UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Allocating road space dynamically over time in complex urban areas

Gabriel Costa Valença

Supervisor: Doctor Filipe Manuel Mercier Vilaça e Moura
Co-Supervisor: Doctor Ana dos Santos Morais de Sá

Thesis approved in public session to obtain the PhD degree in
Transportation Systems

Jury final classification: **Pass with Distinction and Honour**

2023

UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Allocating road space dynamically over time in complex urban areas

Gabriel Costa Valença

Supervisor: Doctor Filipe Manuel Mercier Vilaça e Moura
Co-Supervisor: Doctor Ana dos Santos Morais de Sá

Thesis approved in public session to obtain the PhD degree in
Transportation Systems

Jury final classification: **Pass with Distinction and Honour**

Jury

Chairperson: Doctor Luís Guilherme de Picado Santos, Instituto Superior Técnico, Universidade de Lisboa

Members of the Committee:
Doctor Luís Guilherme de Picado Santos, Instituto Superior Técnico, Universidade de Lisboa
Doctor Filipe Manuel Mercier Vilaça e Moura, Instituto Superior Técnico, Universidade de Lisboa
Doctor Benjamin Büttner, School of Engineering and Design, Technical University of Munich, Alemanha
Doctor Anabela Salgueiro Narciso Ribeiro, Faculdade de Ciências e Tecnologia, Universidade de Coimbra
Doctor Jorge Manuel Lopes Baptista e Silva, Instituto Superior Técnico, Universidade de Lisboa

2023

To my parents who have always been my example and inspiration to do my best.

"(…) Of showing what is meant by grit
Of fighting on when others quit
Of playing through, not letting up
It's bearing down that wins the cup
Of taking it and taking more
Until we gain the winning score

Of dreaming there's a goal ahead
Of hoping when our dreams are dead
Of praying when our hopes have fled
Yet losing, not afraid to fall
If bravely, we have given all

For who can ask more of a man
Than giving all within his span
Giving all, it seems to me
Is not so far from victory. (…)"

George Moriarty.

Abstract

Recently, in many cities worldwide, transportation planning has focused on reallocating road space from automobile to more sustainable transport modes. Mostly in urban areas, road space (from façade to façade) is highly disputed by different urban activities, transport modes, and functions. Road space reallocation has often lacked consideration of demand fluctuations during hours, days, and seasons. Consequently, there are periods when certain spaces are oversupplied, while others are undersupplied. The hypothesis of this work is that there is a potential to allocate road space dynamically over time when demands are complementary or even disputed. Potentially, big data and emerging sensing technologies can be useful for short-term decision making, since these technologies can characterize different demands in real-time. Transport demand management and control technologies may be used for allocating space dynamically, informing the transitions to users, and connecting infrastructure to users (if/when needed). The main objective of the thesis is to explore where, when and how road space can be allocated dynamically over time. The thesis explores the applicability of allocating road space dynamically in areas of cities that have very disputed, but limited space to fulfill all demands. We propose a site selection methodology for choosing zones that are complex to reallocate road space and discuss the main local criteria necessary for different solutions of *dynamic road space allocation*. Also, the levels of technological adoption and requirements, along with the main challenges and opportunities for dynamic design are discussed in various technological contexts, ranging from no use of technology to a context where all transport modes and infrastructure are connected. Additionally, we discuss the risks and applicability of using artificial intelligence to improve public participation of both stakeholders and decision makers from interdisciplinary fields in road space allocation projects. In sum, we conclude that *dynamic road space allocation* is context oriented, where different solutions differ in terms of implementation complexity, technological requirements, and social acceptance. It is essential to have the right balance between the frequency of dynamic changes, the use of technology, and the number of proposed solutions, maintaining most of the street's characteristics in a logical orientation.

Keywords: Street design; road space allocation; street space distribution; smart cities; urban design

Resumo

Recentemente, o ordenamento dos transportes tem-se centrado na redistribuição do espaço rodoviário do automóvel para modos de transporte mais sustentáveis. Principalmente nas áreas urbanas, o espaço urbano (de fachada a fachada) é altamente disputado por diferentes atividades, modos de transporte e funções urbanas. A redistribuição do espaço urbano não considera as flutuações da procura durante as horas, os dias e as estações do ano. Consequentemente, há períodos em que certos espaços estão saturados, enquanto outros estão subocupados. A hipótese deste trabalho é que existe um potencial para atribuir espaço rodoviário de forma dinâmica ao longo do tempo quando as procuras são complementares ou estão em disputa. As tecnologias de sensorização emergentes podem ser úteis para a tomada de decisões a curto prazo, uma vez que podem caracterizar as diferentes procuras em tempo real. As tecnologias de gestão e controle da procura de transportes podem ser utilizadas para realocar espaços de forma dinâmica, informar as transições aos utilizadores e conectar a infraestrutura aos utilizadores (se necessário). O principal objetivo da tese é explorar onde, quando e como o espaço urbano pode ser realocado de forma dinâmica ao longo do tempo, explorando a aplicabilidade da atribuição dinâmica do espaço urbano em áreas nas cidades que possuem um espaço muito disputado, mas limitado para atender a todas as demandas. O trabalho propõe uma metodologia de seleção de zonas complexas na cidade para a realocação do espaço rodoviário e discute os critérios locais necessários para diferentes soluções de alocação dinâmica do espaço da rua. Além disso, são discutidos os níveis de adoção tecnológica, bem como os principais desafios e oportunidades da concepção dinâmica em vários contextos tecnológicos, desde a não utilização de tecnologia até um contexto em que todos os modos de transporte e infraestruturas estão conectados. Complementarmente, discutimos os riscos e a aplicabilidade da utilização da inteligência artificial para melhorar a participação pública em projetos de realocação do espaço rodoviário. Em resumo, concluímos que a atribuição dinâmica do espaço rodoviário é *context-oriented*, diferindo em termos de complexidade de implementação, requisitos tecnológicos e aceitação social. É essencial ter um equilíbrio correto entre a frequência das alterações dinâmicas, a utilização de tecnologia e o número de soluções propostas, mantendo as principais características da rua.

Palavras chaves: Design de ruas; alocação do espaço rodoviário; distribuição do espaço rodoviário; cidades inteligentes; design urbano

Acknowledgements

Steve Jobs once said that it is only possible to do great work if you love what you do. Pursuing a Ph.D. is a long and hard process. Throughout the years, while some papers, project applications, and scholarship proposals were successful, others were not. Having this passion is what maintained the work consistency and contributed to taking a step back to improve the work and keep going. However, I believe that having people that you trust, support, and believe in you is equally important for enjoying this process of learning and even overcoming obstacles. Although a Ph.D. is viewed by many as a lonely experience, I was extremely lucky to have met many people who did not make me feel alone and helped me develop ideas, learn new methods, exchange knowledge, and collaborate in different research activities.

First, I would like to thank my supervisors Professor Filipe Moura and Professor Ana Sá for their full support and attention during all these years. I want to thank them both for always being optimistic, pragmatic (when needed), aiming for high standards, and believing in me and in the work that I (we) developed. Thank you for giving me space to be myself and for the always honest and transparent relationship; this made me "feel at home". Also, I would like to thank Professor Moura for all the opportunities and trust that he had in me, helping engage in many activities not related to my thesis that were essential for my learning process. Thank you also for doing everything in your capability to ensure that I had funding during most of my Ph.D. I am certain that this Ph.D. thesis would not have been developed in such an interdisciplinary and effective way if it weren't for the efficiency, attention, detailed revision, and support of both Professors Filipe Moura and Ana Sá. To both my supervisors, all my gratitude and admiration. Thank you.

To Professor Carlos Azevedo from the Technical University of Denmark, I would like to express my appreciation for the opportunity to spend six months in Copenhagen as part of the Machine Learning for Smart Mobility research group. Thank you for the weekly meetings, all the support given, and the opportunity to work with you. It was an enriching experience on both personal and professional levels. Chapter 7 of this thesis was developed mainly under the supervision of Professor Azevedo mostly during the time I was in Denmark.

I would like to thank Professor Luis Picado Santos, which together with Professor Filipe Moura gave me the opportunity to work on the Sustainable Urban Mobility Plan of the city of Loures during the time I was performing my doctoral studies. Although the Loures project was not directly related to the thesis, some of the knowledge acquired was indirectly used to develop research ideas. Besides that, I want to thank Professor Santos for all his attention, experience, guidance and institutional support as the coordinator of the Ph.D. program in Transportation Systems at the Instituto Superior Técnico, along with his Secretary Mrs. Teresa Afonso for her very efficient and kind support during all these years.

I would like to also thank Professor Benjamin Büttner and his supporting staff Mr. Aaron Nichols and Mrs. Corinna Niederreiter from the Technical University of Munich for allowing me to be part of the Doctoral Training Network held by the EIT Urban Mobility. Being part of the group was one of the most important accomplishments during my Ph.D. in terms of professional development, awarding me funding to go to Denmark, but most importantly performing interdisciplinary courses, participating in Annual Forums, and especially meeting and exchanging knowledge with top Ph.D. candidates and researchers in Europe.

I would like to express gratitude to all the professors who are part of the Ph.D. program and have given me classes in the first year, specifically, Luis Picado Santos, Filipe Moura, Rosário Macário, Álvaro Seco, Anabela Ribeiro, António Pais Antunes, Jorge Pinho de Sousa, and João Abreu e Silva. I would also like to thank the members of the STREETS4ALL project who have contributed to developing Chapter 4, namely Freddy Nogueira, Professor Patrícia Baptista, Gonçalo Santos, Manuel Marques, Professor Ana Sá, Professor Carlos Azevedo, Professor António Pais Antunes, and Professor Filipe Moura.

I am grateful to my colleagues who have contributed to many research discussions during coffee breaks, lunch, and meetings, especially to those who mostly contributed as Rosa Félix, Miguel Costa, Paulo Cambra, Freddy Nogueira, Mateus Humberto, Shanna Lucchesi, Mariza Queiroz, and Maurício Fontalvo. My special thanks to Rosa Félix with whom I engaged in very productive dialogue, being the person, I referred to when I had doubts during all these years of my Ph.D. Besides presenting to me the basics of R programming, she was always very kind and patient to help me when I struggled in developing some codes. I would also like to thank Miguel Costa who was also a visiting Ph.D. scholar in Denmark during the time I was there and helped me understand deep learning concepts and fix some codes.

Thank you to my family who have always supported me and cherished all my achievements, encouraging me to continue my journey. To my grandmother Vera, who unfortunately is not with us anymore, but would certainly be proud of this moment, thank you for everything. To my friends that I have made in Portugal, thank you for being my escape from work, and making all this journey very pleasant. To Thais Oliveira, thank you for being by my side, for being my "jury", for

celebrating with me every small accomplishment, and also for being patient in more stressful moments.

Last but not least, I dedicate this work to my parents and could not have done it without them. They have always been my idols and source of inspiration. Both are university professors, which inspired me to follow the path of academia. My mother, Maria Helena Braga e Vaz da Costa, is passionate and dedicated to what she does; my father, Márcio Moraes Valença, has an incredible work ethic, organization skills, and wisdom. Both of them have always given me all the support that I needed to follow my dreams and to have always the best education possible. Particularly, my father has always motivated me to not be afraid to try and to always aim high, but also acknowledge that nothing is accomplished easily, especially in academia. All my dedication during these years has not been only for me, but in respect and gratitude for everything my parents have given me. Thank you for pushing me, and more importantly, for all your unconditional love and support.

Institutional Support

This work is part of the research activity carried out at the research centre of Civil Engineering Research and Innovation for Sustainability (CERIS) and the Centre for Innovation in Territory, Urbanism and Architecture (CiTUA) at the Instituto Superior Técnico, in the framework of the following projects UIDB/04625/2020 (CERIS), and UIBD/05703/2020 (CiTUA), funded by the Portuguese national funds through the Fundação para a Ciência e a Tecnologia (FCT).

During my Ph.D., I worked on projects that gave me financial support, some of which were directly related to my thesis. From January 2021 to December 2022, I received a scholarship to work on the elaboration of the Sustainable Urban Mobility Plan of Loures funded by the Association for Training and Development in Civil Engineering and Architecture (FUNDEC) at the Instituto Superior Técnico. From January 2023 to date, I have received a scholarship (BL250/2022-IST-ID) to work in the project "STREETS4ALL – Dynamic and Equitable Reallocation of Urban Street Space", funded by FCT, under the grant PTDC/ECI-TRA/3120/2021.

As a member of the Doctoral Training Network, I received an additional financial support for my stay at the Technical University of Denmark from May 2022 to October 2022, funded by the EIT Urban Mobility, where I did part of my research.

Finally, I am grateful to all the institutions that supported my research during my Ph.D.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AI	Artificial Intelligence
AVs	Autonomous Vehicles
BLIP	Bus Lane with Intermittent Priority
CAD	Computer-aided Design
CAV	Connected Autonomous Vehicle
CTM	Cell Transmission Model
CVAE	Conditional Variational Autoencoder
DBL	Dedicated Bus Lane
DC-GAN	Deep Convolutional Generative Adversarial Network
DLA	Dynamic Lane Assignment
DLR	Dynamic Lane Reversal
DTM	Document Term Matrix
DTTR	Dynamic Transitions of Traffic Regimes
FCD	Floating Car Data
GANs	Generative Adversarial Networks
GDPR	General Data Protection Regulation
GPS	Global Positioning System
GTFS	General Transit Feed Specification
IBL	Intermittent Bus Lane
ICT	Information and Communication Technology
IDYL	Information-Based Dynamic Lane Schemes
IoT	Internet of Things
ITS	Intelligent Transportation Systems
LDA	Latent Dirichlet Allocation

SDG	Sustainable Development Goals
VANETs	Vehicular Ad hoc Networks
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything

Chapter 1

1 Introduction

1.1 Background

Car-centric planning has prioritized investments in capacity expansion for increasing the level of service of motorized vehicles, prioritizing high traffic speeds. As traffic jams increased in the main cities also due to the densification of urban areas, the socio-economic and environmental impacts became evident, noticing how the traditional transportation framework is unsustainable in the medium-long term (Banister, 2008, 2011; United Nations, 2019). Currently, the main impacts of promoting transport policies in favor of increasing car-use are well known, e.g.: economic inefficiency; consumption of large amount of urban space; energy consumption; air pollution aggravating global warming and worsening negative health impacts; and inequality (European Commission, 2004).

Although recent movements have invested in reallocating space from the car to sustainable modes and activities, still most space occupied by transport infrastructure in urban areas is dedicated to traffic lanes and parking. Even though automobile infrastructure requires significantly more space than cycle lanes, sidewalks, and bus lanes, the space allocated for the car is often greater than their actual modal share (De Gruyter et al., 2022; Gössling, 2016). On the contrary, sustainable transport modes have habitually less space than their modal share, even though they require less space (De Gruyter et al., 2022; Gössling, 2016). Allocating space to more sustainable modes is a key point for transport justice, since not everyone has financial conditions to own a car, nor are the spaces fairly designated according to the number of trips of each transport mode (Gössling, 2016; Gössling et al., 2016).

At the same time, public space faces conflicting roles, struggling to accommodate high speed infrastructure, sustainable mobility, and spaces for leisure, commerce, social interactions and political domain (Zavestoski & Agyeman, 2015). Scholars have claimed that streets have two main types of functions that compete for space in urban streets: i) spaces that allow the flow of people and goods (e.g., traffic lanes, bus lanes, cycle lanes); and ii) spaces for interaction and access to local services and commerce (e.g., parking, sidewalks, markets, benches, parks) (Bertolini, 2020; De

Gruyter et al., 2022; P. Jones et al., 2007; von Schönfeld & Bertolini, 2017). Thus, urban streets encompass two primary functions that compete for space, although they are named differently by authors. Spaces that are designed for the movement of people and goods are associated with the *mobility or movement function* by von Schönfeld and Bertolini (2017) and Austroads (1988, 2015), and with the *link or movement function* by P. Jones et al. (2007). Adjacent areas alongside the road, which provide access to land uses, amenities, and serve as places of leisure, socio-economic activities and interaction are attributed to prioritizing the *access function* (Austroads, 1988, 2015), or *place function* (P. Jones et al., 2007), or *stationary function* (von Schönfeld & Bertolini, 2017).

Traditionally, the amount of space dedicated for mobility/movement/link and access/place/stationary functions is dependent on the road hierarchy classification of the street. The importance of each function is dependent on the street's role within the network, acknowledging that not every street has sufficient space or should prioritize all street functions and users (N. Hui et al., 2018). While arterials prioritize the mobility function, local access streets predominantly focus on the access function. Car-centric planning is characterized by the traffic lanes serving the mobility function, and parking spaces the access function of streets (Seco et al., 2008). However, diverse initiatives - such as complete streets, tactical urbanism, and street experimentation - have been put into place to reallocate road space to more sustainable modes and to make streets more livable.

Even though these initiatives are a step forward to improve accessibility and promote more livable spaces, they are not absent from limitations. What all these concepts have in common is that they each prioritize a user group or function of the street. On one hand, complete streets are defined as streets that can accommodate all transport modes safely prioritizing the street's mobility function (McCann, 2005; Zavestoski & Agyeman, 2015). Even though complete streets aim to promote space for different modes of transport, they put them in dispute for space and fail to consider the street's place function, or that spaces could eventually be shared and do not necessarily require to accommodate all users (N. Hui et al., 2018; Mehta, 2015; Nello-Deakin, 2019; Zavestoski & Agyeman, 2015). On the other hand, tactical urbanism and street experiments aim at remarking and repurposing streets and parking spaces focusing on temporary and pop-up measures to move from car-centric to more people-centric streets, when required (Bertolini, 2020). Most of these practices are held in streets with low traffic volumes, not facing political or public acceptance challenges of contesting car space, focusing on the place function of the street (Gehl, 2013).

The problem is that most performance evaluation of these designs are mainly qualitative and based on before-and-after reports. According to N. Hui et al. (2018), having only a qualitative approach to evaluate street designs is an issue when one function of the street may impact the other, the space is not sufficient to accommodate all uses, and tradeoffs and establishing priorities are necessary. Ultimately, there is a lack of guidance on how much space should be allocated for each function or user group and their impacts. These issues occur especially in streets that have competing demands but limited space, referred to in the context of this research as "complex" (P. Jones, 2016). Complex streets face a dilemma to serve both mobility and access functions (typically classified as main and local distributors); have high volumes of traffic and public transport competing for space; are key destinations of trips; have high densities; and diverse land use with different opening and closing hours of activities and services, influencing fluctuations of different modal demands. There is a political resistance to challenge the status quo in complex spaces due to the need to make tradeoffs, the lack of guidance, and eventually the lack of public support (Gössling, 2016; Hysing et al., 2015; P. Jones, 2016). A citation below from the European Commission (2013, 5), recognizes the importance of setting priorities on urban space usage and the challenge to reallocate road space for more sustainable modes.

"Loading and unloading spaces, bus lanes, cars, parking, pedestrian facilities, cycle lanes and parking all compete for urban road space and cities have to manage these competing demands according to local priorities and circumstances."

Furthermore, street designs often lack consideration of the temporal variations of how urban spaces are used. In different times of the day, the need of the urban space may be different, according to opening and closing hours of commerce, offices and services and the fluctuations of demands. For example, traffic lanes and parking spaces are often underused. While traffic lanes are designed to fulfill a maximum volume usually during peak hours, in non-peak hours the space is oversupplied for its use, being inefficient and indicating the necessity of cities to not only reallocate space for sustainable mobility and place activities, but also consider demand fluctuations in its design.

It is important to acknowledge that for many years, the costs and time to collect traffic count data were high. Consequently, long-term projects, such as capacity expansion infrastructure projects (e.g., highways), were based on traffic counts and rigorous data, while short-term projects, such as repurposing street sections and parking, were generally less informed. However, with recent technologies of data collection and processing, such as video camera analytics, Floating Car Data (e.g., Google Maps or Waze), and Bluetooth, it is possible to collect data in real-time and characterize urban and transport dynamics. Thus, these emerging sources of information can be tools for planning cities and reallocating road space in a shorter-term – minutes, hours, days - (Batty, 2013).

Eventually, road space could be allocated dynamically according to demand-driven and the street's function requirements over time. This solution could minimize the problem of limited space since spaces would not be underutilized at certain times, serving properly its function and use. For example, traffic lanes could serve as bus lanes during peak hours, and during non-peak hours the lane could be mixed with traffic, or parking spaces of offices during the day could also serve restaurants at night when the offices are closed. Demand management technologies such as variable message signs, LED or flexible bollards could be used to change the configuration of space and inform users of the transitions.

It is important to mention that, in practice, allocating road space dynamically over time is not new in urban areas, although the literature is still scarce. Some examples exist today as illustrated in Figure 1 and Figure 2. Figure 1 presents two examples of simple changes in public space dynamically focusing on the street's place function. Figure 1a and Figure 1b illustrate the example of Lund in Sweden that reconfigured the space dynamically in different seasons. It is interesting to notice how adaptations to the street were focused to different audiences. While the space in Figure 1a was designed for children to play, Figure 1b has a more adult public. Figure 1c and Figure 1d present an example of Lisbon in Portugal that every Thursdays and Fridays a market is placed on the sidewalk during the day, promoting social-economic activities. Thus, while in the first case the changes were in seasons, the second example presented daily dynamic changes to the street.

Figure 2 illustrates four examples of allocating road space dynamically over time. Figure 2a illustrates a dynamic bus lane mixed with bicycles and taxis during weekly peak hours. In non-peak hours and weekends, other motorized vehicles can use the lane, when demands are low. Figure 2b illustrates a pedestrian and cycle zone from Monday to Saturday from 10AM to 4PM, allowing only cars with people with disabilities to enter the zone during this time. Figure 2c illustrates a pedestrian zone that only allows loading from 7PM to 11AM when the shops and restaurants are closed. Figure 2d illustrates a restaurant reclaiming a traffic lane to put tables when cars are not permitted to use the street.

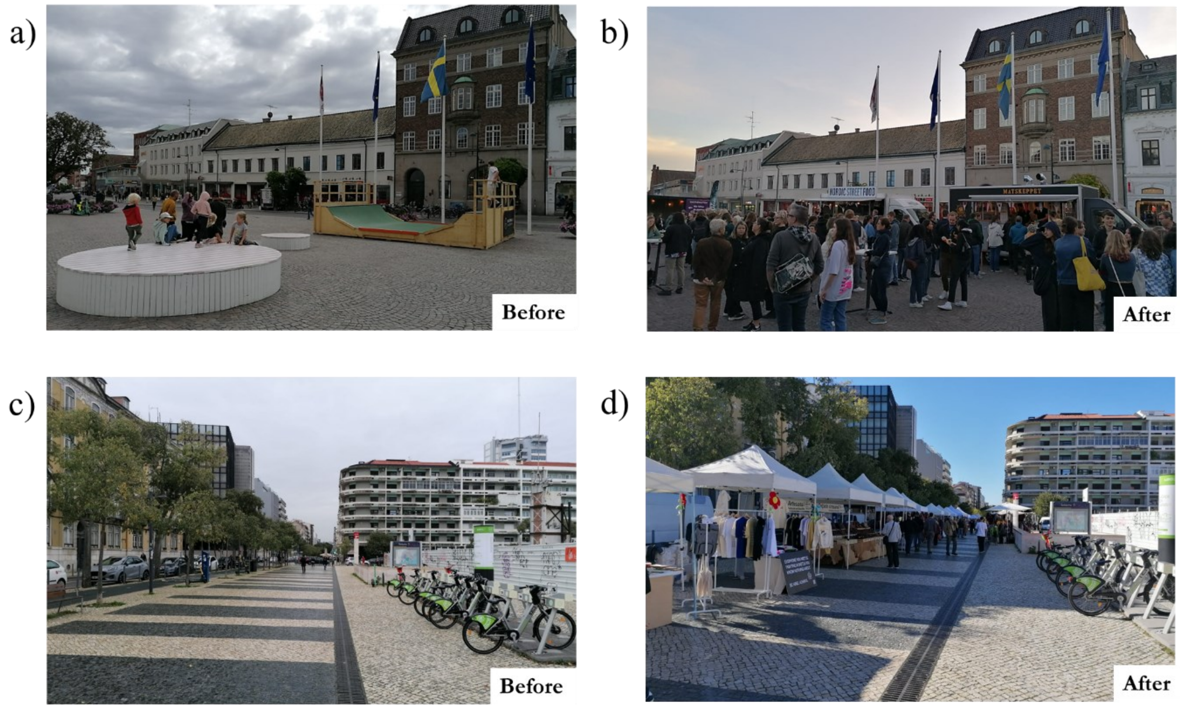

Figure 1: Before and after examples of dynamically allocating road space over time. Seasonal changes in space in Lund, Sweden (a and b), and weekly changes in space in Lisbon, Portugal (c and d).
Source: Author.

Figure 2: Examples of allocating road space dynamically. a) Dynamic bus lane during peak hours in London, England; b) Dynamic pedestrian zone from 10AM to 4PM Mondays to Saturdays in London, England; c) Pedestrian zone with dynamic loading from 7PM to 11AM in Brighton, England; d) Restaurants reclaiming the traffic lane dynamically in Brighton, England.
Source: Author.

The examples of allocating road space dynamically over time are still very punctual and placed in less complex sites. Most of the examples presented in Figure 1 and Figure 2 (except Figure 2a) present situations where there is a clear policy initiative to reclaim streets for pedestrians, cyclists and activities, in streets with low traffic volumes. The hypothesis of this work is that main avenues with limited and contested spaces can also benefit from allocating road space dynamically.

Most of the practical examples of allocating road space dynamically that exist today use simple technology such as vertical and horizontal signaling to inform the dynamic transitions to users. However, the relationship between adapting road space dynamically and new sources of data collection and processing and urban space management and control is not clear. Also, the differences between emerging practices of road space allocation and the contexts in which they are generally applied and studied is still a gap. Allocating road space dynamically may also face diverse challenges, and not be coherent in all contexts, as well as different solutions may require different criteria. Finally, the benefits and the configuration of emerging concepts of street design and road space allocation may not be clear for all stakeholders. The use of technology could potentially guide better comprehension of the design. This thesis comprehensively assesses these gaps, emphasizing the importance of studying this topic.

1.2 General objective and research questions

The **general objective** of the thesis is to discuss and evaluate the coherent ways to reallocate road space dynamically over time in complex streets in urban areas that face limitations in space and dispute in uses.

In this work, four main **research questions** (RQ#) are proposed to achieve the general objective of the thesis.

- **RQ1**: What are the differences between emerging road space allocation solutions and their relationship with new sensing, management and control technologies?

- **RQ2**: How can we allocate road space dynamically in complex urban streets?

- **RQ3:** Where and when can we allocate road space dynamically over time?

- **RQ4:** Can technology be a tool to guide decision-making processes and enable interdisciplinary comprehension of allocating road space dynamically?

1.3 Thesis outline

This thesis is divided into eight chapters, including this introductory chapter and the Conclusions which examines how the work developed addresses the research questions and satisfies the general objective of the thesis. Additionally, the Conclusion discusses the limitations, explores policy implications, and outlines future work scenarios. This thesis was structured following a paper-based approach. Chapters 2 to 7 are papers that were developed following a logical sequence and building up from the previous knowledge and papers. The decision to follow a paper-based thesis was to give more visibility to the work produced.

This section succinctly explains how each chapter (paper) contributes to one another. Prior to each chapter, introductory sections have been included to offer context and explain in more detail what was learned until that point, and how the following chapter contributes towards solving the gaps found in the preceding chapter(s). Thus, these introductory sections presented before each chapter aim to present to the reader the connection between the chapters and a brief preview of what to expect in each one. The chapters have been slightly adapted from the original papers, excluding self-citations that are now chapters of the thesis. Instead of referring to published papers, the text refers to the findings of previous chapters to ensure a link between them. However, the essential content of the papers remains unaltered to maintain consistency in terms of format and copyrights, assisting the reader to know what to expect.

The chapters of the thesis are grouped into two main parts. Chapters 2, 3, and 4 are grouped into **Part A: Literature Review and Conceptualization**. Part A consists mainly of reviewing the state-of-the-art of the main emerging concepts of road space allocation (Chapter 2), defining the concept of *dynamic road space allocation* applied in urban areas (Chapter 3), and establishing the levels of technologies in terms of sensing, transport management and control required for *dynamic road space allocation* and emerging practices (Chapter 4). Chapters 5, 6, and 7 are grouped into **Part B: Implementation**. Part B mainly consists of a site selection methodology to identify zones that face complexity to reallocate road space, with the potential to reallocate space dynamically in a city (Chapter 5); define local criteria to choose streets within the selected zones that are appropriate for implementing different *dynamic road space allocation* solutions (Chapter 6); and evaluate the use of artificial intelligence for assisting stakeholders from different backgrounds to understand and contribute to innovative street design projects (Chapter 7). Figure 3 presents a framework of the outline of the thesis associating with the research questions that are answered in each chapter.

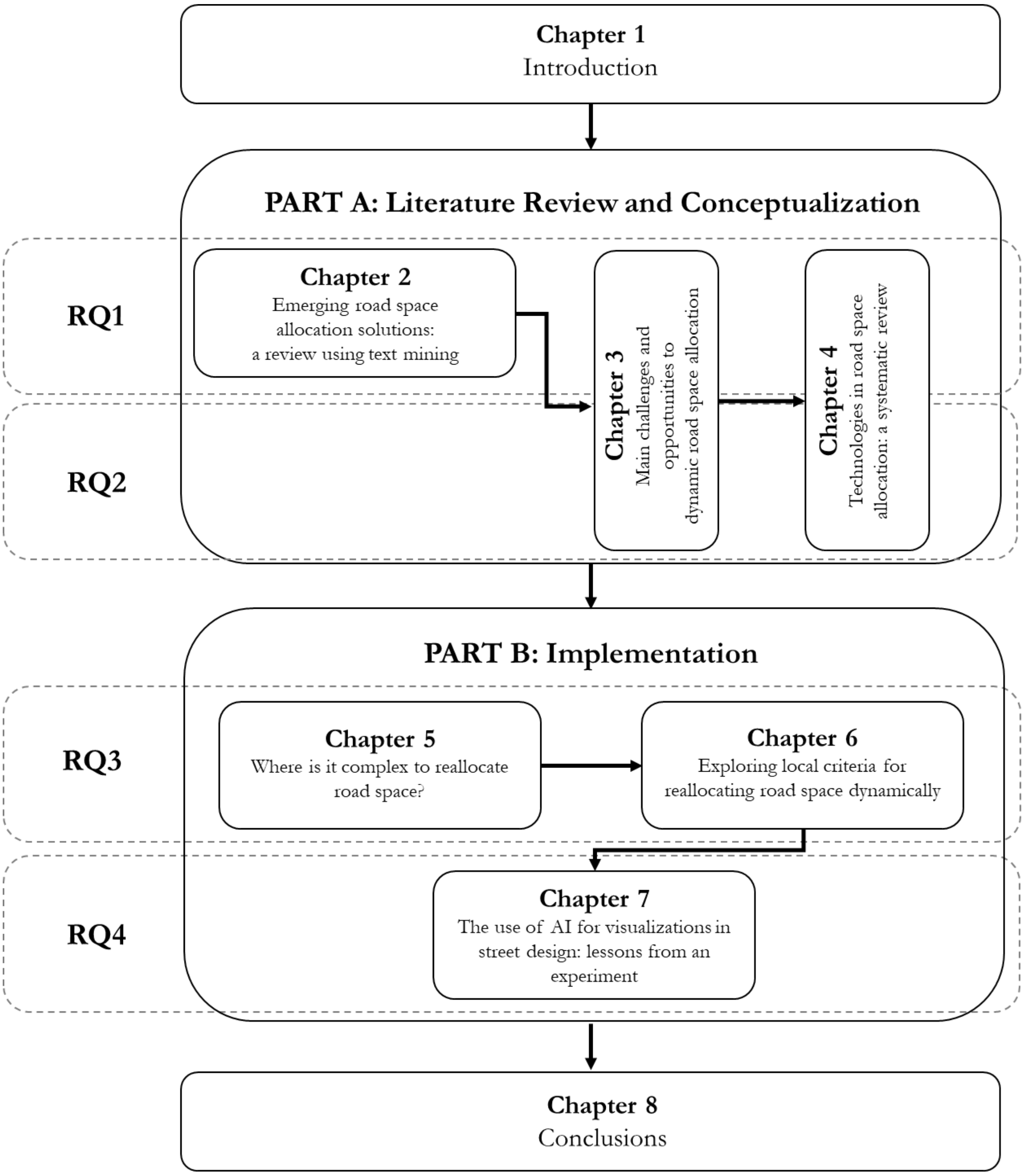

Figure 3: Framework of the outline of the thesis.
Source: Author.

Chapter 2 brings on the first discussion related to emerging practices in road space allocation by examining the literature of the most relevant journals in Transportation and Urban Studies. The objectives of this chapter are to discover how new forms of road space allocation emerged in the literature; differentiate main concepts; and find the gaps in the literature. Initially, a historical analysis of the literature is assessed in order to discover the main topics in the literature over time and how emerging concepts such as big data and smart cities influenced new forms of road space allocation. The results from the review indicate that emerging road space allocation strategies can be dynamic, intermittent, temporary or flexible. We define each emerging practice of road space allocation according to the literature since the differences between concepts are not previously established. Additionally, we explain where these concepts are usually implemented according to the road hierarchy classification, which transport modes and urban space are considered in their architecture, and how they are dependent on technology. We conclude that allocating road space dynamically over time has not been investigated in complex and urban areas, justifying it to being a pertinent area of investigation.

Chapter 3 defines the scope of study and introduces the concept of *dynamic road space allocation*. This definition was informed by the findings of the previous literature and the identified gaps discussed in the preceding chapter. Thus, *dynamic road space allocation* was defined based on characteristics of "dynamic" and definition proposed in Chapter 2. This chapter discusses the definition and conceptual assumptions for allocating road space dynamically in urban and complex areas in the city. In this chapter, there is an initial discussion on the challenges, opportunities, technological solutions, and methodological framework on how road space can be reallocated dynamically to use space more efficiently.

Chapter 4 fulfils the gaps of Chapters 2 and 3 discussing in more detail how technology is used in emerging practices in road space allocation, and specifically on allocating road space dynamically. Chapter 2 reviews the main concepts of emerging practices and discusses the technological dependence of each practice, and Chapter 3 proposes some transport management and sensing solutions for allocating road space dynamically. Nonetheless, they do not go into details on the levels of technology required for each type of practice. Chapter 4 discusses the technologies required for each emerging practice of road space allocation and classifies them in smartness levels of technology adoption, including their requirement for communication between vehicles and infrastructure, sensing, demand management technologies and control. We conclude that allocating space dynamically over time can range from scenarios with no technological integration to those with full connectivity between vehicles, infrastructure, and control.

Chapter 5 is the first chapter in Part B following the literature review and the conceptualization of the object of study. The main objective of Chapter 5 is to propose a methodology for selecting zones in a city (at the municipality level) that are complex to reallocate road space and may potentially be used for allocating road space dynamically. This chapter follows up the gap that allocating road space dynamically is not studied in complex and more urban areas (refer to Chapter 2). In Chapter 5, the conceptual assumptions discussed in Chapter 3 are used to select complex zones. In summary, zones that are complex to reallocate road space have limited space to fulfill mobility and access functions, dense and diverse land use, high connectivity to other areas of the city, and face traffic and public transport congestion during some time of the day. Thus, in these zones, allocating road space dynamically may be a solution, since space is very disputed, and may be underused in certain times of the day. The morphology of the road network, land use characteristics, and traffic and public transport dynamics were considered as essential elements to be evaluated for the site selection. Lisbon is used as the case study of the methodology. In total, 20 zones of 200x200 meters were selected as potentially viable for reallocating road space dynamically.

Chapter 6 continues the analysis of Chapter 5, but in a more local context. While Chapter 5 selects zones in a municipality level, Chapter 6 evaluates the layout, geometric and functional characteristics of the streets within the selected 200x200 meter zones. A workshop with experts was held for them to decide which streets and explain why they are potentially more appropriate for reallocating road space dynamically for three different solutions. Consequently, experts defined and ranked local criteria for different *dynamic road space allocation* solutions, concluding that criteria vary according to the solution proposed. One of the findings of the chapter was that before proposing solutions for reallocating road space, it is necessary to evaluate if there are conflicts and disputes for space. Decisions on which solution to reallocate road space may not be evident for stakeholders and practitioners of different backgrounds, especially if solutions proposed are innovative and not within the state-of-practice.

Chapter 7 discusses the idea and presents an experiment of using artificial intelligence to generate road space allocation solutions based on street images. This idea is based on the finding of the previous chapter, that solutions of *dynamic road space allocation* may not be evident for stakeholders of different backgrounds. The streets images used in our experiment were from the selected complex zones in Chapter 5. Also, the proposal of using artificial intelligence for generating visualizations of different road space allocation solutions, can be used for guiding workshops, promoting more participative and interdisciplinary decision-making in street design projects, and increasing the speed of proposing solutions.

1.4 Methodological approach

This Ph.D. thesis explores both qualitative and quantitative methods to answer the research questions and achieve its general objective. Also, the Thesis contributes to linking methods and promoting a wide range of interdisciplinary approaches including those from transportation engineering, urbanism, artificial intelligence, and social sciences. It is important to mention that the methods chosen in each chapter of the thesis were used for achieving the objective and to respond to the research questions, and not simply for implementing the tools. Although innovative methods are proposed in this thesis, they are the means rather than the focus of the work. However, the interdisciplinary range, complexity and open access tools used in this work are a major contribution of the research, contributing to transparency and open science.

Chapter 2 presents a systematic review of the papers published in the most relevant journals in Transportation and Urban Studies combining a qualitative assessment of the literature and text mining techniques using R programming. The filtering process of the abstracts separates the literature into two groups. First, abstracts were considered eligible if they were important for providing a historical context of how new forms of road space allocation emerged. We grouped the selected abstracts into periods of five years and used word frequency algorithm in each period. Thus, it was possible to evaluate the most cited words in a group of abstracts for each period, relate them with the important urbanism and transportation landmarks, and build up an historical context of emerging road space allocation strategies. Second, papers that were directly related to emerging road space allocation were considered eligible for full paper reading, evaluation of the research gaps, and conceptualization. Prior to the qualitative assessment of full papers, we executed a topic modelling and created a bigram on all eligible full papers. The topic modelling calculates the probability of a word being together with another one in all eligible papers. This was important for classifying the papers into the most important topics. Bigrams were used to interpret and contextualize the topics, as they are networks that present the most frequent combinations of two words being together. Using text mining in literature reviews is innovative and was developed in this chapter, being an important tool for visualization of main patterns in text, organization of ideas, and building an historical context of the literature. Also, all the codes, data and guidelines are freely available for reproducing the results and for researchers to replicate the methodology in other literature reviews.

Chapter 3 is dedicated for the conceptualization of the object of study, using part of the literature found in Chapter 2. In this chapter, we include references from other sources, not retrieved in the systematic review of the previous chapter focusing on the conceptual assumptions, challenges and opportunities for *dynamic road space allocation* in urban and complex areas.

Chapter 4 presents a systematic literature review of the technologies used in road space allocation following the PRISMA methodology. Unlike Chapter 2 that only focused on the main journals of Transportation and Urban Studies, we used the Scopus and Web of Science databases to retrieve papers, and consequently expand the review. After the selection of keywords, we read and filtered the abstracts. The abstracts that were within scope were eligible for the full paper reading. After reading full papers, papers that were considered out of scope were excluded, with the final eligible papers remaining for the qualitative assessment of the literature. Besides reviewing the sensing, communication, and control technologies used in emerging road space allocation, we also proposed a classification of technology adoption from Level 0 (no technology) to Level 5 (full connectivity). The definition of technology levels on new forms of road space allocation is particularly relevant for enabling policy makers to understand the requirements, capabilities, and limitations of different types of road space allocation solutions.

Chapter 5 proposes a methodology for selecting zones in a city where road space is limited and complex to reallocate and has a potential for reallocating space dynamically. Spatial and temporal criteria and indicators were chosen for the site selection on a macro scale. QGIS and R programming were used for data treatment and analysis. Grid zones of 200 x 200 meters were created to join many indicators. Zones were classified as not complex, complex, and very complex to reallocate road space, depending on the requirements met. The spatial and temporal indicators proposed are briefly explained as follows.

The spatial analysis uses network centrality and land use indicators to examine the road space allocation dilemma, connectivity of the network and land use density and diversity. Centrality indicators are used to analyze the morphology of a network. We used these indicators to evaluate the road network's functions, considering that nodes are intersections, and links are street segments. The betweenness and closeness centrality measures were used to calculate the mobility and access function of the network, respectively. The betweenness centrality measures the number of shortest paths (road segments) that pass through a node (intersection). The highest the betweenness value, the more likely the street segment is in a higher road hierarchy and has more space dedicated for circulation (mobility). Closeness centrality measures how nodes (intersections) are closer to one another. High values of closeness are likely to indicate local access streets, since intersections tend to be closer, and routes are less direct. Thus, zones that face the dilemma of allocating road space are the ones that have values that are not in the lower and upper bounds of betweenness and closeness. For the connectivity of the network, we used the degree centrality that measures the number of paths (road segments) that pass through a node (intersection). Thus, if an intersection has higher values of degree, it connects to more places in the city.

We used the sum of all population centroids of a Census block within a zone to calculate the density and then divided by the average value of all zones. For the land use diversity, the entropy index was chosen. The entropy index is an indicator from 0 to 1 that shows how heterogeneous are the categories evaluated. On one side, when the value is 0, only one land use type is present. On the other side, when the value is 1, there is an equal number of considered land use types in a zone. While land use density is more related to the intensity of demand, land use diversity influences its fluctuations throughout the day, enabling dynamic settings.

The temporal analysis was realized for examining how traffic and public transport demands vary over time. If zones have high traffic and public transport conditions at least one hour a day, there is a dispute for space. We used General Transit Feed Specification (GTFS) data to analyze the frequency of buses that pass on a bus stop at each zone per hour from 6 AM to 11 PM. The traffic conditions were evaluated by using Google Traffic API data collected once every hour from 6 AM to 11 PM. We considered that there is a dispute in road space if traffic or/and public transport have high or heavy traffic at least one hour a day. If zones have low or medium level of service of traffic and bus during the whole day, then probably the road space is underused most of the time.

