinders data-sharing strategies. As a respondent from the private sector explained, "We have so much data but don't know how to make a profit on it, so we keep it".

One step towards overcoming obstacles to data sharing could be collaboration within the public sector. Technology used in private parking systems is not integrated with the technology used in managing freight parking operations or even with other users of, for instance, public transport and public biking systems. Moreover, enforcement agents use divergent systems to control parking for private cars and LZs, and, sometimes, their systems are not connected to the ones that users have for LZ check-in and check-out. On top of that, cities within the same metropolitan area may have parking technologies that are incompatible, which requires users to install as many applications as cities visited during a delivery route.

> At the regional level, there are several problems, and there are several urgent tasks. So, let's say that the most important is the lack of communication among different cities and between them with actors of the supply chain. (Respondent from the public sector)

Apart from coordination in the public sector, sharing data with private companies should be initiated by understanding what data they have available, their needs and their roles in freight operations. For instance, transport operators could have GPS data but lack information about recipients, which could be available upstream in the supply chain (e.g. among shippers). Therefore, freight parking systems should follow a supply chain logic that involves companies in providing data instead of only individual users of parking stalls. The provision of information by private actors should also be motivated with incentives that show them the benefits of sharing data (e.g. savings in urban deliveries due to improved curbside management).

> It is possible to have a company profile, and you can associate different plates with this profile. So, the driver does not need to register any information, only LZ check-in and check-out. There will be a company profile which will contain all the information regarding the vehicle, economic activity and receivers' location. (Respondent from the public sector)

Regarding data analytics tools, ML represents a convenient way to handle data, analyse them and use results as input for policymaking. Descriptive, predictive and prescriptive models can be integrated into parking systems so that urban transport planners and the private sector can base their decisions on forecasted and actual conditions. The public sector already has information about parking, but most uses documented are oriented towards controlling parking and collecting fares. ML in curbside management could expand the use of data by linking them to actions that de-conflict the curb and make freight operations more sustainable.

Service dissemination

The benefits of digitalising the curb become tangible when data-driven decisions foster urban sustainability and improve public space services for all actors who lay claim to it. For instance, parking technology in LZs represents a means to spur cleaner vehicle technologies by allowing only certain vehicle types to use them, thereby motivating modal shifts. They can also encourage operations at off-peak hours, the use of pricing incentives and/or access regulations, which bring operational and sustainability benefits while freeing up space for other users when needed. Such technology also contributes to influencing drivers' behaviours by not only making them comply with curbside regulations but also reducing the stress of finding available parking stalls. Therefore, although transport-related technology and cleaner energy are in the spotlight of strategies for the decarbonisation of transport, digitalisation has been highlighted as a necessary vehicle for the sustainability agenda to be able to decarbonise transport because it supports modal shifts and initiatives for managing demand.

> Digitalisation is a key enabler of decarbonisation. Simple solutions like mobile apps make parking not so complicated with just check-in and check-out. Probably the technology can be better. Let's say an automatic check-in could be implemented, maybe even with Wi-Fi or Bluetooth connections. But I think it's a low-cost solution that can be used to promote cleaner vehicle technologies and shift delivery routines to off-peak hours. (Respondent from the public sector)

Overcoming barriers to data sharing thus becomes critical to achieving the expected effects of digitalising the curb. Public and private sectors agree on the target but face limitations in their means to achieve it. Curbside management should consider actions to motivate stakeholders' willingness to share data on common platforms, the realisation of which requires systems interoperability. Along with technological infrastructure, those actions should consider the development of business models, incentives for private companies, organisational capabilities and clear communication about how collected data will be used. Impacts evaluation should also be regularly conducted to demonstrate how data-driven decisions benefit society in general.

> We are too scared for data sharing. The reason for modern businesses' success is data. Can we use our data in a better way? How can one share data in a reliable way? It's not a technical problem but a problem with the business model and how to earn money. It's not

> a technical problem, but who owns and controls it. It should drive us to sustainability. (Respondent from the private sector)

Stakeholders' perceptions agreed on the relevant role of digitalisation in enhancing freight curbside management. The following sections summarise research contributions that, leveraged by data from parking technologies, assessed curbside supply-demand for freight operations and the impact of interventions on SDG11.

4.2. Paper I: "Smart loading zones: A data analytics approach for infrastructure network design in freight curbside management"

Paper I contributes to the supply-related focus of RQ1 by investigating the elements of design that urban transport planners should consider when allocating curbside space for freight operations. The paper elaborates on the decision-making process conducted in the planning and management of LZs based on a proposed definition of SLZs. The paper also advances a data analytics approach for designing LZ networks using the case study of Vic, Spain. Insights from the results additionally contribute to answering RQ2 by illustrating the benefits of digitalisation in providing data to improve decisions in freight curbside management.

Purpose

Paper I's aim is twofold: to propose a conceptual approach to studying and developing SLZs and to develops a data analytics approach for designing SLZ networks that defines the number, location and size of LZs under stochastic freight parking demand.

Method

To define *SLZs*, literature on freight curbside management was grouped into a three-level framework for addressing strategic (i.e. long-term), tactical (i.e. midterm) and operational (i.e. short-term) decisions regarding LZ infrastructure, regulations and information and communication technology (ICT). The paper focuses on the strategic decision-making level, specifically on designing LZ networks. In a case study, ML clustering algorithms (i.e. *k*-means and DBSCAN) and optimisation methods (i.e. integer linear programming) illustrated the use of app-based data from freight parking operations to support decisions about locating and allocating LZs amid variability in demand.

Results and contributions

The authors built on previous definitions of LZ and digital LZ (see Figure 13) to define *SLZs* as

> Stop delimitated areas, where freight loading and unloading operations take place, equipped with technologies that provide real-time information for vehicle detection, parking space monitoring, and parking assignment, where data coming from connected infrastructure and mobile devices are used by public authorities, space owners/managers, and private companies to make informed decisions that enhance operational efficiency and urban liveability.

The paper presents the LZ interventions, choices and relevant questions guiding the implementation of SLZs based on previous research at strategic, tactical and operational levels. As the case study, the City of Vic provided empirical evidence to address strategic decisions related to designing LZ networks.

A greenfield analysis showed the results of clustering establishments around centroids (i.e. potential LZ locations) in a continuous solution space based on establishments' location, demand for deliveries and weighted distances to potential LZ locations. The two clustering algorithms (i.e. *k*-means and DBSCAN) were compared to identify the one with the most establishments covered within a walking distance of 75 m from the corresponding centroid. Taking those centroid locations as a basis, the optimisation programme involved adjusting the solution of the greenfield analysis with discrete feasible locations on the curbside for LZs. It also revealed the optimum LZ size, given in terms of the number of parking stalls during each hour throughout the day. Results showed how an optimised number, location and size of LZ improved occupancy levels (i.e. from 18% in the current case to 80% in an optimised scenario) while freeing up curbside space for other users (i.e. for freight operations that vary during the day). The total number of LZs changed from eight in the current scenario to five in the optimised one. Service coverage was also improved by allocating LZ to establishments within walking distances no greater than 75 m.

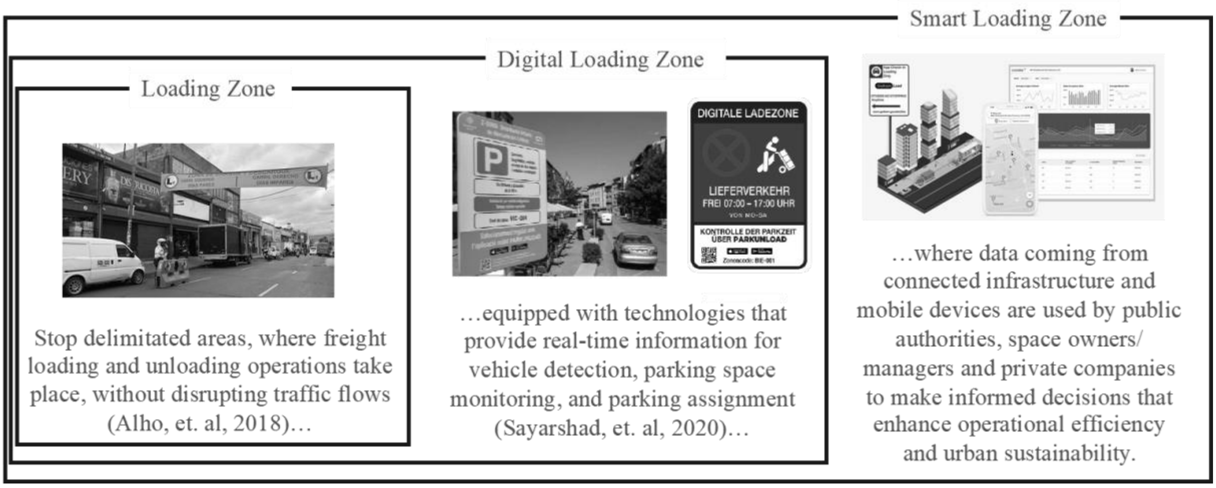

Figure 13. Definition of SLZs
Source: Adapted from Paper I

Paper I's chief contribution is the conceptualisation of SLZs and their management. It provides tools for urban transport planners constantly challenged by the trade-off between land use optimisation due to the scarcity of public space and demands for service provision (i.e. establishments' needs for freight accessibility). The deployed modelling approach for designing LZ networks allows urban transport planners to reconcile the mentioned trade-off based on accurate data about when and how much space is required for parking for freight operations. The paper also demonstrates how dynamic LZ size (e.g. varying every hour according to fluctuations in demand) provides a solution for achieving curbside supply–demand equilibrium. This paper also shows how freight parking data availability enables curbside space redistribution when demand for freight parking is low.