Chapter 6 evaluates local criteria for selecting streets within the complex and very complex zones detected in Chapter 5 that have the potential to reallocate road space dynamically over time. A workshop with experts was undertaken in order to select criteria for different solutions of *dynamic road space allocation*. The workshop gathered members from academia, local authorities, and public and private transport operators. In the first task, participants had to write down individually current and future technologies as well as examples of allocating road space dynamically. In the second task, each group received cards that presented information related to all the streets within the complex and very complex zones detected in Chapter 5. Each group received cards from 4 zones. Each card was attributed to a street that intersected a zone. For example, if a zone had five streets intersecting its area, the group would receive 5 cards for that zone. The group had to choose for each zone, which street had the highest potential for allocating road space dynamically for three different solutions: i) allocating a traffic lane for a bus lane dynamically; ii) allocating a traffic lane for a cycle lane dynamically; or iii) allocating a traffic lane or parking space for expanding a pedestrian area (e.g., markets and tables for restaurants). In the last task, the groups had to think about the criteria they took to choose the street and rank them for each solution. At the end, conclusions regarding applicability and challenges were taken from the exercises and discussions.

Chapter 7 explores the use of generative deep models in street images for guiding innovative road space allocation projects such as allocating road space dynamically. Generative deep models are artificial intelligence models that generate "fake" data, similar to the original data by using neural networks. Generative deep models have recently been commercially released for image generation (e.g., DALL-E-2 and Midjourney) and text generation (e.g., CHAT-GPT). Still, many developments and learnings are being done with generative deep learning models since only with recent advances in computational power has it been possible to use this type of technology. In this chapter we explore the use of a Conditional Variational Autoencoder (CVAE), a type of generative deep model, for generating street images that are conditioned by features of the image (e.g., transport modes, urban furniture, etc). Images and their assigned features are imported in an encoder, neural network that reduces the dimensionality of data, until a latent space. From the latent space, data is then upscaled to its initial dimensionality in a decoder, generating similar images to the imported data. For example, if participants in a workshop want to visualize a street with wider sidewalks, the model would generate many scenarios in which the size of the sidewalk would vary. It is important to mention that an experiment was executed, and thus, the lessons taken are more important than the results *per se*. This chapter took an experimental approach to an emerging technology. Future work should assess its full development.

1.5 Scientific contributions

As revealed in the last subsection, the thesis was elaborated by joining six full papers. It is important to mention that the scientific contributions of this Thesis exceeded the expectations and publication goals established within the Project Thesis defense (December 2019). The Project Thesis proposed a total of three conference presentations and three submitted papers to peer review journals during the PhD.

In the moment of the Thesis Defense, four chapters were already published in top rated peer-review journals. One chapter is under review (Chapter 4) and only the last paper (Chapter 7) has not been submitted to any journal. Also, most of the work done was discussed with the research community through presentations in conferences, having in total six presentations in international and national events. Furthermore, another major contribution of the Thesis was to provide the background and knowledge for writing a proposal and receiving the grant for the 3-year STREETS4ALL project, funded by the *Fundação para a Ciência e a Tecnologia* (FCT). The specific scientific contributions of each chapter are presented below:

- *Chapter 2*

Status of journal: **Published** ✓

Valença, G., Moura, F., & Morais de Sá, A. (2023). How can we develop road space allocation solutions for smart cities using emerging information technologies? A review using text mining. *International Journal of Information Management Data Insights*, 3(1), 100150. https://doi.org/10.1016/j.jjimei.2022.100150.

Conference presentations:

Valença, G., Moura, F., & Morais de Sá, A. (2022). Road space allocation strategies that change over time: A systematic review using text mining. *Oral presentation at the Transport Research Arena (TRA)*, Lisbon, Portugal.

Valença, G., Moura, F., & Morais de Sá, A. (2022). Using Text Mining to Perform Literature Reviews in Transport and Urban Studies: A Case Study on Emergent Road Space Allocation Solutions. *Oral presentation at the 18th Portuguese Research Group in Mobility and Transportation Meeting (GET 2022)*, Porto, Portugal.

- *Chapter 3*

Status of journal: **Published** ✓

Valença, G., Moura, F., & Morais de Sá, A. (2021). Main challenges and opportunities to dynamic road space allocation: From static to dynamic urban designs. *Journal of Urban Mobility*, 1(100008). https://doi.org/10.1016/j.urbmob.2021.100008.

- *Chapter 4*

Status of journal: **Submitted to journal**

Valença, G.; Nogueira, F.; Baptista, P.; Santos, G.; Marques, M.; Morais de Sá; A.; Azevedo, C.; Antunes, A.; & Moura, F. Technologies in Road Space Allocation: A systematic review. *Submitted to the Journal of Urban Technology*.

- *Chapter 5*

Status of journal: **Published** ✓

Valença, G.; Moura., F; Morais de Sá, A (2023). Where is it complex to reallocate road space? *Environment and Planning B: Urban Analytics and City Science*. https://doi.org/10.1177/23998083231217770

Conference presentations:

Valença, G.; Moura., F; Morais de Sá, A (2022). Using network centrality and land use indicators to define candidate zones for dynamic road space allocation. *Poster presentation at the Transportation Research Board 101st Annual Meeting*, Washington, USA.

Valença, G.; Moura., F; Morais de Sá, A (2021). A site selection methodology for implementing dynamic road space allocation. *Oral presentation (online) at the 13th CITTA Conference on Planning Research: Planning for Human Scale Cities*, online.

- *Chapter 6*

Status of journal: **Published** ✓

Valença, G.; Moura., F; Morais de Sá, A (2023). Exploring criteria for reallocating road space dynamically: lessons from a workshop with experts. *Journal of Urban Design*. https://doi.org/10.1080/13574809.2023.2240245.

Conference presentations:

Valença, G.; Moura., F; Morais de Sá, A (2022). Selecting streets and local characteristics for implementing scenarios of dynamic road space allocation. *Poster presentation at the Transport Research Arena (TRA)*, 2022, Lisbon, Portugal.

Valença, G.; Moura., F; Morais de Sá, A (2022). Evaluating local criteria for implementing Dynamic Road Space Allocation. *Oral presentation at the AESOP Annual Congress*, online.

- ***Chapter 7***

  Status of journal: **Currently not submitted**

Part A.

Literature Review and Conceptualization

Chapter 2

What we have learned so far

The first chapter – the Introduction – established the initial context, the background, the objective and research questions and structure of the thesis. In summary, there are streets in urban areas that have limited and disputed uses, raising dilemmas about how much space should be allocated for different urban functions and uses. The hypothesis of the thesis is that complex streets may benefit from allocating road space dynamically according to demand and policy goals. However, there is still a gap in the relation and differences between different emerging road space allocation solutions, where they are usually applied, and which modes and function they prioritize.

What to expect in Chapter 2

The rise of new remote sensing, transport demand management, control technologies, and transport modes may have influenced new forms of road space allocation, such as intermittent bus lanes and dynamic lane allocation. In this chapter, the relationship between transport planning and technology-oriented concepts (e.g., big data, smart cities) with (smart) road space allocation solutions is discussed. A historical background is performed to contextualize how different concepts and important urbanism and transportation landmarks may have influenced new forms of road space allocation. Also, the differences between new forms of road space allocation are explained as well as their dependence on technology, how space changes with demand, and if the solutions are permanent or not. In this chapter, we conclude that there is a lack of studies on reallocating road space dynamically over time in urban and complex spaces, which means that it is a valid object of study.

Chapter 2

2 Emerging road space allocation solutions: a review using text mining

This chapter has been published as: Valença, G., Moura, F., & Morais de Sá, A. (2023). How can we develop road space allocation solutions for smart cities using emerging information technologies? A review using text mining. *International Journal of Information Management Data Insights*, 3(1), 100150. https://doi.org/10.1016/j.jjimei.2022.100150

2.1 Introduction

Road infrastructure projects are mainly based on medium to long-term planning, while short-term planning is usually less informed. Recently, new sources of data collection and analysis have not only increased the amount and diversity of available information but also made it possible to plan cities in a shorter-term – minutes, hours, days (Batty, 2013). Traditionally, transport infrastructure projects are based on a traffic-flow peak-hour evaluation to ensure a capacity to accommodate a maximum traffic flow volume. However, this type of planning is inefficient in using urban space since the space is often underutilized in non-peak hours. New technologies, such as mobile phone applications, video analytics, and sensors, have made it possible to monitor public spaces in a 24-hour framework (Herath & Mittal, 2022). Also, mobile phone applications are influencing how people move by indicating traffic routes that have shorter travel times. Consequently, real-time applications and the internet are weakening the role of long-term planning since mobility patterns are changing and adapting to real-time information. Big data has made it possible to evaluate urban dynamics, and fluctuations of multimodal demands and provide reliable data for real-time and short-term planning.

The advent of big data has leveraged the development of the smart city concept and its implementation. There is no unique definition of what "smart" means in terms of city development (Herath & Mittal, 2022; Moura & De Abreu e Silva, 2019). Nonetheless, most definitions include using Information and Communication Technology (ICT) to plan cities. ICT is the group of technologies that can collect, process, and share large volumes of data in real-time for more reliable decision-making (Berglund et al., 2020). ICT can be integrated with urban systems and other technologies, such as intelligent traffic signals to optimize traffic during peak hours (Chauhan et al., 2016). Smart city solutions and technology should focus on citizen needs and their capabilities to adopt and adapt to changes promoted by smart initiatives (Lytras et al., 2021). As stated by Kar et al. (2019), technology should be seen as a tool rather than the goal *per se*. One of the components of smart cities is planning for a smarter mobility, including traffic management, sustainable transportation, and intelligent routing (Herath & Mittal, 2022). In terms of smart traffic management, big data and ICT can be used to collect real-time data and communicate the infrastructure to adapt road space in minutes, hours, or days according to demands and policy goals.

Nonetheless, most common practices of road space allocation do not consider the changes in travel behavior and demand volumes over time (Wey & Huang, 2018). However, in reality, transportation networks and land use are dynamic, as we consider the different spatial-time scales of the public space usage that happen during the hours, days, or weeks. Many designs and policies have recently been focused on reallocating traffic lanes and parking spaces to sustainable transportation. Smart and emergent designs can potentially adapt road space to accommodate different needs during the day according to transport volumes or modify transport behaviors to achieve policy objectives over time (Gössling et al., 2016). However, there is still a high political and community resistance to challenging car space, especially in busy avenues with limited space and disputing uses (Banister, 2008; P. Jones, 2016). Also, allocating road space for different needs over time may be a strategy for challenging car use. For example, permanently reallocating a traffic lane to a bike lane in busy avenues may be politically challenging. However, introducing the bike lane only during some periods (e.g., non-peak hours) can increase cycling levels and eventually can become politically easier to convert the temporary bike lane to a permanent one. Big data and ICT technologies have an essential role in modern ways of dealing with transportation problems (Herath & Mittal, 2022), specifically in promoting smart road space allocation strategies. To the best of our knowledge, there has not been a review on smart road space allocation solutions and their relationship with big data and smart cities. In this context, this chapter presents a systematic review to identify the gaps in the literature and distinguish the discussions on smart road space allocation.

We propose a systematic literature review methodology using text mining to discover the historical context and the main topics addressed in emerging road space allocation solutions. Text mining techniques have been used to find statistically significant patterns in unstructured text (Kumar et al., 2021). According to Kumar et al. (2021), text mining has mainly been studied and applied in social media, online product and service reviews, customer satisfaction, and reactions during a crisis. Recently, some applications of text mining in literature reviews have been proposed (Karami et al., 2021; Kushwaha et al., 2021; Martinelli, 2022; Zarindast et al., 2021). Text mining becomes essential in reviews when the number of documents is vast, manual analysis is not viable, and it is very time-consuming (Kumar et al., 2021). Consequently, most text mining proposals in literature reviews are applied in cases where it is impractical to analyze the papers qualitatively, as shown in Karami et al. (2021), Kushwaha et al. (2021), Martinelli (2022), and Zarindast et al. (2021).

Nonetheless, even with a small number of documents, text mining can provide an initial analysis of the text, demonstrating the main topics and patterns, before qualitatively analyzing the documents. Unlike the other proposals, this chapter aims to use text mining as a complementary and initial analysis before qualitatively analyzing the papers. We propose using text mining to not only detect the patterns and main topics in existing literature but also provide a historical context on the evolution of concepts throughout the periods. The proposed methodology is reproducible to other topics and research fields. Also, it was possible to compare the results from the text mining techniques to the content of the full documents due to the small number of documents for evaluation purposes. Consequently, we reflect on the results and limitations of using text mining in systematic literature reviews. This chapter aims to give insights into the following research questions:

- What is the historical context of smart road space allocation solutions, and when did big data, ICT and smart cities rise in the main literature of transportation and urban studies?

- What are the differences between smart road space allocation solutions and their relationship with ICT and big data?

- What do we learn, and what are the limitations of using text mining in conventional systematic literature reviews?

The next section explains the proposed methodology. The following section addresses the results from the quantitative analysis of the literature that is twofold: temporal evolution of the papers by using frequency word counts on filtered abstracts; and detection of the main topics of full eligible papers by using topic modeling and bigrams. Sequentially, a section qualitatively characterizes the eligible full papers, defining the terms dynamic, intermittent, temporary, and flexible in road space allocation solutions. Then there is a section for the discussion. We conclude with conclusions, future developments, and references.

2.2 Methodology

This chapter proposes a methodology for using text mining to perform systematic literature reviews in two main directions: i) analyzing the evolution of concepts and topics explored throughout time, and ii) Detecting the main topics expressed in literature. The first steps are similar to other reviews. Initially, the keywords for extracting the papers were selected. Secondly, the journals were selected based on the classification of InCite (InCites Journal Citation Reports, 2018). The next step was to extensively collect all the papers within the selected journals, extract each paper's title, publication year, authors, and abstract, and fill the information into an Excel sheet. Sequentially, we performed a filtering process where we grouped papers into two groups: i) relevant papers for examining the temporal evolution of topics and concepts in the literature and how they relate to historical urban planning landmarks (Historical context analysis); ii) papers that were directly related to the theme and selected for a full paper analysis (Specific paper analysis). In the first group, we separated the abstracts into groups depending on the year of publication and used word frequency counts to examine the most cited words in different periods of time. In the second group, we used topic modelling to analyze the main topics in the full papers and bigrams to give context and meaning to the topics. The selected papers for the specific analysis were directly related to dynamic/temporary/intermittent/flexible applications in road space allocation. It is important to mention that papers considered eligible for the specific analysis were also included for the historical context analysis. Finally, we read the full papers and examined the literature gaps.

2.2.1 Search strategy

The systematic review's first step was defining the keywords used for selecting journal papers. Secondly, the journals were selected based on the classification of InCite (InCites Journal Citation Reports, 2018). The key words selected were: big data; complete streets; Intermittent Bus Lanes/ IBL/ Bus Lane With Intermittent Priority/ BLIP; reversible lane; road diet/ lane diet; shared spaces/ shared streets/ woonerf; smart cities; smart urban mobility/ smart mobility; space allocation; traffic calming/ traffic-calming; urban regeneration/ urban revitalization/ urban requalification. The keywords aligned with "/" represent the different words used to obtain more results in the journal pages by applying the function "OR" in the journal webpage. We decided to only use the words intermittent, temporary, dynamic, and flexible on the keywords that were established concepts or definitions. In the filtering process, we selected the papers that considered these types of solutions.

We selected the ten journals with higher impact factors in the Transportation or Transportation & Science categories and the Urban Studies category. We chose these sources to focus on the most relevant literature in the fields. Note that the scope of the journal had to be relevant to the objective proposed by this chapter. Consequently, some journals were not included in the analysis due to the lack of relevance, and the sequential highest impact factor journal was included (if considered relevant). We used the function "Article title, Abstract, Keywords" for paper selection. At this early stage, all papers were collected and assigned to a spreadsheet with an ID, Keyword, Journal, Title, Authors, Year of Publication, and Abstract. Full journal papers, City profiles, and review papers in English were included, meaning that book reviews were not involved in this analysis. There were no restrictions regarding the year of publication of the papers.

2.2.2 Inclusion and exclusion criteria

After defining keywords, journals and collecting the papers, the abstracts of all the papers were scanned and classified into two categories: historical context analysis; and specific paper analysis. The same paper could be included in both groups. All papers in the specific paper analysis were important and included in the historical context analysis. The following subsections explain in more detail the criteria for including and excluding papers for each respective group.

Historical context analysis

We included all papers that were considered relevant to give a historical context and emphasize important problematics and landmarks that may have influenced emergent urban design solutions. Papers that focused on other topics or the keyword had a different meaning than expected were excluded from the analysis. The filtered abstracts were separated into groups depending on the year of publication by joining papers into five-year periods. Sequentially, frequency word counts were performed in each period. The goal was to analyze the main tendencies, concerns, and concepts of each period and how these concepts relate to emerging road space allocation practices.

Specific paper analysis

The papers included for the specific paper analysis had to be related to smart road/lane allocation strategies that change use or function over time. Included papers could also analyze urban and traffic dynamics or address sensing or demand management technologies that could enable smart road space allocation strategies. The selected keywords were very broad to include papers in the historical analysis and find the relation between big data and smart cities with smart road space allocation. The full papers of this group were screened and filtered once more. After excluding non-relevant papers, topic modelling and bigrams were executed in the full eligible papers to provide an initial interpretation of the papers. Then, we performed a qualitative analysis of the papers.

2.2.3 Text mining specifications

We used the statistical software R version 4.0.0 and the *tm* (Feinerer et al., 2008) and *topicmodels* (Grün & Hornik, 2011) libraries to run the frequency counts on abstracts (historical context analysis) and topic models and bigrams on full papers (specific paper analysis). The quantitative analysis of the text used the following terminology, based on the definition proposed by Blei et al. (2003):

- A word or a term is a discrete unit of data, labeled to be an element part of a vocabulary indexed by $\{1, \ldots, V\}$;
- A document is a sequence of N words represented by $d = (w_1, w_2, \ldots, w_n)$, where w_n is the n^{th} word in the sequence;
- A corpus is a collection of M documents represented by $D = \{d_1, d_2, \ldots, d_M\}$;
- A topic is a multinomial distribution of all words contained in the vocabulary.

According to text mining best practices, before running the models, we performed preprocessing techniques in the text. Initially, we lowercased all the words in the text since the algorithm cannot distinguish the same word with different case letters. All stop words that do not contribute to interpreting the results were removed (e.g., "and", "if", "the"). All numbers, single letter words, punctuation, and white space were also extracted from the corpus. We opted to use the lemmatization process that normalizes the words to obtain the dictionary form of the word. This process is crucial because it removes inflectional endings and groups words with the same or similar meaning.

Term frequency counts of filtered abstracts for a historical context analysis

A common approach to measure word frequency in a corpus is to use the tf-idf method (Bastani et al., 2019; Roque et al., 2019; Salton & McGill, 1983). In this approach, the term frequency (tf) is the number of times a word appears in a document, while the inverse document frequency (idf) weighs the word depending on how often it appears in a corpus. Thus, if a word appears in every document many times, it is classified as not very important.

In our approach, we are interested in the frequency of the entire corpus (tf). Nonetheless, measuring the inverse document frequency (idf) is irrelevant because our goal is to analyze the historical context and relate the most cited words with the prominent urban planning landmarks over time. Thus, we first grouped the abstracts in a 5-year publication period. Each period was assigned as a corpus with M Documents. This procedure allowed the algorithm to run each corpus independently from the others. Due to the small number of papers, we made an exception to the 5-year corpus at the first publication years (1978 to 1985). Then in each corpus, we counted the number of times a word appeared and implemented a normalization procedure according to the expression:

$$fw_{,D} = \frac{Nw_{,D}}{\max\left(Nw_{i,D}\right)}$$

(Equation 1)

Where:

- $\max(Nw_{i,D})$ corresponds to the maximum number of occurrences of all the words present in a corpus;
- *w* is a word included in a corpus D;
- A *document* is a sequence of *N* words represented by $d = (w_1,\ w_2, \dots, w_n)$, where w_n is the n^{th} word in the sequence;
- A *corpus* is a collection of *M* documents represented by $D = \{d_1,\ d_2, \dots, d_M\}$;

Latent Dirichlet Allocation (LDA) and bigrams for specific paper analysis

LDA is an unsupervised topic model that uses Bayesian inference to estimate the distribution model of terms in documents. LDA was initially proposed by Blei et al. (2003) to detect latent topics presented in text documents. The documents used in the LDA do not need prior labeling. However, we labeled the topics after our analysis. We used the LDA to discover the main topics in the papers that refer to smart road space allocation that change over time. Furthermore, we opted to use bigrams that consider the most frequent sequence of two words together, with the purpose of better interpreting the topics.

The words from the analyzed documents are assigned to topics based on the statistical structure of the data (L. Sun & Yin, 2017). The model considers "the bag of words" assumption, in which the order of words in a document is irrelevant. Also, we can disregard the order of the documents in the corpus due to the exchangeability supposition (Blei et al., 2003). The exchangeability supposition means that the documents and words are twofold: conditionally independent, which condition regards a latent parameter of a probability distribution; and identically distributed. From this assumption, a Document-Term-Matrix (DTM) is generated, containing the word frequencies of each document.

The LDA consists of the following steps:

- Prior definition of the number of topics K, where each topic with index $k \in [1, K]$, is related to a multinomial word distribution ψ_k. ψ_k is originated from a prior Dirichlet word per topic distribution with parameter β. Thus, $\varphi_k \sim \text{Dirichlet}v(\beta)$;

- Taking into account the formulated topics, a multinomial topic distribution for each document (θ_d) is established. θ_d is initially associated from a Dirichlet topic per document distribution with parameter α. Thus, $\theta_d \sim \text{Dirichlet}k(\alpha)$.

- A topic $z_{dn} \in [1, K]$, from a multinomial distribution $k(\theta_d)$ is associated with each word in each document d. Then, each word w_{dn} is designated from the multinomial distribution $v(\psi_{z_{dn}})$. Thus, this step is divided into two processes: i) select a topic $z_{dn} \sim \text{Multinomial}k(\theta_d)$; ii) select a word $w_{dn} \sim \text{Multinomial}v(\psi_{z_{dn}})$.

It is essential to distinguish that words in documents are observed variables, ψ and θ are latent variables, and α and β are hyperparameters. After obtaining the marginal probability distribution of each document, the probability of a corpus takes into account the product of the marginal probability of all single documents. Thus, the probability of a corpus is defined as (Blei et al., 2003):

$$p(D|\alpha, \beta) = \prod_{d=1}^{M} \int p(\theta_d|\alpha) \left(\prod_{n=1}^{N_d} \sum_{z_{dn}} p(z_{dn}|\theta_d)\, p(w_{dn}|z_{dn}, \beta) \right) d\theta_d$$

(Equation 2)

There are many methods for estimating LDA parameters, such as the variational method, expectation propagation, and Gibbs sampling (Jelodar et al., 2019). We used the Gibbs sampling method proposed by Griffiths and Steyvers (2004) due to its wide applicability, simplicity and efficiency in inferring LDA parameters (Jelodar et al., 2019; Roque et al., 2019; L. Sun & Yin, 2017).

We executed LDA to model the K number of topics in eligible journal papers. All full papers considered eligible for the topic modeling were converted from PDF files into *.txt files. In this process, we tokenize a sequence of strings into terms. We opted to apply two types of tokenization: separating the strings into unique words and a sequence of two following words. Before running the models, we manually removed from each text the information of the authors and journal, acknowledgments, funding, supplemental material, disclosure statement, and references. This data cleaning ensures that the information provided by the model was only from the text body of the paper. We used the default parameter values of the library for β (0.1) and the initial value of $\alpha \left(\frac{50}{M}\right)$ suggested by Griffiths and Steyvers (2004).

2.3 Results

2.3.1 General overview of the results

Figure 4 presents the systematic literature review methodological framework. We propose that the abstracts are filtered into two groups: Historical Context Analysis and Specific Paper Analysis. While the former has a first analysis of the abstracts, the latter focuses on analyzing full eligible papers. The Historical Context Analysis gives a background on the evolution of topics and concepts that have influenced smart road space allocation solutions. The Specific Paper Analysis explores papers directly related to road/lane space allocation that changes over time.

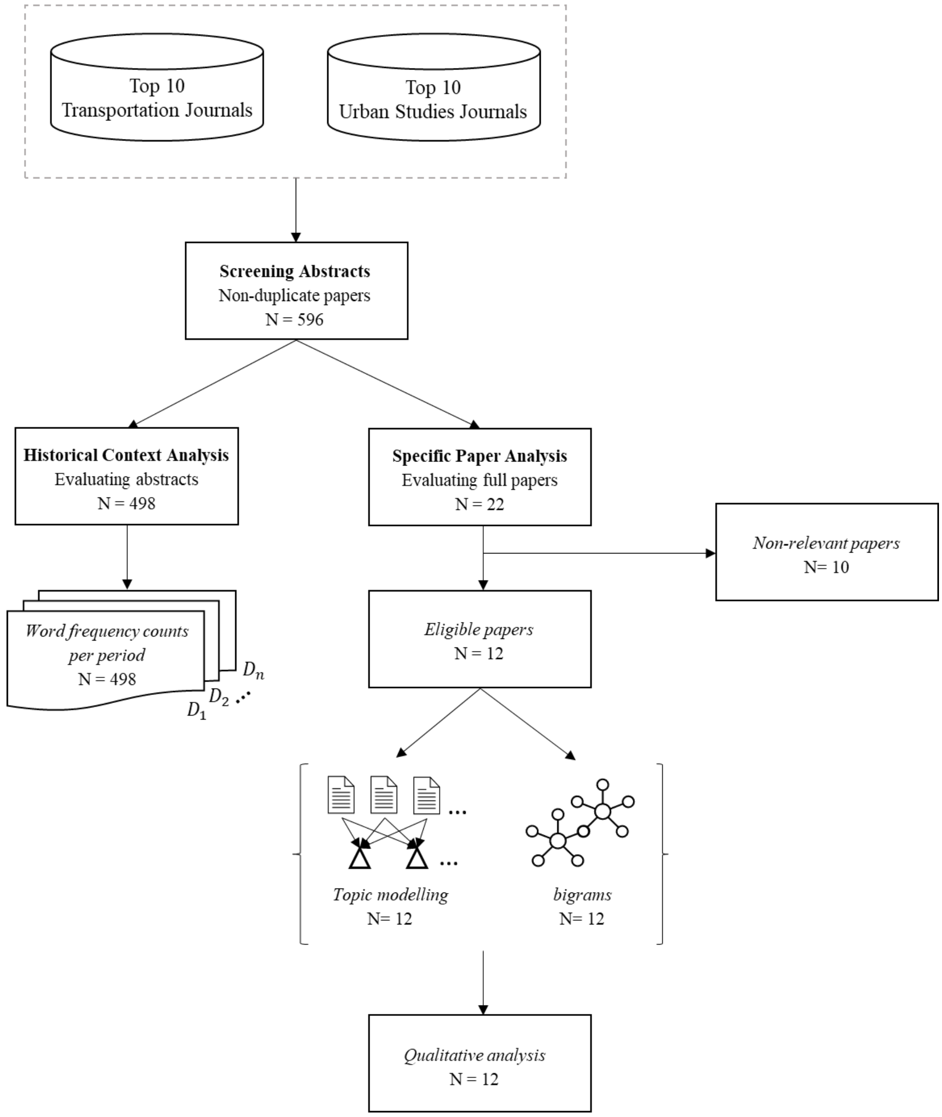

Figure 4: Detailed *methodological framework of the systematic review.*
Source: Author.

2.3.2 *Historical context analysis*

This sub-section discusses the development of urban and transport concepts that influenced smart road space allocation. As mentioned in the methodology section, we analyze the most frequent words in the filtered abstracts throughout the periods. The filtered abstracts are separated in a five-year publication period (Except from 1978 to 1985). Figure 5 compares the time evolution of each keyword's published papers with important landmarks, while Figure 6 illustrates normalized plots of the most frequent words that appear in each period. The total number of papers differs in each period. Nonetheless, the collection and filtering process of the papers were based on the same criteria.

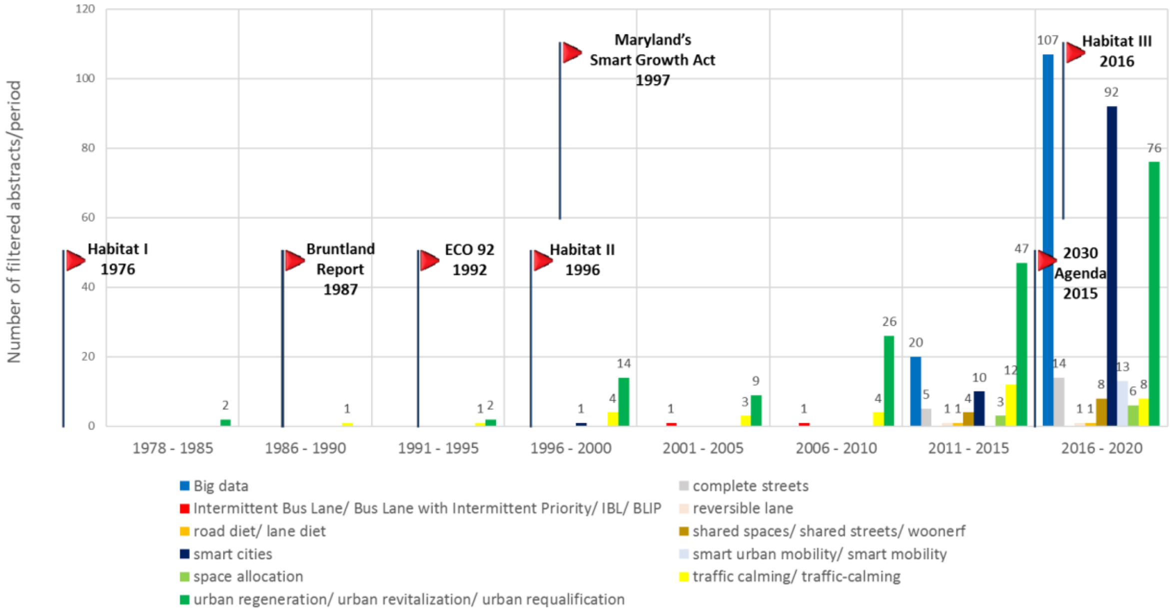

Figure 5: Historical evolution of papers per keyword.
Source: Author.

As the sample of papers is small in the first three periods (from 1978 to 1995), the analysis of the word counts is inconclusive. However, interesting words already appear, giving some preliminary insights into the historical context at the time, such as "revitalization", "development", "cultural", "economic". Additionally, crucial historical planning landmarks happened during this time and are aligned with these words (Refer to Figure 5 and Figure 6). In 1976, the United Nations held its first conference on human settlements, entitled Habitat I, which aimed to discuss the impacts of rapid and uncontrolled urbanization (United Nations, 1976). Just over ten years later, the Bruntland Report was a seminal official document that initiated the sustainability movement (United Nations World Commission on Environment and Development (WCED), 1987). In 1992, the conference ECO 92 was held in Rio de Janeiro, Brazil. It was the first time the political community acknowledged the importance of conciliating socio-economic activities with preserving natural resources. This fact led to the development of the sustainable development concept and a plan for the following decades, entitled Agenda 21 (United Nations, 1992). An important paper from this sample analyzes the rise and implementation of culture-led practices in urban policies as a tool for urban regeneration (R. Griffiths, 1995).

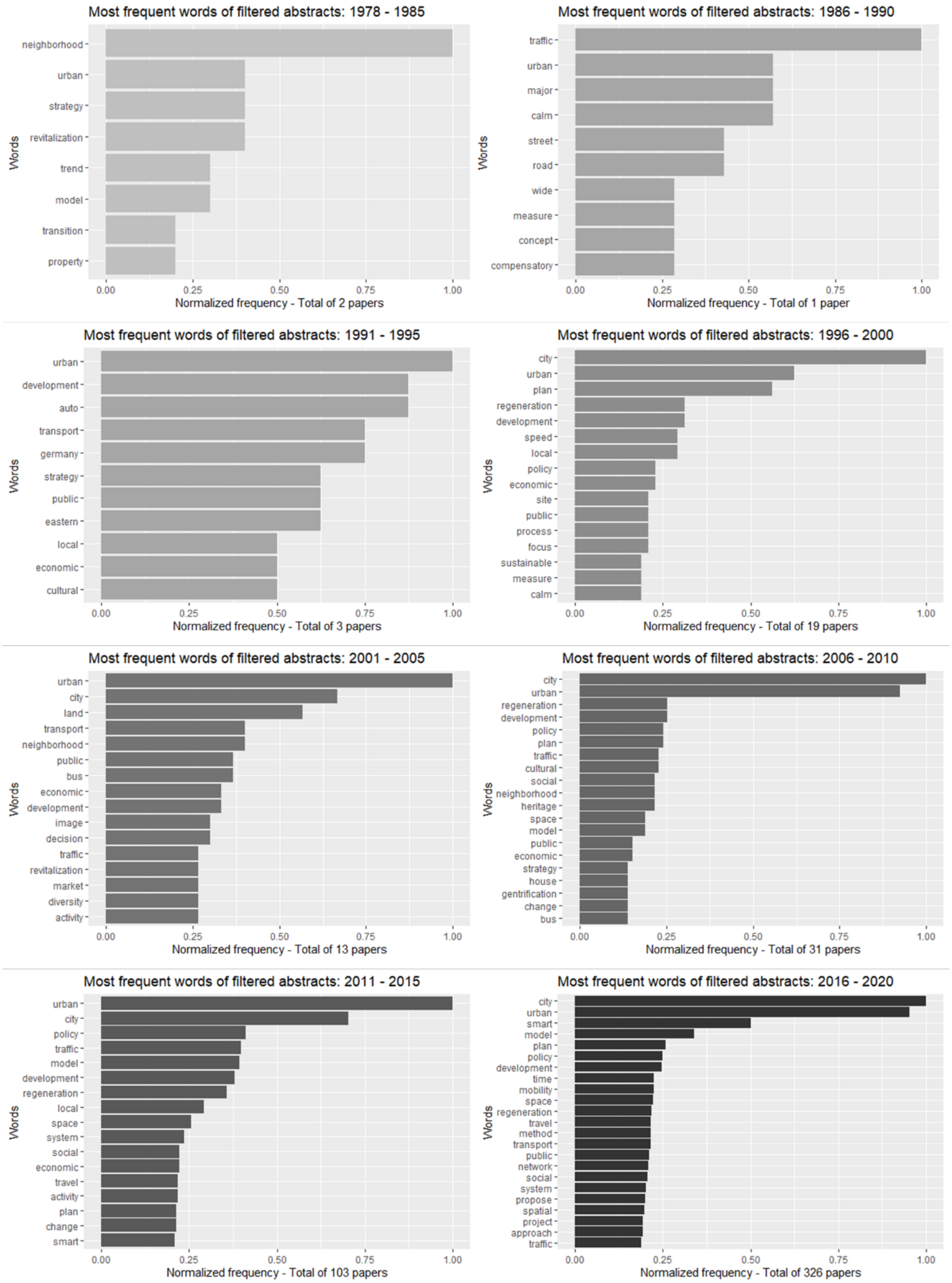

Figure 6: Most frequent words of filtered abstracts.
Source: Author.

On the other side, traffic-calming schemes began to arise in neighborhood environments in the 1980s and were strongly studied by Hass-klau (1990, 1992). The increase in traffic accidents resulted in street designs that reduced traffic speed, especially in dense pedestrian and local neighborhood environments. In the 1990s, the rise of congestion problems related to emissions, accidents, and urban sprawl resulted in increasing concerns about how road space was being designed. Words such as "traffic", "calm", "urban", "street", "road", "auto", "local" indicate this concern.

From 1996 to 2000, there was a rise in the number of published papers; however, still focusing on urban regeneration, sustainable development and traffic calming measures. The dependence on the automobile, the rise in housing costs, air pollution, and social displacements caused by urban sprawl were significant concerns in the late 1990s. In 1996, twenty years after the first conference, the United Nations held Habitat II. The human settlement conference developed the Habitat Agenda, which focused on achieving sustainable development in cities and villages worldwide until 2020 (United Nations, 1996). Relevant papers with more than 100 citations regarding urban regeneration and development were published at this time (Bremner, 2000; Couch & Dennemann, 2000; Gomez, 1998; Meyer & Lyons, 2000). Furthermore, the Maryland Smart Growth, and Neighborhood Conservation Act was decreed in 1997. The term "smart growth" was initially mentioned by this legislation and would influence the creation of the organization Smart Growth America, responsible for complete streets policies in the future. The legislation held in the state of Maryland aimed to reduce sprawling effects by ensuring more compact, dense, mixed-use, and pedestrian-oriented designs (Daniels, 2010). The words "sustainable", "development", "policy", “plan”, "city", "urban", "regeneration", "local", and "economic" give an insight into how these landmarks influenced the literature (Figure 6).

Traffic calming continues to be a topic in the literature, since words such as "speed", "calm", "local", and "urban" appear. The first paper related to smart cities was published in the main literature during this period, even though it was way ahead of its time (Mahizhnan, 1999). The paper brings the first insights into how Singapore aimed to become a smart city. Smart cities are only mentioned again by Herrschel (2013) and have had a significant rise in publications thereon (Figure 5).

In the first decade of the XXI century, intermittent bus lanes and bus lanes with intermittent priority are proposed respectively by Viegas and Lu (2004) and Eichler and Daganzo (2006). These papers are the first appearance of smart road space allocation strategies in the literature. Both methodologies treat the bus lane intermittently, allowing other vehicles to use the lane when the bus is not approaching the intersection and informing the driver not to use the lane, otherwise. The use of vehicle-to-infrastructure communication and ICT in these solutions is a pioneer proposal of using technology in adapting the use of road space over time. The words "bus", "public", and "transport" (Figure 6), which arise in the early 2000s, are an indication of the transit priority strategies as a consequence of the sustainable development policy from the previous years. Furthermore, words such as "land", "space", "diversity", "activity", "social", "market", and "change" are present. These words suggest a shift from car-oriented designs to ensuring more diverse land use, livable streets and acknowledging the social function of the street. This means that streets began to be treated not only for moving purposes but also as an essential element of social interactions, culture, and commerce. Following this vision, planning design concepts such as complete streets (McCann, 2005) and shared spaces (Hamilton-Baillie, 2008a, 2008b) were established and began appearing in the main literature in the following periods.

From 2011 to 2015, there was a more diverse amount of papers per keyword. Big data is initially and significantly studied at this time, having the second-highest number of papers (Figure 5). Complete streets, shared spaces, road diets, space allocation, and reversible lanes also appear in the literature. The term "space" indicates the challenge and concern of managing road and urban space. Additionally, if "public" is linked to "space", and also "social", this can reinforce that public spaces begin to be treated as a place to stay through place-making initiatives. These spaces have the purpose of gathering and connecting people through inclusive designs. It is interesting to notice the appearance of the words "smart" and "model" suggesting a shift towards using technology to sense the urban space and for smart transport demand management. Nonetheless, in this initial literature evaluation, the relation between smart and sustainable urban and transport management solutions is unclear.

From 2015 to 2020, the amount of literature has increased substantially. Since the sample of documents is way higher than other periods, the frequency plot is more reliable. At this time, Habitat III was held in 2016, proposing a New Urban Agenda to discuss how to achieve the Sustainable Development Goals defined in the 2030 Agenda (United Nations, 2015, 2016). Recently, big data and smart cities have significantly erupted (Figure 5), rising as main topics in transportation and urban studies journals. As abundant, the term "smart" becomes one of the most cited words. The term "mobility" appears and gains more relevance than "traffic". The former term can be related to two words in the frequency plot: urban mobility and smart mobility. These terms respectively relate to sustainable transportation (walking, cycling, transit) and emergent transportation (shared mobility, micro-mobility, autonomous vehicles). This fact suggests that more research is inclined towards sustainable and smart mobility than in previous periods. The high number of papers related to urban revitalization demonstrates, even more, the concern in ensuring more livable and sustainable spaces. Lately, many studies have been in the direction of using emergent and smart technologies and big data. However, in this preliminary analysis, it is unclear whether these emergent technologies are related to urban and road design. Nonetheless, it suggests that both sensing and transport demand management technology can be used to adapt road space over time according to different demands, political goal, and functions (e.g., mobility, access, place, social).

2.3.3 Specific paper analysis

Figure 7 presents the topic-specific word probabilities of the 12 full papers. Figure 8 illustrates the network graph of the most common bigrams of these papers. Note that the bigram colors were created *a posteriori* of the algorithm to illustrate words that appear in the topics. The number of topics in the topic modeling is a prior input to the model. There is no optimum measure to define the number of topics in a model. However, Mcfarland et al. (2013) suggest evaluating the topics regarding their relevance of transmitted information and overfitting. Considering this criterion, we selected six topics since fewer topics transmitted less information while a higher number of topics began to repeat topics. The bigrams presented in Figure 8 are essential to give context, coherence, and interpret the relationship between the many words in each topic. The results already separate the different smart road space allocation solutions into the topics, providing an initial interpretation of the differences between them. Based on our interpretation of the results, we defined labels for the topics, explained below:

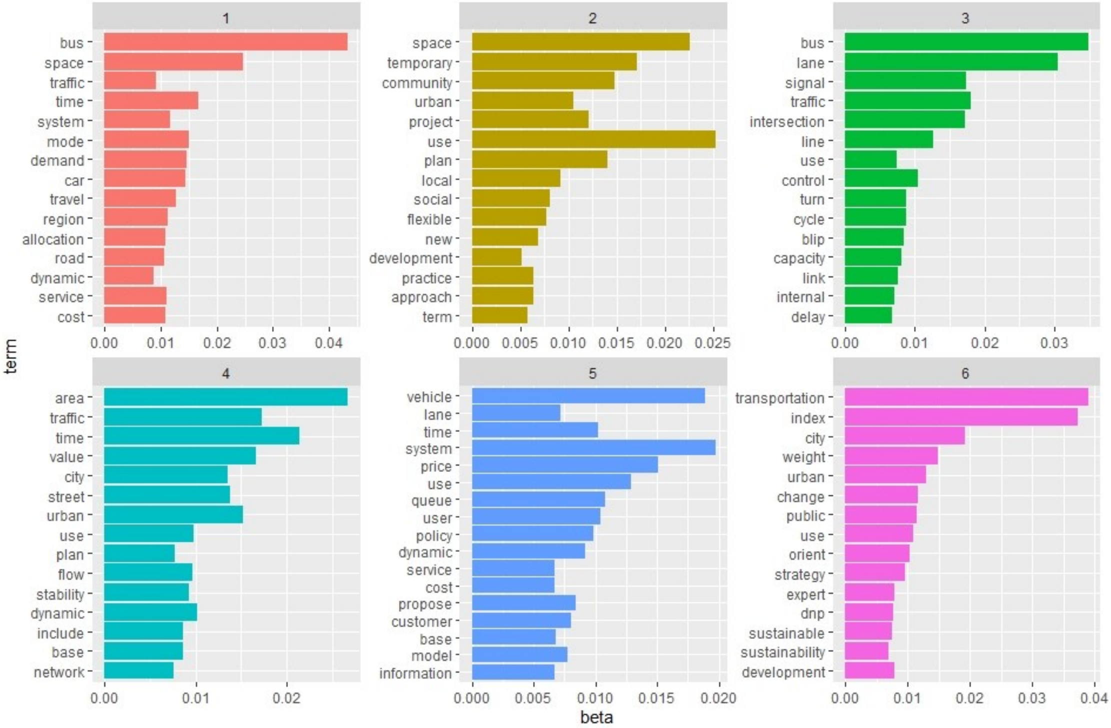

Figure 7: Topic-specific word probabilities of full eligible papers.
Source: Author.

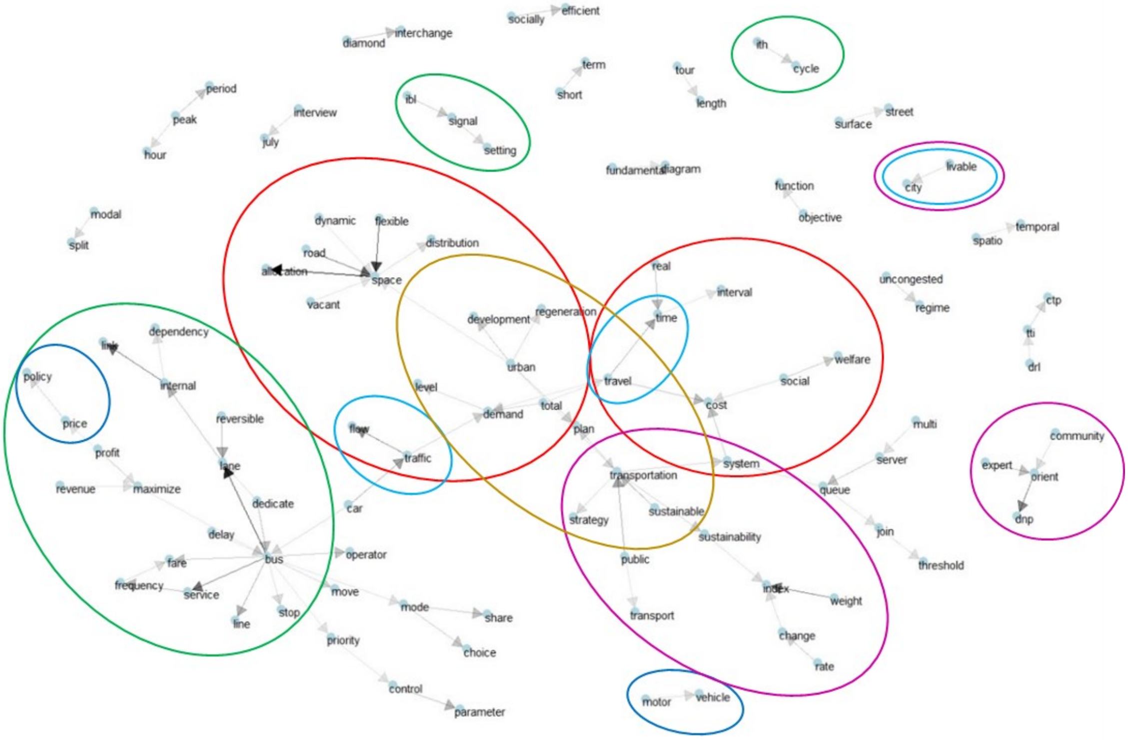

Figure 8: Network graph of common bigrams in the literature.
Source: Author.

Topic 1: "Dynamic space allocation on a regional scale."

According to the bigram (Figure 8), as the word "dynamic" usually comes before "space" and sequentially to "allocation", this topic was named after dynamic space allocation. This topic reveals that dynamic space allocation literature primarily focuses on assessing motorized traffic. The words "bus", "car", "service", "mode" and "traffic" reveal this character (Figure 7). Besides, the bigram demonstrates that "car traffic", "bus service" usually appear together. At the same time, the term "mode" is usually preceded by "bus" and followed by "share" or "choice". The appearance of the term "demand", which is usually expressed as "traffic demand", "total demand", and "travel demand", indicate that road space is dynamically adapted according to variations of motorized traffic demands. The term "time" is usually preceded by "travel", while "cost" can be linked together with "travel" and "system". The latter term is usually preceded by "transportation". Thereby, the focus in assessing travel time, travel cost, and transportation system cost is a lead that the papers focus on the performance evaluation (generalized cost of traveling) of such solutions. The terms "region" and "system" may indicate the scale of the implementation of dynamic space allocation.

Topic 2: "Temporary urban space solutions."

Temporary solutions are expressed in this topic. We decided to indicate the focus of this topic as "temporary" instead of "flexible" due to the higher word probability (Figure 7). Nevertheless, it is inconclusive at this point the difference between these terms. Terms such as "project", "use", "plan", "practice" and "approach" indicate how temporary solutions have already been placed and are being analyzed by the literature. The terms "community", "social" and "local" demonstrate how temporary solutions are focused on enhancing people-oriented neighborhoods or have public engagement. If we consider the word "flexible" as meaning adaptable, this may indicate that temporary space solutions have adaptable planning and practices.

Topic 3: "Intermittent lane allocation."

The word "blip", an acronym for 'bus lanes with intermittent priority' is expressed in this topic. Furthermore, the term "signal" is usually preceded by "ibl", which is an acronym for 'intermittent bus lanes' (Figure 8). Also, "bus" and "lane" have the highest word probabilities of the topic and usually appear together. For this reason, we opted to indicate this topic as intermittent lane allocation in transport systems. The terms "bus" and "traffic" indicate the modal priority in such solutions. The term "cycle" can be misinterpreted as cycling mode. This term is usually grouped as the "ith cycle" as demonstrated in the bigrams. As the term "cycle" has a high probability of being in the same topic as "signal", "intersection", and "control", this indicates that "cycle" refers to cycle lengths in signal control systems. The word "delay" is grouped with "bus", which specifies that intermittent solutions aim to reduce transit delays. Terms such as "intersection", "signal", "control", "capacity", and "link" confirm the focus on performance evaluation. The terms "link", "internal", and "line" are usually linked to "bus", demonstrating how the literature on intermittent solutions is focused on public transportation services.

Topic 4: "Dynamic space allocation on a municipality scale."

Whereas Topic 1 inclined a regional or inter-city application of dynamic space allocation, Topic 4 suggests a neighborhood or municipality scale application due to the appearance of the terms "network", "street", and "city". The term "city" is frequently preceded by "livable" (Figure 8), in which some road allocation practices have advocated towards this direction (e.g., road-diets, public space revitalization, complete streets.). In contrast, the terms "traffic" and "flow" are usually combined, suggesting an inclination towards optimization of traffic flow in urban environments. The word "time" also suggests this interpretation due to "travel" being the most common predecessor of "time" and a variable to measure traffic flow. Thus, the priority of dynamic lane/road space allocation is to improve traffic or transit performance independently of the application scale (Topic 1 and Topic 4).

Topic 5: "Policies towards dynamic space allocation."

As the terms "dynamic" and "policy" are present in this topic, we defined its focus as referring to these terms in urban environments. Also, "price" is usually followed by "policy". Terms such as "user" and "customer" demonstrate how dynamic applications may be demand-dependent. Words such as "model", "price", "cost", "time", "queue", "lane" and "vehicle" emphasize that the dynamic road/lane space allocation aims to optimize the generalized cost of traveling (Figure 7). Also, the term "vehicle" is frequently preceded by "motor" (Figure 8). This analysis suggests that dynamic road/lane space allocation focuses only on traffic and transit performance, lacking assessment for active modes.

Topic 6: "Sustainable transportation policy."

We defined this topic as sustainable transportation policy due to the presence of the terms "transportation", "sustainable", "sustainability", and "strategy" (Figure 7). The term "sustainable" is usually followed by "transportation", while "sustainability" is preceded by "transportation" (Figure 8). The term "public" appears regularly as "public transportation". These findings indicate an inclination of this topic in assessing public and active transportation strategies. Furthermore, terms such as "city" and "orient" (oriented) indicate this direction, since frequently these terms are preceded respectively by "livable" and "community". The words "weight" and "index" indicate that the documents evaluate sustainability indexes since both terms typically appear together. Nonetheless, it is noted that the terms "dynamic" or "intermittent" are not present in this topic.

2.3.4 Qualitative analysis

The literature on emergent urban space allocation strategies is still scarce. Smart cities and big data only began to be significant in the literature from 2011, as demonstrated in Figure 5. Consequently, big data and ICT applications in road space allocation are still low. In the 12 eligible papers, there is a lack of definition of some of the emergent terms in assessing smart road space allocation. Although all eligible papers refer to temporary, dynamic, intermittent, or flexible road space allocation solutions, some of them are incoherent with each other. Based on the literature, we propose defining the main characteristics of smart road space allocation solutions, specifically the differences between temporary, dynamic, intermittent, and flexible solutions, summarized in Figure 9 and detailed, respectively.

Temporary

According to Galdini (2020), temporary solutions are executed when there is a need for innovation and change in the urban space. These practices are usually used for revitalizing vacant public spaces to promote social interactions, economic activities, and environmentally friendly designs (Ferreri, 2019; Galdini, 2020). Carr and Dionisio (2017) define "Flexible Spaces" as the regeneration of underused public spaces with temporary and informal solutions. Thereby, it is interesting to notice that temporary designs mentioned by Ferreri (2019) and Galdini (2020), are defined as "Flexible Spaces" by Carr and Dionisio (2017). Besides, the authors propose that "Flexible Spaces" have minimal regulation, are reconfigurable, and democratically accessed by people who want to use the space.

Site selection for the temporary use of public space is poorly mentioned in the literature (Galdini, 2020). As a result, temporary solutions are usually based on experimental projects. These solutions usually have an uncertain time to finish and are planned to be non-permanent (Ferreri, 2019; Galdini, 2020). However, temporary designs can become permanent if they have successful outcomes. Temporary solutions can have two forms: community-oriented place-making; and pop-up or tactical practices. The former is a participatory policy that considers people's needs and opinions in all or some stages of the project (Ferreri, 2019; Galdini, 2020). While the latter usually relies on quick and responsive pop-up solutions, lacking or having minimal community participation in decision-making (Ferreri, 2019). Although temporary solutions can be modified if they have undesirable results, this type of design is usually not adaptable regularly (e.g., over the hours or days). When applied in the street, temporary solutions can appear in form of pop-up bike lanes or parklets. These experimental solutions are usually quick, responsive, cheap, and focused on active transportation or place-making initiatives.

Nonetheless, these solutions are usually fixed and lack adapting to different demands or needs during the day. For example, a parking space that serves offices during the day could also operate as spaces for restaurants to put tables at night, when offices are closed. There is a potential for using big data to evaluate the efficiency and effect of these temporary solutions in order for them to become permanent or eventually adapt dynamically to different needs. In a smart city, these temporary, quick, and responsive solutions (e.g., pop-up bike lanes and parklets) could be used with simple technology, such as introducing flexible bollards that separate uses.

Dynamic vs Intermittent

Way before the rise of literature on big data and smart cities (recall Figure 5), Viegas and Lu (2004) developed the Intermittent Bus Lane (IBL). IBL prioritizes transit by informing drivers not to enter the lane when the bus is approaching the intersection and use it otherwise. The position of the bus is detected by sensors or communicated by the transport authorities. Depending on the bus's position, transit signal priority, variable message signs and flashing LED in-pavement lighting are activated when the lane is exclusively dedicated to the bus and turned off if other vehicles can also use the lane. A similar concept, denominated Bus Lanes With Intermittent Priority (BLIP), was proposed by Eichler and Daganzo (2006). The main difference is that the IBL only considers vehicles entering the lane, while the BLIP considers that the vehicles already in the lane also need to leave when the bus is approaching the intersection. This adjustment avoids queues ahead of the buses, reducing transit signal priority dependence. Nonetheless, both concepts lack considering traffic dynamics and bus operation frequency (F. Zhang et al., 2018).

Serok et al. (2019) and Wey and Huang (2018) analyze how urban and traffic dynamics vary over time. According to Serok et al. (2019), real-time data and variation of traffic demand analysis could be used to propose new solutions that adapt urban space, transit frequencies, transit signal and traffic demand management accordingly to the fluctuations of demand. In this direction, sensing and demand management technologies could come into play. Also, the evaluation of the impacts regarding these new solutions could also be evaluated over time with the rise of big data (Wey & Huang, 2018). As mentioned, the rise of big data in the main literature since 2016 (refer to Figure 5), has helped evaluate urban and traffic dynamics in a 24-hour timeframe. Before, it required intensive labor and high costs to perform this evaluation.

Furthermore, before big data, decision-making was mainly based on historical data. Now, decision-making can be executed in real-time. Sayarshad and Gao (2018) propose an on-demand transit system that adapts the routes and frequencies according to real-time information. The authors propose a dynamic optimization model for enhancing a control policy for selecting vehicles and routes in a demand-responsive mobility system. Nonetheless, the authors do not relate the dynamic routes and frequencies with how the infrastructure will support these changes.

N. Zheng and Geroliminis (2013) compare road space allocation strategies (static and dynamic) of buses and automobiles in a macro-scale environment. The study relies on the problem that traffic and bus lanes can be underutilized at certain times of day and should adapt to multimodal demand fluctuations. The static approach considers a dedicated bus lane in the center of the road. The dynamic space allocation changes its configuration over time according to the bus demand. The changes were executed in three periods of the day (before peak hour, peak hour, and after peak hour) to avoid too many changes in the system. In practice, many changes in the system would make it difficult to be implemented. The dynamic allocation approach uses the urban space more efficiently than the static one, since it reduces the space for transit that is underutilized in off-peak periods and increases the space dedicated to the bus during peak-hours when the demand for passengers is higher (N. Zheng & Geroliminis, 2013).

C. Wang et al. (2016) introduce the Dynamic Circulation Lane Allocation and have similar findings as N. Zheng and Geroliminis (2013). The former study develops a system architecture in a smart city context (IoT and ICT) for dynamic lane allocation in highways for buses, rescue vehicles, and private vehicles. The Dynamic Circulation Lane Allocation aims to share lanes between different modes when the space is poorly occupied, or there is a lack of space to allocate all modes statically. In this proposal, sensors detect the multimodal demands over the day, and the management system decides how the lanes should be allocated. The management system then informs the horizontal and vertical signaling to adapt accordingly. According to C. Wang et al. (2016), reallocating road space dynamically in heavy traffic environments may not be efficient. It justifies keeping a dedicated bus and priority vehicle lanes during peak hours when the demand is high. On the other hand, in non-peak hours, bus and priority vehicle lanes can be mixed with traffic and allocated dynamically.

F. Zhang et al. (2018) examine dynamic lane allocation in a bi-modal environment (automobile and transit) by allocating space according to fluctuating demands. The paper considers the interaction between traffic flows and road space allocation by optimizing system cost, public transportation profit, and user cost. This study also asserts that bus lanes should be exclusively dedicated during peak hours and mixed with traffic during non-peak hours.

J. Zhao, Liu et al. (2015) developed a methodology for improving the performance of signalized diamond interchanges that connect highways in urban and suburban environments by adopting dynamic reversible lanes. The dynamic reversible lane is executed in the internal link of the signalized diamond interchange by changing the direction of the lane according to traffic dynamics. Dynamic reversible lanes differ from the other dynamic space allocation studies since they are only directional movement changes and do not assign the lane to other transport modes or urban functions.

Summing up, although dynamic and intermittent road space allocation solutions are similar, some differences distinguish both concepts, as shown in Figure 9. The main difference is that dynamic applications consider fluctuations of demands and are usually adapted in periods (e.g., peak and non-peak hours). In contrast, intermittent applications are reactive to the position of priority vehicles, changing how the lane is used in real-time. Intermittent strategies are technologically dependent since they rely on vehicle detection and ICT. Dynamic solutions can use technology as well but are not fully dependent. Historical data and traditional vertical signaling may change the configuration of space dynamically in less complex situations. Potentially, a traffic lane can become a recreational cycling lane in low-traffic periods such as Sundays or evenings. Dynamic solutions can be permanent or non-permanent depending on the level of investment and technology used to sense and manage the road. On the other hand, intermittent solutions are often permanent due to the high cost and time for changing signaling and ICT infrastructure. Thus, while intermittent solutions are only applied with smart city infrastructure, dynamic solutions are not dependent on a technologically developed system.

Flexible

Ferreri (2019) and Galdini (2020), use the term "flexible" to define the planning and process of temporary urban space solutions. According to Galdini (2020), the lack of flexibility in norms and regulations is a barrier to implementing rapid and temporary solutions in urban space. In comparison, Ferreri (2019) claims that pop-up infrastructure and temporary solutions are based on flexible and short-term planning. Galdini (2020) also uses this term to refer to adaptable design characteristics of temporary spaces, as mentioned in:

> *"Thanks to the transformable and temporary character of their elements, spaces become flexible and capable of adapting to spatial and functional changes over time."*

As mentioned, Carr and Dionisio (2017) use the term "flexible" to define the concept "Flexible Spaces", referring to temporary design in vacant spaces. F. Zhang et al. (2018) refer to flexible in dedicated bus lane designs to explain how lane management can be dynamically adapted throughout the day according to multimodal demands. Here "flexible" has a similar connotation as "dynamic". While J. Zhao, Liu et al. (2015) refer to flexibility as a planning tool and an intrinsic characteristic of the system to enhance dynamic designs. The terms "flexible" and "flexibility" are confusing terms in the literature. They may refer to temporary or dynamic road designs or the planning process of these designs. Therefore, we do not recommend using this term to define a type of urban and road allocation solution. We suggest that flexibility should be used to characterize how adaptable the planning process may be, as illustrated in Figure 9. In conclusion, temporary, dynamic and intermittent solutions need to have a flexible planning process in order to adapt to changeable factors through time (e.g., demand, urban dynamics, urban functions, etc.).

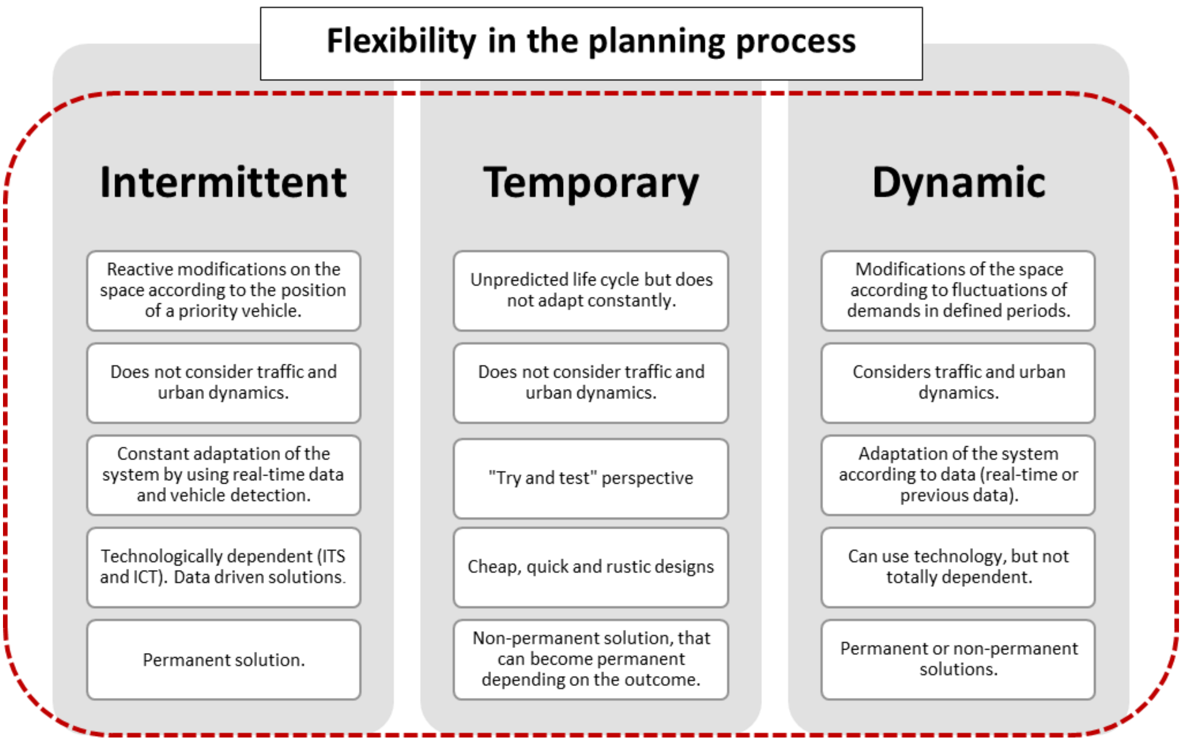

Figure 9: Definition of flexible, intermittent, temporary and dynamic applications of road space allocation solutions. Source: Author.

2.4 Discussion

2.4.1 Research gaps and contributions to the literature

Temporary and dynamic applications in road space began to be published in 2013, being in line with the rise of emerging concepts and methods (refer to Figure 5). Intermittent road space allocation is published way ahead of their time. It is important to emphasize that intermittent bus lanes were seminal in smart road space allocation, even before the rise of big data and smart cities in the literature.

On one side, temporary solutions are mainly held in local access streets to achieve place-making and reclaim vacant public spaces. On the other side, intermittent and dynamic solutions are mainly studied in arterials and highways and focused on traffic performance. Ultimately, smart road space allocation solutions are poorly studied in more urban and complex environments, where there is a high dispute and limited space to fulfill access/place and movement functions. It is necessary to consider active transportation and different land-use throughout the day in more complex environments. The few studies mentioned in this review do not consider active transportation or shared mobility when allocating space. Only C. Wang et al. (2016) recommend that pedestrians and cyclists receive information on their smartphones about current road conditions when allocating road space dynamically. Still, the lanes are not allocated to them, and the possible conflicts with vehicles are not considered in the dynamic lane management architecture.

Dynamic and intermittent proposals only take into account the carriageway overlooking the adjacent space (e.g., sidewalks) and buildings. This gap needs to be considered if these smart road space allocation solutions are implemented in more complex spaces due to the significant influence of land-use density and diversity in mode choice and fluctuations of demands of daily trips, respectively (Cervero, 1996). The main literature on dynamic and intermittent solutions is strictly related to the movement function of the road, allocating space to different modes of transport. Still, these initiatives can potentially allocate the space to non-transport initiatives or the mix between transport and place-making initiatives. For example, a traffic lane could become a market or an expanded space for restaurants and bars during underused times. A gap to be fulfilled is in terms of user acceptability and whether these smart road space allocation solutions can promote social exclusion. As Lytras et al. (2021) mentioned, some smart solutions may not be accessible or easy to understand for all users. Future studies need to assess how different smart road space allocation solutions may have different acceptance levels. Chapter 6 presents an initial discussion on how different applications of allocating road space dynamically can achieve different levels of social acceptance.

The use of big data and ICT to detect transport and urban dynamics and communicate to the infrastructure is important for not only allocating road space for different demands over time, but also adapting in case of an unpredictable event. For example, if an accident occurs, a lane in the opposite direction can be allocated until the traffic returns to normal. Additionally, smart road space allocation solutions could also allocate urban space efficiently and better in case of a sudden change in travel patterns. This was the case during the beginning of the Covid-19 pandemic when traffic lanes became vacant, and recreational walking and cycling trips increased. A smart infrastructure could potentially have allocated underused traffic lanes to pedestrians and cyclists not only to adapt to the current need but also to promote social distancing.

Ultimately, urban space is scarce, and these smart solutions can allocate space for different needs during the day, as many transport modes and urban functions have disputing or complementary demands. When the demands of all transport modes are high (e.g., peak hours), there is a policy dilemma regarding how much space should be allocated for a certain transport mode. On the contrary, when demands are complementary, there is a transport mode with higher demand than others at a certain time. Therefore, road space could be dynamically allocated to higher needs when urban space is underused. While sensing technologies and big data are essential for detecting multimodal and multifunctional fluctuations of demand, transport demand management technologies have the role to adapt the space according to policy goals and underused spaces. Although this chapter discusses briefly how technology can be used in smart road space allocation solutions, in Chapter 4, we develop a road space allocation smartness level framework, similar to the Driving Automation Levels (Society of Automotive Engineers, 2019) and the Bicycle Smartness levels (Kapousizis et al., 2023). Emerging transport modes such as autonomous and connected vehicles require vehicle-to-vehicle and vehicle-to-infrastructure communications, while other transport modes are not dependent on these types of technologies. Different smart road space allocation solutions may be more appropriate depending on the transport modes involved, local context, and policy goals. This smartness level may help researchers and policy makers to determine which types of sensing and transport demand management technologies are required or suggested for different smart road space allocation solutions.

2.4.2 Implications for practice

Large databases require text mining techniques to be able to detect patterns. Nonetheless, we argue that conventional literature reviews with a smaller number of documents may also include such techniques. Our approach demonstrates that using text mining before reading the full documents can provide an initial analysis of the papers, and organize the ideas into topics, and through time, as explained by the method. With a small sample, it was also possible to analyze if our analysis of the topics and bigrams were coherent with the qualitative analysis held *a posteriori*. We conclude that text mining in conventional systematic literature reviews achieves satisfactory results. Nonetheless, it is important to be very rigorous on the preprocessing techniques since this step significantly impacts the results. Programming techniques such as R and Python enable an interactive and rigorous assessment of each method step. Text mining applications using *"black box"* softwares, which provides only the final output, are often less informative due to weaker preprocessing.

Although the R programming libraries used in this method are not new, an application of the methods to literature reviews has not been made. We provide an open-access dataset, code, and guidelines to ensure the reproducibility of the results and also the generalizability to other research fields. This initiative is a step that goes in line with more collaborative, open-data, and data-driven projects in Information Sciences (Kar & Dwivedi, 2020).

2.4.3 Limitations and future research directions

This paper has opted to perform a systematic literature review on smart road space allocation solutions on the top 10 transportation and urban studies journals. This methodological choice allowed us to collect the most relevant literature on the fields in question. We limited the analysis to these journals in order to include all the periods of published papers to perform the historical analysis. We wanted to maintain the review on a reasonable number of papers to introduce text mining techniques in the literature while also being able to perform a qualitative analysis. The choice of limiting within the transportation and urban studies areas was to have a more focused analysis on the contributions being held in these research fields. As some of the selected keywords were very interdisciplinary and popular such as "smart city" and "big data", expanding the review and applying text mining techniques could lead to results not within the interest of this paper. Also, we contribute to whether using text mining in a small number of documents contributes or not to the analysis. Nonetheless, we acknowledge that expanding the review to common databases such as Scopus, Web of Science, and Google Scholar can provide more eligible papers, or even expand to other research areas. Chapter 4 presents an expanded and more recent review focusing on the technologies applied to smart road space allocation. We believe this step is relevant, especially on topics requiring a more interdisciplinary analysis. It would be interesting to expand the review to analyze the role of big data, smart cities and smart road space allocation on adapting to changes in travel behavior during the Covid-19 pandemic. Specifically, in this topic, other fields of research are very relevant for a more interdisciplinary approach such as economics, psychology, and health information management.

A limitation of using topic models is that researchers need to define the number of topics before the model. There is a need for interactively running models to define the number of parsimonious topics that provide sufficient information. Additionally, it may not be clear to understand all the information included in a topic and its relation to the research questions. Using n-grams is essential for interpreting the information on the topics. An example was the word "cycle" that often is related to bicycle, but appeared in the bigram as "ith-cycle". After interpreting the topic in our case, we concluded that "cycle" is actually the cycle time of traffic signals. Human interpretation and previous knowledge on the researched topic can influence the results' interpretation quality. Therefore, we believe that text mining does not replace the review or the human interpretation but is a tool to assist and help organize the main tendencies of the documents.

2.5 Conclusion

This chapter analyzes the main literature on emerging road and urban space allocation strategies. We propose a systematic review methodology and provide the code to use text mining on abstracts and full papers. Initially, we used word frequency counts in abstracts to provide historical background and context to the analysis. This step was linked to the main urban landmarks and events that contributed to smart road space allocation solutions. Sequentially, we analyzed the full eligible papers (as defined per our criteria) using topic modeling and bigrams to detect patterns. Although text mining does not give a complete analysis nor replaces reading the papers, it can be important for an initial interpretation and detection of document patterns. Ultimately, both text mining proposals on abstracts and full papers are reproducible in future literature reviews on other transportation topics and research fields.

Based on the literature, we define and discuss the differences between using terms such as dynamic, intermittent, temporary, and flexible in smart road space allocation solutions. This definition is essential to guide towards a clear and standard definition of each type of solution. The term "flexible" is confusing and misused. We suggest that "flexible" is used to describe the planning process of smart road space allocation. The historical evaluation of the papers allowed us to analyze how urban policies shifted from a traffic-centered performance and safety evaluation of the street in the 1970s and 1980s to considering streets also as an important public space. Also, despite a significant rise in studies regarding emergent concepts such as smart cities and big data, few papers consider these approaches in road space allocation.

The literature on temporary solutions focuses on policies related to public space revitalization through experimentation. Consequently, temporary solutions have an uncertain time to finish and are maintained or removed depending on their outcome. Intermittent strategies perform reactive lane management, allocating the lane according to the bus's position. Nonetheless, Intermittent Bus Lanes and Bus Lanes with Intermittent Priority lack considering traffic and urban dynamics and are not suitable in heavy traffic environments. Dynamic lane allocation allocates the lane to different uses in different periods of the day (e.g., peak and non-peak periods) according to multimodal demands. Most studies on dynamic space allocation focus on traffic and bus performance. The few studies on smart road space allocation do not include active transportation or emergent forms of transport in allocating road space intermittently or dynamically and are more focused on suburban areas, highways and arterials. Urban and complex spaces are not considered in these designs.

One of the leading literature gaps is using these smart solutions to achieve sustainable development goals and more livable cities. While emergent solutions are focused on allocating space according to fluctuations of demand, policy makers often allocate road space according to their policy goals (F. Zhang et al., 2018). Potentially, it is possible to allocate space dynamically or intermittently to increase a specific transport mode, even if the existent demand is not high (e.g., increase cycling levels). In a smart city, urban space planning is essential to achieve sustainability. In more urban environments, smart road space allocation solutions should not only focus on more efficient use of space in terms of performance – travel times and emissions -, but also focus on achieving transport justice goals and people-centric spaces. Road space allocation strategies that change over time should consider public acceptability and how the many socio demographic segments are able adapt to road space changes.

2.6 Replication and data sharing

The code, data, and guidelines for reproducing the results of this paper can be found at: https://github.com/valenca13/LiteratureReview_TextMining.

Chapter 3

What we have learned so far

In Chapter 2, different types of smart road space allocation were defined. Dynamic changes to road space are dependent on fluctuations of demand and are usually held in periods (e.g., peak and non-peak) rather than in real-time. Studies on allocating road space dynamically are predominately in the direction of dynamic lane allocation and dynamic reversible lanes focusing on traffic performance, considering only motorized vehicles and transit, and lacking consideration of the adjacent space of the road. Applications of dynamic lane allocation and dynamic reversible lanes are usually studied in highways and arterials, lacking applications in more urban and complex areas, where there is a high dispute but limited space to fulfill both mobility and access street functions.

What to expect in Chapter 3

Chapter 3 brings an initial discussion on the conceptual assumptions, possible applications, technological solutions, and challenges and opportunities for reallocating road space dynamically over time in complex and urban environments. We define the concept of *dynamic road space allocation* which is the object of study of the thesis, based on the definition of "dynamic" and the gaps found in the previous chapter. Highly disputed spaces could potentially be allocated dynamically for different modes or functions when they are underutilized. Technologies such as LED in pavement lighting and variable message signs could be used to manage the space and inform users of dynamic transitions. Also, sensing road space and using big data could characterize different demand patterns and fluctuations, providing data to help decide when and who to reallocate road space dynamically over time. Reallocating road space dynamically may face many challenges related to equity, financial and technological constraints, built environment restrictions, enforcement, legal framework/ regulation, governance of data ownership and usage, as will be discussed in the following chapter.

Chapter 3

3 Main challenges and opportunities to *dynamic road space allocation*

This chapter has been published as: Valença, G., Moura, F., & Morais de Sá, A. (2021). Main challenges and opportunities to dynamic road space allocation: From static to dynamic urban designs. Journal of Urban Mobility, 1(100008). https://doi.org/10.1016/j.urbmob.2021.100008

3.1 Introduction

After many decades of car-centered planning, many cities are now favoring people-centric planning in line with the United Nation's Sustainable Development Goals (SDG). For instance, SDG11 aims to "Make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations, 2015). Also, the European Union's White Paper aims to reduce at least 60% of transport GHG emissions by 2050 and proposes more efficient transport systems with better traffic demand management, land-use planning and reallocation of urban space for sustainable modes of transport (European Commission, 2011). The problem is that urban space is a contested space of which transport facilities use a significant amount. As cars took up more urban space than other transport modes, cities struggled with increasing congestion levels and carbon dioxide and other polluting emissions. The issue of justice and equity of road space allocation arises, besides health and environmental impacts (Banister, 2008; Gössling et al., 2016). Although scarce, road space (from façade to façade including roads, parking, bicycle lanes, and sidewalks) must allocate all the functions needed to support economic activity and create livable and equitable urban spaces (von Schönfeld & Bertolini, 2017).

Although, in many developed world cities, the road space initially planned for the automobile has begun to be reallocated for sustainable transportation alternatives (I. H. Jones, 2014), still, urban road space is often idling–e.g., congested multilane avenues during peak hours are often underutilized in off-peak hours. Likewise, on-street parking in residential areas is scarce overnight but underutilized during the day when residents leave to work. Other examples could be given. Thus, planners could reallocate idling road space for other transport purposes (e.g., bus or cycling lanes) or urban functions (e.g., markets, promenades) without critically jeopardizing levels of service of current road users. Such approaches exist today, such as nighttime parking or on-street weekend markets. However, these designs are predominantly local and static, and often they follow a fixed rule; or they are temporary (e.g., pop-up cycle lanes). Complex and dynamic situations are not considered in these types of solutions when there are changeable patterns of demands and activities throughout the day. Overall, they do not reallocate space according to demand-responsive criteria for varying mobility or access needs.

In this context, we propose the concept of *dynamic road space allocation* to better respond to the scarcity of space in some urban areas and its dispute for competing uses and functions. Therefore, this proposal aims to contribute to achieving more equitable and efficient patterns of road space distribution (from façade to façade) in urban areas. In this context, *dynamic road space allocation* aims to reallocate road space according to current and potential multi-modal and multi-functional uses of the road space in pre-established time gaps (e.g., peak hour and non-peak hour). The main goal is to accommodate the many uses and functions that the public space may have, with fluctuations of intensity and type of demand over time, while addressing severe problems of today's cities, such as congestion, sustainability, equity, and safety. Big data, Information and Communication Technology (ICT) and Intelligent Transportation Systems (ITS) can be used as relevant tools for designing adaptive road space solutions. Namely, they can define where, when, and how the road space can be dynamically changed when mobility and access needs vary over time without severely compromising the level of service of concurring modes.

The objective of this chapter is to discuss the state-of-the-art, main challenges and opportunities, technical solutions, indicators for site selection, and propose a methodological framework for implementing *dynamic road space allocation* in contested and scarce urban spaces. The motivation of this approach is to improve the sustainability of urban mobility by making active modes and transit more attractive by reserving more space when traffic lanes are underutilized (e.g., non-peak hours). Furthermore, reallocating space for sustainable modes in specific periods of the day or week can potentially attend to existent and latent demands and increment equity and efficiency in the use of a scarce resource as road space is.

First, a background is presented to discuss the similar concepts, applications, and gaps to be fulfilled to introduce the concept of *dynamic road space allocation*. Then, we present the conceptual assumption for selecting the most appropriate zones for implementing *dynamic road space allocation*. There is a following section reviewing the potential use of big data and data-driven technologies for implementing the dynamic urban concept. Sequentially, we demonstrate the existing technical solutions that can be used for *dynamic road space allocation*. Next, a section is reserved for discussing the challenges and the opportunities that this concept may face. Then, we suggest a methodology for implementing *dynamic road space allocation*. Finally, the main conclusions and references are presented.

3.2 Background

The proposals of the Intermittent Bus Lane (IBL) and the Bus Lane with Intermittent Priority (BLIP) were seminal in using transit signal priority to reallocate traffic lanes in real-time for buses and automobiles. The IBL and BLIP allocate the bus lane to motorized vehicles when the bus is not approaching the intersection, and prioritize buses otherwise (Eichler, 2005; Eichler & Daganzo, 2006; Viegas & Lu, 2004). Compared to dedicated bus lanes, IBL and BLIP, improve the effectiveness of transit signal priority since green phases for traffic and buses do not need to be separated, and partially overcome the road's capacity reduction (Xie et al., 2012). IBL was the first proposal to use LED in-pavement lighting and variable message signs to indicate to the driver if they can or not use the bus lane (W. Wu et al., 2018). However, both approaches do not consider different demands and patterns of traffic flow during the hours, days and seasons (F. Zhang et al., 2018). This fact may lead to long car queues in the bus lane during peak hours, which decrease the performance of these schemes.

The limitations of IBL and BLIP related to traffic dynamics influenced the literature on dynamic lane allocation to improve transit capacity and efficiency (Xie et al., 2012; F. Zhang et al., 2018). Even though they are similar, dynamic lane allocation in transit applications differ from IBL and BLIP schemes mainly in three aspects: considers traffic fluctuations over the hours; adaptations of the lane tend to be in periods of the day rather than in real-time; uses historical or real-time data but are not dependent on vehicle detection as IBL and BLIP. Besides transit priority schemes, dynamic lane allocation has been studied for opening the hard shoulder for traffic in peak hours (Mehran & Nakamura, 2009); reversible lanes (Hausknecht et al., 2011; J. Zhao, Liu, et al., 2015); and dynamic lane reversal for autonomous vehicles (S. Chen et al., 2022; Duell et al., 2016).

An example of dynamic lane allocation that considers traffic dynamics is the "Dynamic Circulation Lane Allocation" proposed by C. Wang et al. (2016). This system analyses the dynamic allocation of lanes in expressways for buses, rescue vehicles and automobiles. In low traffic periods, the bus lane is treated intermittently, in a similar approach to BLIP. Instead of using vehicle detection on the buses, the bus drivers request the right-hand lane when approaching the traffic upstream. Thereby, all traffic lanes are dedicated to general vehicles when there are no buses and dedicated to buses otherwise. However, when all lanes are congested the right-hand lane is reserved exclusively for the bus during the whole period ("static mode"). The "dynamic" factor, in this case, is the consideration of traffic dynamics in deciding which approach to implement (intermittent – adaptations in real-time; or static – dedicated bus lane). On the other side, Zhang et al. (2018) propose that some lanes are exclusively dedicated for buses in peak periods and shared with all vehicles during off-peak. N. Zheng and Geroliminis (2013) evaluates dynamic lane allocation in expressways for automobile and buses by moving from the city center to the periphery in three periods (peak hour and before and after off-peak hours). Both approaches consider pre-established periods during the day and believe that the changes should not be executed too often as it would be unpractical to implement (F. Zhang et al., 2018; N. Zheng & Geroliminis, 2013). Real-time adaptations of the road space require that users are adequately informed and that regulations are strictly in line with user safety (C. Wang et al., 2016).

While robust literature focuses on dynamic lane management in expressways and arterials, little has been done considering urban environments, signalized intersections, and other road hierarchy classifications (Alhajyaseen, Najjar, et al., 2017). As demonstrated, most literature on dynamic lane allocation is focused on capacity expansion and travel time reduction. Although in freeways and arterials, the mobility function of the road should be prioritized, this focus is just not sufficient in urban environments and in lower network hierarchy levels where there are much more complexity and functions to fulfill (e.g., access and social spaces). Therefore, dynamic lane allocation has limitations that preclude its application in urban environments.

The literature on dynamic lane allocation is mainly focused on increasing traffic performance considering only motorized vehicles (automobile and bus). Even the papers that consider traffic flow over time, lack in considering other modal demands, activity needs and the "place" status of the street. Additionally, the demands of active transportation and their interaction with motorized vehicles are not considered in terms of performance and safety. Only the traffic lanes as part of the public space are considered in these examples. Sidewalks, housing, commerce, and other critical urban features are not taken into account. In this context, we propose the concept of *dynamic road space allocation* to fulfill the limitations of dynamic lane allocation in urban environments. The following section demonstrates the conceptual assumption for implementing *dynamic road space allocation*.

3.3 Conceptualization of dynamic road space allocation

Unlike dynamic lane allocation, the concept of *dynamic road space allocation* should characterize the urban space in two separate entities: i) space of the road network, ii) space of the buildings (Berghauser Pont et al., 2019; Hillier, 1996). Both types of urban space have a significant influence on travel behavior. While the road network is more related to the intensity of multimodal demand, land-use patterns and associated activities are more likely to influence the fluctuations of demand intensity during the day (Berghauser Pont et al., 2019). Therefore, the *dynamic road space allocation* should consider demand intensity and fluctuations over time to change its use appropriately. To implement *dynamic road space allocation,* we believe that locations must require four main aspects that will be explained sequentially: held in main or local distributors following the mobility x access dilemma; have high connectivity of the road network; be in dense urban areas; and have diverse land uses[1].

3.3.1 Street space: mobility vs access dilemma

The amount of urban space dedicated for mobility or access functions of the road network has traditionally been assigned in detriment of its hierarchy classification (Austroads, 1988, 2015; Seco et al., 2008), following not only geometric characteristics, but also its topology and function (Barthelemy, 2017; Seco et al., 2008). It is important to emphasize what we mean by mobility and access space. On one hand, the space dedicated to traffic lanes to fulfill traffic flow requirements, and movement of people and goods is usually assigned for the mobility function. On the other hand, the space dedicated to accessing activities through parking spaces or sidewalks usually fulfills the access function. Figure 10 shows how the road network is often classified in detriment to its mobility and access functions in a four-level classification: arterials, main distributors, local distributors, and local access. The designs of mobility and access spaces in the network are historically assigned according to this classification. As demonstrated in Figure 10, the arterials and

[1] Chapter 5 presents an implementation of the conceptual assumptions mentioned in this chapter to case study of Lisbon. However, in Chapter 5, besides considering spatial attributes (street morphology and land use characteristics), we also considered temporal attributes. We measured the fluctuations of traffic and public transport demands throughout the day using Google Traffic API and GTFS datasets, including them also as criteria for selecting potential sites for reallocating road space dynamically.

freeways prioritize space for mobility. As a result, the application of dynamic lane allocation in this hierarchy level is coherent since the performance of the road network should be prioritized. However, in main and local distributors, besides the mobility function, space for access should also be given, which does not align with the literature of dynamic lane allocation. On one hand, main distributors have the primarily function to connect the arterials to local areas, while also providing space to access activities. On the other hand, local distributors connect local access streets to more mobility-oriented streets, but prioritizing access space for activities and pedestrians (Refer to Figure 10).