4.3. Paper II: "Enabling factors and durations data analytics for dynamic freight parking limits"

Paper II contributes to answering RQ1 by identifying factors that urban transport planners should consider when implementing regulations for flexible LZ management from the supply side of curbside management. Knowledge of those factors enable tailoring regulations for freight parking operations that consider variability in demand across time and customised rules according to operational features (e.g. type of commodity delivered). Regarding the demand side, the paper explores significant associations between features of freight operations and parking durations. The paper also addresses RQ2 by exemplifying how data from a curbside digitalisation strategy can improve estimations of the demand for parking.

Purpose

Paper II aims to identify factors that enable dynamic parking duration limits in parking regulations and to assess data analytics tools that support their design based on an explanatory analysis and estimated forecasts of freight parking durations and LZ occupancy levels.

Method

The research presented in Paper II involved using qualitative methods (i.e. semi-structured interviews and a focus group) to collect data conducive to identify factors of leveraging flexible LZ management. A quantitative approach (i.e. generalised linear modelling) was used to assess the significance of variables that influence freight parking durations and evaluate analytical tools (i.e. queueing models and ML algorithms) in terms of their accuracy in forecasting freight parking durations and LZ occupancy levels.

Results and contributions

The codification of qualitative data collected from 10 interviews and a focus group resulted in the identification of four major factors of leveraging flexible LZ management: dynamic public space allocation, estimations of parking demand, enforcement-related capabilities and data-sharing strategies.

Assessing the use of public space implies identifying users of the curbside and their varying demands for space. It also entails defining hierarchies in the ROW due to the scarcity of infrastructure and conflicting demands for space. In connection with that factor, estimating the demand for parking is required to understand how the demand for space behaves across time so that the allocation of space and regulations about curbside use (e.g. parking limits, vehicle restrictions and types of permits) can incorporate dynamic elements according to variability in demand. The third factor, enforcement-related capabilities, aims to ensure that users comply with the designed regulations so that the system's performance maintains expected levels in terms of parking turnover, traffic, emissions and safety. Last, data-sharing strategies and their analytics are fundamental for the success of the other three factors because they are the basis for collecting data about the curbside, digital enforcement and data-based decision-making by public and private actors.

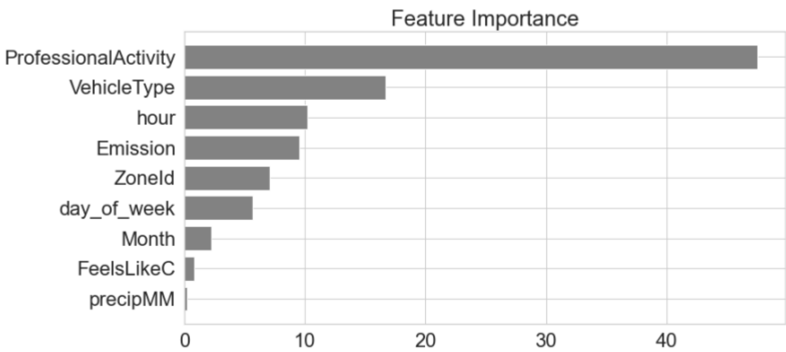

Figure 14. Ranked importance of features in explaining variability in parking durations
Source: Paper II

In the case study, involving more than 103,000 parking records of freight vehicles in Vic, Spain, big data from the parking operations allowed assessing the significance of variables, which revealed that professional activity (i.e. type of commodity), type of vehicle, the hour of the day and emissions (i.e. vehicle technology) were the most relevant factors when explaining variability in parking durations (see Figure 14). CatBoost outperformed the other ML algorithms and queueing models in forecasting freight parking durations and LZ occupancy levels.

Paper II contributes to the field of freight parking by elucidating factors of successfully implementing dynamic regulations based on demand conditions and how data analytics can support the definition of dynamic parking limits that facilitate flexible curbside management. Formal representations from queuing theory and ML were deployed and tested in the studied context, and, as a result, insights about their use and parametrisation are another of the paper's contributions. Tailor-made regulations can be designed by applying those models to specific contexts and areas of cities.

The proposed model for estimating parking durations and LZ occupancy levels showcases how variable the demand for curbside space is throughout the day and week. In response, the curb should be adapted for uses other than simply freight parking. Last, the methods analysed constitute advanced tools for designing parking profiles for zones without data available and suggest possible analytics applications in parking enforcement driven by data-sharing schemes.

4.4. Paper III: "Freight trip generation models: Using establishments' data to understand the origin of urban freight traffic"

Paper III contributes to answering RQ1 by revising quantitative modelling tools and practices in estimating freight demand. Published as a book chapter, it compiles available methodological approaches to develop FTG models based on data from establishments.

Purpose

The purpose of Paper III is to describe methodological choices, statistical procedures, data requirements and empirical settings for estimating freight demand in urban contexts by reviewing literature addressing FTG modelling.

Method

Paper III builds on a literature review aimed at collecting data about research on FTG modelling and applications following a taxonomy of methodological approaches, data inputs, geographical scope and transferability tools (see Figure 15). The review included an application of FTG modelling in a case study of Stockholm, conducted by the paper's first author in a research project that predates this thesis.

Results and contributions

Paper III describes sources of data for estimating freight demand and reflects on the drawbacks of traditional sources (e.g. surveys and direct observation) and current opportunities with the upsurge of new technology that allows capturing probed data about freight demand. It also reviews methodological techniques and their implications in terms of cost, complexity, statistical procedures and time. Significant variables for inferring freight demand are also reviewed that constitute a relevant input for designing forms of data collection and delimiting the scopes of modelling and the utilisation of results. Last, the paper identifies uses of FTG modelling—for instance, supporting transport policies and investing in infrastructure—and their links with other modelling techniques, including agent-based models, demand models and microsimulation.

As for empirical findings from the case studied, evidence suggests the significant impact of commercial activities on freight traffic and the importance of providing the right access to freight delivery infrastructure (e.g. LZs) to reduce the potential impacts on congestion and the urban environment.

Paper III thus contributes to illuminating the current state and future challenges of estimating freight demand with FTG models, as well as indicates connections between modelling outputs and urban freight initiatives (e.g. policies, plans and projects) led by public and private actors.

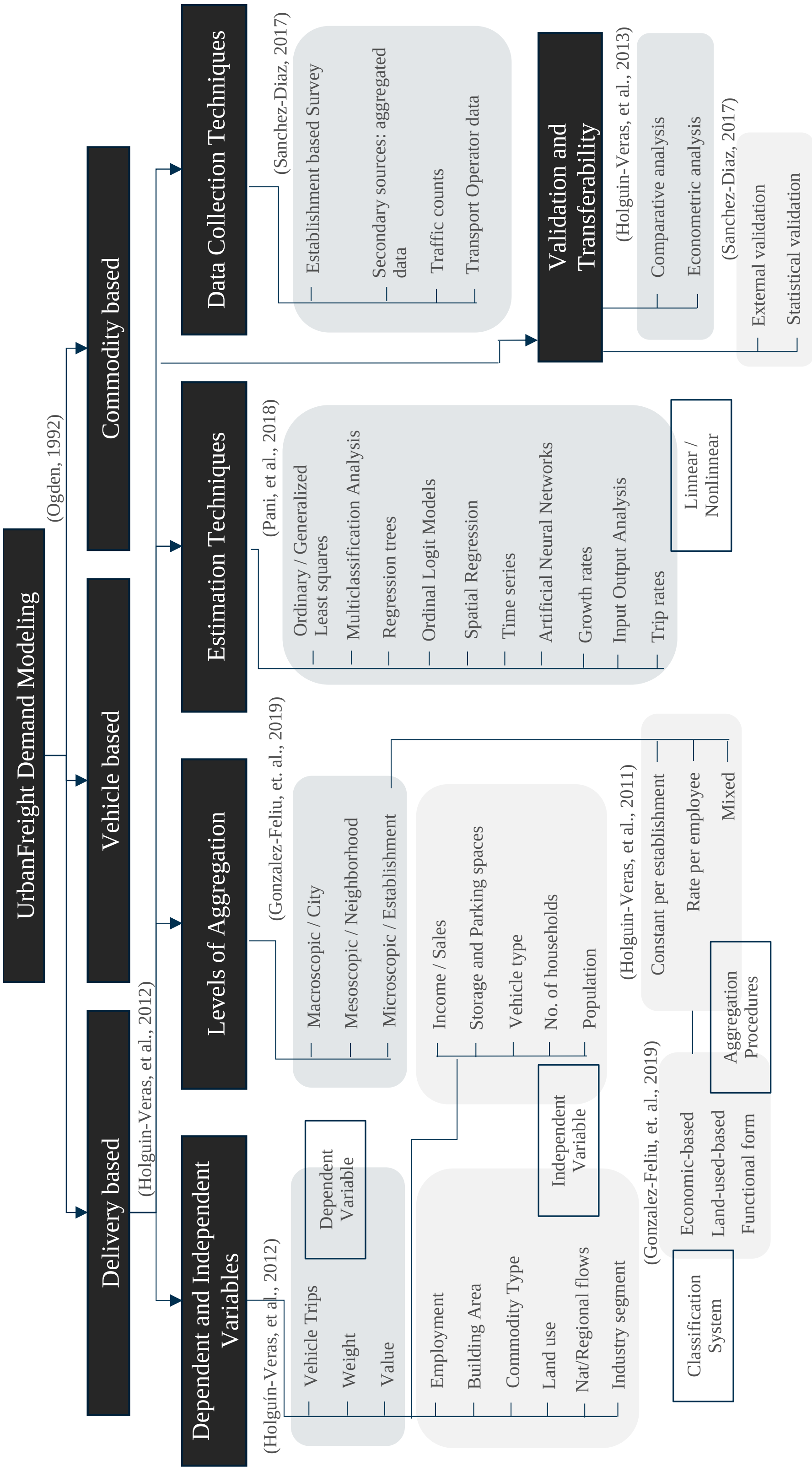

Figure 15. Taxonomy of FTG modelling
Source: Paper III

4.5. Paper IV: "Uncovering freight curbside management effects on cities' sustainable development goals: A systematic literature review"

Paper IV contributes to answering RQ3 by exploring the potential effects of curbside management interventions on SDGs, namely SDG11 (i.e. sustainable cities and communities). It is based on connections identified in the literature between metrics for SDG11 and selected key performance indicators (KPIs) of freight curbside operations (see Figure 16).

Purpose

Paper IV aims to explore how curbside management interventions can make freight parking practices sustainable by reviewing reported quantifications of performance measures and linking them to metrics for SDG11.

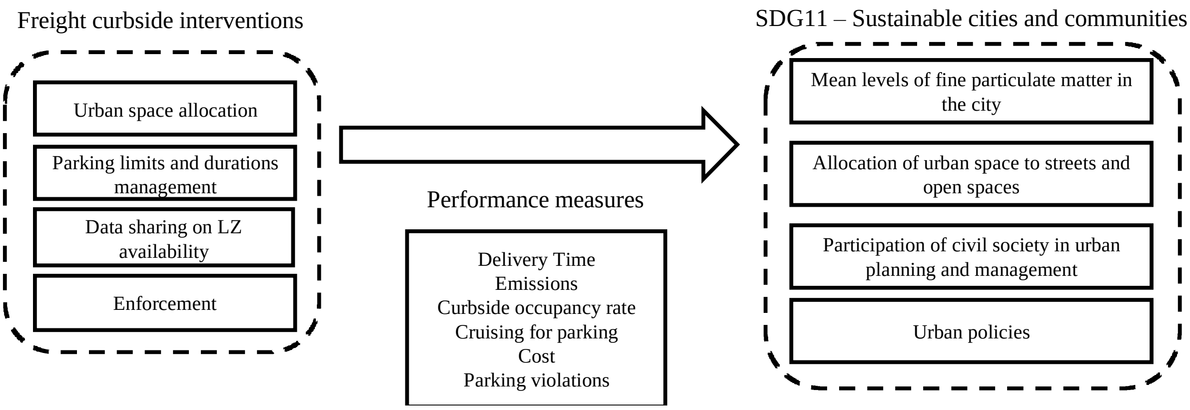

Figure 16. Connections between SDG11 metrics and curbside management interventions
Source: Paper IV

Method

A meta-analysis was performed to explore curbside management's effects on the realisation of SDG11 based on a systematic literature review. Aside from the KPIs of freight parking operations (i.e. delivery time, emissions, occupancy rate, cruising, cost and parking violations), data about empirical evidence, context(s) studied and methods reported in the 55 works reviewed were also collected.

Results and contributions

The meta-analysis revealed that interventions in the allocation of public space, parking limits, data sharing and parking enforcement have had three major positive impacts on the realisation of SDG11. First, available space for parking and information about its occupancy reduce cruising (↓12.8%–100%) and, therefore, greenhouse gas emissions (↓5%–95%). Second, effective space management supported with technologies frees up space for other users (up to 70%) while increasing LZ occupancy rates (up to 60%) as well as preventing cruising and illegal parking. Third, curbside management improves public and private decision-making and reduces the last-mile deliveries' durations (up to 78%) and costs (up to 27%).

Paper IV's contributions lie in pinpointing how beneficial or detrimental freight parking interventions are for cities' sustainability and in quantifying the effects of curbside management on the achievement of the UN's SDGs for assuring universal access to safe, inclusive, green public spaces.

4.6. Summary of papers' contribution

The type of contribution of each paper is summarised in Table 7. Conceptual or theoretical contributions involve new or improved definitions of existing constructs or concepts. Methodological contributions refer to developing novelty methods to study the problem under investigation. Contributions in research into practice/utilisation include insights that practitioners can use to approach the solution of practical problems.

Table 7. Summary of papers' contribution

	Type of contribution		
	Conceptual / Theoretical	**Methodological**	**Research into practice / Utilisation**
Paper I	Definition of SLZ and decision-making framework.	Data-driven tools for freight parking space allocation.	Illustration on how to solve trade-off between public space optimisation and service provision.
Paper II	Factors for leveraging responsive LZ management.	Comparison of modelling tools for estimating parking durations and forecasting LZ occupation.	Insights on how to design flexible parking regulations and their implications in curbside management.
Paper III	Taxonomy of FTG modelling.	Review of freight demand estimation methods.	Implications of freight estimations on urban transport planning. Data challenges in estimating freight demand.
Paper IV	-	-	Review of curbside management effects on sustainable development goals.

5. Discussion

This chapter discusses the results of the research conducted for this thesis in light of the research aim and RQs, as well as discusses the research's contributions and limitations. As mentioned in Section 1.3, this thesis explores significant factors at play in managing curbside supply and demand for freight parking operations and contributes to current understandings of the need for and uses of data to inform curbside management decisions and gauge their impacts on SDGs. Answers to the three RQs were needed to achieve that aim and are addressed in the following sections.

5.1. Factors determining curbside supply and demand for freight parking (RQ1)

RQ1 addressed the factors determining curbside supply and demand for freight parking. From the supply side, understood as the provision of infrastructure for freight parking operations, results from the interviews showed that flexible curbside management is critical to equilibrate scarce parking infrastructure with variable parking demand. Interviewed actors confirmed what was found in the literature regarding how the allocation of fixed space may lead to an oversupply of infrastructure when freight parking demand is low. The excess of infrastructure and fixed regulations on the use of such space thus prevent other users from using curbside space, even if it is empty. Conversely, overlooking freight operations in the allocation of space or the insufficient provision of space for such operations in relation to demand leads to cruising for parking or illegal parking, which are detrimental to the environment, mobility and nearby establishments. Therefore, this thesis answers RQ1 from the supply side by identifying factors that facilitate flexible curbside management.

The content analysis of data from the 10 interviews and of data collected in the general research project (i.e. focus group interviews) revealed four major factors of successfully leveraging flexible curbside management: an understanding of the uses of public space, knowledge about and management of parking durations, enforcement-related capabilities and data-sharing strategies.

Urban planners could consider those four factors in designing and implementing curbside regulations to ensure that supply-side conditions satisfy users' demands dynamically over time. For instance, in the studied case, city authorities may revisit the SLZ programme based on the findings from data analytics (i.e. data-sharing strategies) regarding the use of space (i.e. an understanding of the uses of public space), parking durations (i.e. knowledge about and management of parking durations) and parking violations (i.e. enforcement-related capabilities). Figure 17, showing the gap between freight parking occupancy and LZ capacity, reveals conditions of curbside oversupply and undersupply at specific times during an average week. Those profiles were built with data about parking durations and demand across time. Beyond that, the factor of enforcement-related capabilities appeared to be fundamental to making users comply with rules for using the curbside and users' hierarchy in the ROW. More broadly, estimations of the use of capacity were valid due to being based on actual curbside operations.

Information about curbside operations can also be used for inducing users' behaviours based on patterns of demand. For instance, regulations about parking durations may encourage higher turnover at peak hours while motivating longer operations to occur during less congested times. Demand-driven interventions can also take advantage of flexible curbside management to open up space for diverse uses when freight parking demand is low and other specific modes want to be promoted (e.g. biking and walking).

Flexible curbside management implies dynamic provision of infrastructure. The parking occupancy profile shown in Figure 17 identifies the number of parking stalls needed at different times of the day and/or week. Overcapacity was evident in the case study, although LZ Vic-003 was an exception, but can be solved by reducing the number of available stalls or merging existing LZs based on criteria of geographical coverage. Data about walking distances and establishments' locations are needed, however, to conduct greenfield analysis and optimise the design of LZ networks, as showcased in Paper I. The critical input for those models is parking demand.

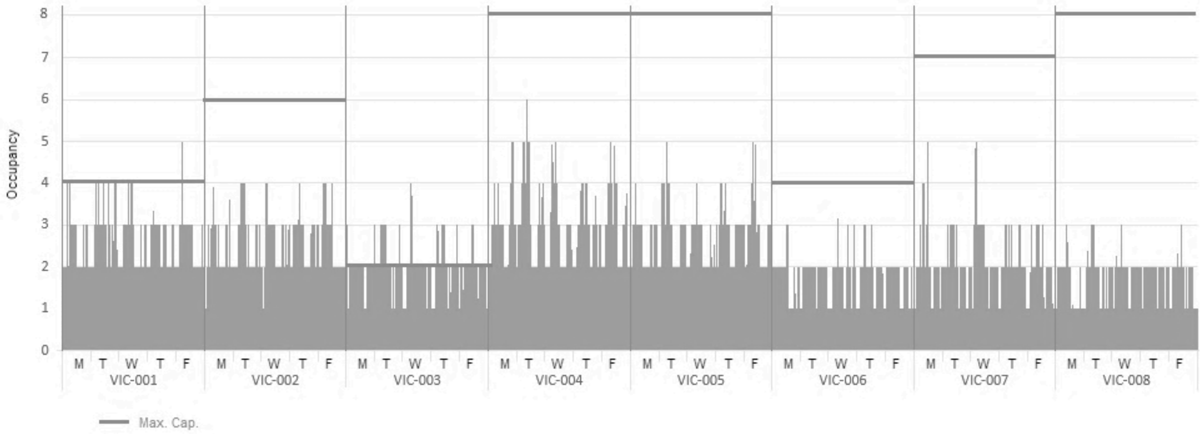

Figure 17. Freight parking occupation profile
Source: Paper II

Factors determining parking demand were identified with quantitative models. As addressed in Paper III, FTG models represent a feasible way to estimate parking demand when establishments' data are available. The literature review on FTG revealed three significant variables for explaining freight demand estimations: the size of establishments (i.e. in terms of area or number of employees), the type of economic sector and the intermediary role of the establishment in the supply chain. Geographical factors were also found to be significant, namely land market value, district classification and geographical location of establishments. The challenge of using FTG for estimating parking demand lies in modelling the relationship between establishments' demand for freight and the number of deliveries that a freight vehicle performs per stop, an obstacle that can be overcome through probed freight parking operations, as addressed in Papers I and II.