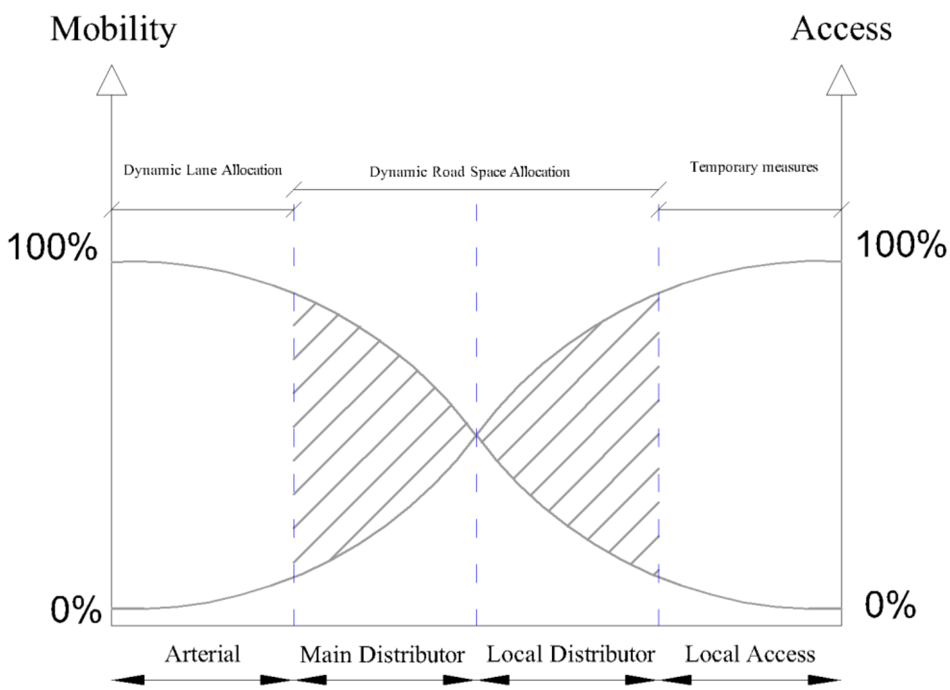

Figure 10: Road hierarchy classification and road space allocation dilemma (hatched area of the graph are the functions' overlapping zones). Source: Author. Adapted from Austroads (1988)

As urban planning is often static, reallocating space in roads within a zone near the overlapping area (hatched area in Figure 10) may not be evident for decision-makers to which function to prioritize. Additionally, the need for urban space to fulfill mobility and access functions may not be constant throughout the day but vary according to demand fluctuations and different activities along the hours. In many cities, main and local distributors were previously designed to prioritize traffic performance and access through parking spaces. Recently, urban practices such as road diets and complete streets began to change this paradigm. While road diets aim to remove traffic lanes to allocate to other transport modes or purposes, complete streets aim to redesign streets to give space to all transport modes by also reallocating parking spaces, for example (Valença

& Santos, 2020; Zavestoski & Agyeman, 2015). Although these practices give more space to sustainable transportation, they still fail to completely consider the street as a dynamic entity. As a result, they do not adapt their design to variations of multimodal demands and activities throughout the day (Mehta, 2015). With the tendency to reallocate space for sustainable transportation through initiatives such as road diets and complete streets, the dilemma arises from the amount of space that should be reallocated, the limited space to fulfill both access and mobility functions, and the consequences on traffic jams. Potentially, implementing *dynamic road space allocation* in this context may overcome this dilemma and even face political and public resistance to reallocate space for sustainable transportation, by adding the flexibility dimension of planning. It is also important to consider the connectivity of the road network. The connectivity of the network determines if the road appropriately satisfies its primary function.

On the other hand, local access streets are usually less complex than main and local distributors. In this case, experimentation pop-up initiatives and other temporary measures may be more suitable than *dynamic road space allocation* due to the high priority on the access function of the street. As many local streets are car-oriented, with the access space being mainly attributed to parking, revitalization of these spaces is important to change this paradigm to a more sustainable one. Simple, cheap and quick initiatives of remarking streets and repurposing car parking to playgrounds or parklets, for example, have demonstrated positive impacts on modal shift away from car, safety, physical activity and increase in social interactions (Bertolini, 2020).

3.3.2 Building space: density and diversity

It is known that fluctuations of multimodal demands over time are more influenced by the land use than the road network (Berghauser Pont et al., 2019). According to Cervero (1996), while land use density is more likely to influence mode choice, land use diversity is related to the fluctuation of trips during the day. When both land use density and diversity are combined, active transportation tends to rise, since activities become closer to work and home, such as restaurants and shops (Cervero, 1996; Cervero & Kockelman, 1997). Mixed land-use patterns also enable the implementation of *dynamic road space allocation*. For example, parking spaces for office workers during work hours can serve restaurants at night (Cervero, 1996), not only as parking but also as parklets. The different spatial and temporal needs of the built environment, especially in diverse and dense neighborhoods, characterizes an intensive urban dynamic that should be considered in urban designs. Thus, flexible planning could better deal with uncertainties and better accommodate the many roles that the public space and street may have over time (von Schönfeld & Bertolini, 2017).

The following section demonstrates how big data can be used to detect demand intensities and fluctuations over time.

3.4 Big data and data driven technologies as tools for implementing *dynamic road space allocation*

The high connection of people through internet applications, smartphones, and other mobile devices has transformed the way of collecting and analyzing data. The scale of data has substantially increased through sources such as social media, mobile applications, Point of Interest, and GPS. Big data has transformed the sense of urgency in urban planning. Urban planning traditionally relies more on medium and long-term planning focusing on horizons of years, as short-term management of cities is often less informed than long-term planning. Recently, with real-time big data, it is possible to plan cities based on data in a shorter-term - minutes, hours, days - (Batty, 2013).

Furthermore, new mobile phone apps have modified the way people move. For example, Waze and Google Maps optimize people's travel time routes by redirecting to less busy routes. These apps are utility-based and do not consider public well-being or livable environments. Real-time apps are influencing urban dynamics which weakens the role of long-term planning (Serok et al., 2019). In this context, many forms of sensor technologies that provide big data are being used for planning cities. A vast amount of literature has been developed in understanding travel behavior and patterns (Calabrese et al., 2013; S. Li et al., 2020; Orellana & Guerrero, 2019; Ren et al., 2020; Z. Wang et al., 2018), traffic performance and forecast (L. Li et al., 2015; Yingcheng Li et al., 2019; Osorio-arjona & García-palomares, 2019; Toole et al., 2015; Y. Zhao et al., 2018), and land use and urban development (E. C. M. Hui et al., 2020; W. Liu et al., 2020; Martín et al., 2019; J. Park & Kim, 2019; Zhu et al., 2017).

The advent of crowdsource big data has provided a new way to sense and understand the complexity and dynamicity of public space. It is possible to analyze the dynamics of the city by evaluating spatio-temporal human activities and mobility patterns (L. Cai et al., 2019). Serok et al. (2019) analyze how traffic flows vary over time but lack consideration with activity patterns; Kang et al. (2012) identifies individual routes through mobile phone data to relate changeable mobility patterns with urban morphology. However, the authors do not take into account the many functions that public space may have. Tu et al. (2017) use social media and mobile phone location data to analyze the hourly changes of public space functions, travel patterns, and activities. In any case, the dynamic urban functions discussed by Tu et al. (2017) were only in a temporal dimension, lacking the relationship with spatial patterns (L. Cai et al., 2019). Therefore, with recent technology and big data analysis it is possible to analyze some aspects of urban dynamics and travel behavior by using a data-driven approach.

Sensors, video analytics, or apps such as Waze can be used to detect patterns and urban dynamics in order to propose different scenarios of reallocating space dynamically over time. Ultimately, the use of big data can detect and classify the fluctuations and patterns of travel behavior and public space usage in a 24-hour time frame. Traditionally, transport flows are detected through manual traffic counts in peak hours, to plan the infrastructure for a capacity when there is maximum demand. The problem is that outside the peak hours, infrastructure is often underutilized, and could be used for another purpose. Thereby, the use of big data can give support to an informed short-term planning. Different solutions of *dynamic road space allocation* could be defined through simulation scenarios based on the demand data collected, land use and policy priorities. An example of a case study on using big data to evaluate different approaches for *dynamic road space allocation* is demonstrated in Figure 11. It is important to mention that this is an example, in a case where city municipality is not virtually connected through ICT.

Ultimately, some of these new proposals to plan cities have appeared not from urban planners, but from technology developers. Urban planners have criticized many emergent city planning proposals (e.g., smart cities) and new technologies, arguing that data-driven cities without knowledge and theory are worthless (Batty, 2013). On the one hand, big data and new technology can be a massive source of information and data. On the other hand, there is doubt whether these emergent technologies and forms of planning can actually promote efficiency, sustainability and equity in urban environments. A line of criticism of big data enquires which purpose data is used and who gets to use it. In this direction, Zuboff (2015) defines "surveillance capitalism" as the use of big data and data-driven technology in order to modify people's behavior to earn profit and market control. According to the author, private companies such as Google, use illegitimate mechanisms of data extraction to predict user behavior and create new markets of control (Zuboff, 2015). Open data from social media for example, is used to not only direct people to buy products and services, but also to influence people in changing opinions of matters such as politics. The concern of Zuboff (2015), is that companies would use this data to build profiles. Then, ads, marketing and other techniques are used to change the behavior of each profile, not for the wellbeing of the community, but for the own company's interest.

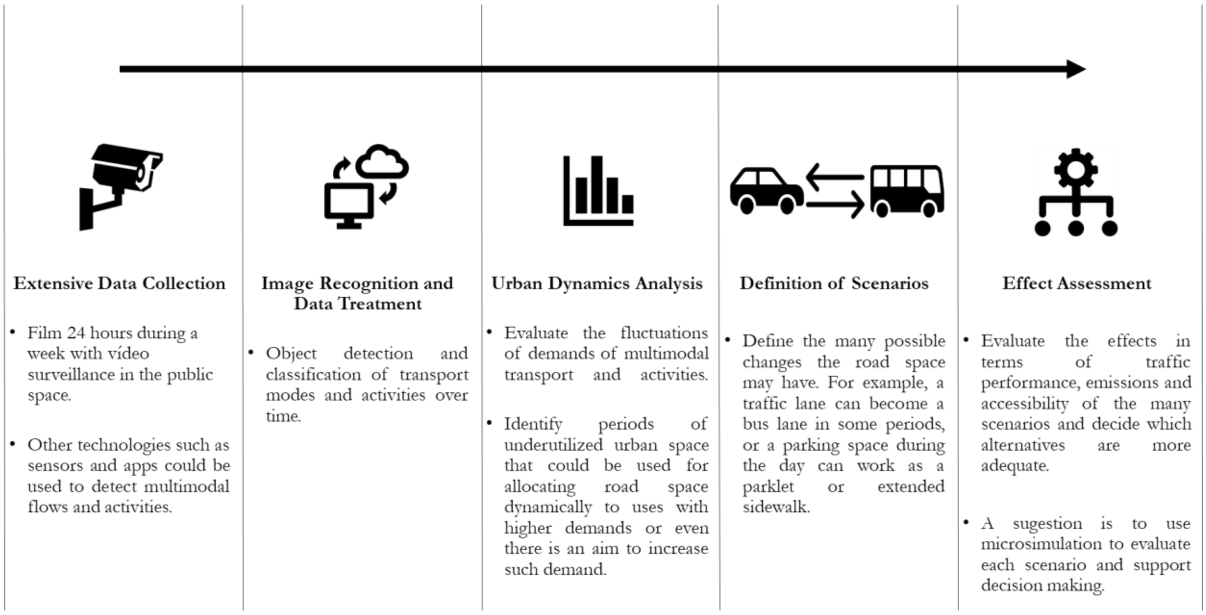

Figure 11: Example of a case study of using big data to evaluate scenarios for *dynamic road space allocation*.
Source: Author.

The use of big data and ICT technology to plan and connect cities and people is directly related to the concept of smart cities (Moura & De Abreu E Silva, 2019). Albino et al. (2015) discuss how smart cities are defined in the literature from 2010 to 2014. The authors conclude that smart cities are multi-faceted and are treated in two dimensions: hard (Engineering and technological emphasis) and soft (social-economic, policy, and education). However, the concept tends to shift from a technological perspective to focus mainly on people and community needs. A city that is only connected does not necessarily mean that it is smart if the technology is the end in itself (Albino et al., 2015; Kummitha & Crutzen, 2017; Moura & De Abreu E Silva, 2019). Some authors claim that the private sector will manage the urban space in smart cities (Hogan et al., 2012). This is certainly a concern regarding surveillance capitalism, so that doubts remain as to whether smart cities can achieve sustainable development and social inclusion (Datta, 2015).

Kummitha and Crutzen (2017) expand the review from Albino et al. (2015), by defining four main perspectives of thinking in the literature related to smart cities: Restrictive; Reflective; Rationalistic (or Pragmatic); and Critical school of thought. All perspectives of thinking are related to the levels of hard and soft dimensions mentioned by Albino et al. (2015) that are respectively named differently in the paper: technology-driven method and human-driven method. Restrictive thinking considers ICT, the Internet of Things (IoT), and data-driven cities as an essential part of smart cities. Still, it does not consider the needs of the community, social inequality, or sustainable development. Reflective thinking considers that technology should enhance human knowledge, habits and characteristics that contribute to economic activity. However, many criticize its technology-centered perspective, where the private sector holds the main role in structuring smart cities, and possibly withholding to address the social complexity of cities. The Critical school is skeptical to the existence and practice of smart cities in its all. The Rationalistic school shifts the focus from technology to people, in which technology should be used in contexts based on the needs of the citizens (Kummitha & Crutzen, 2017). Kummitha and Crutzen (2017, p. 47) so refers to the Rationalistic school:

> *"it is not the technologies that smart cities need to give significant attention; they need more to focus upon enabling citizens to enhance their capabilities, who then utilize their skills and capabilities to invent and promote the usage of technology while addressing their own problems."*

In this thesis, we follow the Rationalistic school to assess how road space allocation can be used dynamically to the extent that technology is used to adapt the infrastructure to respond better to mobility or access requirements, not the other way around. Even though the Rationalistic school is seen as a utopic goal by some authors (Datta, 2015; Jazeel, 2015), we believe that *dynamic road space allocation* should use technology to increase efficiency and equity while enabling more livable environments. While big data can be used to define the different scenarios of *dynamic road space allocation* through urban and traffic dynamics analysis, ICT and ITS could be used to implement such scenarios (more detail in the next section). Finally, we acknowledge and discuss the main challenges to achieve such an approach in section six of this chapter.

3.5 Existent solutions for implementing *dynamic road space allocation*

Using technology is a coherent direction for dynamically allocating urban road space. There are already some technologies that ensuring dynamic urban spaces in pavement design and traffic management. Some of these applications are illustrated in this section and explained how they could be used for *dynamic road space allocation*.

Figure 12 shows examples of ITS tools that are widely used in traffic management. The automatic rising bollard, illustrated in Figure 12a and Figure 12b, is usually used to restrict automobile access in local streets with a high demand for active transportation or allow only residents to enter a certain zone. This tool can be crucial for applying adaptable urban spaces, not only in local and residential areas, being important for managing space for different transportation modes and uses in different periods of the day, week, or season. For example, automatic rising bollards could be used in busier environments (main distributors), where traffic is allowed during the day and restricted during the evening to provide more space for activities such as markets, commerce, or events.

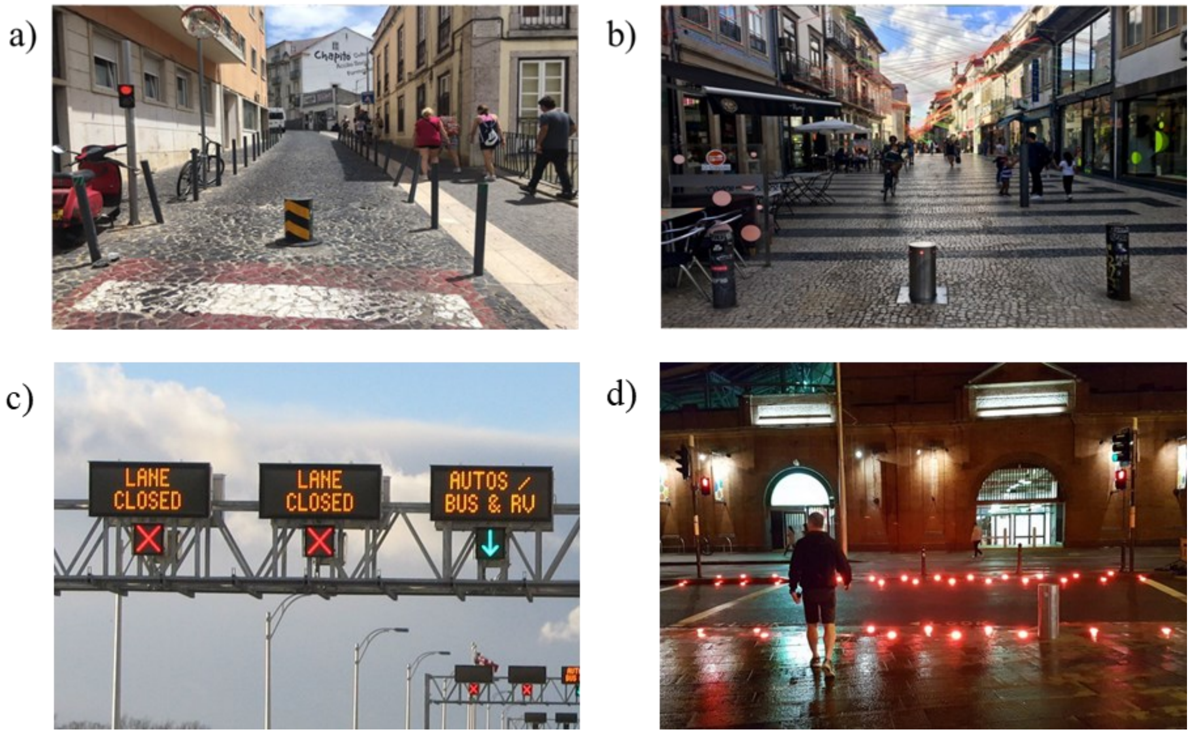

Figure 12: ITS applications in traffic demand management. a) Automatic rising bollard in Lisbon, Portugal; b) Automatic rising bollard in Porto, Portugal; c) Lane control sign; d) LED in-pavement lighting.
Source: a) Author; b) Author; c) Pinterest (n.d.); d) Smart City Streets (n.d.).

Additionally, lane control signs or variable message signs can be used to inform users of the present and future dynamic changes in road space (Figure 12c). LED in-pavement lighting can also be used to indicate the use of public space by changing its color (Figure 12d). As an example, the Intermittent Bus Lanes uses the in-pavement lighting to inform when vehicles can use (green color) or not (red color) the bus lane (Viegas & Lu, 2004). The advantage of these tools is that it is of easy implementation and low cost and already used in many cities. Thereby, the *dynamic road space allocation* can use existing and simple tools for its implementation in some contexts.

The Quayside plan is a smart city master plan developed for the Eastern Waterfront in Toronto, Canada, by the startup Sidewalk Labs (Sidewalk Labs, 2019a), where Ratti (2019) developed the pavement design entitled "Dynamic Streets". The technology differs from a rigid pavement to the extent that it is made of a flexible hexagonal modular paving system that changes the typology and functionality of the street to adapt to people's needs (Ratti, 2019), i.e., the varying demand for socio-economic activities. Figure 13a and Figure 13b present the prototype of the "Dynamic Streets", while Figure 14 illustrates the application of this paving system. The LED lighting in the center of each module, modifies the use of public space by indicating different uses by simply changing its color. Besides that, bike racks, and bollards can be plugged into the pavement modifying its use. Auxiliary variable message signs can inform users of the different functionalities of the public space at each moment of the day or week.

It is interesting to notice that the Quayside Plan proposes to implement "Dynamic Streets" in a shared space design context, as shown in Figure 14a. This is because the lack of segregation between transportation modes would allow modifying the street typologies by changing the in-pavement lighting colors and informing the space's function with variable message signs. Also, other street typologies proposed by Sidewalk Labs (2019b) target the physical segregation between modes of traffic, using "Dynamic Streets" only in curbs to allow parking during traffic peak hours, and promote other activities in non-peak hours (refer to Figure 14c and Figure 14d). Such proposals rely on the complete streets approach in busy traffic environments, where there is segregated space for motorized vehicles and sustainable transportation but add a dynamic feature by implementing the dynamic curb (refer to Figure 14b, Figure 14c, and Figure 14d). In this case, only a unique street section adapts dynamically through time. This type of adaptation is interesting in more congested roads where dynamic allocation is not in the road carriageway but in its adjacent public space. Thereby, during the morning and peak hours, the dynamic curb can be used for parking or vehicle drop-off at work, and during the night they provide space for different activities, for instance, fairs, local markets, or pedestrian facilities (refer to examples in Figure 14c and Figure 14d).

Although the criteria in choosing a shared space or a complete street approach is not clear, it may depend on the street's hierarchy classification. The difference between speeds of active transportation and automobile is a major issue in terms of safety. Therefore, some environments may need, at least at some periods, segregation between transportation modes. Additionally, in streets previously developed for automobiles, and already physically segregated, it may not be practical nor economically feasible to transform the road into a shared space. *Dynamic road space allocation*, complete streets and shared spaces are context-oriented, thereby needing to consider local characteristics of the site.

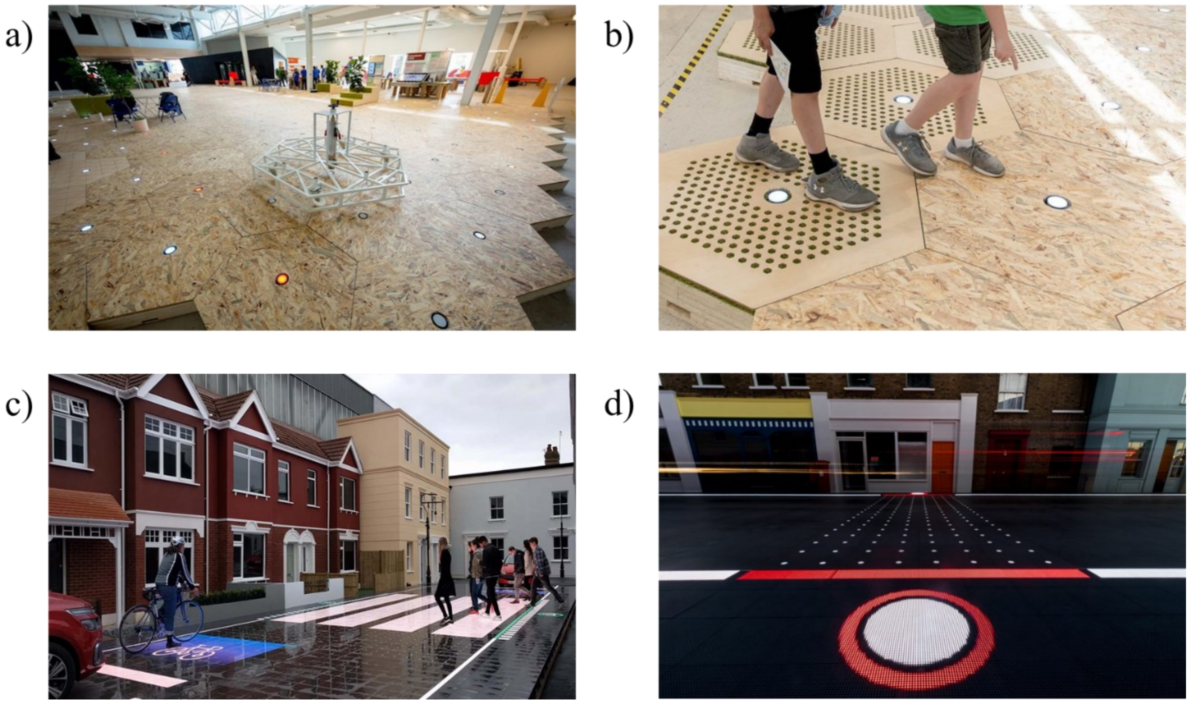

Figure 13: a), b) Illustration of the prototype of the Dynamic Street.
c), d) Illustration of the Starling Crossing prototype.
Source: a) Ratti (2019); b) Ratti (2019); c) Umbrellium (2017); d) Umbrellium (2017)

The prototype of a more sophisticated technology already exists for allowing the road pavement signals to change reactively in real-time according to multimodal flows. Umbrellium (2017) proposed an interactive pedestrian crossing that responds in real-time aiming to make pedestrians, cyclists, and drivers safer and more aware of each other (refer to Figure 13c and Figure 13d). When pedestrians are on the sidewalk waiting to cross the street, the interactive technology designs a pedestrian crosswalk that appears on the road pavement. Furthermore, the vehicles are also informed to stop with LED variable signs on the pavement. This type of pedestrian crossing is denominated as "Starling Crossing". Here, the prototype was applied in a shared space environment (Umbrellium, 2017). This technique is an example of how real-time data can be used in urban road space to adapt to different user requirements continuously. At last, real-time adaptation may not be practical in some cases. Instead, modifying the use of urban space in pre-established time-gaps (e.g., before peak hour, peak hour, after peak hour) may be more viable than real-time adaptation. User acceptability may be a huge challenge in a system that adapts in real-time, which people tend not to be ready for these new habits.

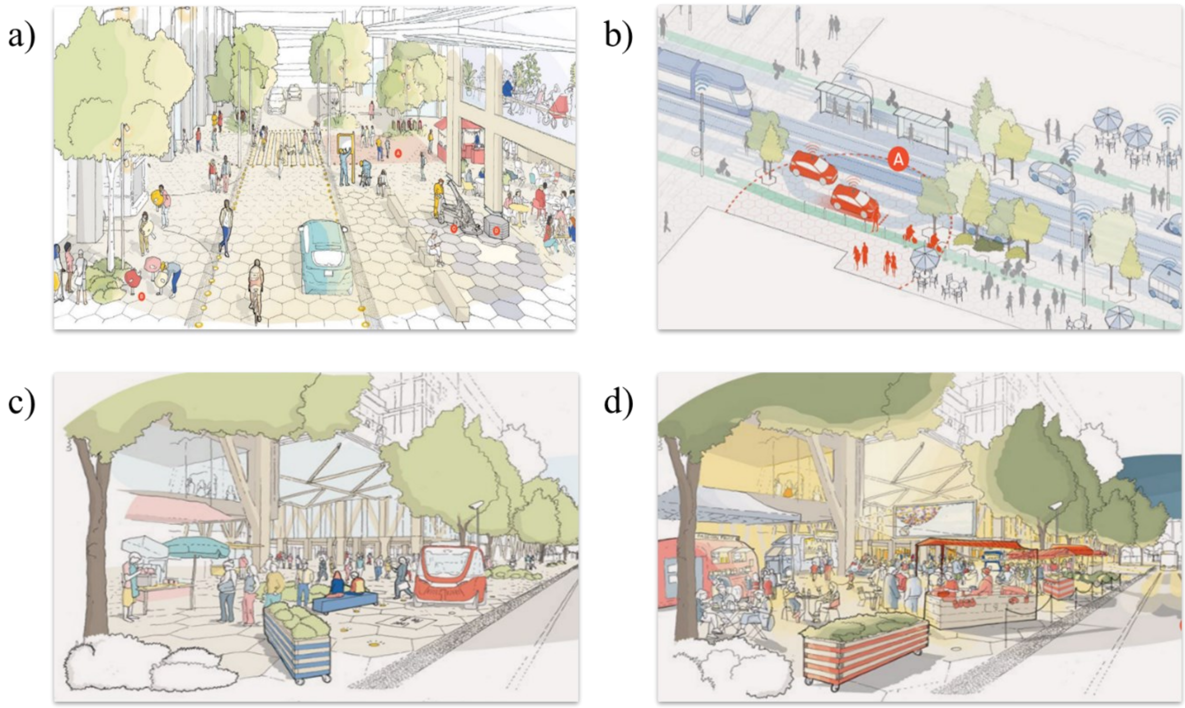

Figure 14: a) Dynamic streets application in shared space design. b) Dynamic streets applied in complete streets design. c) Peak hour example in which space is used for parking and drop-off vehicles. d) Non-peak hour example, where the space mentioned in "c" is used for a market and placemaking.
Source: a) *Sidewalk Labs (2019a)*; b) *Sidewalk Labs (2019b)*; c) *Sidewalk Labs (2019b)*; d) *Sidewalk Labs (*2019b*)*

Technology may assist in ensuring dynamic allocation of space but is not entirely necessary. For example, spaces that are very evident to be underutilized in certain periods (e.g., weekends or night) can be allocated to other uses by simply indicating with a vertical sign (as presented in the examples of Chapter 1). Therefore, we believe that the use of technology is not required (in some cases) for *dynamic road space allocation* but is an important tool for more informed decision making on multimodal demands and as a device for transport demand management. Thus, we propose using big data to detect mobility and human activity patterns over time, and then, use ITS tools to allocate urban space for local accessibility or mobility requirements.

The use of technology for adapting road space dynamically may be a path to make sure all spaces in the road network behave differently but intensively during the day. According to Cervero and Kockelman (1997), the 3D's (Density, Diversity, and Design) are essential factors that influence travel demand behavior and choices. *Dynamic road space allocation* is potentially aligned with the 3D's concept since adaptations to the road space may generate and also shift trips to different transport modes. The density component is assessed in *dynamic road space allocation*, since spaces that were underutilized by a particular mode in some moments can now be allocated for a different mode, with higher demands. Allowing urban space to have different uses over time improves the capability of land-use diversity. As a result, distances between activities tend to vary at different times of day, influencing the demands of active transportation. The design component is essential for an efficient dynamic allocation of road space. A complete street that serves several transportation modes, in a static approach, could potentially serve a wider set of alternatives for each type of mode and include other public space functions if allocated dynamically. Shared spaces could also be transformed in some periods when it is necessary to segregate transport modes or include a certain activity in the urban space (e.g., market, shop, playground). The use of LED in-pavement lighting, vertical signaling, automatic rising bollards or other tools could be used to adapt to the dynamics of the built environment over time.

An example of a possible application of *dynamic road space allocation* is illustrated in Figure 15. For the sake of the example, the street is in a busy, dense, and diverse neighborhood, where there are jobs, restaurants, shops, and residential uses. The priority is to allow citizens to go to work in the morning peak hour, with a bus priority lane, three drive lanes, and parking spaces. In the morning and afternoon non-peak hours, the vehicle and bus demands tend to reduce. Thereby, the bus lane could become shared with other vehicles if the bus supply is lower.

Additionally, one of the drive lanes can be dynamically reallocated for cycling. As a result, people can cycle to restaurants during lunchtime and do not need to return home, for example. ITS tools such as adaptive rising bollards could be used here to ensure safety through separation between active and motorized modes. When people are travelling back home in the afternoon peak hour, the street can adapt back to its original form which is identical to the morning peak-hour configuration. At night, when office-workers do not need to park for business, the parking lot can become space for restaurants, art or other activities. Notice that this is just an example. Elaboration of scenarios must be in detriment of local network, demands, land-use, and cultural and social characteristics.

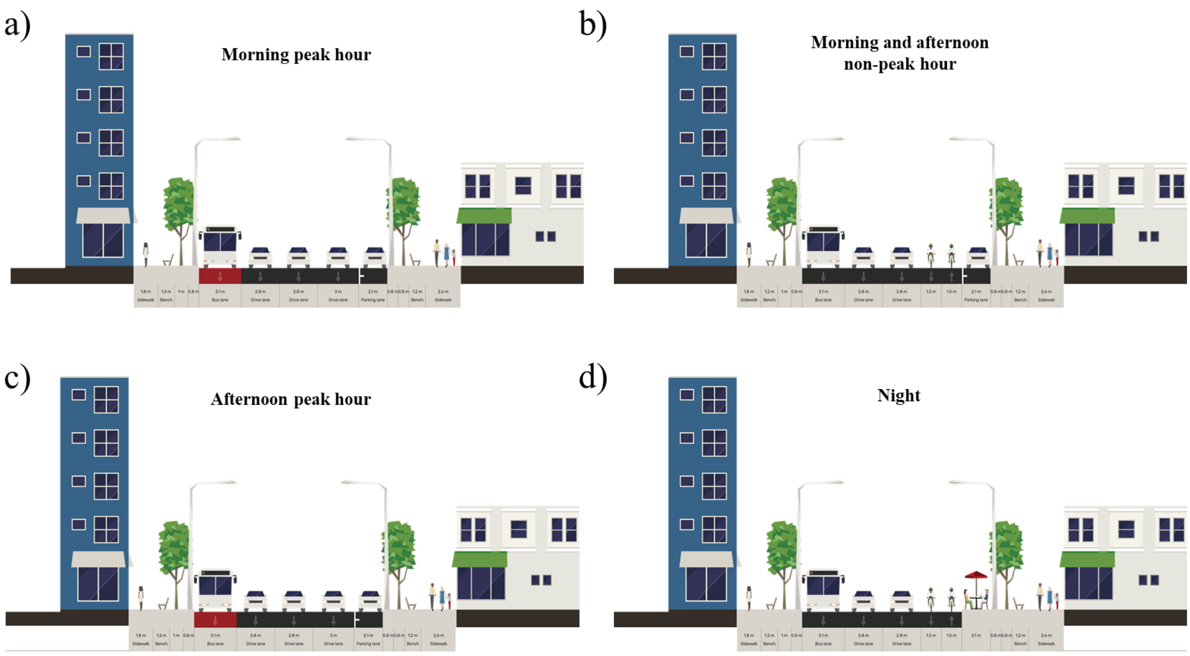

Figure 15: Example of the implementation of *dynamic road space allocation*. Developed with Streetmix[2]
Source: Author.

3.6 Challenges and future opportunities for implementing *dynamic road space allocation*

People may need some time to adapt to changes in how urban space is used. There should be a transition period for the system to adapt. More importantly, the population and stakeholders have to accept the changes and modify their behaviors. Many challenges need to be addressed to implement a dynamic system efficiently. Traditionally, policy/decision-makers show great resistance to change what already has been established for years, mainly when benefits are not clear in the short- to medium-term (Shearmur, 2012). Political acceptance might have to follow public recognition gained from potentially successful showcases (Banister, 2008). As such, public and political acceptance of *dynamic road space allocation* face a set of challenges that are discussed hereafter and summarized in Table 1. We explain each barrier identifying when the involvement of the community or city professionals is appropriate, and the use of technology is relevant to define different *dynamic road space allocation* solutions.

[2] https://streetmix.net/

3.6.1 Equity

The continuous adaptation of the urban space to new functions and the use of ICT and ITS may generate confusion and safety risks, if not implemented properly. For instance, seniors or vision-impaired citizens might not adapt or cannot use smartphone apps or perceive visual variable message signs of the road environment. Therefore, the new technology would prevent them from using the public space. These dynamic measures must be designed for the safety and acceptability of these segments of society. As stated by Banister (2008), sustainable mobility policies perceived as fair, efficient and beneficial to all community segments, are a first step for public acceptance. In this direction, the design process of *dynamic road space allocation* should include public participation to perceive risks, behavior, and fears of different segments of society. In neighborhoods with a high presence of an elderly population, simpler solutions, and few adaptations of road space may be more appropriate. Solutions in favor of reallocating space for restaurants, commerce and more sidewalks tend to benefit these community segments more because they are less likely to bike or drive.

3.6.2 Development stage

How can we integrate the many possible *dynamic road space allocation* scenarios with other infrastructure networks that are important to ensure sustainable cities, like sewage and rainwater drainage networks, water supply, waste management systems, electricity, and communication systems? As we consider the less developed countries, these infrastructures can be limited for some regions. According to Kummitha and Crutzen (2017), one of the main concerns of smart cities, which would encompass the concept of *dynamic road space allocation*, is making policy makers prioritize these innovative projects over more urgent social needs, for example, shelters, basic sanitation, education, or public health. In the longer run, opting for an ICT based *dynamic road space allocation* system could lead to more social inequalities, which would be worse in developing countries. Ortúzar and Willumsen (2011) comment that developing countries have distinctive characteristics from developed countries, such as social disparities, fast and unplanned urbanization, high demand for public transportation, and insufficient economic and technical resources, which need to be taken into account when applying transportation policies. The policy priority of *dynamic road space allocation* needs to be very clear in less developed regions. A more experimental approach to *dynamic road space allocation* could be an option where technical and economic limitations are evident. As an example, traffic lanes could be repurposed to active transportation or commerce during hours when it is evident that traffic lanes are underutilized, such as during the weekends or nights. Nonetheless, a less informed approach of defining scenarios will tend to promote more recreational trips than commuting ones since the reallocation times will be outside the regular working time. Simpler solutions such as vertical and horizontal signaling could indicate the dynamic reallocation of space during the night and weekends.

3.6.3 Built environment

The typology, morphology, and inherent characteristics of the built environment may be resistant to change and even incoherent to implement a dynamic system. The recent urban designs proposed to increase performance and safety, mitigate emissions, and provide more accessible places may not be coherent to many vulnerabilities that the built environment may have in terms of function, technology, and outdated planning (Fatiguso et al., 2017). For instance, historical centers tend to have narrow streets and fragile and old buildings. In other cases, the architectural and environmental protection requirements may be prioritized to maintain the urban space and community's historical, cultural, and social value, more than its performance *per se* (Brandão & Brandão, 2019). Therefore, the built environment characteristics are essential to be considered in the site selection process of *dynamic road space allocation*. A participatory approach with the local community, specialists and stakeholders is needed to evaluate the coherence of implementing *dynamic road space allocation* (Refer to Chapter 6 for more details).

3.6.4 Enforcement

The enforcement challenges of implementing *dynamic road space allocation* can be mainly twofold: firstly, those related to qualification and readiness levels of the municipal technical and governing bodies (including technicians, engineers, architects and other professionals, public managers, and decision-makers); secondly, those related to the severity of governance barriers, such as bureaucracy, time-consuming procedures, complexity of decision-making chains, among other issues. There may be unwilling authorities in some cities, including decision- and policy makers, or even a managing body that deals with transportation policies. This is a major problem in terms of accepting and properly choosing the best alternatives and technological solutions for implementing *dynamic road space allocation*. Nonetheless, activist organizations and the local community have an important role in advocating for more justice and equality in road space distribution. At the same time, transport and urban planners have the role to defining the best scenarios and discussing the implementation of *dynamic road space allocation* to achieve these goals.

3.6.5 Legal framework / Regulation

In some cities, sensing the built environment may have legal restrictions due to data privacy and facial recognition infringements (for instance, the recent EU's General Data Protection Regulation, GDPR - OJ L 119, 04.05.2016). The challenge is not only to use and communicate the information without infringing laws but also to define who has the authority to use the data. Although there are already technical solutions to overcome data privacy issues, such as cloud computing and privacy-enhancing technologies, this does not take into account public fears and misconceptions about revealing personal information. Therefore, the behavior of the citizens concerning data privacy may be more in the perception of the risk, rather than the technological risk itself (van Zoonen, 2016). According to van Zoonen (2016), facial recognition by video surveillance is a highly delicate topic. Lesser intruding technologies such as sensors and infrared videos are preferred in terms of public acceptance for collecting multimodal traffic flows. Thus, the choice of the appropriate data collection technology to define *dynamic road space allocation* scenarios will depend not only on a technological choice, but also on privacy infringements and public fear regarding data privacy. The technology choice is also dependent on how complex the environment is in terms of traffic and urban dynamics, and what kind of intensities and fluctuation of demands are needed to collect. In Europe, for example, the challenge of governmental public managers is to embrace and fully understand how emerging technologies and concepts may not violate the EU GDPR (Cresswell & Pardo, 2001). We argue that citizens and public legislation may change according to the perception over data privacy in a future with fully anonymized ICT usage and big data with open access. Regulation-wise, *dynamic road space allocation* is undoubtedly a challenge. For instance, regulation should define the time span, contextual locations, and dynamic alternatives in the road space due to its very context-oriented design.

3.6.6 Governance of data ownership and usage

The management of data ownership and usage related to public activities directly concerns the concept of *surveillance capitalism*. There are some relevant questions and challenges to be considered that influence transparency and ethical boundaries concerning data extraction, ownership and diffusion such as who owns the data; who gets to use the data; and how to decide what type of data can or cannot be extracted from users. Another concern is ensuring that the data and algorithms used for *dynamic road space allocation* can be democratically contested and open for public discussion. One major issue claimed by *surveillance capitalism* is the extraction of information from users without their knowledge (e.g., social media, daily movements) while capitalizing over the analysis of this data. This practice is a new challenge in terms of privacy protection and legal rights since companies may use this data to modify people's behavior to control and profit (Zuboff, 2015). The main challenge would be to create regulations and manage the data for it to be exclusively used to benefit the public through scenarios that promote more livable cities, not specific companies or few privileged groups in society. Therefore, it is essential that the data collection of *dynamic road space allocation* restricts only to characterizing intensities and fluctuations of multimodal demands to define scenarios for community needs.

3.6.7 Technology

There are still many improvements to be made in terms of sensing and data collection for multiple transportation modes. Motorized vehicles have been counted mainly by induction loops, radars, and laser detectors. Although these are useful and sufficient for many mobility management applications, they require high maintenance costs and are vulnerable to environmental conditions. However, these techniques are not appropriate for classifying and detecting different transportation modes, which is necessary for *dynamic road space allocation*. In this manner, video detection is more appropriate since it can work in real-time, separate and classify objects from a sequence of images and provide contextual information. Urban dynamics and fluctuation of multimodal demands can also be detected by using video-detection. However, video-detection still has its limitations in terms of identifying objects in different weather – rain, fog, and snow - and illumination conditions - day/night and shadows - (Yang & Pun-cheng, 2018). Big data challenges include certainly storing, managing, and analyzing large amounts of data. In the same vein, the many limitations of video streaming devices such as power and storage capacity and processor capability (Aliyu et al., 2018), can be a technological barrier for collecting data to implement *dynamic road space allocation*. Also, the complexity and diverse types of data are a barrier to integrating and comprehensively analyzing the information collected (van Zoonen, 2016). Public managers may have difficulties treating a diverse and dense amount of data to characterize multimodal demands and urban dynamics. Another issue to be faced is the technological failure of the system. If there is a black-out or hacking, what should be done and how to assess this challenge? *Dynamic road space allocation* is not proposed to be dependent on ICT. As the allocation of space is in periods of time, rather than in real-time, public managers may have time to adapt and propose solutions in case of a system failure. In cases where less technological solutions are executed, the impact of a system failure is even smaller.

3.6.8 Socio-cultural aspects

Socio-cultural aspects are essential points that shape the understanding of the world, influence socio-political practices and social constructs – mutual values, assumptions, and beliefs (Bibri & Krogstie, 2017). In this regard, the public acceptance of the *dynamic road space allocation* concept depends on cultural and social idiosyncrasies and the political recognition and willingness to implement such an innovative system. The challenge may be having to make socio-cultural shifts in regions where behavior patterns would need to be changed for the efficiency of this type of planning. To shift and prioritize sustainable transportation in detriment of the automobile may face more significant socio-cultural challenges in terms of public acceptance in regions where the automobile has had more incentives, policies, and infrastructure over time (Hickman et al., 2013). In a dynamic or static form, the reallocation of space can have a low acceptance due to the "culture of the automobile" if not implemented correctly. Potentially, *dynamic road space allocation* can be a strategy for policy makers to introduce the reallocation of space without contesting the space for the automobile in a first moment. For example, traffic lanes could be allocated for cycling only in non-peak hours when traffic is low. As cycling rates in that street will tend to rise, the dynamic cycling lane could eventually become permanent. As stated by Banister (2008), people will tend to accept policies that seem to work, are efficient, and are fair for both the individual and the community. Thereby, politically it may be more acceptable to justify a permanent cycling lane with already a high demand for cyclists in the street.

The challenges identified in this section are dependent on the different levels of city development. Thus, public managers may perceive the benefits and the challenges of *dynamic road space allocation* differently, depending on their location and context. The next section demonstrates a methodology for implementing a concrete *dynamic road space allocation*.

Table 1: Challenges and opportunities of *dynamic road space allocation*. Source: Author.

Dimensions	Possible challenges	Future opportunities
Equity	In highly technological dependent systems, the lack of equal opportunities to access ICT can lead to the exclusion of some groups (seniors and mobility-impaired population).	In a future where new technologies emerge, and citizens are more connected with technology, we should expect that people accept changing patterns of the built environment more easily.
Development stage	In developing countries, it may not be possible to use ICT and ITS infrastructures. In these locations, financial and technological constraints may be the main challenge.	In developing countries, it is an opportunity to reallocate urban space for sustainable transportation, and dynamically use this concept without the need for technology. For example, a parking lane can become a pedestrian lane at night when commerce is closed.
Built Environment	The application of such a dynamic system may not be possible or even coherent in historic city centers, areas of environmental preservation, or sites that lack appropriate infrastructure and activities.	A methodology for appropriate location selection must be developed to determine the time, the possible changes in the built environment, as well as its restrictions.
Enforcement	Lack of qualified municipal professionals; or a managing body that deals with transportation and land-use planning.	These challenges are also an opportunity to assist these municipalities financially and technically through higher government levels of funding and developing qualification courses for public servants.
Legal framework/ Regulation	Data privacy restrictions regarding sensing (video surveillance). How to regulate the different possible changes by time and location and define how much time the changes should be reviewed.	Data collection technologies require improvements, and a decision-making framework must be developed to appropriately implement the proposed concept of dynamic allocation of urban space.
Governance of data ownership and usage	Who owns the data, who gets to use the data, what type of data can be extracted from the citizens, transparency and democratic public engagement in data usage.	Propose regulations that define data extraction, usage and diffusion to avoid surveillance capitalism.
Technology	Sensing technologies that can cope with severe weather and illumination conditions; storage, management, and analysis of big data; integration and analysis of diverse data types, technology failure.	Improve sensing devices in terms of detecting and classifying objects and their storage and power capacity. Enhance integrated solutions for analyzing diverse and large datasets.
Cultural and socio aspects	The "resistance to change" as long-lasting socio-cultural idiosyncrasies can be an obstacle to accepting dynamic space allocation solutions.	An opportunity to prioritize people, not just smart cities itself, and promote a change in behavior from a "car-centered culture", for example, by promoting cultural and social events in the public space through the dynamic use of urban space.

3.7 Methodological framework of dynamic road space allocation

Figure 16 presents the methodological framework for implementing and evaluating *dynamic road space allocation*. The methodology is divided into four main steps: candidate zones; specific analysis of selected zones; data collection and scenario definition; and implementation and monitorization. This four-layer methodological framework has been elaborated to provide guidance in the decision process of *dynamic road space allocation* in tasks such as site selection, data collection and treatment, public and stakeholder engagement, definition of scenarios, simulation and evaluation of effects, definition of appropriate technical solutions, implementation and monitorization. The first and second main steps are related to the site selection of *dynamic road space allocation*. The objective of defining candidate zones is to screen a macro territory to select potential zones that may be appropriate for implementing the concept, based on network and land use indicators, conceptualized in section 3, and implemented to a case-study in Chapter 5. Therefore, the selected zones should face the mobility x access road allocation dilemma, have high network connectivity, and be in dense and diverse areas.

Sequentially, it is essential to have a more specific analysis of the selected zones, considering the many possible barriers to implementing the concept. The objective of the "Specific analysis of selected zones" is threefold: i) analyze the local characteristics of the selected zones (e.g., geometric characteristics, number of parking spaces); ii) evaluate barriers for implementation; iii) verify if the selected zones are suitable for implementing the concept and identify possible streets for intervention. The "context-oriented analysis" refers to analyzing if it is coherent to implement *dynamic road space allocation* based on the following barriers explained in the previous section: equity, development stage, built environment, and cultural and socio aspects. The "expert participation" is important for having a technical view on evaluating local characteristics for implementing different *dynamic road space allocation*, as will be presented in Chapter 6. Moreover, it is an important step to discard any possible zones that may not be coherent to implement the dynamic concept after analyzing the barriers and local characteristics of the zones. In this case, complete streets, road diets, or other static solutions may be more practical. This step considers the previous barriers and also has an important role in facing the enforcement challenge. "Public participation" is essential to understand behaviors, preferences, and cultural and socio aspects to establish the priority of *dynamic road space allocation* scenarios. Additionally, City professionals' participation mainly highlights the challenges of implementing *dynamic road space allocation* solutions in terms of legal framework/regulation and governance of data ownership and usage.

The "Data collection and scenario definition" was explained in section 4 of this chapter, on collecting and treating big data to define scenarios and simulate its effects. This step aims to define the most suitable scenarios for applying the concept. Initially, the choice of the appropriate technology that should be used for data collection is dependent on the data quality and quantity that is required. Moreover, the choice of technology needs to consider not only its technical capacity and costs but also the barriers in terms of legal framework, regulation, data privacy, governance of data, and cultural and socio aspects. Considering cultural and socio characteristics is crucial to selecting the appropriate technology, since people may perceive high risks of infringing data privacy, which may not convey the actual risk. As a result, this may reduce the popularity and perception of the benefits of *dynamic road space allocation*. The technology should be used to identify urban patterns, multimodal demand intensities, and fluctuations. Sequentially, we propose that the many dynamic scenarios are simulated using this data. The selection of the best scenarios is defined by evaluating the effects from the simulations.

After defining the most appropriate scenarios, the last main step has the aim to select the appropriate technical solutions, and implement and monitor the *dynamic road space allocation* scheme. Defining the ICT and ITS tools for implementing the solutions depends on the economic and technical conditions of the agency responsible for implementing the dynamic scheme. Thereby, in less developed sites, or in places where you have restrictions of the built environment and deficient technical professionals, it may be more appropriate to select simpler solutions and scenarios. Also, the choice of the tools may be dependent on the hierarchy classification of the street. While main distributors usually have segregated spaces for transport modes, local distributors may have spaces that are shared between different modes (Seco et al., 2008). This distinction would imply different solutions, as discussed in section 5 of this chapter. After implementing the solution, it is essential to continue to evaluate the scenario to adapt it in case of different needs and functions of the public space or unexpected outcomes that may occur. The levels of user acceptability towards the solution influence achieving policy goals and increasing active transportation demands, for example. Evaluating user acceptability regularly is a direction to achieve a more just and equitable allocation of road space. Therefore, adapting the road space dynamically to the detriment of user behavior, preferences, and community needs can potentially achieve more sustainable, livable, and dynamic environments.

The methodology presented in Figure 16 has a direct influence in dealing with the barriers. Multicriteria analysis, surveys, and focus groups are proposed to engage multidisciplinary specialists, community, and city managers in the decision-making process. As a result, it is possible to plan and discuss solutions to potential barriers in many dimensions with diverse members of society in an early stage of the decision-making process. Additionally, the participation of these community members during policymaking also contributes to defining what solutions are more feasible and may have more positive effects. Therefore, mixing top-down and bottom-up relations can provide more suitable solutions and deal better with the barriers of *dynamic road space allocation*.

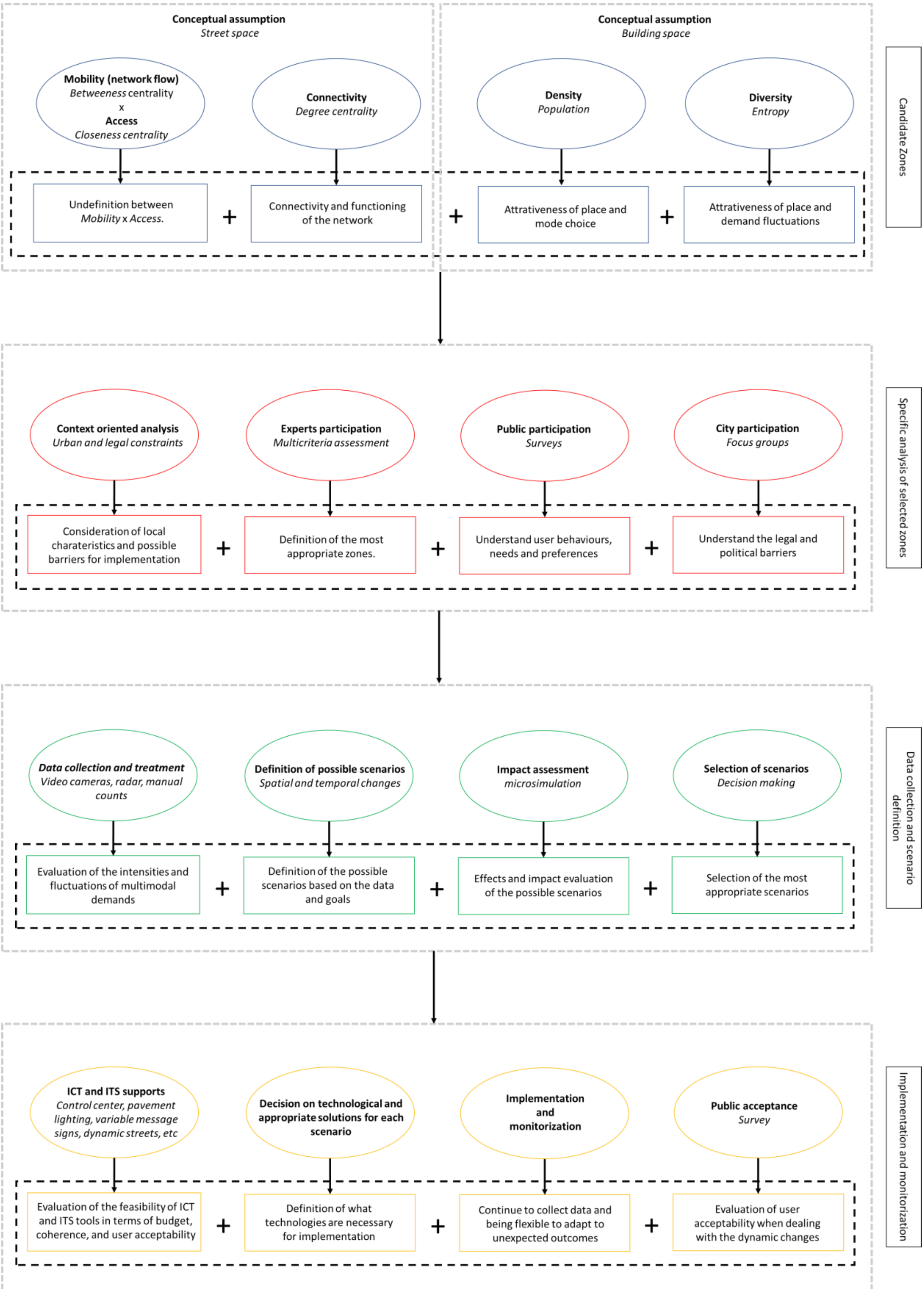

Figure 16: Methodological framework for an elaboration of *dynamic road space allocation*.
Source: Author.

3.8 Conclusions

The limited and contested amount of road space is a dilemma for policy makers to reallocate space to efficiently balance access and mobility dimensions while addressing sustainability and equity challenges. There are no methodologies or guidelines to define the amount of space that should be reallocated from automobiles to sustainable transportation, besides the impacts that it may have on the corresponding service levels. Especially if we consider busy avenues with diverse land uses. There may be moments when part of the infrastructure is underutilized in terms of demand and function. As recent urban planning concepts are also static, they do not consider urban dynamics or changeable demands of the public space.

In this context, we propose the concept of *dynamic road space allocation* to optimize underutilized spaces through more flexible planning, considering the many functions public space may have over time. The use of big data and sensing technology can identify underutilization periods of infrastructures when these could adapt to a different mode or activity. Potentially, it could better attend to existing and latent demand. Notably, big data, Information and Communication Technology, and Intelligent Transportation Systems should be addressed as a tool for more detailed decision-making and efficient road space management. However, they should not be seen as the solution *per se*. These tools are important for defining the appropriate site locations, time gaps, and changes that the road space should have according to the local urban dynamics and context. Also, new technologies allow short-term and quick initiatives to rely on real-time data, rather than experimental designs such as pop-up schemes. *Dynamic road space allocation* takes into account the changes in streets dynamics, functions and demands. At last, urban planning has always been prone to long term planning, which is more susceptive to random and unpredictable events due to the lack of flexibility. Short-term planning may better adapt to the consequences of these events.

Nonetheless, public managers and agencies may face challenges in many dimensions that can become barriers to implementing this concept. We mentioned eight of them: equity, city development stage, built environment, enforcement, legal framework/regulation, governance of data ownership and use, technology, and socio-cultural aspects. A methodology for implementing *dynamic road space allocation* and dealing with the challenges is proposed. Finally, future research must address other dynamic solutions, site selection and performance analysis, and any unexpected impacts that this concept may have on the many aspects of the built environment.

Chapter 4

What we have learned so far

In the previous chapter, the object of study was defined. *Dynamic road space allocation* aims to reallocate road space to multimodal and multifunctional uses depending on different demands and policy goals in urban spaces. Some technological solutions were suggested both in terms of sensing (e.g., sensors, video cameras) and urban management (LED in-pavement, variable message signs). Although some applications of allocating road space dynamically are not dependent on technology, others may be, depending on the users involved and the network's architecture. In Chapter 2, we established the differences between road space allocation strategies that change according to different demand patterns. However, the sensing, management and control technologies required for each type of solution were not detailed. Specifically in the case of allocating road space dynamically, it is not clear the level of technological adoption that is required for different solutions and contexts.

What to expect in the Chapter 4

In Chapter 4, we review the forthcoming and state-of-the-art technologies that can be used for sensing, management and control of users and infrastructures enabling adaptive street designs. We also classify road space allocation solutions into smartness levels, depending on how urban space can adapt to multimodal and multifunctional demands. This classification is particularly relevant for stakeholders and decision-makers to understand the capabilities and limitations of implementing road space allocation solutions in different smartness levels and contexts. We conclude that allocating road space dynamically can range from Level 0 (no use of technology) to Level 5 (fully connected environment).

Chapter 4

4 Technologies in road space allocation: a systematic review

This chapter is currently under review as: Valença, G.; Nogueira, F.; Baptista, P.; Santos, G.; Marques, M.; Morais de Sá; A.; Azevedo, C.; Antunes, A.; & Moura, F. Technologies in Road Space Allocation: A systematic review. Submitted to the Journal of Urban Technology.

4.1 Introduction

The rise of big data and emerging technologies have emerged in smart forms of vehicle propulsion, sensing, and transport demand management. Specifically, technologies have appeared in sensing the infrastructure and vehicles (e.g., video surveillance, eye trackers, sensors, GPS); transport demand management (e.g., adaptive traffic control systems, LEDs, variable message signs); and in connecting the data collected to vehicles and adaptive infrastructure through wireless communication (e.g., vehicle to vehicle communication (V2V), and vehicle to infrastructure communication (V2I)). The existence of these data flows, combined with the need to use urban space more efficiently, has led to emerging concepts to reallocate road space.

As road infrastructure and urban design are usually built to support a maximum demand during peak hours, they are often underused. In Chapter 2 we mentioned that two main lines of smart road space allocation strategies have been proposed to adapt road space according to demand – intermittent and dynamic applications. Intermittent Bus Lanes (IBL) and Bus Lanes with Intermittent Priority (BLIP) were proposed to efficiently use the space of dedicated bus lanes (DBL) that are underused when bus frequency is low (Eichler & Daganzo, 2006; Viegas & Lu, 2004). IBL and BLIP allow other vehicles to use the bus lane when the bus is not approaching the intersection. When the bus is close to the intersection, other vehicles must give their way to the bus. Although intermittent lane allocation uses the bus lane efficiently, it may increase the delay of buses and traffic when traffic flows are high (F. Zhang et al., 2018). In this context, dynamic allocation of space may be more appropriate, adapting road space according to fluctuations of demand (e.g., peak and non-peak hours). Dynamic lane assignment adapts the lane for different transport modes or directional movements in different periods. *Dynamic road space allocation* proposed in the previous Chapter is broader, also considering multi-functional adaptations of the space. For example, traffic lanes during the day could be allocated for bars and restaurants at night. Even though intermittent and dynamic space allocation are similar, they differ mainly in how they adapt to the infrastructure. While intermittent applications allocate space in real-time according to the position of a priority vehicle, dynamic strategies allocate road space in periods according to fluctuations in demand. Although in Chapter 2, we defined and reviewed the state-of-art of smart road space allocation strategies, we did not go into details in the sensing, management and control technologies required for each type of solution.

Many technological developments in sensing and optimizing route choice still do not consider infrastructure adaptations. For example, vehicle route choice traditionally optimizes individual travel time. However, if vehicles are connected to the infrastructure, the road could adapt in real-time (intermittently) or periods (dynamically) and play a role in the optimization. The same concept can be thought at the network level (N. Zheng & Geroliminis, 2013). When autonomous vehicles appear, V2V communication may improve route choice and optimize traffic flows (Tsigdinos et al., 2022). Implementing these concepts of dynamic and intermittent allocation of street space will benefit from using different types of available technologies.

Additionally, sensing technologies may collect data in real time on multimodal patterns and urban dynamics. Importantly, transport modes that are usually neglected in data collection, such as pedestrians, can be incorporated into planning the road scheme. From a broader perspective, transport demand management and ITS tools are important to adapt the road and inform users of the current state of the road or lane.

Even though emerging technologies and road space allocation have been designated as "smart", there is no unique definition of what "smart" is or smartness levels of emerging road space allocation. In this paper, we aim to classify smart road space allocation into smartness levels, following the steps of the automated driving levels (Society of Automotive Engineers, 2019), and the smartness levels of bicycles (Kapousizis et al., 2023).

Cities and urban-related industries can benefit from this classification since it provides a common language and framework for understanding the capabilities and limitations of smart transport infrastructures and demand management. A smartness-level classification allows for clear communication and standardization among industry stakeholders, policy makers, and the public. The smartness levels are based on how much a transport infrastructure can adapt the urban road space to different road users or urban functions, ranging from no smartness at Level 0 to full smartness at Level 5. Each level has a specific set of capabilities and limitations. Understanding these levels contributes to a potentially better matching of technological solutions to each particular urban problem and context. Often, less is more, and the urgency of intervention might require lower-smartness level solutions that can evolve afterward to more sophisticated developments. Furthermore, it is essential to ensure the functionality and safety of the adapted road space and establish regulations and guidelines for the technologies involved.

By defining these smartness levels, the industry can work towards developing more sophisticated and safer solutions while addressing concerns around liability and ethical considerations. Additionally, having a common understanding of the smartness levels will help citizens understand what to expect from intermittent and dynamic road spaces.

We perform a systematic literature review on the state of practice and the off-the-shelves and forthcoming technological solutions that can enable smart road space allocation. Particularly, we answer the following research questions:

- What are the urban sensing and transport demand management technologies that can be applied for implementing smart road space allocation?

- What are the different levels of technology for different emerging lane/road allocation in terms of sensing and demand management?

As a result, the main contribution of this Chapter is to propose a classification of different levels of technology for smart road space allocation in terms of sensing, demand management and control and discuss the effectiveness and difficulties of implementing these concepts. First, we present the methodology of the review. Then, the proposed levels of smartness are presented, followed by the results. Finally, we provide a discussion and conclusion to the paper.

4.2 Methodology

We used the PRISMA methodology to perform a systematic review and to assure reproducibility and avoid biased interpretations of the literature. We explain in detail the procedure presented in this analysis.

4.2.1 Search strategy

The review used the most comprehensive databases - Scopus and Web of Science databases -searching papers by keywords within the scope of the title, abstract, and keywords. We used two categories for search terms. First, we chose keywords related to emerging forms of road space allocation, including dynamic, intermittent, flexible, and shared spaces. Second, we included broad terms to narrow the search to relevant topics using an "AND" function. At least one term in the first category must appear together with the second. The keywords selected for both categories are: 1) "dynamic street*", "dynamic road*", "dynamic lane*", "dynamic circulation", "dynamic space*", "dynamic urban space*", "dynamic public", "shared space*", "flexible street*", "flexible road*", "flexible lane*", "flexible space*", "flexible urban space", "intermittent bus", "intermittent priority", "intermittent lane*", "intermittent road", "intermittent street*"; 2) "distribution", "allocation", "urban sensing", "smart infrastructure", "smart cit*", "urban technology", "transport*", "mobility", "urban design", "urban planning", "traffic".

We acknowledge that "road" and "street" are often used as having the same meaning, as exemplified by Tsigdinos et al. (2022). However, some authors define "street" as being associated with more local neighborhoods and places to stay and socialize, while "road" is a space mainly for movement (P. Jones, 2016). We opted to use both words to encompass all the meanings. Additionally, we used the terms "lane" to refer to a traffic lane and "space" for a generic urban space.

4.2.2 Selection criteria

The review included only papers published in peer-reviewed journals written in English, excluding books and conference proceedings. There were no restrictions in terms of the period of publication. The papers included related to: 1) urban sensing and transport demand management technologies that potentially could be used for demand-responsive road space allocation; 2) emerging strategies of road space allocation sensitive to demand changes.

4.3 Results

Figure 17 presents the PRISMA diagram of the literature review. We extracted 1688 papers from the databases, 823 from Scopus and 865 from Web of Science. After removing duplicates, we screened the title and abstract of 1145 papers. 71 papers were considered relevant for the full-paper examination and the remaining were out of scope or had different meanings to the keywords. Nonetheless, four papers were not available, and 67 papers remained for complete text examination. After reading full papers, twenty-two papers were considered not relevant due to their lack of focus on the sensing or management technologies for road space allocation. Thus, 45 papers remained and were considered eligible. Also, five cited papers from the included papers were considered relevant for the review (snowballing). One paper not indexed in Scopus and Web of Science was also included in our review.

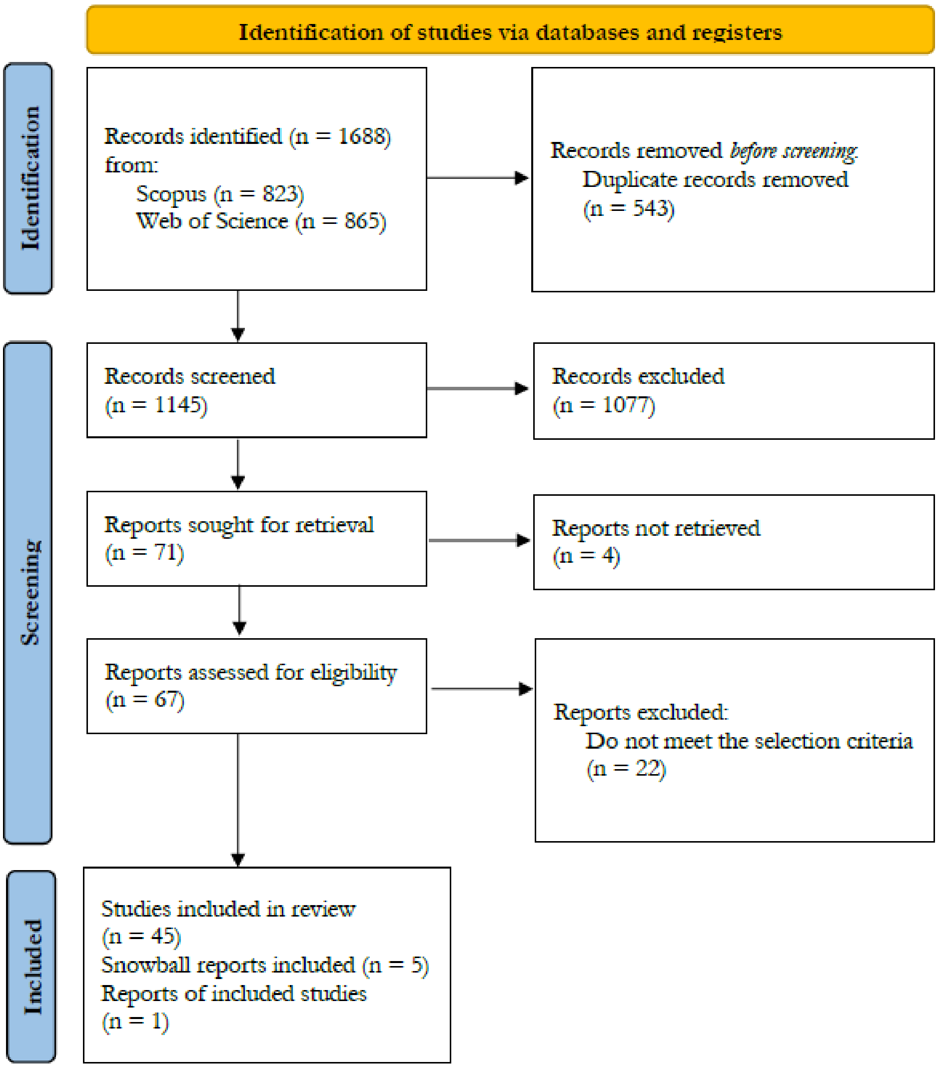

Figure 17: PRISMA literature review framework.
Source: Author.

4.3.1 Typology of smart road space allocation

We classify different levels of technology for road space allocation, which can guide practitioners in the field in understanding the role different technologies can play in deploying smart road space allocation. Table 2 summarizes some sensing technologies, transport demand management technologies, and control features classified according to each proposed smartness level of road space allocation. The proposed scale goes from Level 0 to 5. Figure 18 presents the framework for the road space allocation smartness levels by describing the interaction of each level with sensing and management technologies, following by the control features, which are detailed below:

- **Level 0**: *No use of technology | Road space from façade to façade is controlled by regular signaling and street design*. Regular urban designs normally do not use technology for sensing or managing urban space. Road space allocation strategies such as road diets and complete streets reallocate traffic lanes to more sustainable modes by permanently changing the street's configuration, not adapting to demand fluctuations. Allocating road space dynamically could be done in low complex sites and hours with low demands without the need to sense the urban environment, indicating the dynamic changes by regular signaling.

- **Level 1**: *Demand management technologies with no sensing or sensing with no demand management technologies | Road space from façade to façade is controlled by demand management technologies*. Technologies are applied for sensing the infrastructure but not connected to support road space allocation strategies. Here many technologies are discussed as potentially being helpful in sensing and managing road space, such as eyes trackers and video surveillance.

- **Level 2**: *Demand management technologies and sensors on the infrastructure | Road space from façade to façade is controlled by demand management technologies according to information from sensing.*
Sensing technologies are used to support decision-making and adaptations of the road space through demand management technologies.

- **Level 3**: *Demand management technologies and sensors on the infrastructure and priority vehicles | Traffic lanes are controlled by the communication between priority vehicles and infrastructure (V2I).*
Some vehicles, such as buses, are detected, and the infrastructure adapts according to their position and frequency.

- **Level 4**: *Demand management and sensors on the infrastructure and vehicles | Traffic lanes are controlled by the communication between vehicles (V2V) and vehicle-to-infrastructure (V2I).*
Autonomous and connected vehicles adapt their route according to other vehicles while the infrastructure adapts to demand.

- **Level 5**: *Demand management and sensors on the infrastructure and all transport modes | Road space from façade to façade is controlled by the communication between all transport modes and infrastructure (V2X).*
The system adapts to autonomous and connected vehicles and to the demand of pedestrians, cyclists, and other transport modes and activities.

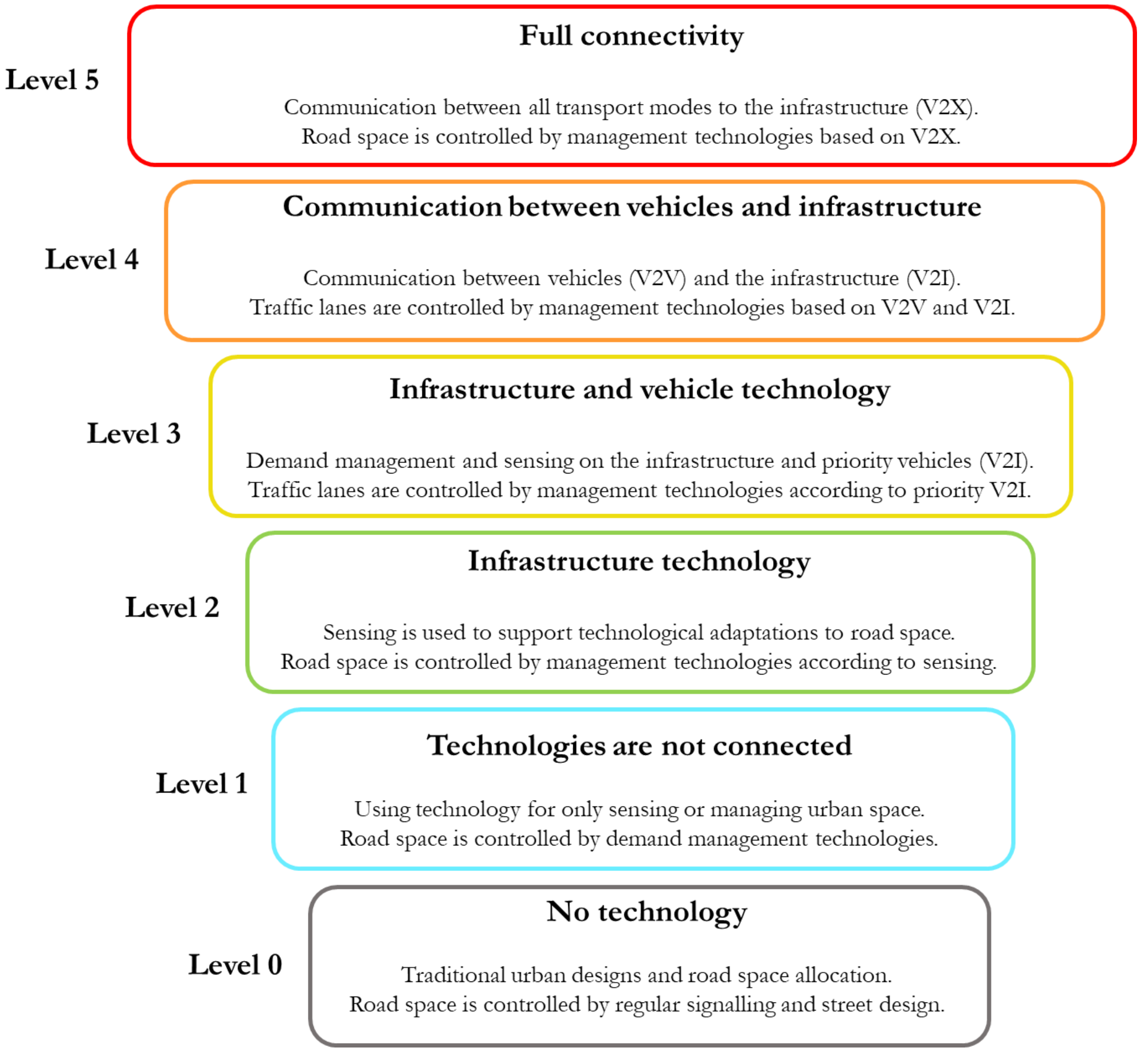

Figure 18: The typology of the level of smartness of road space allocation.
Source: Author.

Table 2: Summary of technologies used for each smart road space allocation levels. Source: Author.

Smart road space allocation levels	Sensing technologies	Transport infrastructure and demand management technologies	Control features (sensing OR/AND management)	Number of papers	References
0	-	-	No sensing / Road space from façade to façade (signaling)	1	Valença et al. (2021)
1	Eye trackers, GPS, and video cameras	In-pavement LEDs, variable message signs, flexible bollards	Motorized vehicles, pedestrians, cyclists, electric scooters (sensing is not used to support decisions) ***OR/*** Road space from façade to façade is controlled by demand management technologies	11	Pashkevich et al. (2022); Kaparias and Li (2021); H. Lee and Kim (2019); Zhi et al. (2020); Nannicini et al. (2010); Kaparias et al. (2012); H. Lee and Kim (2021); Ruiz-Apilánez et al. (2017); Vansteenkiste et al. (2014); van Paridon et al. (2019); Valença et al. (2021)
2	Video cameras, radio-frequency tags, and sensors	Adaptive traffic lights, in-pavement LEDs, variable message signs, flexible bollards, dynamic street lighting	Motorized traffic, pedestrians, cyclists (sensing used to support decisions) */AND* traffic lanes and shared spaces controlled by demand management technologies	13	J. Zhao et al. (2017); Hussein et al. (2016); Mittal et al. (2015); Schönauer et al. (2012); Anvari et al. (2015); Essa et al. (2018); Gouda et al. (2021); Song et al. (2022); Qin et al. (2021); Kidando et al. (2019); Haans and de Kort (2012); Morris and Trivedi (2008); Choosumrong et al. (2014)
3	Vehicle detectors, sensors, induction loops, actuators, V2I	In-pavement LEDs, variable message signs, control system, transit signal priority, pre-signals, in-vehicle unit, GPS receiver	Buses, motorized vehicles (sensing used for controlling priority vehicles) */AND* traffic lanes controlled by demand management technologies	16	Viegas and Lu (2001); Viegas and Lu (2004); Eichler and Daganzo (2006); Kampouri et al. (2022); Chiabaut et al. (2014); Ma and Xu (2020); Currie and Lai (2008); C. Wang et al. (2016); Anderson and Geroliminis (2020); Alhajyaseen, Ratrout, et al. (2017); Assi and Ratrout (2018); Alhajyaseen, Najjar, et al., (2017); Luo et al. (2019); Y. Zheng et al. (2020); J. Zhao, Yun, et al. (2015); Y. Li et al. (2014)
4	Vehicle detectors, sensors, induction loops, actuators, V2V and V2I	VANETs, control center, in-vehicle unit, GPS receiver, 4G modem, and a driver interface.	Buses, motorized vehicles, connected and autonomous vehicles (sensing used for control and connection between vehicles and infrastructure) */AND* traffic lanes controlled by demand management technologies	11	Al-Dweik et al. (2017); Maia et al. (2015); Levin and Boyles (2016); Fu et al. (2021); Chu et al. (2020); Merat et al. (2018); Tsigdinos et al. (2022); W. Sun et al. (2018); Duell et al. (2016); Levin et al. (2019); D. Wu et al. (2017)
5	Neural network framework to track objects through video cameras	Responsive road surfaces with computer-controlled LEDs, and hexagonal modular pavements (*Dynamic Streets*).	All modes (sensing used for control and connection between all vehicles and infrastructure) */AND* Road space from façade to façade	1	Valença et al. (2021)

4.3.2 Results of the review

We present the review results on the technologies used for the proposed levels of smart road space allocation.

Level 0

Level 0 enables the first degree of road space allocation without technology. Consequently, only one reference was included in this level, which explains examples of allocating street space dynamically without technological necessity. In this category, regular urban designs are static and do not vary with demand. However, *dynamic road space allocation* could also be an option in less complex situations.

Dynamic lane assignment in underused periods

Dynamic lane assignment (DLA) is a measure to address traffic demand fluctuation, optimizing the use of the available road space (J. Zhao et al., 2017). This is the most common dynamic solution type found in the literature. In road segments, the two main DLA applications explored by the literature are dedicated bus lane (DBL) and dynamic lane reversal (DLR). Although most literature explores using sensing and transport demand management for DLA, in practice, less complex sites or where the travel patterns are evident may implement these dynamic solutions by simply informing users with traditional vertical and horizontal signaling. For example, DBL can be a dynamic solution without technology since road signs are enough to inform drivers about the period when the lane is used exclusively by buses (usually during peak hours) – refer to Figure 2a for a practical example. On the other hand, dynamic lane reversal could be implemented during the morning peak hour for one direction and the afternoon peak hour for another direction.

Allocating road space dynamically for place and access

Valença et al. (2021)[3] – that refers to Chapter 3 of this work -, discuss that traffic lanes could be allocated dynamically and parking spaces and adjacent spaces for place and access purposes.

[3] The reference to Chapter 3 will be cited as the published paper in this Chapter, since the systematic review only includes journal papers. An exemption was made regarding the exclusion of self-citations to maintain coherency with the methodological criteria. The other chapters will meet the criteria adopted in Chapter 1 to exclude the self-citations to papers linking information to chapters of the thesis.

Also, we claim that road space could be allocated without technology during less complex periods such as nights or weekends. For these applications, collecting much data is unnecessary since the difference between the use of space is evident, having periods where the space is merely used. For example, parking spaces during the day could be allocated for restaurants with removable parklets when offices are closed; or traffic lanes could be allocated for recreational cycling during the weekend, as experienced in practice.

Level 1

In Level 1 the technologies are not used in a comprehensive and integrated way. While some papers mention sensing technologies to detect behavior patterns without the decision to adapt urban space, others focus on traffic demand technologies to allocate road space, but without prior or real-time sensing. In this level, technologies are presented as a potential for being integrated to serve as decision-making tools for road space allocation.

Only sensing / path selection and routing

The emergence of sensing technology has been crucial in the last decades for characterizing transport use. A good example are eye trackers, used for cyclists, pedestrians, and E-scooters, which enable understanding on how users perceive and choose paths based on the road's quality (van Paridon et al., 2019; Vansteenkiste et al., 2014) and how they interact with each other (Pashkevich et al., 2022). Specifically, eye trackers can analyze the visual attention of different transport modes, especially how they reflect on each other at different speeds and safety conditions (Pashkevich et al., 2022). Potentially, eye trackers could be used for decision-making to reallocate road space statically or dynamically based on the subjective safety of users and travel patterns.

Another example is the extraction of information from video data. Kaparias and Li (2021) use video data to evaluate the behavior of motorcyclists in different designs of shared spaces. The motorcyclists' flows before and after intervention were separated hourly to detect trip purposes. Changes in morning and evening behavior were assumed to change commuting behavior. Otherwise, the changes were more likely to be for leisure activities. H. Lee and Kim (2019) evaluated the objective (vehicle speeds) and subjective (fears of an accident) safety of pedestrians on different pavement designs by comparing before and after a project of revitalizing the streets towards shared spaces. For objective safety, the authors considered vehicle speed a proxy of the number of accidents, evaluating vehicle speeds through video surveillance. They had the caution to record before and after the project on similar weather and temperature conditions, which may influence behavior and technology effectiveness. For subjective safety, they realized a crosssectional survey. Objective and subjective safety data could be used to perceive where there is more potential to increase sustainable transportation levels when allocating road space dynamically. Sites that are perceived as dangerous may not increase active travel, in cases where traffic lanes or parking spaces are dynamically allocated. Although shared spaces do not necessarily allocate space dynamically, they lack segregated and user-specific spaces, potentially accommodating easier transitions, changes of function and space usage. Examples of high-level technology using shared spaces for allocating space dynamically and in real-time are presented in Level 5.

Vehicle path selection and routing is another lower smartness-level technology. This traditionally follows the shortest path principle, assuming the shortest travel time as the optimization goal. In recent work, Zhi et al. (2020) explored vehicle path selection based on the vehicle's position in the traffic signal queue, which generated a classification and distribution of vehicles with the cycle lengths and the traffic conditions. Nannicini et al. (2010) use GPS data to propose the fastest automobile routes considering the hierarchy network classification. Still, limitations of the method are related to not considering vehicles without GPS and not knowing if all specific vehicles have GPS (e.g., taxis and police cars). Notably, vehicle path selection algorithms are not integrated with adaptations to road space. Potentially, road space could be allocated dynamically according to how vehicles change their path.

Only traffic demand management technologies

Valença et al. (2021) introduce the concept of *dynamic road space allocation* as allocating road space dynamically for mobility and access purposes. The authors demonstrate the many technological solutions with lower smartness-level solutions that can dynamically adapt road space and infrastructures and inform users of the changes, such as variable message signs, flexible bollards, and in-pavement LEDs. These technologies exist already for informing drivers of variable speeds on highways; restricting car access to city centers; and illuminating traffic lanes at night respectively. These lower smartness-level technologies could adapt road space dynamically by simply changing the colors of LEDs, rising and downing flexible bollards, and informing users how the space is currently used with variable message signs.

Another dimension associated with the introduction of these technologies is user acceptance. Kaparias et al. (2012) used two web-based stated-preference surveys to assess specific person-, context- and design- factors influencing the perceptions of both pedestrians and drivers in shared spaces. The study concluded that pedestrians feel more secure in shared spaces if their presence is clear to other road users and that drivers feel uncomfortable when surrounded by many pedestrians, increasing their alertness (Kaparias et al., 2012). Similar results were obtained by H.