After parking operations from the case study were probed, explanatory models were used to identify the importance of variables when estimating parking durations. Economic activity, vehicle size and the hour of the day were the most relevant factors for estimating parking durations; of them, hour of the day strengthens the convenience of flexible curbside management that establishes rules based on temporal variabilities. Surprisingly, weather conditions did not significantly explain variability in parking durations, which could be explained by the low variability of those factors in the studied context. However, they may become significant in cities where weather conditions are extreme.

5.2. Data-driven curbside management enabled by digitalisation (RQ2)

RQ2 motivated reflections about how digitalisation in freight operations enables data-driven curbside management. As presented in Section 4.1, digitalisation is critical to enhancing curbside management; however, stakeholders' concerns and incentives have to be considered in order to reap its benefits. The use of technology to track freight parking operations is the backbone of the concept of SLZs, which benefit from data analytics fed by digitised operations to make strategic, tactical and operational decisions (see Figure 18).

At the strategic level, digitalisation enables the collection of data regarding arrival rates, parking durations, types of economic activity and parking locations. Those data, complemented with data from establishments and urban form features, are the input for implementing clustering algorithms and solutions for optimising location allocation that support decisions about the provision of infrastructure, as addressed in Paper I (i.e. number, location and capacity of LZs). Those methods can be applied to close the gap identified by the City of Vic as follows: "the best tool that decision-makers can have for managing LZ in urban areas would be the definition of "ratios" [based on zones features] or methodologies to establish the number and location of LZ, similar to what we have for private transport" (City of Vic).

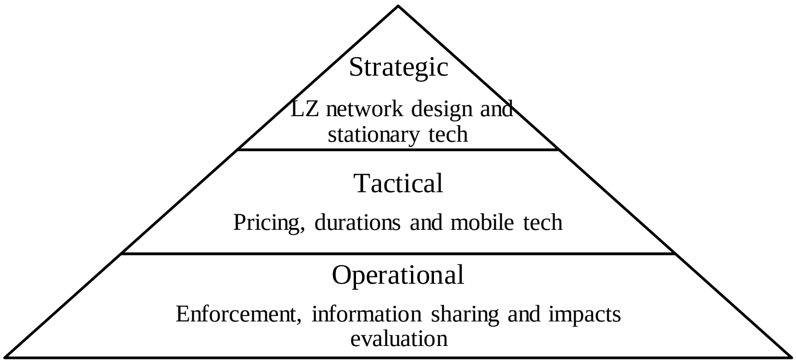

Figure 18. Decision levels in LZ management
Source: Adapted from Paper I

Despite the benefits of digitalisation, urban planners should consider the extent to which different forms of technology provide the data required for making the strategic decisions shown in Table 8. For instance, sensors can provide data about occupancy but not details about vehicle types or economic activity.

Table 8. Curbside management at the strategic level enabled by digitalisation

Decision-making level	**Category**	**Type(s) of decision(s)**	**Relevant question(s)**	**Data enabled by digitalisation**
Strategic	Infrastructure	Number, location, capacity and size of LZs	What is the demand for LZs at different locations? Where and how many LZs should be allocated? How many parking stalls should be provided?	Arrival rates, FTG, parking durations, curbside inventory and distances to establishments
	Public policy	LZ authorisation process	How do public agencies plan the allocation of LZs in the city? What are the relevant criteria?	Space needs by sector and curbside inventory
	ICT	Stationary technology for LZs	What is the most suitable LZ technology for meeting the city's sustainability-related objectives?	LZ occupation, level of service, type of curbside user.

Source: Adapted from Paper I

Regarding tactical decisions, probed parking data proved to be critical to designing and implementing flexible rules about the use and management of LZs. Identifying patterns across time allows the definition of dynamic parking regulations and variable ROW according to fluctuations in parking demand. At that level, probed data about parking durations and operational features of parking operations provide the input needed by models of demand and durations (e.g. ML algorithms or queueing models), as shown in Paper II and summarised in Table 9. Proper duration models lead to accurate forecasts of LZ occupancy, which benefits routing plans by reducing cruising for parking.

Those models may also support pricing schemes, primarily implemented in the United States, that use auction-based systems according to LZ occupancy.

Table 9. Curbside management at the tactical level enabled by digitalisation

Decision-making level	Category	Type(s) of decision(s)	Relevant question(s)	Data enabled by digitalisation
Tactical	Infrastructure	Dimensions of LZs.	What is the size of LZ parking stalls?	Demand for LZs and parking durations in LZs by type of vehicle.
	Public policy	Parking durations and pricing conditions.	What length of space should be provided by LZs? How to design space and time regulations by vehicle size and technology? What is the typical duration of an operation in each LZ? What is the distribution of operations' durations for each LZ?	Estimations from parking duration models (e.g. queueing models and ML algorithms).
	ICT	Mobile technology for LZs.	What is the most suitable mobile technology for involving actors in the efficient use of LZs?	Attributes about curbside users (e.g., vehicle type and commodity).

Source: Adapted from Paper I

Last, operational decisions regarding the enforcement of LZ regulations and monitoring are also enhanced by the digitalisation of the curbside. Technology (e.g. cameras) helps with identifying misuses of LZs and the fines for violations. Data analytics about traffic violations are also input for improved regulations based on users' behaviour. Table 10 summarises relevant questions that can be addressed with data from a digitised curbside and its enforcement.

Table 10. Curbside management at operational level enabled by digitalisation

Decision-making level	Category	Type of decision	Relevant question(s)	Data enabled by digitalisation
Operational	Infrastructure	Public space management	Which LZs are underutilised and which are fully used at times? What is the demand (i.e. number of vehicles and parking durations) for LZs per time of day? What is the likelihood that a parking stall is available at each LZ at different times of the day?	Parking durations by loading zone and time of the day, demand (i.e., number of vehicles and parking durations) per time of day and loading zone
	Public policy	Enforcement mechanisms	Which LZs have the highest number of violations? What are the most common types of violations, types of vehicles and parking durations? What are the features of the most common violators? How can the routing of wardens be allocated and designed?	Violations per loading zone
	ICT	Users' interactions with LZ ICT	How can a data-sharing scheme be designed to foster the efficient use of LZs?	Conflicts among curbside users.

Source: Adapted from Paper I

5.3. Data-driven curbside management's impacts on sustainability metrics for public spaces (RQ3)

RQ3 guided the exploration of the potential impacts of data-driven curbside management on sustainability metrics for public spaces. Given the factors determining the provision of curbside space for freight operations discussed in Section 5.1, interventions were classified into urban space allocation, data sharing, parking limits and enforcement. Based on the evaluated KPI, each intervention was linked to the related metric for SDG11. Figure 19 summarises the results from 72 interventions (i.e., N = 72) found in the systematic literature review, with the increasing (↑) or decreasing (↓) range of the quantified KPIs (to the left) and the identified link to metrics for SDG11 (to the right).