Lee and Kim (2021) and Ruiz-Apilánez et al. (2017), with pedestrians reporting a higher perceived safety level in shared spaces. Consequently, the type of technology deployed will highly influence users' acceptance and adaptation to these new street space reallocation concepts. It may also play a role in providing data for evaluating this adaptation.

Consequently, in the future, it may be possible to communicate the data collected from sensing technologies to data control centers to reallocate space not only to existent demands but latent ones. Additionally, the user's behavior and visual attention are dependent on the user's experience, age, and background. Therefore, by analyzing the behavior of these segments, it may be possible to predict which solutions at what time of day may have a higher acceptance rate.

Level 2

When sensors are available on the infrastructure, a higher level of support can be given to transport demand management.

Sensing technologies for supporting transport demand management

Computer vision advances have supported practices of multi-modal detection, tracking, and classification through video surveillance (Hussein et al., 2016). While in Level 1, video data is used to only analyze transport dynamics, in Level 2, the technology also evaluates the performance of how the street is used. The work proposed by Hussein et al. (2016) detects pedestrian and cyclist conflicts at a shared space intersection. The study analyzes data from one video camera comparing shared space operations between three weekly periods that have different characteristics: the summer period in a car-free shared space; the transition period with the car gradually coming back to operation at the intersection; and the normal period with regular interaction between pedestrians, cyclists, and cars. The authors conclude that conflicts between pedestrians and cyclists decreased during the car-free period. Mittal et al. (2015) propose a dynamic road traffic lights management, that collects demand data through cameras and adjusts the traffic lights' cycle times if traffic conditions are not normal. J. Zhao et al. (2017) use video cameras in intersections to evaluate dynamic lane assignment. Still, video surveillance has limitations, especially in multiple objects tracking and detecting objects prone to varying illumination and shadows, such as pedestrians and cyclists (Morris & Trivedi, 2008).

When redesigning urban space, the interactions between the different transport modes will likely change. For instance, user behavior in shared spaces does not follow a predefined path or obey strict traffic rules, as the urban space design is less constrained (Schönauer et al., 2012). Assessing these interactions has been studied either by developing simulation tools (Anvari et al., 2015; Schönauer et al., 2012) or observing specific locations (Essa et al., 2018; Gouda et al., 2021; Pashkevich et al., 2022). Most studies use video data either for model calibration or usage pattern recognition, aiming to identify important factors for reducing conflicts, such as the presence of adequate traffic signals as well as increased visual attention of different transport mode users (Essa et al., 2018; Pashkevich et al., 2022). Song et al. (2022) propose a multi-target vehicle trajectory detection method in multiple cameras by transferring the trajectory of the same vehicle through neighboring cameras. This method proposes overcoming the limitation of current video surveillance technology that has difficulties tracking the same vehicle across multiple cameras in complex traffic environments.

Qin et al. (2021) research introduces radio-frequency tags and readers along the road environment to collect real-time data. When a vehicle passes through a tag, it communicates with the reader inside it, refining the GPS precision on human-driven cars and autonomous vehicles (AVs). Choosumrong et al. (2014) use real-time data to support GPS inside vehicles to emergency routes based on quick changes in traffic flow. There is a gap and a potential for integrating route choice planning to road space allocation (as mentioned in level 1) in case of an accident or a flood. Therefore, not only would vehicles be guided to change the route to avoid the extraordinary event, but the infrastructure would adapt to the new demands.

Sensing urban space is important to understand demands' multi-modal and multi-functional fluctuation to support short-term decision-making. There will be moments of the day when demands are complementary or conflicting. On one hand, allocating road space dynamically to complementary demands is politically more feasible since one transport mode has more demand than another during that time. On the other hand, it is a political choice and challenge to allocate road space dynamically or statically when all transport modes have high demands to use the space (e.g., peak hours).

Demand management technologies

The same technologies from Level 1 can be used in Level 2. However, adaptations to the road space will be informed in real-time or by historical data at this level. According to Kidando et al. (2019), it is important to understand traffic and urban dynamics and the dynamic transition of traffic regimes (DTTR). The changes between traffic and urban regimes (e.g., free flow and congested) are influenced by diverse elements such as demand, diversity of transport modes, weather conditions, and driver behavior. Transport demand management measures such as variable message signs, variable speed limit, in-pavement lighting, and flexible bollards require understanding these factors to allocate space dynamically (Kidando et al., 2019).

LEDs have modified both street lighting and in-pavement lighting. Haans and de Kort, (2012) examine dynamic street lighting that adapts according to users and weather conditions. Street lighting reduces with less traffic and people, while it increases in stormy weather. The aim of this proposal has been mainly to minimize energy waste. Nonetheless, according to Haans and de Kort (2012), studies have found that street lighting conditions are the main built environment factor influencing pedestrian security perception.

Consequently, if low levels of demand result in low lighting conditions, then, probably, the space will not be able to increase levels of active transport during these periods. Also, Haans and de Kort (2012) found that illuminating pedestrians' immediate surroundings is more important than having light in a distance regarding security perception. Dynamic road lighting is also a technology that could influence latent demand (high lighting in low demand periods) if applied together with other road management techniques such as allocating space dynamically for pedestrians.

Level 3

The presence of sensors on the infrastructure and on (priority) vehicles enables the implementation of demand management strategies associated with using road space.

Intermittent bus lanes and bus lanes with intermittent priority

Dedicated bus lanes (DBL) are of great significance for improving the operation efficiency of public transportation. Nonetheless, DBL requires road space availability and is underused when bus frequencies are low. Intermittent Bus Lanes (IBL), a bus lane model first proposed by Viegas and Lu (2001, 2004), and Bus Lanes with Intermittent Priority (BLIP) (Eichler & Daganzo, 2006) provide an interesting compromise to the lack of road space or underutilization of exclusive bus lanes. IBL and BLIP allow motorized vehicles to use the bus lane when the bus is not approaching the intersection. Otherwise, vehicles are not allowed to use the bus lane, giving the right of way to the bus. The main difference between concepts is that IBL only informs drivers not to enter the bus lane, not considering vehicles that are already using the bus lane. Both sensing and transport demand management technologies are required in IBL and BLIP systems: i) Vehicle detectors providing bus location; ii) a control system that manages the status of the bus lane according to the traffic flow and position of the bus; iii) variable message signs and in-pavement lighting to inform users of the bus lane status (Kampouri et al., 2022). Kampouri et al. (2022) suggest that traffic flows are also measured to evaluate when it is feasible to implement IBL and BLIP. Both concepts prioritize transit by adapting the infrastructure according to the bus's position.

Unlike the original studies, Kampouri et al. (2022) consider transit frequencies and simulate various scenarios to determine the traffic volumes and bus service frequencies to determine if a dedicated bus lane or intermittent bus lane is more appropriate. Empirical results showed that when peak hour volumes range between 1000 and 2000 vehicles, mixing cars and buses on bus lanes may reduce vehicles' queue lengths and cause substantial decreases in greenhouse gas and air pollutant emissions while assuring the financial viability of the experiment. Also, Chiabaut et al. (2014) use a macroscopic fundamental diagram to compare the performance of dedicated bus lanes, intermittent bus lanes, and buses mixed with traffic by considering traffic dynamics. Ma and Xu (2020) adapt the concept of IBL to allow vehicles to use the road when space is empty. On the contrary, IBL and BLIP consider the downstream intersections as the condition for drivers to use or not a lane, which is not clear the effects and feasibility when the distance between intersections is too long (Ma & Xu, 2020).

Dynamic lane assignment with vehicle detection

In Melbourne, a similar approach to intermittent bus lanes is implemented in a dynamic approach, but only during peak hours. Trams in the center of the road are given priority in the peak direction. Induction loops activate variable message signs and in-pavement lighting to inform other vehicles to leave the lane when the tram arrives. In contrast, transit signal priority is used for connecting the tram's position to the infrastructure (Currie & Lai, 2008).

C. Wang et al. (2016) proposed a one-way sharing DBL that allows the use of the bus lane by opposite-running buses at different times. Technology is necessary to ensure that the opposite-running buses are not simultaneously in the same road section. One of the vehicles must be informed to move to an adjacent lane of the same direction, or a bus priority lane needs to be turned on. The infrastructure technology includes sensors on the road and inside the buses or other active vehicles (e.g., ambulances, firefighter trucks), vertical and horizontal signs with actuators to inform drivers about the correct way of the bus lane at each instant, as well as the existence of a temporary bus lane (if needed), and a management system connecting them (C. Wang et al., 2016). Anderson and Geroliminis (2020) claim that DBL, in some cases, does not need total segregation with other vehicles and could share space with a small amount of traffic. The number of vehicles allowed in the bus lane varies according to the demand of buses and traffic over time, without impacting the buses' performance. Similar technologies are also proposed here with in-pavement lighting and variable message signs to inform drivers if they can use or not the bus lane.

In intersections, the dynamic use of space to serve the different flows is commonly controlled by traffic lights. DLA schemes can improve the response to demand by continuously adapting the number of lanes associated with each movement at each approach (Alhajyaseen, Ratrout, et al., 2017). Solutions vary from information-based dynamic lane schemes (IDYL) to solutions using pre-signals. The technology used in IDYL solutions consists in variable message signs or in-vehicle technology that provide real-time information to drivers (humans or robots) about the lane-group configuration during the approach to the signalized intersection (Alhajyaseen, Najjar, et al., 2017; Assi & Ratrout, 2018; Luo et al., 2019). Pre-signal solutions have an upstream stop line controlled by traffic lights. These can be used to implement dynamic exit lanes for left-turn movements (J. Zhao, Yun, et al., 2015; Y. Zheng et al., 2020) and to provide the maximum width capacity for turning movements (Y. Li et al., 2014).

Level 4

Communication between infrastructure and vehicles

Communication of speed limits for drivers is a crucial safety issue. Several studies point out that in-vehicle driver notification, like the system proposed by Al-Dweik et al. (2017), significantly outperforms variable speed limit message signs with a great impact on road safety. Al-Dweik et al. (2017) propose using Adaptive Speed Limits to change speed limits over time according to real-time traffic and weather conditions. This proposal aims to ensure higher safety in expressways. The authors propose that V2V and V2I communications use 4G, vehicular Ad hoc Networks (VANETs), or a mix of both. The systems architecture is composed of: i) a control center required to optimize and inform the speed limit according to traffic and weather conditions and record drivers' speed to a server and apply for tickets in case of speed limit infractions; ii) an in-vehicle unit to inform the real-time speed limit - GPS receiver, 4G modem, and a driver interface -; and iii) sensing stations to collect real-time data (Al-Dweik et al., 2017).

VANETS are systems with vehicles equipped with wireless networking interfaces that can show the current traffic conditions to the driver in a region of interest by their connection with other vehicles and roadside units (Al-Dweik et al., 2017; Maia et al., 2015). Vehicles inside a specific region of influence by the roadside units collect information from the roadside unit. However, vehicles outside this region pass information from vehicle to vehicle. Maia et al. (2015) propose a Video over VANETS that shows drivers a video of the saturated traffic jams in their planned route and allows them to choose another one. The authors claim that showing a video of the current traffic jam is more convincing than a text message on changing routes. Thus, the driver inside a region of interest is informed by a video of where the most critical traffic jams are, allowing them to choose a different route. These technologies may inform drivers about how road space is dynamically allocated at a particular time.

Autonomous and connected vehicles and interaction with road space

Dynamic lane reversal (DLR) designates solutions for changing the lane direction. Levin and Boyles (2016) propose a DLR at minimal intervals of time and for small segment sections, which is only possible with connected and automated vehicle (CAV) technology. The movement control is performed by a link manager in constant communication with the vehicles (Levin & Boyles, 2016). This operational strategy improves road efficiency using the available capacity of the road width to efficiently mitigate congestion (Fu et al., 2021). The current lane reversal solutions for human drivers, use moveable barriers that are modified manually or by road zippers on fixed schedules according to traffic patterns (Fu et al., 2021), which takes time and cannot be done frequently (Levin & Boyles, 2016). Chu et al. (2020) propose dynamically dedicated reversible flow lanes for autonomous vehicles. AVs enter the lane in both directions based on the decisions taken in a control center, according to more precise schedules of routes. Research limitations relate to the lack of consideration of interactions between AVs and human-driven vehicles and the assumption of the same speed for all vehicles.

Considering the expected increase in vehicle automation, operating AVs with mixed traffic may be a considerable challenge. Merat et al. (2018) promoted a questionnaire in three European cities to understand if pedestrians and cyclists felt safe interacting with AVs in shared spaces. This study concluded that pedestrians felt safer if AVs travel in designated lanes and that pedestrians assume they have priority over AVs in the absence of these designated lanes. Also, respondents recognize the importance of receiving information regarding the behavior of AVs, highlighting the possibility of the vehicle acknowledging the presence of pedestrians.

Tsigdinos et al. (2022) believe that fully segregated AV corridors may be the more feasible solution. There is, therefore, a potential to dynamically change the lane dedicated to the AVs, or even use them as reversible lanes. Tsigdinos et al. (2022) revealed concepts that use technology to make roads smarter: vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), fully segregated AV corridors, shared autonomous vehicles, electric vehicle charging stations (vehicle-to-grid), dynamic wireless charging, photovoltaic road. For the intersection context, W. Sun et al. (2018) proposed MCross, a scheme that maximizes intersection capacity by simultaneously utilizing all road lanes. They solve a multi-objective mixed-integer non-linear programming problem to dynamically compute lane assignment and green times.

Based on the increased availability of communications for connected autonomous vehicles (CAVs) compared to human drivers, several methods were presented for dynamic lane reversal (DLR) (Chu et al., 2020; Duell et al., 2016; Levin & Boyles, 2016). Levin and Boyles (2016) propose a cell transmission model (CTM) and consider that lane direction can occur at minimal space-time intervals (a few hundred feet and 6s of time steps). The authors present a heuristic algorithm for the stochastic demand scenario, solving an integer problem. The proposed solution was tested in Austin downtown (TX, USA) in the AM peak and achieved a 21.8% reduction in total system travel time over fixed lanes. This algorithm was applied by Levin et al. (2019), where the authors introduced a max-pressure policy that controls autonomous intersection management and DLR. Like Levin and Boyles, (2016), Duell et al. (2016) also use CTM and propose a DLR model that is responsive to time-varying demand. Chu et al. (2020) present the Dynamic Lane Reversal-Traffic Scheduling Management Scheme for CAVs. Knowing the travel requests from the CAVs, they compute the optimal schedules and routes on dynamically reversible lanes by solving an integer problem. D. Wu et al. (2017) evaluate implementing Bus Lanes with Intermittent Priority in a connected V2V environment. The authors conclude that BLIP reduces bus delays in most scenarios and is more appropriate with four or more lanes. Results from a connected BLIP demonstrate similar impacts to a non-connected environment, reducing efficiency when traffic and bus frequency are high and when the cars' clearing distance is long.

Level 5

The last level assumes a context where the infrastructure adapts to all transport modes. Valença et al. (2021) present two technologies that could be used in Level 5. The *Dynamics Streets* is a flexible hexagonal modular pavement with LED lighting in the middle (Ratti, 2019). Bollards and bike racks can be plugged in the module, and the color of the lights can be changed to allocate spaces differently. A Level 5 Smart City project in Toronto entitled Quayside Plan was proposed for retrofitting the city's waterfront. The project was not implemented due to the economic consequences of the Covid-19 Pandemic (Sidewalk Labs, 2023). The project proposed to have curbless streets independently of their hierarchy. The proposal is that active transport can interact with low speeds vehicles and *Dynamic Streets* are implemented in a shared space environment to effortlessly adapt urban space and interact with other technologies such as dynamic street lighting, adaptive traffic signals, and variable message signs. Also, the project proposes to use Beacons to broadcast navigational information through Bluetooth about how the space is used to active transport and vehicles.

Another technology that was developed is the Starling Crossing that is a responsive road surface with computer-controlled LEDs that modifies the layout of the pedestrian crossing (Umbrellium, 2017). The environment is monitored and connected with cameras that detect multimodal objects through trained neural networks and inform the pavement to respond according to objects positions. When pedestrians are close to crossing the street, vehicles are informed to stop and a pedestrian crossing appears on the road surface. The pilot case study that uses Starling Crossing is also in a curbless environment with low-speed vehicles, segregating modes by interactive road markings in the shared space.

Both technologies challenge the status quo of the street design by allowing sensing and management technologies to be connected to infrastructure, vehicles, and active transportation. The road space from façade to façade and all transport modes are the control features of Level 5, that interact, communicate, and inform the different uses. Thus, space could be allocated dynamically or reactively in detriment of real-time demands of autonomous vehicles, pedestrians, cyclists, or public transport that are detected through sensors or video and communicated to the infrastructure and users. It is important to mention that this is not necessarily the desired future. More studies need to evaluate the impacts of this level in terms of justice, economic viability, and performance.

4.4 Discussion

From the results, it is possible to clearly understand the technological reliance of the adoption of different road space allocation solutions. Figure 19 presents the systematization of these types of solutions with technology and smartness levels. Static road space allocation solutions were not discussed in this paper. Nonetheless, although they may use some technologies to sense or manage urban space, these technologies are not used to adapt road space to different demands over time. Instead, technologies are mostly used to examine safety and behavior patterns for users, as mentioned in Level 1.

Also, intermittent solutions rely on technology since priority vehicles require vehicle detection, and the infrastructure to adapt to their position. Therefore, these solutions require communication between the priority vehicles and the traffic signals, control systems, and demand management technologies. Besides the technical limitations of intermittent solutions, they also need priority vehicles and infrastructure to be technologically developed. Consequently, this may be the main barrier for sites to implement this solution, where financial and technological development is limited.

Dynamic solutions are more flexible since they may use technology but are not overly reliant on it. Dynamic solutions vary their complexity and technology adoption throughout all levels of smartness defined in this paper. Dynamic solutions range from no use of technology by allocating space by vertical and horizontal signaling (level 0) to using V2V and V2I communications for Avs (Level 4) and demand responsive technologies such as *Starling Crossing* and *Dynamic Streets* (Level 5). Interestingly, the technologies mentioned in Level 5 prioritize urban areas and safe interactions between pedestrians and vehicles, which is lacking in the other smartness levels. Also, the acceptability of these solutions by various segments of society requires a more profound understanding. Nonetheless, our smartness classification can guide future studies to narrow their evaluation of user acceptability, behavior, and safety for each level of smartness.

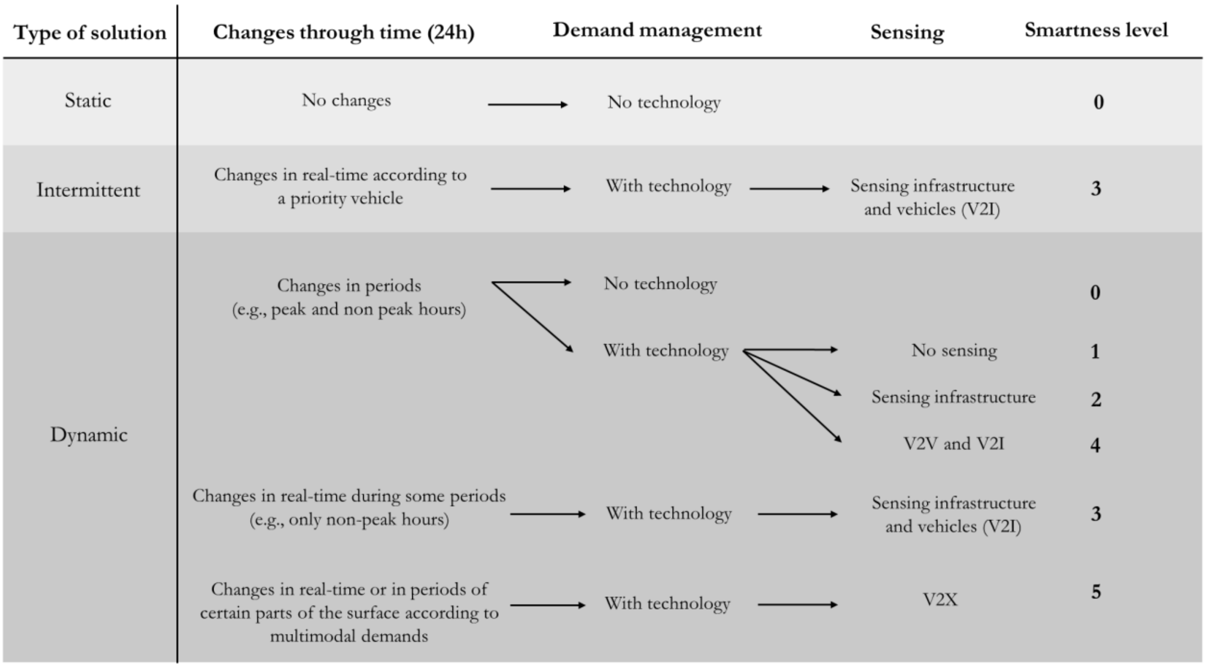

Figure 19: Definition of the road space allocation solution type with technology adoption.
Source: Author.

4.5 Conclusion

The development of technological solutions for transport infrastructure sensing and demand management supports decision-making and road space allocation. This paper aims to review and classify, in terms of technological adoption, many forms of road space allocation. We propose the solutions to be classified from level 0 – no technological adoption -to level 5 – fully connected environment. While level 0 is the state of practice of most road space allocation solutions, level 5 is still theoretical, with few technologies being developed. Our systematic literature review restricted the research scope to journal papers. We acknowledge that this may be a study limitation since many technological developments and innovations appear in commercial websites. We suggest that future reviews include commercial technological innovations. Further work could be performed on the quantifications of the impacts associated with the deployment of these technologies. They must also account for monitoring and KPI that allow for this assessment.

This review does not discuss how to plan cities and if these new technological developments and road space allocation concepts can ensure more just and sustainable environments. Many urban and transportation planners have advocated against smart cities and solutions, arguing that many solutions focus on technology, not the people (Batty, 2013). Our technology-level classification of road space allocation solutions may guide this discussion by examining which levels and solutions meet sustainable development goals. It provides a common language and framework for understanding the capabilities and limitations of smart transport infrastructures sensing and demand management.

Despite the legal aspects regarding data privacy, governance, and cyber security were not discussed in this paper, our classification may guide policy makers to ensure regulations and laws according to different levels of risk associated with each technology adoption level. Furthermore, it is important to ensure functionality and safety, and address concerns around liability and ethics. Overall, having a common understanding of smartness levels can help industry stakeholders, policy makers, and the public communicate effectively and develop more sophisticated and safer solutions for intermittent and dynamic road spaces.

Part B.

Implementation

Chapter 5

What we have learned so far

In Chapter 3, we presented the conceptual assumptions of implementing *dynamic road space allocation* in spaces where limited space is available to fulfill appropriately all competing uses. Specifically, our assumption is that these streets may experience periods when certain sections are underutilized, motivating the space to be allocated dynamically for alternative uses. In summary, complex streets have: i) limited and disputed spaces facing a dilemma on allocating space for mobility or access functions; ii) high connectivity to many areas of the city attracting trips; iii) high density and diverse land uses influencing mode choice and demand fluctuations over time; and iv) have high levels of traffic or/and public transport at least an hour a day. Chapter 3 introduced a discussion on the conceptual assumptions on where to reallocate space dynamically, but still more detail on the indicators and a practical case study are required to validate the site selection criteria.

What to expect in Chapter 5

Chapter 5 is the first chapter of Part B. The chapter presents a methodology of identifying zones that have complex streets – with limited and disputed spaces - to reallocate road space. In these zones there is a potential to reallocate road space dynamically. The conceptual assumptions adopted to select zones are based on the ones described in Chapter 3. Besides the spatial assumptions - mobility vs access dilemma; high network connectivity; dense and diverse land uses -, we include a temporal analysis that analyzes traffic and public transport dynamics over time. Consequently, it is possible to make conclusions on the periods that have more potential for reallocating road space dynamically. Open data is used for implementing the methodology in Lisbon, Portugal. Specifically, our method uses data from Census, OpenStreetMap, Google Maps API, and GTFS.

Chapter 5

5 Where is it complex to reallocate road space?

This chapter has been published as: Valença, G.; Moura., F; Morais de Sá, A (2023). Where is it complex to reallocate road space? *Environment and Planning B: Urban Analytics and City Science*. https://doi.org/10.1177/23998083231217770

5.1 Introduction

Traditionally, the allocation of road space to its different functions is based on the road network hierarchal classification. While in arterials, most space is attributed to traffic lanes, in local streets, there are usually fewer traffic lanes and more space for parking or sidewalks (Seco et al., 2008). Essentially, road space is distributed into two main types of spaces: i) corridors of movement, and ii) places for access and standing/ stillness/ staying (Nello-Deakin, 2019; von Schönfeld & Bertolini, 2017). On one hand, corridors of movement fulfill the mobility/link function and are customarily evaluated by measuring Levels of Services (Handy, 2020; P. Jones, 2016; Valença et al., 2021). On the other hand, access places have been implemented through parking spaces in car-oriented planning cities (Seco et al., 2008). Nonetheless, the 'place' status of the street has regained importance in recent years, acknowledging the place's importance for staying, loading/unloading, playing, socializing or loitering (P. Jones, 2016).

According to P. Jones (2016), the limited street width is one of the main challenges in allocating space for competing demands and functions. Recent road allocation strategies do not tackle the complexity of road space distribution and are often biased towards prioritizing one main function (mobility or access). Strategies such as complete streets and road diets are claimed to promote space for all modes. However, they often fail to consider the place function of the street (Mehta, 2015). Instead, these strategies focus on putting many transport modes to dispute for space in a mobility perspective, ignoring other public space functions and that the space could be shared (Nello-Deakin, 2019; Zavestoski & Agyeman, 2015). Differently, experimentation and pop-up initiatives reallocate the space to promote public spaces, mainly in local areas (Gehl, 2013), where there is less complexity and competing demands and activities.

Nonetheless, in streets with limited available space, there is a political and practical dilemma of allocating road space when high mobility/link and access/place functions need to be fulfilled and there are high traffic volumes and public transport levels (Gössling et al., 2016; P. Jones, 2016; National Association of City Transportation Officials, 2016). Also, the complexity increases when the street is located in a zone with high connectivity to other locations in the city, being a key destination for trips (De Gruyter et al., 2022). Thus, complex spaces have more actors (dense places) and different activities (diverse land-uses) competing for the space (P. Jones, 2016).

Studies on road and street space allocation have tackled road distribution justice (Gössling, 2016; Gössling et al., 2016), however few studies evaluate site selection of zones in the city where it is complex to reallocate space. The site selection of complex zones can guide planners, at an initial stage, to understand which zones require a deeper evaluation to implement the right solution. This is particularly relevant in zones where mobility/link and access/place objectives conflict with one another and where cities aim to prioritize more sustainable forms of transport or place activities such as outdoor dining and parklets (De Gruyter et al., 2022). In this context, this chapter aims to propose a methodology for selecting complex zones that potentially have streets that face a dilemma of allocating road space for both mobility/link and access/place functions.

Additionally, complex zones may require innovative ways of reallocating road space that consider the many modal and activity demands over different times of the day, week or season. For example, traffic lanes can be saturated during peak hours but often are underutilized in off-peak hours, which could be used for another purpose. There is a certain inefficiency in the use of space in static urban designs due to their limitation of not adapting according to urban dynamics in short periods, as discussed throughout this thesis.

In Chapter 3, we propose the concept of *dynamic road space allocation* to reallocate space dynamically over time in complex streets with many diverse needs during the day. In complex zones, it may not be possible to accommodate all uses and functions using static regular street designs. Although in Chapter 3, we suggest a methodology for site selection, we do not go into details nor apply it to a case study. This Chapter fulfills this gap by proposing a method for identifying complex zones for distributing road space that are candidates for dynamically allocating road space. We apply the proposed method for the case study of Lisbon, Portugal.

First, we discuss dynamic applications in road reallocation strategies and the concept of *dynamic road space allocation*. Then, the methodology of the site selection of complex zones is presented, together with the conceptual assumptions for selecting candidate zones for *dynamic road* *space allocation*. Sequentially, we present the case study. Then, the results and discussion are shown. We finish with a conclusion and references.

5.2 From dynamic lane allocation to *dynamic road space allocation*

Dynamic lane allocation proposes to dynamically allocate traffic lanes to different transport modes over periods of the day (e.g., peak and non-peak hours). The main goal is to reduce delays and use the space more efficiently to prioritize a transport mode or allocate underutilized lanes to other modes. Dynamic lane allocation has been researched for transit priority by maintaining a dedicated bus lane during peak hours and mixing with traffic when traffic and bus demands are low (C. Wang et al., 2016; F. Zhang et al., 2018; N. Zheng & Geroliminis, 2013). Other authors have studied how to dynamically open the hard shoulder for traffic during peak hours to optimize traffic flows (Mehran & Nakamura, 2009). The concept of dynamic lane allocation has also been applied as dynamic reversible lanes according to different directional demands over time (Hausknecht et al., 2011; J. Zhao, Liu, et al., 2015); and studied in the case of using autonomous vehicles in expressways (S. Chen et al., 2022; Duell et al., 2016). Overall, dynamic lane allocation has mainly been studied in expressways and arterials. Not much has been done considering urban environments, signalized intersections, and other road hierarchy classifications that have high mobility/link and access/place functions in dispute (Alhajyaseen, Najjar, et al., 2017). Most studies focus on automobile and bus optimization strategies with some rescue and autonomous vehicle applications.

Summing up, DLA only considers the traffic lanes as part of the urban space, lacking consideration of curbs, sidewalks, land use, and interaction with active transportation. Thereby, active modes, urban activities, land use patterns, and the access and place function of the street should be considered when proposing a dynamic allocation of space in urban and complex environments. The concept of *dynamic road space allocation* aims to include the gaps identified in the literature on dynamic lane allocation to allocate space dynamically in urban and complex environments, as mentioned in Chapter 3.

The *dynamic road space allocation*, from *façade* to *façade*, aims to balance the access and place function (i.e., parking, parklets, restaurants) with the mobility/link function (e.g., network multimodal flows) of the urban space over time. *Dynamic road space allocation* is context-oriented and more applicable in complex zones, where there is a dilemma and limited space to allocate for mobility/link or access/place. As complex zones have diverse actors and activities competing for space, *dynamic road space allocation* has the potential to accommodate different uses in a cross-section over time, when a specific space is underutilized or to prioritize a particular mode or activity. While dynamic lane allocation maintains the mobility function by allocating the space to different modes over time, *dynamic road space allocation* can promote both mobility and access functions and adapt the space to mix both functions. For example, a traffic lane (mobility) can be allocated for loading/unloading logistics during only lunch hour (access). Technologies such as variable message signs, in-pavement lighting, and flexible bollards may indicate these transitions. The following section explains the methodology for selecting complex zones that have the potential to implement *dynamic road space allocation*.

5.3 Methodological framework

A methodology for choosing complex zones where *dynamic road space allocation* may be implemented is suggested in Chapter 3. In Chapter 5, we detail and expand the method, applying it to a case study. Figure 20 presents the methodological framework of this study, including the data collection, conceptual assumptions, criteria and indicators, and results of the indicators that match the criteria. This process ultimately culminates with the identification and selection of areas categorized as complex and highly complex for the purpose of reallocating road space.

The zone selection on a macro scale (e.g., municipality or metropolitan scales) considers two main analyses: spatial and temporal. For the spatial analysis, the morphology of the road network and prevailing land use in the zones are considered. While road network characteristics significantly influence demand intensity, demand fluctuations over the day are more related to building activities and land use patterns (Berghauser Pont et al., 2019). Our proposal uses network centrality and land use indicators to evaluate the spatial component for selecting complex zones for reallocating road space. The selected zones must verify all requirements: i) dispute between mobility/link *versus* access/place functions of the road network; ii) high connectivity; iii) high land use densities; iv) high land-use diversity. In terms of the temporal analysis, this study takes into account the dynamics of motorized traffic and public transport. If certain zones experience high traffic demand at any given time of day, reallocating road space becomes more complex due to the fact that road capacity is not consistently underutilized.

Also, if the zone has bus stops with a high frequency of buses during a certain time there is a dispute in road space both on the traffic lane between buses and other vehicles, and on the sidewalk between the bus stop, pedestrians, and activities. The conceptual assumptions marked in orange in Figure 20 are the requirements for having complex zones. The public transport assumption (marked in red) was not considered essential for the zone to be complex, since the other assumptions already fulfill this requirement. However, having bus stops and a high frequency of buses adds more complexity to road space allocation. The criteria and indicators are explained in more detail in the next section.

We adopted a zoning grid to consider both network and land use indicators for Lisbon. The choice of using a grid map zoning over Census blocks was due to the advantage of grouping and comparing road network and land use indicators from different data sources. In addition, Census blocks size varies significantly even in urban areas while grid cells are uniform throughout the territory. In summary, the grid map zoning makes it possible to join and evaluate precise locations and aggregate locations of activities (centroids of census blocks) in the same cell. Additionally, we considered that a complex zone is detected if all conceptual assumptions in orange are met. Very complex zones are the ones that go in line with the conceptual assumption marked in both orange and red (Figure 20). Thereby, the grid ensured that each indicator was calculated independently.

The scale of 200x200m was chosen after testing the methodology in smaller (100x100m) and higher scales (500x500m). We noticed that the 200x200m scale was better adjusted to the centroids of the census blocks. Furthermore, the smaller scale of 100x100m provided approximately the same results, while the scale of 500x500m resulted in a smaller number of selected zones. Also, larger grids will result in a loss of accuracy (e.g., population density and centrality measures can be significantly affected if two heterogeneous blocks are merged into the same analysis zone).

Additionally, the 200x200m scale is appropriate for policy makers to further evaluate the streets in the selected zones for considering which static or dynamic solutions to implement. While smaller scales may not give a complete picture of blocks and the context of some zones, higher scales provide an overload of street options, higher levels of data aggregation, and consequently, overly increase heterogeneity within a zone. The 200x200m zones correspond approximately to an area of 4 blocks of 100 meters each, which allows the evaluation of three intersections. In future studies, when proposing dynamic solutions and collecting data, it makes sense to evaluate the effects of the road segment on the downstream, middle and upstream intersections.

It is important to emphasize that this paper does not evaluate which road segments are more suitable for *dynamic road space allocation*. Instead, from a global perspective, we consider which zones may have the most convenient road segments, according to their network functions and interaction with activities and land use, and traffic and public transport dynamics. We suggest that the criteria for selecting the appropriate road segments and the many *dynamic road space allocation* scenarios within the designated zones are defined in future studies.

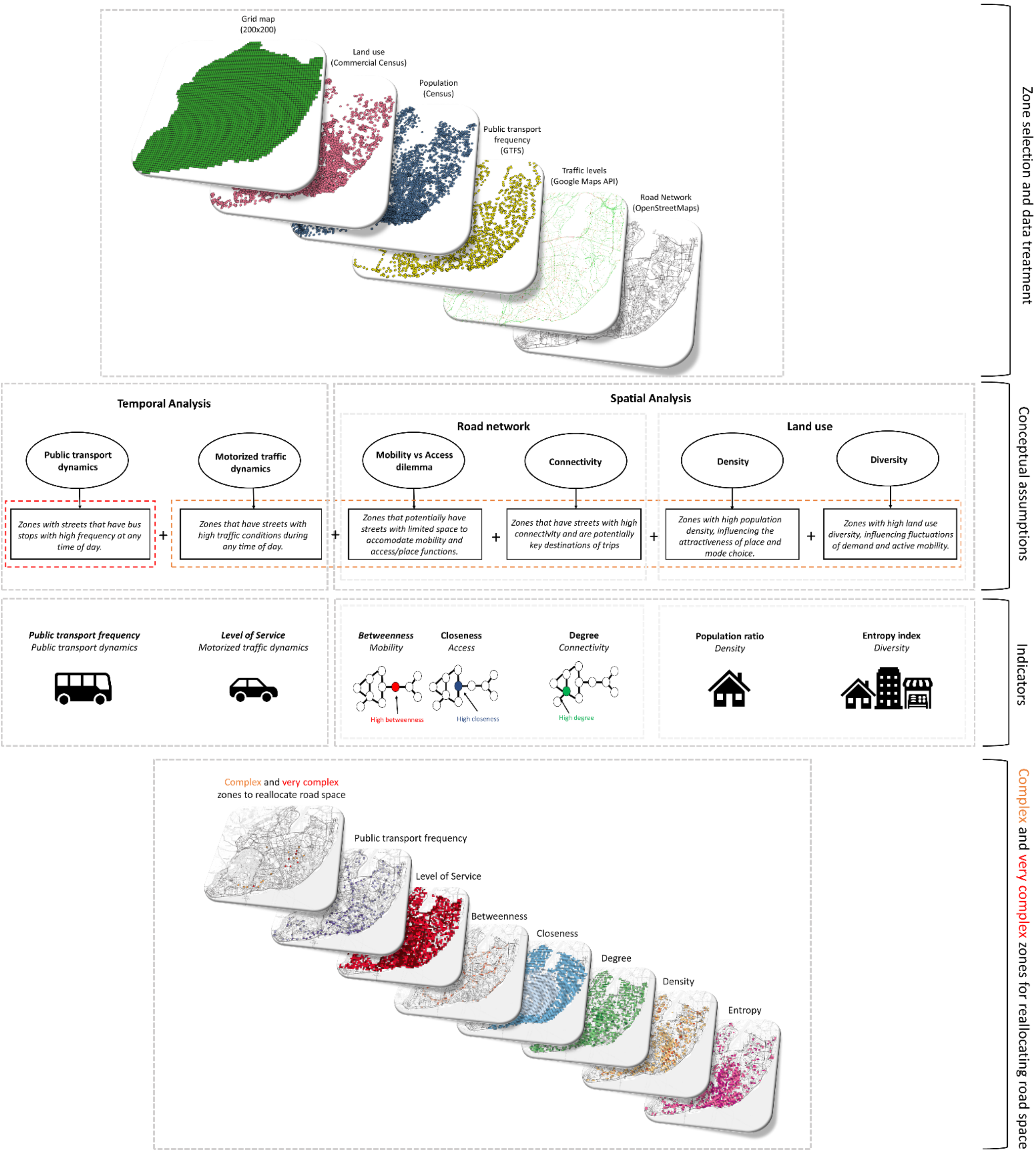

Figure 20: Methodological framework for selecting complex zones to reallocate road space that has the potential for implementing *dynamic road space allocation*.
Source: Author.

5.4 Conceptual Assumptions: criteria and indicators

5.4.1 Spatial Analysis

Road Network: Road space allocation dilemma

While the arterials in an urban environment prioritize mobility (or movement), local streets focus on access to activities and residences. However, when dealing with a zone in the graph near the overlapping area, as illustrated by the hatched pattern in Figure 21a, policy makers may not perceive if they should prioritize access/place over mobility functions or vice-versa. According to Seco et al. (2008), the main distributors are the main challenge in determining which function to prioritize, as illustrated in Figure 21b. Specifically, main distributors often struggle with limited urban space, which is a problem to fully and adequately design for mobility and access. Additionally, many of these roads were previously designed to increase automobile capacity. The amount of space that should be reallocated for sustainable modes and the consequences on traffic jams are still unclear in many cities that seek to transfer traffic lanes to other urban functions.

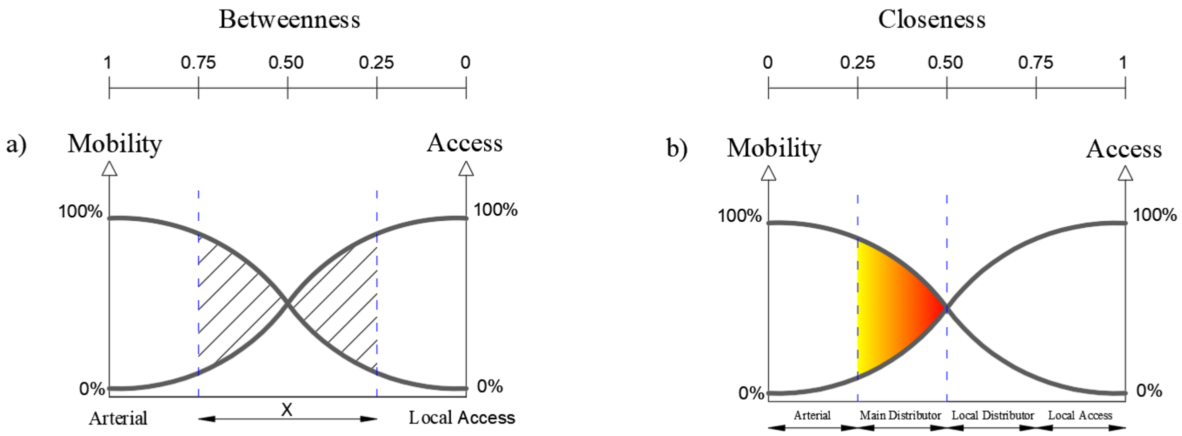

Figure 21: Road hierarchy classification and road space allocation dilemma (hatched and colored parts of the graph are the functions overlapping zones).
Source: Author.

Notably, urban space is a dynamic entity, and thereby it may have different spatial and temporal needs during peak and non-peak hours, weekdays, weekends, and seasons. We highlight in Figure 21a, the overlapping zone where, conceptually, the several types of road network hierarchies can serve one function or the other (i.e., mobility versus access/place), depending on transport demand and activity requirements over time. For example, main distributors could be dedicated to vehicular traffic during peak hours but allocated for active modes (mobility) or parklets (access/place) during non-peak hours. Thus, by dynamically adapting the road space, it may be possible to have a more equitable and just space distribution over time.

We used centrality measures to characterize the road network to evaluate the road space allocation dilemma in the disputed area illustrated in Figure 21a (main and local distributors). Centrality measures can represent the urban street network based on its urban morphology (Demsar et al., 2008). The network configuration is measured through topological distances while considering every node in the network with equal importance and opportunity access (Hillier & Iida, 2005; F. Wang et al., 2011). Even though centrality measures have their limitations in measuring accessibility and demand (Geurs, 2018; Zhong et al., 2014), it has proven to be an effective method to characterize the urban form from a global perspective (Berghauser Pont et al., 2019). We opted to use these measures since they can evaluate the road network configuration that influences mobility patterns (Penn et al., 1998). Therefore, we evaluate the road network effects in each 200x200m grid cell using the centrality indicators explained below. We calculated the average values within each grid cell for each centrality indicator.

Conceptually, betweenness centrality is a measure of network flow, and thereby, it is suitable to evaluate the mobility function of the network (Wasserman & Faust, 1994). Betweenness centrality measures the number of shortest paths that pass through a node. The higher the value of the betweenness of a link and a node in a road network, the more likely it corresponds to a higher hierarchy level of road classification and a network hub, respectively (Barthelemy, 2017). Suppose the betweenness values are classified into four categories from minimum to maximum (0 to 1). In that case, the conceptual dilemma's undefinition area will be in the second (main distributors) and third classification (local distributors), as illustrated in Figure 21a. Betweenness centrality is defined as (Freeman, 1979):

$$C_B(p_k) = \frac{1}{(n-1)(n-2)} \sum_{j \neq k, i \neq k}^{n} \frac{g_{ji}(p_k)}{g_{ji}}$$

(Equation 3)

Where $C_B(p_k)$ corresponds to the betweenness of a node p_k, $g_{ji}(p_k)$ is the number of shortest paths between nodes p_j and p_i which pass through the node p_k, g_{ji} is the total number of shortest paths between nodes p_j and p_i, n is the total number of nodes in the network.

The closeness centrality is a measure of proximity since it measures how close a point is to other network points. More local streets usually have denser nodes than higher hierarchal road classifications (Ozbil et al., 2011). High closeness values indicate minimum distances to the shortest paths in the network. The third level (main distributors) and second level (local distributors) of closeness values are more likely to correspond to the road space allocation dilemma's undefinition area, as demonstrated in Figure 21b. Freeman (1979) defines closeness as (Equation 4):

$$C_c(p_k) = \frac{n-1}{\sum_{i=1}^{n} d(p_i, p_k)}$$

(Equation 4)

Where $C_c(p_k)$ is the closeness of the node p_k; $d(p_i, p_k)$ is the number of shortest paths linking p_i and p_k; and n is the total number of nodes in the network.

After detecting the road network's undefinition area, we use the degree centrality to measure network connectivity, which is an important step to verify how streets are connected and are more likely to fulfill their primary linking function. Additionally, streets with high connectivity tend to be important trip destinations (De Gruyter et al., 2022). The degree centrality is defined by Freeman (1979) and demonstrated in (Equation 5): higher values of degree, levels 3 and 4, are desired on a 4-level scale.

$$C_D(p_k) = \frac{\sum_{i=1}^{n} a(p_i, p_k)}{n-1}$$

(Equation 5)

Where $C_D(p_k)$ is the degree of a node p_k, $a(p_i, p_k)$ is the *ik* component of the node adjacency matrix A, and takes the value of 1, only if nodes p_i and p_k are connected with a link, and *n* relates to the number of nodes in the network, $n-1$ is the maximum number of connections that a point may have to other points in the network.

Land use: Density and diversity

Land use density and diversity significantly affect travel patterns and behavior. While urban densities greatly influence mode choice in daily commuting, mixed land use mainly influences how the trips are distributed throughout the day (Berghauser Pont et al., 2019; Cervero, 1996). However, non-motorized trips tend to rise when there are high densities and diverse neighborhood activities, including restaurants and shops. For example, in a dense and mixed land use environment, office workers would tend to walk to a restaurant to have lunch rather than returning home by car (Cervero, 1996; Cervero & Kockelman, 1997). Additionally, mixed land use enables dynamic settings since parking spaces during working hours for offices can serve restaurants and theaters at night (Cervero, 1996).

In this context, we evaluate land use in two dimensions: density and diversity. Using the Portuguese Census, we considered the population within each cell grid of 200-meters square for calculating the density (Instituto Nacional de Estatística, 2011). We summed the population corresponding to each centroid of all statistical *Census blocks* (smallest geographic unit for available statistical information) within each grid cell. Additionally, we divided the value within each cell by the average of all cells to analyze the population distribution in the territory (Equation 6). The last step is essential for establishing zone selection requirements, discussed in section 5 of this chapter.

$$Den_c = \frac{\sum_{i=1}^{n} Pop_i}{\sum_{n=1}^{M} \frac{Pop_i}{M}}$$

(Equation 6)

Where, Den_c corresponds to the density in the grid cell *c*, Pop_i is the population of centroid *i*, *n* is the total number of centroids intersecting with the grid cell *c*, and *M* is the total number of cells that intersect with at least one centroid.

To calculate the land use diversity, we use the Entropy index. The Entropy index was first applied in information theory (Shannon, 1948), but has been used to calculate land use diversity for several years (Cervero & Kockelman, 1997). The index ranges between 0 and 1, where 0 has homogeneous land use, with only a single land-use type, and 1 has an equal distribution of land-use types. The entropy index is calculated in the following (Equation 7):

$$Ent_c = -\sum_{j}^{N} \frac{[P_j \times \ln(P_j)]}{\ln(N)}$$

(Equation 7)

Where, Ent_c corresponds to the entropy of cell *c,* P_j is the proportion of the category *j*, and N corresponds to the total number of land use categories.

5.4.2 Temporal analysis

Motorized traffic dynamics

When streets have very low traffic demand at any time of day, it tends to be less complex to implement traffic management and road space allocation strategies. Consequently, not only the technical choice to repurpose the space is less complex, but also the acceptability will tend to be higher since the car is not being challenged. Streets with higher car volumes are more likely to be more contested since cars considerably use more space than other transport modes to carry the same number of passengers or freight and, therefore, reclaiming more space than other modes (Gössling et al., 2016). There is a higher challenge to reallocate space in highly congested streets due to limited space, and the need to perform tradeoffs and compromise one mode for another. In many cases, there is a lack of political effort and reluctance to perform changes that will upset drivers (Bozovic et al., 2021).

In this context, we use real-time Floating Car Data (FCD) from Google Maps to evaluate the complexity of reallocating road space within a zone from a temporal perspective. Google Maps tracks the location of mobile devices that users permit to share their location or that are actively using the app. FCD has proven to be a reliable and cost-effective method to collect and analyze traffic data of an entire road network (De Fabritiis et al., 2008). Also, this type of data is very useful to complement data from sensors in the network and evaluate travel time variability over time (Rahmani et al., 2015). The traffic levels in Google Maps are defined by a congestion delay index with color indicators: no traffic delays (green); medium traffic (yellow); high traffic (red); and heavy traffic (crimson).

We extracted real-time traffic data on a Thursday as a representative standard day, every hour from 6 AM to 11 PM. We consider that if a zone does not have any streets with high or heavy traffic conditions at any time of day, then the space is consistently underused. The problem, in this case, is not a lack of space, but rather an oversupply of space when compared to the existent demand. On the other hand, if a zone has a street with high or heavy traffic levels at any time of day, there is a dispute for space, which increases the complexity of reallocating it. We calculate the maximum traffic level of service of every street within each zone from 6 AM to 11 PM. Sequentially, only zones where the maximum value of the level of service is high (level 3) or heavy (level 4) are selected as a requirement for complex zones to reallocate road space. This means that we select zones that have at least one street that intersects the zone, with high (level 3) or heavy (level 4) traffic levels at any time of day. The traffic dynamics indicator proposed in this paper is measured by the equation below:

$$TD_c = max_{s=1}^{N}\left[max_{t=1}^{T}\left(TL_{s,t}\right)\right]$$

(Equation 8)

Where TD_c corresponds to the traffic dynamics indicator of cell *c*, *N* is the total number of streets *s* within a cell *c*, *T* is the total number of hours *t*, and $TL_{s,t}$ is the traffic level of the street *s* at the time *t*.

Public transport dynamics

When public transport operates at a high frequency and the roads are congested, there must be a trade-off between the amount of space that should be allocated for one mode or the other. Solutions, such as dedicated bus lanes, or dynamic bus lanes (e.g., only during peak hours), can be employed to effectively reallocate road space in complex urban environments. Also, when there is substantial demand for both traffic and public transport, the decision to allocate space for one mode over the other depends on the political will to challenge the dominance of cars. Additionally, the presence of bus stops on the street occupies a significant amount of space that is crucial for accommodating pedestrians and facilitating convenient boarding of public transport, further adding to the complexity of the situation.

We use General Transit Feed Specification (GTFS) data to evaluate public transport frequency at bus stops over time. GTFS data contains a standard format of transit schedules including bus stop locations, routes, and trips, available from many public transport agencies. GTFS is a valuable tool for visualizing and analyzing the conditions of the public transportation network (Barbeau & Antrim, 2013). In Lisbon's case study, only data from buses were used since the metro is underground and does not directly compete for road space. The frequency of all trips is more important than only considering a specific route of public transport when making decisions about road space allocation solutions (National Association of City Transportation Officials, 2016).

We calculate the hourly number of bus trips that pass through a bus stop from 6 AM to 11 PM. Sequentially, we calculate the total number of buses per hour within a zone. In this case, it is important to evaluate the zone and not the bus stop separately since the combination of all bus stops within a zone will influence the complexity levels of reallocating road space. We adopt the classification of the Transit Street Design Guide of bus frequency and volume (National Association of City Transportation Officials, 2016). The guide classifies the bus frequencies into four categories based on headways, frequencies, and passenger occupancy levels. However, there are some overlaps of values referring to the bus frequency required for each category. Since we use only the frequencies of buses, we adapted slightly the classification proposed by the guide to have a fixed difference between the levels of classification. We classify the bus frequencies in four levels based on the Transit Street Design Guide, following (Equation 9): low volume (4 or fewer buses per hour); moderate volume (5 to 10 buses per hour); high volume (11 to 20 buses per hour); and very high (above 21 buses per hour).

$$PL_{c,t} = \sum_{b=1}^{B} Bus_{b,t}$$

(Equation 9)

Where, $PL_{c,t}$ corresponds to the public transport level of cell *c* and hour t, *B* is the total number of bus stops *b* within a cell *c*, and Bus_b is the total number of buses that pass at bus stop *b* and time *t* and $PLN_{c,t}$ is defined by:

$$PLN_{c,t} = \begin{cases} 1 \rightarrow & 1 \leq PL_{c,t} \leq 4 \\ 2 \rightarrow & 4 < PL_{c,t} \leq 10 \\ 3 \rightarrow & 10 < PL_{c,t} \leq 20 \\ 4 \rightarrow & PL_{c,t} \geq 20 \end{cases}$$

The public transport dynamic indicator of a zone is measured by the maximum bus frequency level per hour throughout the day. Only selected zones that experience high (level 3) or very high (level 4) bus volumes for at least one hour are taken into consideration. The public transport dynamics indicator proposed in this paper is computed with (Equation 10):

$$PD_c = max_{t=1}^{T}(PLN_{c,t})$$

(Equation 10)

Where, PD_c corresponds to the public transport indicator of cell *c*, *T* is the total number of hours *t*, and $PLN_{c,t}$ is the public transport level defined in (Equation 9).

Thus, the selected zones are chosen by the intersection of all spatial and temporal indicators in the grid cells, classifying zones as complex or very complex. Complex zones comply with all the requirements of the spatial indicators and the traffic dynamics indicator of the temporal analysis. Very complex zones are the ones that comply with the conceptual assumptions of all the indicators proposed by the spatial and temporal analysis. This process will be more specifically explained in section 5.5.

5.5 Implementation

5.5.1 Study area and data sources

The city of Lisbon is the capital of Portugal and our case study, with an area of approximately 100 km^2 and a population slightly above half a million (Instituto Nacional de

Estatística, 2011). The city of Lisbon is part of the Lisbon Metropolitan Area, with 2,8 million inhabitants (Marques da Costa, 2016). The destination of 21.6% of total commute trips in the Lisbon Metropolitan Area is Lisbon, whereas 15.9% of trips are produced or attracted by the city (Instituto Nacional de Estatística, 2011). Figure 22 presents the main areas in Lisbon. The historical area (1) is where the city was founded, being an important area for commerce and tourism. Since the late 1990's and early 2000's, the historical center has suffered from processes of gentrification and studentification, and more recently residents are being displaced by short-term rental markets such as AirBnB (Cocola-Gant & Gago, 2021; Sequera & Nofre, 2020). The river waterfront (2), links to the historical center (1) where some of the main landmarks are located (e.g., Belem Tower, the Jeronimos Monastery, the Commerce Square), and to a new central residential area (7) that was regenerated in the late 1990's to receive the Expo 1998. The consolidated central area (3) corresponds to the main urban expansion of Lisbon during the 1st half of the 20th century centered around the main traditional mixed-use corridors, where the main economic activities were established. The central residential area (5) had its urban expansion during the 1st and 2nd half of the 20th century, while the central residential area (6) has higher densities, expanding during the 2nd half of the 20th century. The Monsanto (8) is an area with low density, being mainly a natural reservation park. The International Airport (9) is located in the north part of the city.

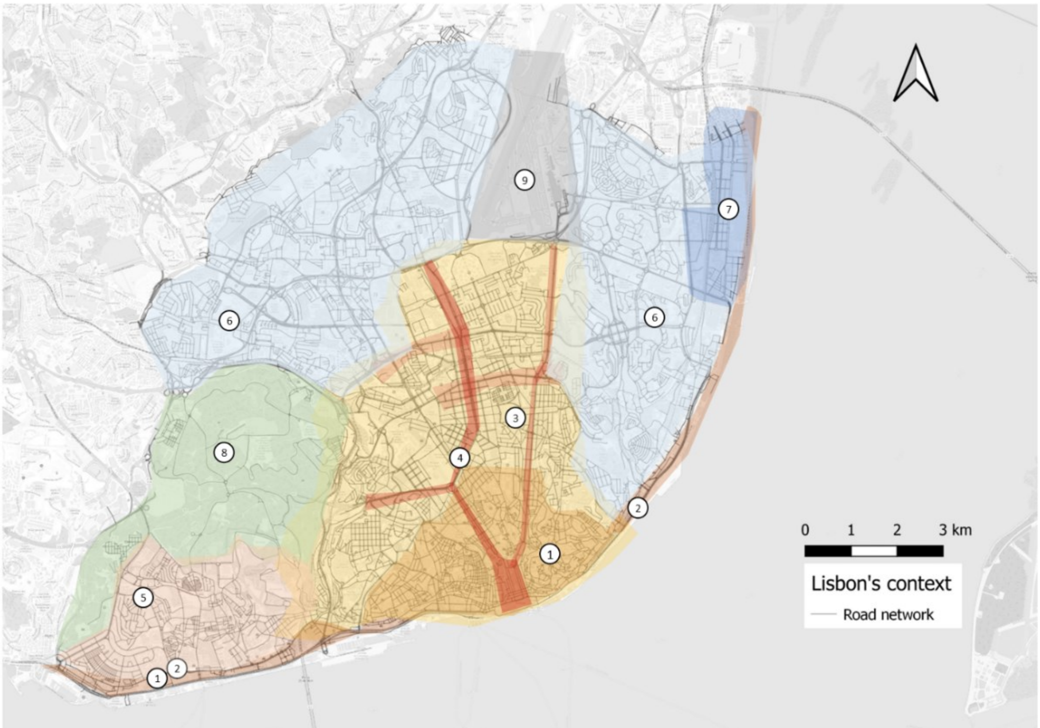

Figure 22: Main areas in Lisbon. 1) Historical area; 2) River waterfront; 3) Consolidated central area; 4) Traditional mixed-use corridors; 5) Central residential area; 6) Central residential area with high densities; 7) Central residential area with mixed-use centralities; 8) Monsanto forest park; 9) International Airport.
Source: Author

We used the centroids of each *Census block* to extract the resident population and the number of mainly residential buildings to calculate the land use density and diversity indicators, respectively. Besides the residential buildings, we used the Commercial Census in Portugal to gather data related to services and shops, restaurants and bars, and hotels to calculate the land use diversity (Câmara Municipal de Lisboa, 2010). We considered four main types of land use to calculate the Entropy index: primarily residential buildings, services and shops, restaurants and bars, and hotels. The road network was extracted from OpenStreetMap and treated using the *sf*, *tidygraph,* and *rgrass7* packages of R version 4.0.3 (Bivand et al., 2021; Pebesma, 2018; Pedersen, 2020). The network typology was cleaned by breaking lines at intersections. As a result, nodes represent intersections, and the edges represent the road segments of the network. We used the *googletraffic* R package to extract real-time traffic conditions from 6 AM to 11 PM on April 27th 2023 (Marty, 2023). The calculations of the frequency of trips that arrived at each bus stop were executed by using the *gtfstools* library (Herszenhut et al., 2022). The GTFS from buses was extracted from the most recent data provided by CARRIS (30 December 2022), the main bus operating agency in Lisbon (Open Mobility Data, 2022). Furthermore, the open-source software QGis 3.18.1 (QGIS Development Team, 2021) was used to develop the maps and calculate the network's centrality indicators (degree, betweenness, and closeness) and land use indicators (density and diversity).

5.5.2 Results

As mentioned before, the indicators for choosing zones with the potential of implementing *dynamic road space allocation* are separated into spatial and temporal indicators. While the spatial indicators used are betweenness, closeness, degree, density, and diversity (Entropy index), the temporal indicators are the motorized traffic dynamics, and the public transport dynamics. We rescaled all the spatial indicators from 0 to 1 using the min-max normalization for each 200x200m zone (except for the Entropy index since the original values already range within this scale). The temporal indicators are categorical variables with four categories each. A zone is chosen to be complex for reallocating road space if all the spatial indicators and the motorized traffic dynamics requirements are met. If all spatial and temporal indicator requirements are met than the zone is considered to be very complex (Table 3). The intersection approach was adopted since it is the combination of the indicators that correspond to complex and very complex zones to reallocate road space and where implementing *dynamic road space allocation* is more appropriate. In other words, these are the zones with higher possibilities of having streets with diverse and intense activities while having limited space to fulfill all necessary functions and demands.

Table 3: Criteria for selecting complex and very complex zones to reallocate road space. Source: Author.

Very complex zones

Complex zones

Type	Indicators	Requirements
Spatial Analysis	Betweenness	$0.25 \leq C_B \leq 0.75$ And
	Closeness	$0.25 \leq C_C \leq 0.75$ And
	Degree	$C_D \geq \mu_{C_D}$ And
	Density	$Den_c \geq \mu_{Den_c}$ And
	Entropy	$Ent_c \geq 0.50$ And
Temporal Analysis	Motorized Traffic Dynamics	$TD_c = \begin{cases} 3\ (High) \\ 4\ (Heavy) \end{cases}$ And
	Public Transport Dynamics	$PD_c = \begin{cases} 3\ (High) \\ 4\ (Very\ high) \end{cases}$

The threshold values of the betweenness and closeness are established based on the road allocation dilemma (Recall Figure 21). Therefore, road segments with values between 0.25 and 0.75 are expected to have conflicting demands between modes and urban functions.

The degree and density mean values were used as the threshold values. This criterion is essential because these indicators are relative to the context of the city. The average density and degree indicators can differ depending on the city. Therefore, these indicators must be city-specific accordingly. In the case of Lisbon, the degree average is 0.5. Approximately 60% of the 200x200 meter cells have higher values than the average. This indicates that most of the zones in the city have network connectivity above the average. The density average is 0.19, and 40% of the cells have a higher population density. 77% of the total population of Lisbon is located within the cells above the density average. This higher population coverage justifies using the average as the density threshold since most of the population meets this condition. Additionally, this criterion demonstrates how most of the population concentrates on only 40% of the territory.

Nonetheless, the absolute value of the Entropy index already represents the diversity of land use and does not need to be compared with the average. We established an entropy threshold of 0.5 since this value represents at least two of the four categories with an equal proportion of land use. Having two types of predominant land use already tends to promote some dynamics to the neighborhood since residents can walk to a shop, for example (Montgomery, 1998).

Table 4 presents the descriptive statistics of all the indicators chosen to select the candidate zones for *dynamic road space allocation*. The indicators' mean and standard deviation represents the proportion of cells within the interval and thresholds established by the criteria. The Q1 and Q3 values represent how 25% and 75% of the values are distributed among the cells. Interestingly, only the closeness has the Q1 value within the interval of the requirement to select complex and very complex zones. In contrast, only the betweenness of the spatial indicators does not have the Q3 value within the screening process requirements. As a result, the betweenness does not comply with the conceptual assumption in most of Lisbon's grid cells. Also, the public transport dynamics indicator does not have Q3 value within the requirements for very complex zones. This result makes sense since some zones lack bus stops, as evidenced by the Q1 value.

Table 4: Descriptive statistics of the indicators for site selection. Source: Author.

Variable	Mean	Std. Deviation	Min	Q1	Q3	Max
Betweenness	0.09	0.12	0.00	0.013	0.12	1.00
Closeness	0.58	0.13	0.00	0.48	0.66	1.00
Degree	0.50	0.18	0.00	0.40	0.60	1.00
Density	0.19	0.18	0.00	0.05	0.29	1.00
Entropy	0.37	0.32	0.00	0.00	0.69	0.95
Motorized traffic dynamics	2.32	1.50	0	1	3	4
Public transport dynamics	0.63	1.05	0	0	1	4

Table 5 presents a sensitivity analysis (SA) of the requirements for selecting zones that are complex and candidates for reallocating road space dynamically. We calculated the elasticities to quantify the sensitivity of the number of selected zones with respect to 10% and 20% variation of site selection indicators. The elasticity (ε) is calculated with (Equation 11):

$$\varepsilon = \frac{(Z_f - Z_i)/Z_i}{(I_f - I_i)/I_i}$$

(Equation 11)

Where Z corresponds to number of selected zones, and *I* corresponds to the site selection indicators.

The results indicate that betweenness and degree centrality are the most sensitive to change, while closeness and entropy are relatively less affected ($\varepsilon < 1$), and density shows slight elasticity. The higher elasticity values of betweenness and degree are expected due to their strong dependence on road hierarchy. The number of streets is not uniform across different levels of road hierarchy. In an urban road network, arterial roads typically have fewer segments compared to local streets. As a result, the betweenness and degree of road segments do not follow a normal distribution. Therefore, it is recommended to define cut-off values for site selection indicators in absolute terms rather than relative terms, such as using percentiles based on the road network segments.

To replicate this method in other cities, it is advisable to test a range of constrained and expanded values for betweenness and degree, as the organizational structure of road networks may influence the number of selected zones. This discretionary approach to defining ranges for betweenness and closeness is acceptable because the proposed method serves as a screening process for identifying zones with higher complexity potential. The final stage of street selection involves a more detailed evaluation of candidate road segments to determine their dynamic allocation potential within each zone.

Figure 23 demonstrates the individual result of each indicator following the requirements and the final selection of zones that intersected all the indicator's conditions. Out of the total 3 675 cells measuring 200x200 meters across the entire territory, all the statistics were derived solely from the 1 660 cells that intersect with a population centroid. This criterion was adopted because 55% of the cells lack population and are therefore not relevant to the analysis. Including them would significantly affect the results. Among the 1 660 valid zones, a total of twenty zones were selected that fully meet the screening process requirements. However, seven of these zones pose significant challenges in terms of reallocating road space due to their complexity. It is interesting to notice a certain continuity in the sequence of the selected zones (Figure 23h), which indicate how these areas in the city have similar characteristics in terms of network connectivity, hierarchy classification of the street, density, diversity of land use, and traffic and public transport conditions. Only one zone locates isolated from the remaining.

Table 5: Sensitivity analysis (SA) of the requirements for selecting complex zones. Source: Author.

Indicators	**SA 1 (+10% of lower and/or upper interval limits, separately)**		**SA 2 (-10% of lower and/or upper interval limits, separately)**		**SA 3 (+20% of lower and/or upper interval limits, separately)**		**SA 4 (-20% of lower and/or upper interval limits, separately)**	
Betweenness	$0.275 \leq C_B \leq 0.75$	$0.25 \leq C_B \leq 0.825$	$0.225 \leq C_B \leq 0.75$	$0.25 \leq C_B \leq 0.675$	$0.30 \leq C_B \leq 0.75$	$0.25 \leq C_B \leq 0.90$	$0.20 \leq C_B \leq 0.75$	$0.25 \leq C_B \leq 0{,}60$
ε	-2.5	0	-1.0	0	-1,5	0	-2	0
Closeness	$0.275 \leq C_C \leq 0.75$	$0.25 \leq C_C \leq 0.825$	$0.225 \leq C_C \leq 0.75$	$0.25 \leq C_C \leq 0.675$	$0.30 \leq C_C \leq 0.75$	$0.25 \leq C_C \leq 0.90$	$0.20 \leq C_C \leq 0.75$	$0.25 \leq C_C \leq 0{,}60$
ε	0	0	0	0,50	0	0	0	0,75
Degree	$C_D \geq 0.55$		$C_D \geq 0.45$		$C_D \geq 0.60$		$C_D \geq 0.40$	
ε	-3		-1,5		1,75		-1	
Density	$Den_c \geq 0.209$		$Den_c \geq 0.171$		$Den_c \geq 0.228$		$Den_c \geq 0.152$	
ε	-1		0		-0,5		-1,25	
Entropy	$Ent_c \geq 0.55$		$Ent_c \geq 0.45$		$Ent_c \geq 0.60$		$Ent_c \geq 0.40$	
ε	0		-0,50		-0,50		-0,25	

Figure 23: Spatial distribution of the indicators and final selection of zones that meet the requirements of reallocating road space dynamically over time: (a) betweenness, (b) closeness, (c) degree, (d) density, (e) entropy, (f) Motorized traffic levels, g) public transport frequency, h) complex and very zones to reallocate road space.
Source: Author.

5.6 Discussion

5.6.1 *Implications for practice*

Figure 24 illustrates the designated zones' spatial distribution and shows examples of road segments from one of the zones (Google Street View images). Most of the selected zones are in the consolidated central area, where most of the economic activity is held around main corridors (Refer to Figure 22). As expected, strictly residential and more local zones in the city were not selected since these usually have lower levels of land-use diversity and values of betweenness and closeness near zero and one, respectively. Therefore, areas with a single land use type predominately tend to be less vibrant and complex.

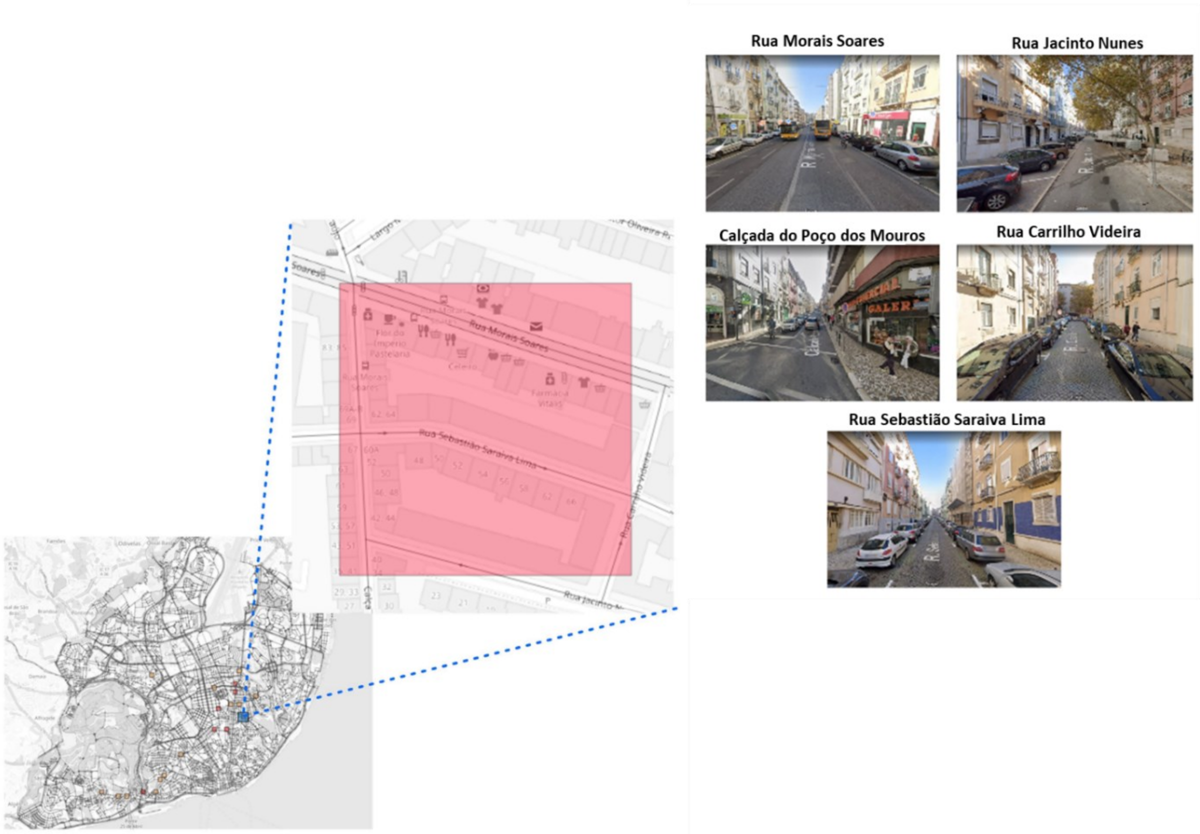

Figure 24: Site selection of complex zones with potential for implementing *dynamic road space allocation*.
Source: Author

The use of the betweenness and closeness values to detect the disputed area of the road hierarchy classification has proven effective since all zones contain road segments classified as main or local distributors (e.g., Rua Morais Soares in Figure 24). As a result, zones containing mostly narrow streets are excluded from the screening analysis. However, since the road network is planned to provide capacity from higher to lower hierarchy classifications, some local streets appear in every zone. Consequently, the following step requires looking in more detail at each zone, identifying which streets have underutilized spaces and have a dispute between uses over the hours, days, and season. This sequential step from this methodology is important because different solutions may require different local criteria for being implemented. Thus, some streets may be more suitable for implementing some solutions than others, as will be discussed in more detail in the next chapter.

We observe that the zones have similar characteristics. Most zones have car-oriented streets, from two to five traffic lanes. Parking spaces are present in all zones, especially in streets that were car-oriented planned. Interestingly, most streets with more space dedicated to parking and traffic lanes tend to have less dedicated space for sidewalks and arborization. This fact confirms how road space is disputed and limited. On the other hand, we detected three zones that have a more equitable distribution of space. In these zones, traffic lanes are restricted to a maximum of two lanes, allowing more room for sidewalks and arborization.

Detecting zones that may allocate road space dynamically over time is important for informing policy makers about the sites they should consider carefully. Additionally, the methodology is replicable for other cities and can be adapted to detect potential zones for other types of road space allocation. For example, by adapting the requirements of the indicators, it is possible to detect zones that have streets with more potential for implementing 30km/h zones. In this case, lower levels of street connectivity and betweenness, and higher values of closeness would be expected.

5.6.2 Challenges and opportunities

Road space management is essential in complex zones since they are the most likely to have issues related to public health, safety, and equity. Congestion delays have a significant direct impact on air quality, resulting in higher health risks for on-road users and people living close to the road (K. Zhang & Batterman, 2013). Crashes and fatalities between vehicles and active mobility are more likely to happen in complex zones. Evidence has demonstrated that zones with more transit stops and higher road width have a higher probability of pedestrian crashes (Pulugurtha & Sambhara, 2011; Ukkusuri et al., 2012); density (Amoh-Gyimah et al., 2016; Pulugurtha & Sambhara, 2011) and diversity of land use have a positive influence in the number of pedestrian and bicycle crashes (Amoh-Gyimah et al., 2016; P. Chen, 2015); and traffic volume is positively related to the number of intersection crashes of motorized vehicles, pedestrians and cyclists (C. Lee & Abdel-Aty, 2005; J. Wang et al., 2017).

Although there is a need to manage road space adequately in complex zones that have disputed and limited spaces, they often require tradeoffs. While traditional urban designs have a range of fixed solutions, dynamic road space allocation can increase the number of possibilities to accommodate different demands, actors, and functions over days, weeks, or seasons. Also, allocating space dynamically is important because it can be used to increase the accessibility of different modes and manage space more efficiently in terms of its use (Gonzales et al., 2010). As mentioned by Miller (2018), travel times of different transport modes vary along the day. Consequently, the accessibility to activities is also different depending on the time and transport mode. Potentially, road space could be allocated dynamically to improve accessibility of a certain mode to essential services (e.g., hospital, workplace, groceries) in moments of the day when accessibility is low.

In terms of justice, few studies calculate the space distribution of streets. Most non-academic reports claim that space allocation is often "unfair" since there is recurrently an imbalance between modal share and space distribution (Gössling et al., 2016; Nello-Deakin, 2019). Nello-Deakin (2019) believes that analyzing road space distribution by modal share is problematic since it does not take into account other functions of the public space, and it is biased, being used only when the modal split of active transport is higher than the space they occupy. While Gössling et al. (2016) propose to measure the distribution of space by distance traveled, Nello-Deakin (2019) suggests evaluating the distribution of speeds as a measure of transport fairness. Although both approaches are a step towards evaluating road space allocation, they lack consideration of how the space is actually used over time.

We argue that the efficiency and justice of streets may be measured not only by the amount of space occupied by each mode or function but also by how it is used over time. In this perspective, complex streets present the most significant obstacles in achieving a balanced distribution of space. These streets experience high demands for various uses, while simultaneously facing scarcity in available space (e.g., street width, number of traffic lanes) to accommodate all demands and functions (e.g., mobility, access, and place). Although there is a need to manage road space adequately in complex zones that have disputed and limited spaces, they often require tradeoffs. While traditional urban designs have a range of fixed solutions, *dynamic road space allocation* can increase the number of possibilities to accommodate different demands, actors, and functions over days, weeks, or seasons.

We acknowledge that allocating road space dynamically has its many challenges as described in Chapter 3, including safety, acceptability of users, built environment restrictions, and cultural aspects. However, these challenges can have different levels depending on the type of solution, the time interval of the dynamic application (e.g., hours, days, or seasons), and local context.

Also, the challenges and opportunities to allocate road space dynamically are different depending on the fluctuations of different demands and activities. Figure 25 and Figure 26 illustrate in two zones the types of fluctuations of demand that influence the complexity of allocating road space. Road space could have disputed (red), complementary (green) demands or be vacant (yellow). We used the data from Google Maps traffic and GTFS presented in this paper. The example has its limitations such as it does not consider the demands of other modes of transport and the occupancy levels of land use over time (e.g., offices, services, restaurants).

Figure 25 presents the fluctuations of demand of a zone that was selected as very complex located in the consolidated central area, therefore, meeting all the spatial and temporal requirements. In this case, the demand for buses is high or very high during the whole day, while the demand of automobile varies from low to very high during the day. There is a difference of at least two levels between the demand of buses and motorized vehicles during the morning and afternoon peaks hours (7AM to 9AM and 6 PM to 8 PM and 9 PM to 10 PM), indicating that the demand is complementary. The space dedicated to the automobile at this time is underused and could be dynamically allocated to the bus. When demand is complementary there is an indication that the space is being inefficiently used, since one mode or activity has a higher demand than others. In this case, allocating space dynamically has its highest potential, being justified by differences in demands.

During the other hours illustrated in Figure 25, demands are disputed, meaning that they have high and similar levels of service. When demands are conflicting, that means that there is a dispute for space between demands at the same time. In this case, the decision to allocate space for one mode or another (statically or dynamically) depends on policy goals and the will to challenge car space. The complexity is higher since the space is being heavily used and it is limited to accommodate both uses.

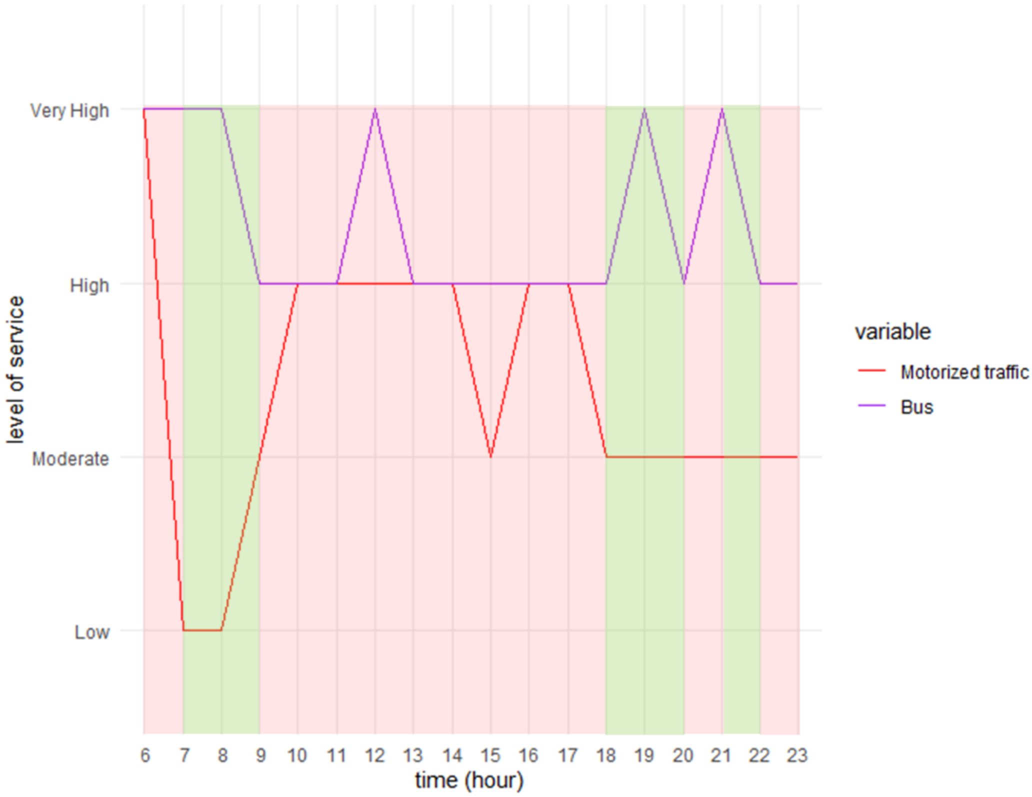

Figure 25: Motorized traffic and public transport level of service per hour from 6 AM to 11 PM from a very complex zone located in the consolidated central area.
Note: Disputing demands (Red); Complementary demands (Green).
Source: Author

Figure 26 presents the dynamics of a zone that did not meet the site selection requirements. The zone is located in the central residential area with high densities, close to the Airport (Refer to Figure 22). This example represents a residential area, with low diversity of land-use, characterized by having two peaks of motorized traffic demand; residents leaving to work in the morning; and residents coming back home in the afternoon peak hour. In this zone the demand for public transport is low. Consequently, the space for mobility is vacant by both modes most of the time.

In zones where spaces are totally vacant for mobility, we believe that *dynamic road space allocation* may not be suitable due to the priority to fulfill mainly the access and place function of the street. Instead, initiatives of remarking streets and repurposing car parking for active transportation and socioeconomic activities are indicated to increase safety, physical activity, and social connections in local areas that are predominately car-oriented (Bertolini, 2020).

Figure 26: Motorized traffic and public transport level of service per hour from 6 AM to 11 PM from a zone that was not selected within the criteria, located in the central residential area with high densities.
Note: Complementary demands (Green); Vacant spaces (Yellow).
Source: Author

5.7 Conclusion

This chapter proposes a method to detect zones in the city with complex environments, i.e., zones where allocating road space statically to all types of demands may be a political and operational dilemma. Those are the zones with the potential for allocating road space dynamically over time. The method combines road network and land use indicators to determine locations with main and local distributors, high motorized traffic and bus congestion levels, high road network connectivity, and dense and diverse land uses. Zones with these characteristics tend to have scarce urban space to fulfill the street's mobility/link and access/place functions. Furthermore, these zones tend to have high intensity and fluctuation of multimodal demands, leading to underutilized spaces at certain times of the day.

A dynamic allocation of underutilized road space in specific periods of the day can potentially satisfy the street's multimodal mobility/link or access/place functions requirements. Also, the different opening and closing hours of commerce, work, and services influence the fluctuation of demands during the day. Traditionally, urban design has lacked consideration of urban dynamics, diverse activities, and working hours schedules. The *dynamic road space allocation* may be appropriate to fulfill this gap.

Thus, it is necessary to evaluate the feasibility of implementing dynamic solutions in each zone based on possible barriers that may occur. The selected zones may have streets with morphological and topological characteristics of the built environment that may not be coherent or able to implement *dynamic road space allocation* (e.g., hilly streets or historic neighborhoods with environmental and architectural protection). Other barriers in terms of user acceptability and equity of proposed solutions must be considered. These local and context-oriented criteria will be discussed in more detail in Chapter 6.

Importantly, our selection method indicates the potential complex zones in the city but does not delimit the extent of the interventions. This limitation should be detected in a more specific analysis of the zones considering local characteristics through workshop activities or expert interviews, as will be presented in the next chapter. An example was given of how to define the intervention periods (e.g., peak and non-peak hours or day and night) based on the fluctuations of multimodal demands. It is essential to characterize the temporal patterns of land use and multimodal demands to detect when demands are competing or complementing each other. Consequently, it is possible to propose different dynamic solutions to accommodate different demands, especially when certain spaces are underused.

A contribution of this work is that the method proposed is parsimonious only requiring open-source data from OpenStreetMap, Census, Google Maps, and General Transit Feed Specification. The next chapter presents a workshop with experts that analyzed the streets within the selected zones to define local criteria for implementing *dynamic road space allocation*. After selecting the potential street segments and intersections, it is possible to evaluate their characteristics and propose solutions for dynamically allocating road space over time.

Chapter 6

What we have learned so far

In Chapter 4, dynamic solutions for reallocating road space were classified into smartness levels. Dynamic allocation of road space can vary from Level 0 (no use of technology) to Level 5 (fully connected environment). Consequently, each level has its capabilities and limitations, which should be considered when proposing solutions. Also, there are many challenges for reallocating road space such as restrictions with built environment, enforcement, and socio-cultural aspects, as mentioned in Chapter 3. In Chapter 5 a site selection methodology was proposed to identify zones in a city where there is a potential for reallocating road space dynamically. However, the method is a screening process on a municipality scale, requiring more information details within the selected zones of local criteria for choosing the most appropriate solutions considering the challenges, barriers, and local context.

What to expect in the Chapter 6

Chapter 6 is the following step of the site selection process initiated in Chapter 5. While Chapter 5 proposed a methodology for selecting aggregate criteria to select potential zones of intervention, Chapter 6 proposes to analyze in more detail the streets for intervention within the selected zones and define and rank local criteria for different *dynamic road space allocation* solutions. A workshop with experts was performed with three main objectives: i) discuss the technological and possible solutions for reallocating road space dynamically; ii) select streets for intervention within the selected zones of Chapter 5 for different *dynamic road space allocation* solutions; and iii) define and rank local criteria for different *dynamic road space allocation* solutions. The results suggest that street-level site selection criteria can be classified into three typologies (functional, geometric, and layout) and vary across solutions.