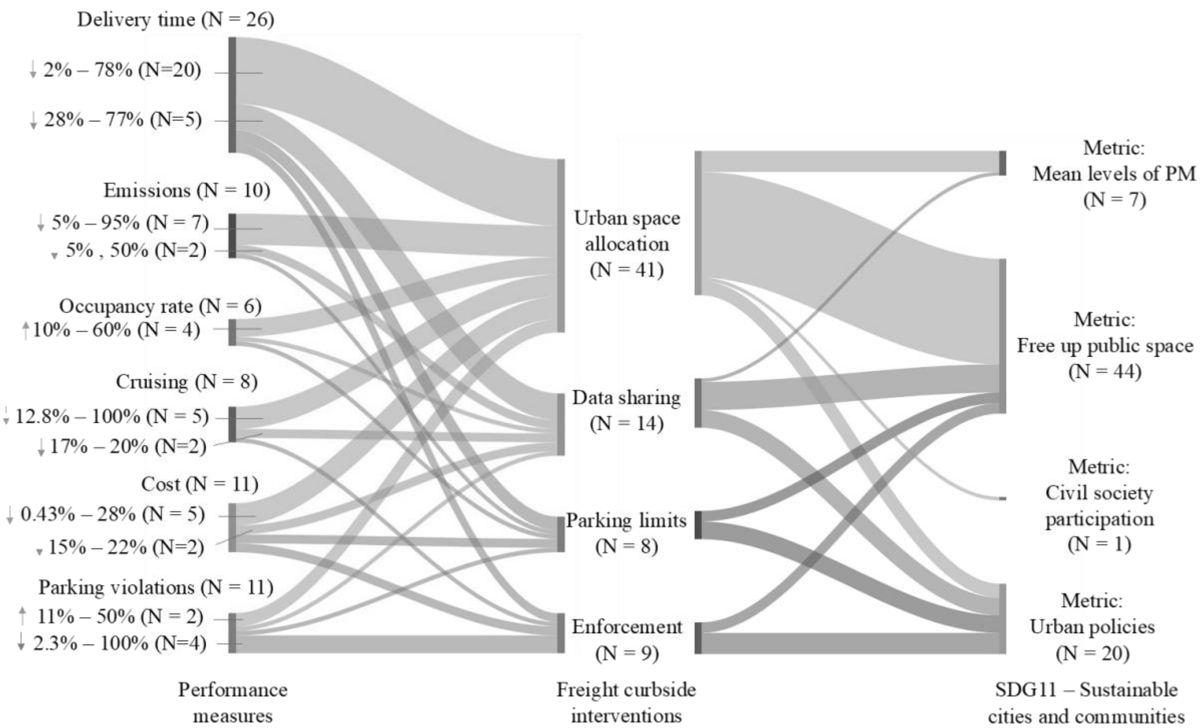

Figure 19. Curbside interventions' impacts on sustainability
Source: Paper IV

Most interventions have been related to allocating public space for freight operations (N = 41). Evidence from the collected reports suggests that providing space for freight operations benefits cities' sustainability because it reduces cruising (↓12.8%–100%), its associated emissions (↓5%–95%) and the efficiency of last-mile deliveries measured by delivery time (↓2%–78%) and cost (up to 27%). Those KPIs of effective space management for freight are aligned with SDG11 by reducing mean levels of particulate matter and freeing up space for other users, the latter due to reductions in congestion when fewer parking violations and less cruising occur. Nonetheless, those impacts can be overshadowed if a static allocation of space aggravates supply–demand imbalances for curbside uses other than freight.

Data-sharing, the second-most popular initiative, refers to technological implementations that enable the exchange of data between curbside infrastructure, users and space managers. Most of the benefits were quantified in terms of improved delivery times (↓28%–77%) because the intervention makes the availability of LZs visible and supports pre-booking systems that reduce cruising (↓17%–20%) and thus emissions (↓5%, 50%) and costs (↓15%–22%). Although data-sharing schemes are becoming popular in the contribution of curbside management to metrics for SDG11 regarding urban policies for the use of public space, they remain underdeveloped, partly because drivers, in the case of booking systems, find it challenging to comply with booking times due to traffic delays in congested areas. During the interviews conducted in Study 1, one carrier, a logistics service provider, stated, “It is impossible for us to know when a driver will be at a certain LZ when there are 70–80 delivery points an operator must make”.

Regulating and enforcing parking limits are common actions that policymakers take in curbside management. Most of the collected reports regarding those interventions have contributed to metrics for SDG11 when it comes to urban policies and freeing up public space because they encourage higher turnover, modal shifts and compliance with regulations. Their performance measures are primarily parking violations, cost and delivery time, albeit ranges of increment and decrement vary from one case to another.

Only one report was found to contribute to the metric for SDG11 regarding civil society’s participation. Stakeholders’ engagement has been overlooked in the definition of freight parking policies and interventions, which has stifled the potential effects of curbside management on urban sustainability. It has also led to users’ insufficient knowledge about ROW rules, which only adds pressure on means of enforcement that may cause confrontations between users and parking wardens over costs due to fines issued or illegal uses of the curb.

In conclusion, interventions in data sharing, enforcement, parking limits and the allocation of public space can contribute to the goals of reducing emissions, managing congestion, making delivery times efficient and ensuring equitable access. However, some trade-offs therein need to be assessed, and new approaches are needed that focus on citizens’ engagement in freight curbside management.

5.4. Contributions

The research conducted for this thesis has contributed to the study of freight curbside management from the perspective of urban transport planning. Moreover, the thesis has answered three RQs aimed at addressing the research gaps mentioned in Table 1. For supply, on the one hand, a data analytics approach has been proposed to support flexible curbside management based on modelling variability in demand and contrasting it with the capacity of curbside infrastructure provided. The time-variant method allows identifying opportunities for freeing up curbside space for other users when freight parking demand dips. The proposed two-step method thus expands upon past research (e.g. Comi, Moura and Ezquerro, 2022) by considering the stochastic behaviour of parking demand by using big data about parking operations and flexible sizes of LZs across time. Beyond the data analytics approach, the research conducted for the thesis also revealed critical factors for implementing dynamic curbside regulations that, aside from the technological aspects mentioned in Mor, Speranza and Viegas (2020), require the flexible allocation of curbside space for freight operations, an understanding of parking durations and enforcement-related capabilities.

To the field of curbside management, the research conducted for this thesis has also contributed an approach to defining *SLZs*, one built on previous conceptualisations (Alho *et al.*, 2018; Sayarshad, Sattar and Gao, 2020). The definition includes elaborations on the scope of different decision-making levels that involve the implementation of technology, data-driven regulations and the dynamic management of the infrastructure available.

On the other hand, for demand, explanatory assessments of variability in parking durations were conducted using probed parking operations from the case study. Findings confirmed and expanded the results obtained by Low, Duygu Tekler and Cheah (2020) regarding the significance of variables such as type of commodity and location when estimating freight parking durations. In the research for this thesis, temporal variables were added (e.g. the hour of the day and weather conditions) that are fundamental for flexible curbside management. That latter finding was possible given the availability of technologies that tracked all of the operations occurring across time (e.g. a time window of 18 months in the case study), thereby outperforming analyses that consider limited observations within specific windows of time, as suggested by Jaller *et al.* (2021). The research also involved reviewing significant variables and modelling methods used when data about establishments are available and indicated challenges when using FTG to estimate parking demand.

The research conducted for this thesis also involved comparing queueing models and ML algorithms to forecast the occupancy of LZ. Those models overcome the challenge of stochasticity in parking demand, highlighted as a research gap in the literature (Gardrat and Serouge, 2016; Jaller *et al.*, 2021). Tailor-made regulations can be designed by applying those approaches to specific contexts and urban areas. Those tools may also allow transport companies to plan routing for urban distribution while knowing the availability of LZs in advance and thereby improving delivery times by reducing cruising and/or illegal parking.

Last, as for equilibrating curbside supply and demand, this thesis has contributed to understandings of digitalisation's role in fostering data-driven freight curbside management. Managerial implications of data availability due to curbside digitalisation were highlighted and analysed through specific applications in a case study. The research conducted for the thesis, in examining the impacts of those data-driven decisions on KPIs targeting curbside supply–demand equilibrium from the perspective of urban transport planning, has expanded upon the contributions of Butrina *et al.* (2017) from the private sector's perspective and further explored connections between curbside management and urban sustainability using the UN's SDGs. Results from the research suggest that interventions in data sharing, enforcement, parking limits and the allocation of public space may contribute to accomplishing the goals of reducing emissions, managing congestion and implementing urban policies for public space and equitable access. Along those lines, the thesis has also pointed to some trade-offs when implementing those interventions that need to be assessed.

5.5. Limitations

The research conducted for this thesis had several limitations that should motivate further attempts to delve more deeply into the study of curbside management, both within the author's current doctoral study and in future projects. This section describes three major limitations of the research regarding its scope, theoretical contributions and methods.

In terms of scope, the study of curbside occupancy considered freight parking operations only. Due to limitations in the availability of data, the research did not consider transport activities such as on-foot deliveries or vehicles trajectories before heading to the LZs. Modelling approaches and results are subject to change under a broader scope of analysis, including conditions of multiple curbside users with their own demands, dynamics and variabilities. Therefore, urban transport planners should be aware that the results presented in this thesis could be a solution to the problem but only a partial one. Thus, further analyses need to handle the needs of all actors using the curbside, their behavioural aspects and variabilities regarding land use.

From a theoretical perspective, this thesis is not framed by any theoretical perspective but follows the conceptual framework of urban transport planning to conduct studies in the empirical and actual domains of CR (see Figure 9). Contributions to the real domain (i.e. theory, constructs and frameworks) are on the agenda for the next half of the research to be conducted for the doctoral thesis. For instance, in the realm of urban planning theory, future work could contribute to the discussion about the allocation of public space considering multiple users, including reflections about the implications of different perspectives in public space distribution, for instance, utilitarian, that seeks to maximise the total utility of the system, sufficientarian, that seek to minimise public space resources distributed among every individual and egalitarian that seeks uniform distribution among all individuals (Lefebvre-Ropars, Morency and Negron-Poblete, 2021).

Last, regarding the methods, the quantitative study of parking operations was limited to a specific case study. Further efforts should consider data from multiple cases and identify nuances among them. Transferability analysis would also enrich the research conducted in the field by illuminating how urban conditions affect the suitability of the methods and their results. Concerning the qualitative study, the convenience sample of interviewees could be expanded with actors from more cities and users of different forms of technology. Moreover, because impact assessments of the proposed solutions were conducted only at the level of the literature review, future contributions should consider empirical data to evaluate the impacts of curbside management decisions on urban sustainability.

6. Conclusions and directions for future research

This chapter presents the major conclusions of the research conducted for this thesis and a final section that introduces avenues for future research aimed at developing liveable streets.

6.1. Conclusions

This thesis has explored significant factors in managing curbside supply and demand for freight parking operations. Regarding the supply side, the research conducted for the thesis was built on the idea of developing flexible curbside management to avoid the unsustainable effects of uses of static space found in past research. The dynamic allocation of public space, regulations on parking durations, enforcement-related capabilities and data-sharing were the most relevant factors for implementing flexible curbside management. Based on those factors, a definition of *SLZs* has been proposed, and decision-making at the strategic, tactical and operational levels has been described.

A case study guided the quantitative assessment of significant factors determining freight parking demand. Commodity type, vehicle type and the hour of the day were the most relevant variables for explaining the variability in freight parking durations. Although contextual attributes regarding location and weather conditions were also assessed, they were not the most significant factors; however, their significance could change in other contexts with more extreme conditions. The research also revealed significant variables in and methods for estimating freight demand when establishments' data are available as well as possible challenges in translating freight demand into parking space demand for freight deliveries.

This thesis has analysed data-intensive needs and proposed the implementation of data analytics to facilitate curbside management decisions. Using probed data about parking operations, the research showed the benefits of data analytics (i.e. ML, queueing models and optimisation programmes) in estimating parking durations, forecasting LZ occupancy and designing LZ networks. Results from the implementation of the models in the case study showed optimal solutions for the allocation of space that freed up curbside space when parking demand dropped, as well as acceptable accuracy in predicting parking occupancy compared with other published models.

Digitalisation has been the backbone of discussions about data sources and data analytics. The thesis has reflected on the role of digitalisation in curbside management to conclude that accelerating digital transitions requires the interoperability of systems, data analytics tools and incentives for all actors to get involved in making the solutions a working reality. For instance, business models (e.g. parking management systems, routing applications involving LZ occupancy and mobility-as-a-service solutions) can boost the digitalisation of the curbside.

Last, an exploratory study was conducted to collect data about the reported impacts of implementing such technology on SDGs, namely SDG11, with an emphasis on metrics related to universal access to safe, inclusive, green public spaces. Findings suggest that interventions in curbside management contribute to improving cities' sustainability due to reductions in delivery times and eliminating cruising and double parking. Targeting the decarbonisation of transport in curbside management represents low-hanging fruit because it does not require high investments, compared with infrastructure or energy-transforming technologies, and, with a managerial commitment, it can lead cities to reduce particulate matter emissions generated by freight transport. Nonetheless, trade-offs in the implementation of curbside intervention were also observed.

6.2. Towards liveable streets: Directions for future research

Reflections on the problematisation of the curbside and the scope of contributions on the topic so far suggest that, aside from supply–demand equilibrium, research should examine the challenge of fairly distributing public space when considering multiple users' needs and how different decisions affect citizens' well-being.

Urban planning theory can provide a convenient theoretical framework for the second half of the research conducted for the author's doctoral study because its foundation helps in studying the typical outcomes of urban planning in terms of citizens' wellness and under what conditions conscious human activity can produce a better city for all citizens (Fainstein, 2005). Urban planning is concerned with the consequences of the spatial distribution of resources on citizens' behaviour. Thus, one of its main hypotheses is that land use and characteristics of the built environment can shape decisions about aspects such as urban transport. Seemingly, in the path ahead for the research, a potential hypothesis to be tested is that decisions about curbside management can shape parking and streetside freight operations as a means to improve urban sustainability. The study of freight operations should include other users of the curbside and, in that case, would require frameworks such as liveable streets that aim at turning streets from arenas of conflict into safer, healthier public spaces. On that count, RQs that may inspire future research include:

- What are the conflicts between streetside users and freight operations on urban streets?
- How do conflicts between streetside users and freight operations influence liveability on urban streets?
- How can cargo (un)loading be facilitated while minimising negative impacts on liveability?

7. References

Aiura, N. and Taniguchi, E. (2005) ‘Planning on-street loading-unloading spaces considering the behaviour of pickup-delivery vehicles’, *Journal of the Eastern Asia Society for Transportation Studies*, 6, pp. 2963–2974. https://doi.org/10.11175/easts.6.2963.

Alho, A., Silva, J. de A. e and Sousa, J.P. de (2014) ‘A State-of-the-Art Modeling Framework to Improve Congestion by Changing the Configuration/Enforcement of Urban Logistics Loading/Unloading Bays’, *Procedia - Social and Behavioral Sciences*, 111, pp. 360–369. https://doi.org/10.1016/j.sbspro.2014.01.069.

Alho, A.R., Silva, J. de A. e, Sousa, J.P. de and Blanco, E. (2018) ‘Improving mobility by optimizing the number, location and usage of loading/unloading bays for urban freight vehicles’, *Transportation Research Part D: Transport and Environment*, 61, pp. 3–18. https://doi.org/10.1016/j.trd.2017.05.014.

Allen, J., Browne, M. and Cherrett, T. (2012) ‘Survey Techniques in Urban Freight Transport Studies’, *Transport Reviews*, 32(3), pp. 287–311. https://doi.org/10.1080/01441647.2012.665949.

Al-Turjman, F. and Malekloo, A. (2019) ‘Smart parking in IoT-enabled cities: A survey’, *Sustainable Cities and Society*, 49, p. 101608. https://doi.org/10.1016/J.SCS.2019.101608.

Appelbaum, D., Kogan, A., Vasarhelyi, M. and Yan, Z. (2017) ‘Impact of business analytics and enterprise systems on managerial accounting’, *International Journal of Accounting Information Systems*, 25, pp. 29–44. https://doi.org/10.1016/J.ACCINF.2017.03.003.

Appleyard, D. (1980) ‘Livable Streets: Protected Neighborhoods?’, *The Annals of the American Academy*, 451(1), pp. 106–117. https://doi.org/10.1177/000271628045100111.

Baudel, T., Dablanc, L., Alguiar-Melgarejo, P. and Ashton, J. (2016) ‘Optimizing Urban Freight Deliveries: From Designing and Testing a Prototype System to Addressing Real Life Challenges’, *Transportation Research Procedia*, 12, pp. 170–180. https://doi.org/10.1016/J.TRPRO.2016.02.056.

Beck, H. (2009) ‘Linking the quality of public spaces to quality of life’, *Journal of Place Management and Development*, 2(3), pp. 240–248. https://doi.org/10.1108/17538330911013933.

Bertolini, L., Clercq, F. le and Straatemeier, T. (2008) ‘Urban transportation planning in transition’, *Transport Policy*, 15(2), pp. 69–72. https://doi.org/10.1016/J.TRANPOL.2007.11.002.

Bhaskar, R. (2008) *A Realist Theory of Science*. London: Routledge. Taylor & Francis Group.

Browne, M., Dubois, A. and Hulthén, K. (2022) ‘Transportation as a loosely coupled system: a fundamental challenge for sustainable freight transportation’, *International Journal of Sustainable Transportation* [Preprint]. https://doi.org/10.1080/15568318.2022.2103756.

Bryman, Alan. and Bell, E. (2015) *Business Research Methods, 4th edition*. Oxford University Press.

Butrina, P., Girón-Valderrama, G. del C., Machado-León, J.L., Goodchild, A. and Ayyalasomayajula, P. (2017) ‘From the Last Mile to the Last 800 ft: Key Factors in Urban Pickup and Delivery of Goods’, pp. 85–92. https://doi.org/10.3141/2609-10.

Butrina, P., Le Vine, S., Henao, A., Sperling, J. and Young, S. (2020) ‘Municipal adaptation to changing curbside demands: Exploratory findings from semi-structured interviews with ten U.S. cities’, *Transport Policy*, 92, pp. 1–7. https://doi.org/10.1016/J.TRANPOL.2020.03.005.

Campbell, S., Holguín-Veras, J., Ramirez-Rios, D., González-Calderón, C., Kalahasthi, L., Wojtowicz, J. (2018) ‘Freight and service parking needs and the role of demand management’, *European Transport Research Review*, 10(2), pp. 1–13. https://doi.org/10.1186/S12544-018-0309-5.

Central London Freight Quality Partnership (2021) ‘Current Freight Issues Group (CFIG) Meetings notes.’, *CLFQP - Online meeting*. London.

Comi, A., Buttarazzi, B., Schiraldi, M., Innarella, R., Varisco, M. and Rosati, L. (2017) ‘DynaLOAD: A simulation framework for planning, managing and controlling urban delivery bays’, *Transportation Research Procedia*, 22, pp. 335–344. https://doi.org/10.1016/j.trpro.2017.03.049.

Comi, A., Moura, J.L. and Ezquerro, S. (2022) ‘A Methodology for Assessing the Urban Supply of On-street Delivery Bays’, *Green Energy and Intelligent Transportation*, p. 100024. https://doi.org/10.1016/J.GEITS.2022.100024.

Comi, A., Schiraldi, M.M. and Buttarazzi, B. (2018) ‘Smart urban freight transport: tools for planning and optimising delivery operations’, *Simulation Modelling Practice and Theory*, 88, pp. 48–61. https://doi.org/10.1016/j.simpat.2018.08.006.

Dablanc, L. (2007) ‘Goods transport in large European cities: Difficult to organize, difficult to modernize’, *Transportation Research Part A: Policy and Practice*, 41(3), pp. 280–285. https://doi.org/10.1016/J.TRA.2006.05.005.
Dalla Chiara, G. and Goodchild, A. (2020) ‘Do commercial vehicles cruise for parking? Empirical evidence from Seattle’, *Transport Policy*, 97, pp. 26–36. https://doi.org/10.1016/J.TRANPOL.2020.06.013.
DeBow, C. and Drow, M. (2019) ‘Curbside Management: Managing access to a valuable resource.’, *The Parking Professional*. https://www.parking-mobility.org/2019/05/06/curbside-management-managing-access-to-a-valuable-resource/ (Accessed: 16 October 2022).
Dezi, G., Dondi, G. and Sangiorgi, C. (2010) ‘Urban freight transport in Bologna: Planning commercial vehicle loading/unloading zones’, in *Procedia - Social and Behavioral Sciences*. Elsevier Ltd, pp. 5990–6001. https://doi.org/10.1016/j.sbspro.2010.04.013.
Diehl, C., Ranjbari, A. and Goodchild, A. (2021) ‘Curbspace management challenges and opportunities from public and private sector perspectives’, *Transportation Research Record*, 2675(11), pp. 1413–1427. https://doi.org/10.1177/03611981211027156.
Dumbaugh, E. and Li, W. (2010) ‘Designing for the Safety of Pedestrians, Cyclists, and Motorists in Urban Environments’, *Journal of American Planning Association*, 77(1), pp. 69–88. https://doi.org/10.1080/01944363.2011.536101.
Easton, G. (2010) ‘Critical realism in case study research’, *Industrial Marketing Management*, 39(1), pp. 118–128. https://doi.org/10.1016/j.indmarman.2008.06.004.
Emanuel, M., Schipper, F. and Oldenziel, R. (2020) *A U-turn to the future: Sustainable urban mobility since 1850*.
Flick, U. (2019) *An introduction to qualitative research*. Berlin: SAGE Publishing.
Fransoo, J.C., Cedillo-Campos, M.G. and Gámez-Pérez, K.M. (2022) ‘Estimating the benefits of dedicated unloading bays by field experimentation’, *Transportation Research Part A: Policy and Practice*, 160, pp. 348–354. https://doi.org/10.1016/J.TRA.2022.03.023.
Gardrat, M. and Serouge, M. (2016) ‘Modeling Delivery Spaces Schemes: Is the Space Properly used in Cities Regarding Delivery Practices?’, in *Transportation Research Procedia*. Elsevier B.V., pp. 436–449. https://doi.org/10.1016/j.trpro.2016.02.077.
Gevaers, R., van de Voorde, E. and Vanelslander, T. (2011) ‘Characteristics and typology of last mile logistics from an innovation perspective in an Urban context’, *City Distribution and Urban Freight Transport: Multiple Perspectives*, pp. 56–71. https://doi.org/10.4337/9780857932754.00009.
Gonzalez-Feliu, J. and Sánchez-Díaz, I. (2019) ‘The influence of aggregation level and category construction on estimation quality for freight trip generation models’, *Transportation Research Part E: Logistics and Transportation Review*, 121, pp. 134–148. https://doi.org/10.1016/j.tre.2018.07.007.
Hammami, F. (2020) ‘The impact of optimizing delivery areas on urban traffic congestion’, *Research in Transportation Business & Management*, 37, p. 100569. https://doi.org/10.1016/J.RTBM.2020.100569.
Holguín-Veras, J., Amaya, J., Sánchez-Díaz, I., Browne, M. and Wojtowicz, J. (2020) ‘State of the art and practice of urban freight management: Part I: Infrastructure, vehicle-related, and traffic operations’, *Transportation Research Part A: Policy and Practice*, 137, pp. 360–382. https://doi.org/10.1016/J.TRA.2018.10.037.
Holguín-Veras, J., Amaya Leal, J. and Seruya, B.B. (2017) ‘Urban freight policymaking: The role of qualitative and quantitative research’, *Transport Policy*, 56, pp. 75–85. https://doi.org/10.1016/j.tranpol.2017.02.011.
Huang, Z. (2003) *Data integration for urban transport planning*. Utrecht University. https://dspace.library.uu.nl/handle/1874/563 (Accessed: 13 October 2022).
Hui, N. *et al.* (2017) ‘Measuring the completeness of complete streets’, *Transport Reviews*, 38(1), pp. 73–95. https://doi.org/10.1080/01441647.2017.1299815.
Ionita, A. *et al.* (2018) ‘Where to park? predicting free parking spots in unmonitored city areas’, *ACM International Conference Proceeding Series*, 18. https://doi.org/10.1145/3227609.3227648.
Iwan, S. Kijewska, K., Johansen, B., Eidhammer, O., Małecki, K., Konicki, W. and Thompson, R. (2018) ‘Analysis of the environmental impacts of unloading bays based on cellular automata simulation’,

Transportation Research Part D: Transport and Environment, 61, pp. 104–117. https://doi.org/10.1016/j.trd.2017.03.020.

Jaller, M., Rodier, C., Zhang, M., Lin, H. and Lewis, K. (2021) *Fighting for Curb Space: Parking, Ride-Hailing, Urban Freight Deliveries, and Other Users*. https://doi.org/10.7922/G22N50JJ.

Jaller, M., Holguín-Veras, J. and Hodge, S.D. (2013) 'Parking in the City', *Transportation Research Record: Journal of the Transportation Research Board*, 2379(1), pp. 46–56. https://doi.org/10.3141/2379-06.

Kalahasthi, L.K. *et al.* (2022) 'Joint modeling of arrivals and parking durations for freight loading zones: Potential applications to improving urban logistics', *Transportation Research Part A: Policy and Practice*, 166, pp. 307–329. https://doi.org/10.1016/J.TRA.2022.11.003.

Kawamura, K. *et al.* (2014) 'Analysis of Factors that Affect the Frequency of Truck Parking Violations in Urban Areas', *Transportation Research Record: Journal of the Transportation Research Board*, 2411(1), pp. 20–26. https://doi.org/10.3141/2411-03.

Kim, H., Goodchild, A. and Boyle, L.N. (2021) 'Empirical analysis of commercial vehicle dwell times around freight-attracting urban buildings in downtown Seattle', *Transportation Research Part A: Policy and Practice*, 147, pp. 320–338. https://doi.org/10.1016/j.tra.2021.02.019.

Kladeftiras, M. and Antoniou, C. (2013) 'Simulation-Based Assessment of Double-Parking Impacts on Traffic and Environmental Conditions', (2390), pp. 121–130. https://doi.org/10.3141/2390-13.

Lefebvre-Ropars, G., Morency, C. and Negron-Poblete, P. (2021) 'Toward a framework for assessing the fair distribution of space in urban streets', *Transportation Research Record*, 2675(7), pp. 259–274. https://doi.org/10.1177/0361198121995196.

Letnik, T, Peruš, I., Božičnik, S. and Mencinger, M. (2019) 'On fundamental principles of the optimal number and location of loading bays in urban areas', *Transport*, 34(6), pp. 722–740. https://doi.org/10.3846/transport.2019.11779.

Letnik, T., Mencinger, M. and Peruš, I. (2020) 'Flexible Assignment of Loading Bays for Efficient Vehicle Routing in Urban Last Mile Delivery', *Sustainability*, 12(18), pp. 7500. https://doi.org/10.3390/su12187500.

Lin, T., Rivano, H. and le Mouel, F. (2017) 'A Survey of Smart Parking Solutions', *IEEE Transactions on Intelligent Transportation Systems*, 18(12), pp. 3229–3253. https://doi.org/10.1109/TITS.2017.2685143.

Lopez, C., González-Feliu, J., Chiabaut, N. and Leclercq, L. (2016) 'Assessing the impacts of goods deliveries' double line parking on the overall traffic under realistic conditions', in *Information Systems Logistics and Supply Chain: ILS Conference 2016: Building a Resilient Future*. Bordeaux.

Low, R., Duygu Tekler, Z. and Cheah, L. (2020) 'Predicting Commercial Vehicle Parking Duration using Generative Adversarial Multiple Imputation Networks', *Transportation Research Record: Journal of the Transportation Research Board*, 2674(9), pp. 820–831. https://doi.org/10.1177/0361198120932166.

Macário, R. (2021) 'Home Deliveries and Their Impact on Planning and Policy', *International Encyclopedia of Transportation*, pp. 413–417. https://doi.org/10.1016/B978-0-08-102671-7.10785-7.

Malik, L. Sanchez-Diaz, I., Tiwari, G. and Woxenius, J. (2017) 'Urban freight-parking practices: The cases of Gothenburg (Sweden) and Delhi (India)', *Research in Transportation Business and Management*, 24, pp. 37–48. https://doi.org/10.1016/j.rtbm.2017.05.002.

Manzano Dos Santos E, and Sanchez-Díaz I. (2016) 'Exploring carriers' perceptions about city logistics initiatives'. *Transportation Research Record: Journal of the Transportation Research Board*, 2547(1), pp. 66–73. https://doi.org/10.3141/2547-10.

de Marco, A., Mangano, G. and Zenezini, G. (2017) 'Classification and benchmark of City Logistics measures: an empirical analysis', *International Journal of Logistics Research and Applications*. 21(1), pp. 1–19. https://doi.org/10.1080/13675567.2017.1353068.

Marsden, G., Docherty, I. and Dowling, R. (2020) 'Parking futures: Curbside management in the era of "new mobility" services in British and Australian cities', *Land Use Policy*, 91. https://doi.org/10.1016/J.LANDUSEPOL.2019.05.031.

McLeod, F. and Cherrett, T. (2011) 'Loading Bay booking and control for urban freight', *International Journal of Logistics Research and Applications*, 14(6), pp. 385–397. https://doi.org/10.1080/13675567.2011.641525.

Meyer, M.D. (2016) *Transportation Planning Handbook*. 4th ed. ITE (Institute of Transportation Engineers). Wiley.

Mingardo, G., van Wee, B. and Rye, T. (2015) 'Urban parking policy in Europe: A conceptualization of past and possible future trends', *Transportation Research Part A: Policy and Practice*, 74, pp. 268–281. https://doi.org/10.1016/J.TRA.2015.02.005.

Mitman, M.F., Davis, S., Armet, I. and Evan, K. (2018) 'Curbside Management Practitioners Guide', in *Transportation Research Board Annual Meeting*. Washington.

Mor, A., Speranza, M.G. and Viegas, J.M. (2020) 'Efficient loading and unloading operations via a booking system', *Transportation Research Part E: Logistics and Transportation Review*, 141, p. 102040. https://doi.org/10.1016/j.tre.2020.102040.

Muñuzuri, J. *et al.* (2017) 'Improving the design of urban loading zone systems', *Journal of Transport Geography*, 59, pp. 1–13. https://doi.org/10.1016/j.jtrangeo.2017.01.004.

Muñuzuri, J., Alho, A. and de Abreu e Silva, J. (2019) 'Evaluating freight loading/unloading parking zones characteristics, usage and performance in Southern', *European Transport \ Trasporti Europei*, (73).

Murtagh, N., Odeleye, N.-D. and Maidment, C. (2019) 'Identities as Enabling Conditions of Sustainability Practices in Urban Planning: A Critical Realist Exploration with Planners in England', *Urban Planning*, 4(4), pp. 86–97. https://doi.org/10.17645/up.v4i4.2263.

Næss, P. and Jensen, O.B. (2010) 'Urban land use, mobility and theory of science: exploring the potential for critical realism in empirical research', *Journal of Environmental Policy & Planning*, 4(4), pp. 295–311. https://doi.org/10.1002/JEPP.114.

National Academies of Sciences, E. and M. 2022 (2022) *Dynamic Curbside Management: Keeping Pace with New and Emerging Mobility and Technology in the Public Right-of-Way, Part 1: Dynamic Curbside Management Guide and Part 2: Conduct of Research Report*. Washington, DC. https://doi.org/10.17226/26718.

Nourinejad, M. and Roorda, M.J. (2017) 'Parking enforcement policies for commercial vehicles', *Transportation Research Part A: Policy and Practice*, 102, pp. 33–50. https://doi.org/10.1016/j.tra.2016.04.007.

OECD (2018) *The Shared-Use City: Managing the Curb Corporate Partnership Board Report Corporate Partnership Board CPB*.

Ogden, K. (1992) *Urban goods movement: a guide to policy and planning*. Aldershot Hants England; Brookfield Vt. USA: Ashgate.

Ortúzar, J. de D. and Willumsen, L.G. (2011) *Modelling Transport*. Third Ed. Chichester: John Wiley & Sons Ltd.

Papachristou, I.A. and Rosas-Casals, M. (2018) 'Cities and quality of life. Quantitative modeling of the emergence of the happiness field in urban studies', *Cities*, pp. 1–18. https://doi.org/10.1016/j.cities.2018.10.012.

Patier, D. *et al.* (2014) 'A New Concept for Urban Logistics Delivery Area Booking', *Procedia - Social and Behavioral Sciences*, 125, pp. 99–110. https://doi.org/10.1016/j.sbspro.2014.01.1459.

Pinto, R., Lagorio, A. and Golini, R. (2019) 'The location and sizing of urban freight loading/unloading lay-by areas', *International Journal of Production Research*, 57(1), pp. 83–99. https://doi.org/10.1080/00207543.2018.1461269.

Plowden, B. (2020) 'Creating healthy streets for sustainable cities – delivering public health benefits through redesigning London's streets', *Cities & Health*, 4(2), pp. 156–161. https://doi.org/10.1080/23748834.2019.1685852.

Provost, F. and Fawcett, T. (2013) 'Data Science and its Relationship to Big Data and Data-Driven Decision Making', *Big Data*, 1(1), pp. 51–59. https://doi.org/10.1089/BIG.2013.1508.

Regal-Ludowieg, A., Sanchez-Diaz, I. and Kalahasthi, L. (2022) 'Using machine learning to predict freight vehicles' demand for loading zones in urban environments', *Transportation Research Record: Journal of the Transportation Research Board*, 2677(1), pp. 829–842. https://doi.org/10.1177/03611981221101893.

Rodrigue, J.-P. (2020) 'The Geography of Transport Systems', *The Geography of Transport Systems*. https://doi.org/10.4324/9780429346323.

Rodriguez-Valencia, A. (2014) 'Urban Right-of-Way Allocation Problem: Considering All Demands'.

Rosenblum, J., Hudson, A.W. and Ben-Joseph, E. (2020) ‘Parking futures: An international review of trends and speculation’, *Land Use Policy*, 91, p. 104054. https://doi.org/10.1016/J.LANDUSEPOL.2019.104054.

Säfsten, K. and Gustavsson, M. (2020) *Research methodology-for engineers and other problem solvers*. Lund: Studentlitteratur AB.

Sánchez-Díaz, I. (2017) ‘Modeling urban freight generation: A study of commercial establishments’ freight needs’, *Transportation Research Part A: Policy and Practice,* 102, pp. 3–17. https://doi.org/10.1016/J.TRA.2016.06.035.

Sanchez-Diaz, I. *et al.* (2020) ‘A time-efficiency study of medium-duty trucks delivering in urban environments’, *Sustainability (Switzerland),* 12(1), p. 425. https://doi.org/10.3390/SU12010425.

Sanchez-Diaz, I., Altuntas Vural, C. and Halldórsson, Á. (2021) ‘Assessing the inequalities in access to online delivery services and the way COVID-19 pandemic affects marginalization’, *Transport Policy,* 109, pp. 24–36. https://doi.org/10.1016/J.TRANPOL.2021.05.007.

Sanders, P., Zuidgeest, M. and Geurs, K. (2015) ‘Liveable streets in Hanoi: A principal component analysis’, *Habitat International,* 49, pp. 547–558. https://doi.org/10.1016/J.HABITATINT.2015.07.001.

Sayarshad, H.R., Sattar, S. and Gao, H. (2020) ‘A scalable non-myopic atomic game for a smart parking mechanism’, *Transportation Research Part E: Logistics and Transportation Review,* 140. https://doi.org/10.1016/j.tre.2020.101974.

Schmid, J., Wang, X. (Cara) and Conway, A. (2018) ‘Commercial vehicle parking duration in New York City and its implications for planning’, *Transportation Research Part A: Policy and Practice,* 116, pp. 580–590. https://doi.org/10.1016/j.tra.2018.06.018.

Sheikh-Mohammad-zadeh, A., Saunier, N. and Waygood, E.O.D. (2022) ‘Developing an Objective Framework to Evaluate Street Functions’, *Sustainability,* 14(12), p. 7184. https://doi.org/10.3390/SU14127184.

Shoup, D. (2011) *The High Cost of Free Parking*. Taylor & Francis (CAM).

Smart Cities Collaborative (2020) *Principles for universal curbside language & standards*. https://www.parking-mobility.org/2019/05/06/curbside-management-managing-access-to-a-valuable-resource/ (Accessed: 16 October 2022).

Smith, M. (2020) *Cities: the first 6,000 years*. New York: Penguin Random House.

Tamayo, S. Gaudron, A. and de La Fortelle, A. (2018) ‘Loading/Unloading Space Location and Evaluation: An Approach through Real Data’, in E. Taniguchi and R.S. Thompson (eds) *City Logistics 3: Towards Sustainable and Liveable Cities*. London, UK: WILEY, pp. 161–180. https://doi.org/10.1002/9781119425472.ch9.

Taniguichi, E. James, J., Barber, R., Imanishi, Y. and Debauche, W. (2012) *Public sector governance of urban freight transport.* PIARC Technical Committee B.4. France.

Tavafoghi, H., Poolla, K. and Varaiya, P. (2019) ‘A Queuing Approach to Parking: Modeling, Verification, and Prediction’. *arXiv*. https://doi.org/10.48550/arXiv.1908.11479.

Thayne, J. and Andersen, C.S. (2017) ‘STREETS AHEAD Integrating Design and Technology in Future Streets’.

Trochim, W.M. (2002) *Research Methods Knowledge Base*. http://trochim.human.cornell.edu/kb/index.htm (Accessed: 18 May 2021).

United Nations (2015) *Transforming our world: the 2030 Agenda for Sustainable Development*. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (Accessed: 15 February 2022).

Victor, D.J. and Ponnuswamy, S. (2012) *Urban transportation: planning, operation and management*. McGraw-Hill Education LLC.

Wahid, R. (2020) *Smart Loading Zone Applications for Urban Last Mile Delivery*. Chalmers University of Technology.

WCED (1987) *Our Common Future*. New York.

Xiao, Y. and Watson, M. (2017) ‘Guidance on Conducting a Systematic Literature Review’. *Journal of planning education and research,* 39(1), pp. 93–112. https://doi.org/10.1177/0739456X17723971.

Yang, B. Tian, Y., Wang, J., Hu, X. and An, S. (2022) ‘How to improve urban transportation planning in big data era? A practice in the study of traffic analysis zone delineation’, *Transport Policy,* 127, pp. 1–14. https://doi.org/10.1016/J.TRANPOL.2022.08.002.

Yang, S. Ma, W., Pi, X. and Qian, S. (2019) ‘A deep learning approach to real-time parking occupancy prediction in spatio-temporal networks incorporating multiple spatio-temporal data sources’, *Transportation Research Part C: Emerging Technologies*, 107, pp. 248–265. https://doi.org/10.1016/j.trc.2019.08.010.

Zhang, L. and Thompson, R.G. (2019) ‘Understanding the benefits and limitations of occupancy information systems for couriers’, *Transportation Research Part C: Emerging Technologies*, 105, pp. 520–535. https://doi.org/10.1016/j.trc.2019.06.013.

Zhang, W. and Wang, K. (2020) ‘Parking futures: Shared automated vehicles and parking demand reduction trajectories in Atlanta’, *Land Use Policy*, 91, p. 103963. https://doi.org/10.1016/J.LANDUSEPOL.2019.04.024.