Chapter 6

6 Exploring local criteria for reallocating road space dynamically

This chapter has been published as: Valença, G.; Moura., F; Morais de Sá, A (2023). Exploring criteria for reallocating road space dynamically: lessons from a workshop with experts. *Journal of Urban Design*. https://doi.org/10.1080/13574809.2023.2240245

6.1 Introduction

Road space is one of the cities' most disputed and contested spaces (Gössling, 2016). Still, the automobile dominates most infrastructure through traffic lanes and parking spaces. Even though active transportation and public transit require less space than the automobile, these modes often lack space, especially in car-oriented streets (Talavera-Garcia & Soria-Lara, 2015). As the infrastructure is built to support maximum automobile capacity, there are periods when the traffic lanes are usually underutilized. Therefore, a problem of efficient use of road space also arises from this type of planning (Gössling, 2016; Gössling et al., 2016).

Furthermore, urban space is complex, with diverse activities, services, and dynamics, requiring a need to design streets to accommodate both movement and place functions (Nello-Deakin, 2019). The complexity arises from the diverse needs and demands during the day, which are often neglected by road space allocation measures. As a result, a dilemma in how much space should be allocated for each function and how efficiently the space is being used is still a gap to be filled, especially in more complex and disputed urban or peri-urban spaces. Recently, the problematic of urban space has received attention, having projects funded by the European Union to investigate how to allocate road space dynamically over time. The MORE project investigates the technologies to allocate road space dynamically, the Flexcurb on adapting the infrastructure dynamically for logistics, and the Streets4All on identifying where, when and how to allocate road space dynamically overtime in urban and complex areas (P. Jones, 2018; Moura & Antunes, 2022; POLIS, 2022).

In Chapter 3, we propose reallocating space dynamically according to different mobility and access needs over time as a possible solution for scarce and disputed urban spaces. Traffic lanes or parking spaces can be reallocated to other transport modes or activities in specific periods, especially when spaces are idling. Technologies such as LED in-pavement lighting, variable message signs, and flexible bollards, among others, could inform different uses of the public space in different periods of the day, week, or season. Nonetheless, similar to other urban designs, *dynamic road space allocation* is context-oriented and may only be appropriate in certain urban zones.

In Chapter 3, the conceptual assumptions for defining zones that have the potential for implementing *dynamic road space allocation* are presented as: i) zones with main avenues that have contested and limited space to distribute to both mobility/link and access/place functions (P. Jones et al., 2007); ii) very connected urban avenues that tend to be relevant to key destinations (De Gruyter et al., 2022); iii) dense urban areas that make places more attractable (Cervero & Kockelman, 1997); and iv) high diversity of land uses that influence mode choice and different peaks of activities and demands (Berghauser Pont et al., 2019; Cervero, 1996; Cervero & Kockelman, 1997). Consequently, zones with these requirements usually have complex streets that are congested or/and have high public transport frequency with limited space to simultaneously fulfill mobility/link and access/place needs and different opening and closing hours of work, commerce, and services.

Based on the conceptual assumptions from Chapter 3, in Chapter 5 we propose some indicators for selecting complex zones with streets that potentially face the dilemma of reallocating road space. The methodology was applied to the city of Lisbon. Nonetheless, the proposed methodology considers indicators on an aggregate level – i.e., at the municipality scale – and does not consider local characteristics, built-environment restrictions, or socio-cultural aspects. The methodology selects zones of 200x200 meters but not the specific streets for intervention. As a result, some solutions for dynamically allocating road space may not be adequate in some streets, and the criteria for choosing the appropriate solution are still lacking. This Chapter's main objective is to address this gap and discuss the applicability, limitations, and local site selection criteria for identifying potential streets for implementing different *dynamic road space allocation* solutions.

A workshop with experts was executed to achieve two main objectives: i) Select streets within the selected zones detected in Chapter 5 that have the potential of allocating space dynamically for different solutions, and ii) Define and rank local criteria for different *dynamic road space allocation* solutions.

The present chapter follows with section two, explaining the motivation, the selection of participants, and the workshop format. Section three presents the ranking of criteria for allocating road space dynamically, and the key points from the workshop session. Section four discusses the main results. Finally, the conclusions and references of the paper are presented.

6.2 Methodology

6.2.1 Participants

Workshops have been used as a tool to discuss the barriers, policy, and implementation of emerging topics that are still not well known or established (İmre et al., 2021; Junghans et al., 2018; Kesselring & Freudendal-Pedersen, 2021). The decision to perform a workshop with Lisbon's members of academia, local authorities, and public and private transport operators was to ensure an expert and diverse view on the topic in question. Personalities of transportation, urban planning and transport infrastructure expertise were invited to encourage a diverse perspective on the topic. Participants were chosen based on their expertise, knowledge of Lisbon's context, and political influence in implementing policies in the city. The few practical applications and literature on reallocating road space dynamically over time require a technical viability check at the operational level. Therefore, at this stage of the study, only experts were included. Other stakeholders, such as residents, commerce, and street users, will necessarily participate in future moments, such as discussing the acceptability of *dynamic road space allocation* and the requirements during the transition period to adapt to changes in the built environment.

Guidelines to perform workshops do not state the ideal number of participants. However, they suggest a small number of participants when there is a need to have a deep and expert view on an emerging topic (Candelo et al., 2003; Lauttamäki, 2014). Taking this into account, a total of 10 participants were present in the session forming two groups of three and one group of four, as illustrated in Figure 27. It is essential to acknowledge that the participants have previous knowledge of Lisbon's local characteristics, including two former Mobility City Councillors and one former Urbanism City Councillor. Table 6 shows the participants' profiles and the assigned groups. The groups were selected according to their background, making them the most heterogeneous. The group's names were chosen from an organizational perspective, matching the colors of the post-its on their table and their identification badge.

Table 6: Profiles of the workshop participants. Source: Author.

Participant	Group	Gender	Area	Educational background	Professional sector (current and past)	Job level	Special qualification
1	Yellow	Male	Urban planning and mobility	Ph.D.	Academia and Municipality	Tenured professor	Former Lisbon's Mobility City Councillor
2	Yellow	Female	Civil engineering and Transportation	Master's degree	Municipality	Director	Worked with urban mobility for the past 20 years
3	Yellow	Male	Architecture and urbanism	Master's degree	Consultancy	Director	Experience in traffic calming and road reallocation projects
4	Green	Female	Territory and Urban Planning Engineering	Ph.D.	Academia	Researcher	Experience in cycling research and cycling infrastructure projects for the Municipality
5	Green	Male	Transportation	Master's degree	Consultancy and Municipality	Director	Former Lisbon's Mobility City Councillor
6	Green	Male	Civil Engineering and Transportation	Ph.D.	Academia	Tenured professor	Vast experience in pavement and infrastructure projects and research
7	Pink	Male	Territory and Urban Planning Engineering	Master's degree	Municipality	Urban planner	Former Lisbon's Urbanism City Councillor
8	Pink	Male	Transportation	Ph.D.	Consultancy, Academia, and Municipality	Director and Tenured professor	Former Lisbon's Urbanism City Councillor and experience working on intermittent bus lanes
9	Pink	Female	Civil Engineering and Transportation	Ph.D.	Academia and Consultancy	Researcher and engineer	Experience in transport safety projects and active mobility research
10	Pink	Male	Civil Engineering	Master's degree	Municipality	Engineer	Responsible for elaborating urban mobility projects in Lisbon's City Hall

Figure 27: Participants of the workshop held in Lisbon.
Source: Author

6.2.2 *Workshop session*

The workshop was executed on January 21st, 2022, and lasted four hours. The session was recorded with all members' consent. The recordings were transcribed manually on a statement-by-statement level and sequentially organized into topics. Before the workshop began, each participant was assigned to a pre-established group and received the necessary material for the session (ID badge, pen, notebook, and post-its). In the beginning, the moderator gave a welcome speech, assured the confidentiality of the discussion, and explained the summary and the workshop's agenda. In sequence, each participant introduced themselves. Then, the moderator gave a ten-minute presentation with an overview of the topic and the workshop's objectives.

The workshop was divided into three main tasks aligned with the session's objectives. Figure 28 presents the framework of the three main tasks executed in the workshop. The tasks in the workshop progressively increased their complexity (Krueger and Casey, 2015). The first task was a "warm-up" question and a more straightforward exercise. Participants had to identify examples of allocating road space dynamically and technologies that were used for sensing and managing these solutions. Each group discussed for 5 minutes and wrote their findings on post-its. Finally, the groups exposed their results to the whole session, giving the post-its to the moderator.

In Task 2, the groups were given cards with photos of all the streets within the previously selected zones in Lisbon detected in Chapter 5, which has the potential for allocating road space dynamically. Each group randomly received cards from four of the 200x200m zones within the possible twenty selected zones. The number of cards matched the number of streets that intersected the designated zones. An example of the front and back of a card is illustrated in Figure 28 (specifically in the second step of Task 2). The front of the card shows two photos, the name, zone's number, and location of the street within the Municipality. The zone is presented in a neighborhood scale on the back of the cards to provide the streets' location. Examples of the cards used in the workshop are present in the Supplementary Material 1. The groups had to choose one street in each zone that they considered the most appropriate for implementing three different *dynamic road space allocation* solutions proposed in the exercise. The dynamic solutions were:

- Allocating a traffic lane to a bus lane dynamically in a certain period of the day;
- Allocating a traffic lane to a cycle lane dynamically in a certain period of the day;
- Allocating a traffic lane or parking space to expand sidewalks dynamically in a certain period of the day.

The moderator also gave a sheet to each group, where they had to write the selected street for the three different solutions in each zone. It is essential to mention that the moderator asked the groups to consider periods of the day with high intensity, diversity of activities, and complexity in distributing road space. In this activity, there was a 20-minute discussion within each group. Then participants debated for 45 minutes on the main criteria, difficulties, and critical aspects to consider when selecting a street for each solution to allocate road space dynamically.

Each group had to show the selected streets and explain why they chose them for each solution. This chapter does not go into the details of which streets were chosen since this detail is essential for the data collection and implementation of the solutions. Instead, this chapter focuses on the discussion and criteria of why the participants chose these streets. The criteria discussed in Task 2 but organized and ranked in Task 3 are presented in section 6.3.1. The key topics of discussion from Task 2 and Task 3 are presented in section 6.3.2.

In Task 3, each group was given a sheet with many physical characteristics of streets and urban design qualities selected from the literature for improving active and sustainable transportation, road safety, and place-making (Figure 41 in the Supplementary Materials 2). The groups could choose to use this sheet to guide the selection of criteria for choosing the street. Nonetheless, the groups could also select criteria that were not present in the sheet, having the sheet only for promoting a discussion in the group. The groups discussed which criteria were most important for the street selection and ranked them accordingly on another piece of paper in a 20-minute exercise. Finally, all participants presented their results in a 30-minute discussion.

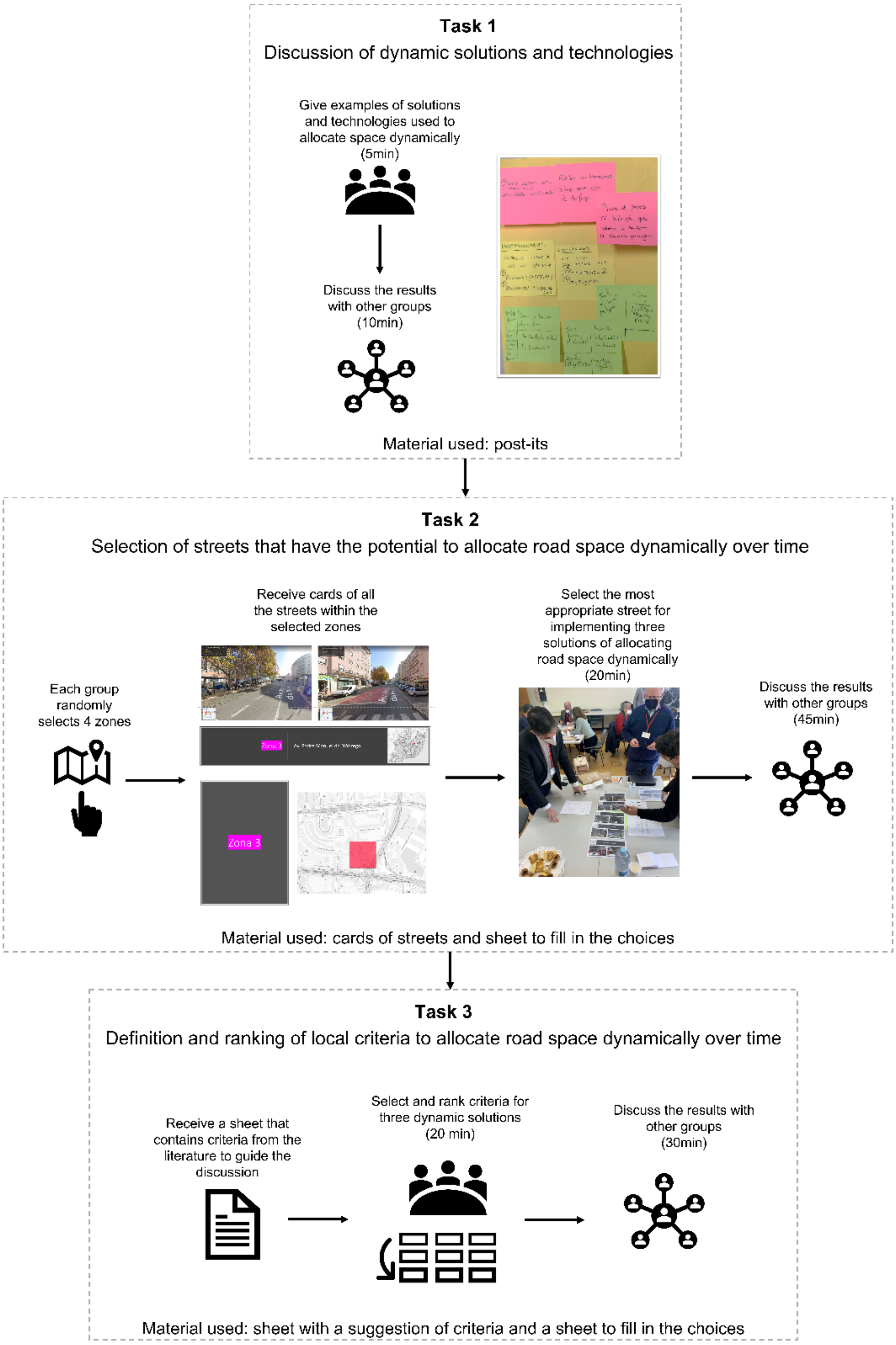

Figure 28: Framework of the workshop presenting the three main tasks.
Source: Author

6.3 Results

6.3.1 Criteria for selecting sites

In the second task, the groups selected the appropriate streets and discussed the main criteria for choosing these streets for three types of *dynamic road space allocation* solutions. Then, the criteria were organized and ranked from the most to the less important in the third task. The groups could choose how many criteria they considered relevant. Table 7, Table 8, and Table 9 present the ranking for each solution, respectively. Three main types of criteria appeared during the discussions: i) geometric characteristics - referring to the street dimensions (e.g., width, distance from façade to façade, number of lanes); ii) functional characteristics - referring to the use of the street (e.g., traffic volume, pedestrian activity); and iii) layout characteristics – referring to the space organization (e.g., existence of green spaces, parking spaces, commercial activities). The most important considerations are presented below.

In the first solution – allocating a traffic lane to a bus lane dynamically –, the green and yellow groups considered that having variations of volume and frequency of public transport in certain periods of the day is paramount. Otherwise, if the volume and frequency are constant (high or low), it does not make sense to prioritize this solution for *dynamic road space allocation*. If the demand for buses is constantly high, then dedicated bus lanes are more indicated (National Association of City Transportation Officials, 2016). If public transport demands are constantly low it is economically challenging to justify public transport priority (Currie et al., 2007). Additionally, the dispute for space between public transport and the traffic volume was considered an essential aspect in detecting if the street has the potential to allocate space dynamically for the bus. If both volumes are constantly low, there is no need to reallocate space dynamically. At the same time, both aspects considered by the green and yellow groups are aligned with the first criteria of the pink group. The group discussed that it only makes sense to prioritize a dynamic solution if there is an intense conflict between at least two uses for the same space, in this case, traffic volume and public transport volume. The green group was more specific giving examples of conflicts, as presented in their 5th and 6th criteria (Table 7).

An essential criterion that the three groups considered was the street cross-section geometry, and thereby if there is enough space to allocate a bus. The green group defined that it was essential to consider if there are enough lanes to allocate for a bus dynamically. Sequentially, if the number of lanes is appropriate, then the whole geometry of the street (from façade to façade) should be considered. It is interesting to notice how the criteria considered were very similar between the three groups. Therefore, the main criteria to consider in solution 1 are intensity and conflict between the traffic and public transport volume and the available space and coherence of the solution.

Table 7: Ranked criteria from the three groups for solution 1 - allocating a traffic lane to a bus lane dynamically. Source: Author.

Type of criteria (geometric/ functional/ layout)	**Criteria**	**Groups' ranking of criteria**		
		Green	**Yellow**	**Pink**
Functional	Variation of frequency and volume of public transport during the day.	1st	1st	-
Functional	Traffic dynamics and volume.	2nd	2nd	-
Geometric	Number of available lanes.	3rd	3rd	-
Functional	Existence of an intense dispute between at least two uses.	-	-	1st
Geometric	Width (from façade to façade) and length of the street.	4th	4th	2nd
Functional	Existence of 2nd row of buses.	5th	-	-
Functional	Existence of pick-up and drop-off vehicles.	6th	-	-

In solution 2 – allocating a traffic lane to a bike lane dynamically – the discussions were similar to solution 1. Nonetheless, the criteria that ensured road safety appeared as an important topic in the debate. The three groups considered the traffic volume and speeds as essential aspects. The pink group explicitly concluded that using a dynamic bike lane is inappropriate if the traffic volume and speeds are very high. Instead, a segregated bike lane should ensure safety between modes, being in line with studies evidencing that separation is a key aspect of cyclist pleasure and safety perception (Barrero & Rodriguez-Valencia, 2022). On the other side, the pink and green groups considered that the space could be shared if the traffic volume and speeds were too low that are more common in narrower streets as evidenced by Sarkar et al. (2018). Therefore, there would be no need for dynamically allocating space. These considerations are aligned with the requirement of *dynamic road space allocation* to be in the conflicting and intense areas that are not at the extremes of the road hierarchy. The street's geometry and the number of lanes were also considered in solution 2.

Table 8: Ranked criteria from the three groups for solution 2 - allocating a traffic lane for a bike lane dynamically. Source: Author.

Type of criteria (geometric/ functional/ layout)	Criteria	Groups' ranking of criteria		
		Green	**Yellow**	**Pink**
Functional	It should not be dynamic if the space can be shared without constraints.	1st	-	3rd
Geometric	Existence of direct routes for cyclists.	2nd	-	-
Functional	Traffic dynamics, volume and speeds.	3rd	1st	2nd
Functional	Existence of an intense dispute between at least two uses.	-	-	1st
Geometric	Number of available lanes.	2nd	-	-
Layout	Existence of adequate public lighting.	-	3rd	-
Geometric	Slope.	4th	4th	-
Geometric	Width (from façade to façade) and length of the street.	10th	-	4th
Geometric	The possibility of implementing a two-direction dynamic bike lane in a traffic lane.	5th	-	-
Functional	Presence of cyclists	6th	-	-
Layout	Existence of car parking.	7th	-	-
Functional	Existence of dense and diverse land use.	8th	-	-
Layout	Presence of green spaces.	9th	-	-

Moreover, all groups considered the slope as a relevant aspect. If the street has enough space but is not flat, then the bike lane should be segregated and static due to the different modal speeds. Other aspects that were considered relevant by the green group were direct routes for cyclists, land-use diversity, and the presence of public and residential parking. While the green group found it essential to have already cyclists circulating on the street, the pink group reinforced that the dynamic bike lane could be used to promote new cyclists (latent demand). Thereby, the dynamic allocation of space could be implemented even with a few cyclists currently using the street. This solution could promote policy goals such as increasing active mobility by reallocating space for cycling in less complex times (e.g., weekends or non-peak hours). From the debates it is evident that dynamic bike lanes are the most challenging solution, having only specific applications that could work well mainly due to safety restrictions.

While in solutions 1 and 2, the criteria were related to the mobility function of the street, solution 3 – allocating a traffic lane or parking space to expand pedestrian space dynamically - had aspects related to place and access functions. Furthermore, most of the streets selected for solution 3 were of local access, different from the other two solutions. The existence of commercial and social activities, open-air restaurants and bars, green spaces, and land-use diversity were mentioned as important to enhance pedestrian activity, as evidenced by the literature (Barrero & Rodriguez-Valencia, 2022; Cambra & Moura, 2020; Y. Park & Garcia, 2020). The yellow and green groups mentioned that parking spaces for residents could be dynamically reallocated for parklets, open-air restaurants, or bars during the day and return to parking during the night. Nonetheless, the green group mentioned that this solution has a dilemma, as stated:

> *"If it is not desired that residents use their cars, but available parking is restricted in residential areas during the day, does this policy induce residents to use their cars in the city during the day?"*

Aspects such as road length, geometry, traffic volume, the conflict between two uses (e.g., parking spaces and pedestrian volume), the possibility of being a shared space between modes, and the presence of activities were also mentioned in solution 3. Therefore, since these aspects were present in all three solutions, it is a lead that they are the most important to consider, independently of the solution. The width and length of the street and the conflict between different demands are acknowledged to be the main constraints for allocating road space statically or dynamically (P. Jones, 2016). It is interesting to note that although some criteria are aligned with the criteria of allocating road space statically, others are specific for adopting *dynamic road space allocation*. Examples of specific criteria for allocating road space dynamically include the variability of public transport volume and frequency as a potential for dynamically using the space dedicated to the bus and the possibility of the place being shared as a restriction for allocating road space dynamically.

Table 9: Ranked criteria from the three groups for solution 3 - allocating a traffic lane or parking space to expand pedestrian space dynamically. Source: Author.

Type of criteria (geometric/ functional/ layout)	Criteria	Groups' ranking of criteria		
		Green	Yellow	Pink
Functional	If the space can be shared, it should not be dynamic.	1st	-	-
Functional	Traffic dynamics, volume, and speeds.	-	1st	2nd
Functional	Existence of an intense dispute between at least two uses.	-	-	1st
Layout	Presence of commercial and social activities.	2nd	4th	-
Functional	Existence of dense and diverse land use.	-	3rd	-
Layout	Existence of car parking.	5th	2nd	-
Geometric	Sidewalk width and length.	3rd		
Geometric	Width (from façade to façade) and length of the street.	4th	-	3rd
Layout	Existence of car parking.	5th	-	-
Functional	Presence of urban noise.	-	5th	-
Layout	Existence of pick-up and drop-off vehicles.	6th	-	-
Layout	Existence of outdoor dining and bars.	7th		
Functional	Presence of pedestrians.	8th		
Layout	Presence of green spaces.	9th		

6.3.2 *Key point from the debates*

Acceptability

One of the main concerns of implementing dynamic changes in the road space was how people accept and adapt to such changes. According to one participant from the pink group:

> *"There is a challenge to communicate the transitions when road space is allocated dynamically, especially in short periods (e.g., peak and non-peak). Before a policy concern, citizens have a cognitive difficulty understanding quickly and adapting to dynamic changes."*

In the same direction, a yellow group participant stated:

> *"The local communication of dynamic changes is crucial to finding social support from the various stakeholders and actors. For example, the Municipality has not been able to solve the transitions of loading and unloading logistics for several mandates. Some issues are not a question of technology or political effort but due to the structure of small businesses being extremely chaotic and undisciplined. Therefore, some segments do not seem to be able to adapt quickly to dynamic changes. In certain places, there is an easier adaptation than in others."*

The opinion of the yellow group participant is that implementing certain urban designs and policies may not have the expected change to certain segments that are already accustomed to certain mobility patterns for years. To avoid economic activity segments from parking their vans to load and unload products on sidewalks and in traffic lanes, it would require other types of policies rather than reallocating road space. For example, according to Havârneanu and Havârneanu (2012), when surveillance and fines for illegal parking are not performed effectively, the temptation to violate the rules is higher due to lower fear of penalty. These insights demonstrate how before proposing dynamic solutions, it is necessary to consider local characteristics and people's behavior in using the space. If not, citizens may not be willing to change and adapt to changes, which may lead to low acceptance.

Dynamic allocation for the same or different functions

When dealing with *dynamic road space allocation*, one participant from the yellow group highlighted the different levels of complexity depending on the type of change. It is usually less complex if the space maintains the same urban function when allocating space dynamically over time. An example given was a Bus corridor that, in non-peak hours, could be mixed with traffic, or a parking space for commerce during the day that could serve as parking for residents at night. Both examples maintain the urban function: of providing circulation or parking (access), respectively. The participant stated that higher complexity arises when changes in urban functions are implemented in the same space. For example, a traffic lane or parking space can become a "place" at different times (e.g., parklets, markets, or leisure activities).

On the other hand, the green group pointed out that even if the type of solution is the same for several contexts, some are more favorable than others:

> *"The space the bus can occupy has an advantage over all the other uses because it is a controlled fleet with controlled drivers and a controlled system. Therefore, it is plausible to*

think of case studies in which the space of the bus lane can be allocated dynamically because the driver is fully informed and has all the context information to know how to adapt to the dynamic changes."

The same participant also mentioned how the number of possible solutions depends on the policy goals:

"Is it an option to decrease the car's level of service to allocate road space dynamically? If this is not an option, and space can only be allocated during non-peak hours, there is, in fact, a restricted number of solutions. Otherwise, the options available to us are much greater. This is not a criterion, but a political decision about what you want to achieve from these dynamic solutions."

The implementation and proposal of dynamic solutions in urban spaces have more possible solutions in cities that are politically inclined to challenge and restrict car use and car space. In order to challenge car space, dynamic solutions must be implemented effectively, promoting small and gradual behavioral changes, and being seen as reasonable and fair by the public. Public acceptance will consequently drive political acceptance, influencing engagement and how policy makers will be more prone to implement certain types of solutions (Banister, 2008).

Periods of dynamic changes

One of the main discussions was how much time certain spaces should be allocated dynamically to different uses. The yellow group emphasized that the periods of dynamic changes may be considered according to the type of intervention. If the circulation or access/place function is maintained, allocating the space in peak and non-peak hours is plausible. Nonetheless, if the space's function is changed, the group was skeptical about the acceptability and technical application in short periods. Instead, for these types of solutions, it would be more coherent to adapt the space in less complex situations such as day and night, and weekdays and weekends. The green group also reinforced how spaces could be allocated dynamically in less complex periods:

"It is way more complex to allocate space dynamically over hours. If you think about days, usually in the city, often on Sunday, those are days with less demand and conflicts, being possible to restrict the access of a street or a block. For that, simple technology or tools are required such as cones and someone to put them there and take them out."

In the same line of thought, the pink group discussed how the shorter the periods of dynamic changes, the higher the need for technology to implement the solutions:

> *"When the dynamic allocation of space is not throughout the day according to hours but weekly, or only one day of the week, or at festive periods, this lowers the need for technology. Consequently, it makes it easier to believe it is applicable and manageable."*

According to the discussions, the complexity of *dynamic road space allocation* arises with a higher number and shorter periods of change. Additionally, dynamic adaptations in shorter periods require more technology to sense the space and manage and inform users about the changes.

Continuity of road segments

While the groups analyzed the road segments, some noticed that the profile and local characteristics changed along the street. The yellow group observed that:

> *"Curiously, two streets that the group analyzed have transversal profiles that change along the stretch. It is hard to propose a single solution for the whole street."*

The green group emphasized the challenge of proposing a unique solution for a road segment that changes significantly along the segment in terms of geometry and its use. An example was given:

> *"In one street that was discussed, the intensity of demands is high in one part of the segment but very low to justify a permanent or dynamic cycle lane in another part of the segment. A shared lane at 30km/h would solve this low-intensity segment's problem, possibly having two solutions in the same street."*

From the discussions, it was evident that the continuity of the geometric characteristics of streets and their intensity of use must be considered when proposing a solution for road space allocation.

Local context

In some cases, the groups decided not to use dynamic changes due to their previous knowledge of the area. For example, when discussing a particular street where a traffic lane or parking space could be dynamically allocated to a cycle lane, the yellow group stated that:

"Although there was sufficient space, it did not make much sense to put a cycle track on the carriageway when you have the central promenade, which is much more pleasant and safer for cycling."

The pink group stated the importance of considering the local context and the policy goal in deciding where to allocate space dynamically or statically:

"The dynamic change did not seem to make sense in two cases that were analyzed due to the lack of intensity and diversity of use in the street that justifies a dispute over the circulation space. The adjustments should involve safety improvements, traffic calming, etc., but they would not require dynamic solutions."

An example was given related to a street that is a main distributor:

"In this case, the cycling lane should be permanent, not dynamic, because traffic speeds are high and difficult to control during the day. So, road safety is the main criterion to consider in this case for not using dynamic road space allocation."

These examples demonstrate how allocating road space is context-oriented and the importance of involving stakeholders and local actors in the planning process.

The nature and intensity of the conflicts

The pink group hesitated to select streets for dynamic solutions in Task 2. One of the members stated:

"Before implementing dynamic allocation of road space, a typification of the nature and intensity of the existing conflicts in each street should be assessed. Therefore, from the typification of problems and intensity, it is possible to decide if there should be: i) no alteration of the pre-existing road circulation space; or ii) dynamic changes that require adjustments on the road space."

From this statement, it is clear that detecting the functions and transport modes that are disputing for space in the street in specific periods of the day is a prior task to examining geometric and urban design characteristics. For example, if delivery vans are parking on the traffic lane and sidewalk during lunch hour, there is a conflict between the delivery vans, traffic volume, pedestrians, and commercial activities. Consequently, it is possible to propose different road space allocation solutions by detecting this problem.

6.4 Discussion

From the discussions in the workshop, it was clear that initiatives of road distribution – static or dynamic - are context-oriented. As stated by Jones (2016, 10):

> *"Some urban authorities have determined that street design should be based on a fixed street user priority (e.g., pedestrians first), but this is too simplistic to be rigidly applied. Basing the design on the relative importance of the Link/Movement and Place function of a street provides a basis for developing a more context-sensitive design."*

The workshop discussions were focused on the disputes of different uses and functions (link/movement vs. access/place) rather than fixed characteristics of the street or proposed solutions, being in line with the statement by Jones (2016, 10). Before defining solutions for road space allocation, a typification of how the space is disputed in terms of uses and functions is required. As exemplified by De Gruyter et al. (2022), in spaces where there is a conflict between movement and place functions, some modes are often undersupplied while others are oversupplied. As suggested by the discussions, achieving an equitable balance between both functions is not only a practical dilemma but also a political one (De Gruyter et al., 2022; Gössling et al., 2016; P. Jones, 2016).

The debates revealed that it is only coherent to distribute space dynamically over time if there are: i) complementary or ii) disputing demands at a certain time. The former refers to reallocating road space for a different use with higher demand or to promote a latent demand when spaces are underutilized at a certain time, as mentioned throughout the thesis. The latter refers to prioritizing one use over another when demands are high and competing for the same space in a certain period. Here, there is a trade-off between promoting a certain mode (e.g., buses) and possibly restricting an existing one (e.g., car use). In this case, deciding whether to allocate road space dynamically is conditioned by the political goal and intensity of the problem. Vacant spaces, and therefore underused most of the time, lack a dispute between at least two uses. Therefore, it is not coherent to reallocate road space dynamically when complexity is very low (refer to Figure 26).

The debates also indicate that reallocating road space dynamically must not aim to disruptively change the design of the street. As mentioned by Hebbert (2005), the road hierarchy classification influences the speeds, volumes, road widths, and how streets are conceived. Allocating road space dynamically must be the most parsimonious as possible considering the road hierarchy rationale, having the right balance between the frequency of dynamic changes, technology use, and the number of proposed solutions. Reallocating the use of space dynamically should maintain most of the street's characteristics in a logical orientation, since unexpected and disruptive changes may cause low acceptance and a rise in the number of accidents. As mentioned in the results, some solutions are more likely to work than others in certain road hierarchies and contexts.

Road space allocation projects are usually influenced by political premises and goals. As mentioned in the workshop, if the city has the will to promote road space allocation solutions that challenge the space for the car during peak hours, then there are much more options for allocating road space dynamically. On the other hand, cities unwilling to challenge car space are likely to only consider *dynamic road space allocation* during less complex periods, such as closing a traffic lane for recreational cycling on Sundays. Finally, it is necessary to analyze the coherence of the solution, if there is enough available space, green spaces, and cultural and social patterns. Therefore, a guidance to reallocate road space dynamically on a street level is proposed: 1) characterize conflicts of uses and underutilized spaces over time; 2) propose solutions that could reallocate underutilized spaces or contested spaces in certain times; and 3) verify the coherence and suitability of the solution in terms of geometric, functional and layout characteristics. As mentioned, the policy objectives of the municipality directly influence the type and number of possible solutions proposed in step 2.

6.5 Conclusions

Allocating road space dynamically over time has been studied mainly for traffic performance in highways and arterials, as evidenced in Chapter 2. In this chapter, the opinions of experts are gathered regarding the feasibility of allocating road space dynamically in more urban and complex areas through a workshop activity. This is a pioneer work that gathers a discussion on the local characteristics, and acceptability issues necessary for implementing dynamic solutions. In Task 1, experts had to propose current and future technologies for allocating road space dynamically over time. In Task 2 of the workshop, participants chose streets of Lisbon's pre-selected zones that could potentially implement solutions for *dynamic road space allocation*. With the corresponding outcomes of this exercise, guidance for policy makers to select streets that could implement such solutions was achieved. In Task 3, experts determined and ranked a set of criteria they followed in selecting streets prone to implementing *dynamic road space allocation* solutions. Also, they identified the type of data and information that should be evaluated before executing the solutions on selected streets.

One of the paper's main contributions was demonstrating that street-level site selection criteria vary according to *dynamic road space allocation* solutions. Similar criteria for several solutions were given distinct importance levels in different street contexts. Some criteria proposed by the participants differed from static road space allocation criteria, which require new indicators and forms of evaluating the public space. From the discussions, a framework was proposed revealing that before proposing road allocation solutions, it is necessary to characterize the conflicts and complementary uses of the street over time, which requires a crucial prior step of intense data collection of the diverse demands and activities.

According to Tzamourani et al. (2022), few studies assess the relationship between emerging road space allocation and public acceptance. This paper gives an initial assessment of which types of *dynamic road space allocation* solutions may achieve higher social acceptance. Even though current and future technologies can implement the solutions addressed, acceptability and the risks of not adapting well to the dynamic transitions were significant issues raised in the debates. Moreover, the simpler the solution, the less technology is required, and better acceptance can be expected from technology adoption laggards. This chapter fills a gap in discussing the applicability of solutions of dynamic space distribution that also change the built environment function (e.g., from mobility to access or otherwise). Dynamic solutions that change the function of the street were considered more complex to implement on an hourly basis (e.g., changes in peak and non-peak hours) than the ones that maintain the same function over extended periods within a day or several days. The participants agreed that dynamic measures that change urban space function are more feasible considering a broader time interval (e.g., weekdays and weekends or one day a week).

In the end, policy makers may use the criteria and guidance from the workshop to choose streets where *dynamic road space allocation* solutions can be implemented more successfully. A limitation of the workshop is that the street photos included in the cards were taken from Google Street View. Consequently, aspects such as public lighting and security are not so clear. Also, the images' stillness does not illustrate the dynamic nature of the streets, e.g., traffic or pedestrian volumes. Nonetheless, the limitation of only looking at pictures encouraged the participants to think about important aspects not depicted in the images, while resorting to videos or emerging visualization tools can be used in future workshops. The next chapter discusses the importance of visualization in street designs projects and the use of artificial intelligence to guide public participation.

Chapter 7

What we have learned so far

In Chapter 6, one of the main conclusions from the workshop was that, before proposing solutions to reallocate road space, it is necessary to characterize the uses and user conflicts in urban space. As mentioned throughout the thesis, determining how much space to allocate, and which use or function to prioritize may not be evident. Also, innovative designs and *dynamic road space allocation* solutions of different smartness levels (especially the ones with higher technological dependence) may not be equally understood by stakeholders and practitioners of different backgrounds, which highlights the need for new forms of project visualizations and participation.

What to expect in Chapter 7

Chapter 7 proposes to discuss the applicability, importance, and risks of using artificial intelligence for visualizations in street design processes. An experiment using a generative deep model was performed to generate many visualizations of streets images. There is not a unique way to design a street. Consequently, the fast generation of many visualizations of a specific street could motivate public discussion, and guide workshop activities in street design projects. This idea is particularly relevant in proposing innovative solutions that are not evident for all stakeholders.

Chapter 7

7 The use of AI for visualizations in street design: lessons from an experiment

7.1 Introduction

Kevin Lynch introduced the concept of "imageability", arguing that a set of physical characteristics of the environment influence how people visualize, perceive and experience public spaces (Lynch, 1960). Lynch argues that there are 5 main elements in the public space that influence mental images: paths, edges, districts, nodes, and landmarks. The color, shape, and urban form of streets is an element that has a strong effect on the mental or memory images of the place and how people understand concepts and designs. In street design planning, the Imageability elements can be used to simplify complex scenarios into basic visualization tools that clearly communicate a design proposal (Al-Kodmany, 2001).

Street design projects mobilize the expertise of professionals with diverse backgrounds, requiring an interactive and collaborative process. In practice, there is a challenge to communicate and interactively generate design solutions (Kim et al., 2022). Also, visual tools to communicate to the wider public are often scarce (Batty et al., 2001; Noyman & Larson, 2020). Usually, street reallocation and urban designs projects are developed through a sequence of stages that take significant time and effort: i) problem definition; ii) data collection and analysis to support the problem formulation; iii) definition of objectives; iv) proposal of solutions; v) choice of solution (Batty et al., 2001). Visualization and communication are essential for clearly providing knowledge of all the design stages to the policy makers and the general public.

According to Batty et al. (2000), the most effective way to communicate the proposal and choice of solutions is by using visual forms. Urban visualizations are essential during the initial stages of urban design, especially when projects are innovative and not well established (as is case of dynamically reallocating road space); and the evaluation of many alternative designs is required (Batty et al., 2001; Noyman & Larson, 2020). Computer-aided Design (CAD) and other types of architecture software are usually used in public meetings, but face many limitations, including: arduous work in complex designs; do not offer real-time visualizations; and do not support multi-user collaborative designs (Noyman & Larson, 2020). These limitations prevent stakeholders and policy makers from interactively designing urban solutions. Consequently, visual tools are only used to present the selected solution, being prone to mostly minor corrections in the final phases of decision-making. Still, images are mostly used in practice (Wergles & Muhar, 2009). However, the proposal of solutions during the initial steps of street design is often schematic and lacks street-level details (Noyman & Larson, 2020), reinforcing the need to propose tools that face these challenges, and limitations.

We acknowledge that a small number of studies have focused on the perceptions and emotional responses of different types of visualizations, levels of detail, and visual angles in urban environments (Wergles & Muhar, 2009). Al-Kodmany (2001) argues that people have different mental maps of the space, differing in their understanding of different levels of detail. The author discusses that photographic images may be too realistic and complex, while sketches can simplify and focus only on one aspect. On the other hand, using realistic images can promote deeper discussions on diverse problematics regarding the street section, although there are challenges of not making the discussion get out of topic.

However, moving from one representation to multiple representations of solutions enables stakeholders to analyze the problem in different contexts and scenarios. Also, visualizations seem to be very efficient in the planning stage, since it turns concepts and ideas more tangible, stimulate discussions and help planners understand concepts more easily (Batty et al., 2001; Wergles & Muhar, 2009). Our hypothesis is that generative artificial intelligence models may be valuable tools for guiding public meetings, communicating innovative ideas and street designs and integrating the public into the design process. Multiple visualization of images would require a coordinated and organized session to result in valuable information, instead of confusing the participants (Pietsch, 2000).

As many urban projects are time-consuming and the communication of innovative projects may not be clear without visualizations, speeding up this process through AI may ease the communication, public participation, and understanding of street space reallocation projects. As an example, if we want less cars or change the sidewalk width in a street, ideally, the algorithm could input an image of the street, and propose one or several solutions with different numbers of cars or with different sizes of sidewalk. Also, this tool can be very useful in more innovative solutions in urban design, where the understanding of emerging concepts may not be simple. For example, in applications where more than one generated solution can be used in a street, by allocating the space for different uses dynamically over time (e.g., hours, days or seasons). In this context, the objective of this chapter was to experiment in practice how to develop a generative deep model for helping stakeholders to visualize street space allocation projects in real-time. As it was an experiment, the results were not satisfactory, but the lessons learned in process of developing the work are valuable for future developments of this type of technology.

The importance and innovation of this project will be further discussed in the following section. Sequentially, we explain the proposed methodology, followed by the results. Then, we discuss the main contributions of the project, the learning experiences, and research agenda. Finally, we conclude with the main findings and replication and data sharing section.

7.2 Background

Applications of Artificial Intelligence to improve the process of urban planning and design has been a key topic for almost AI's history, and more recently generative deep models have gained importance due to technological advancements (Quan et al., 2019). Generative models are used to produce new data that are similar to real data. When neural networks are used, the subclass of these models is named deep generative models. Generative deep models have proven to be effective in multiple tasks, including image generation (Johnsen et al., 2022). Generative modelling in urban planning and design has been applied for automatically generating: land-use configurations based on the spatial, socioeconomic and mobility characteristics of surrounding zones (D. Wang et al., 2021, 2022); neighborhoods using cost and solar energy performance metrics (Nagy et al., 2018) and a wide range of metrics (Sidewalk Labs, 2020); apartment floor plans (Para et al., 2021); architecture façades (C. Sun et al., 2022); forms of buildings (H. Zheng & Yuan, 2021); and urban form (Quan, 2022).

In public participation, computational tools have been focused on the communication of urban design through visualizations, rather than integrating the public to propose their solutions, as mentioned in the introduction of this chapter (Quan, 2022). However, two innovative projects have recently been proposed for a more participative urban design using generative models; named DeepScope and PlacemakingAI. Noyman and Larson (2020) developed the DeepScope, a multi-user real-time platform for visualization and proposal of urban design solutions. The DeepScope is composed of a physical model with LEGO bricks that represent urban elements and uses (e.g., streets, buildings, parking, etc) that users can move and change their characteristics within the cell grids of the physical model. As users change the configuration of space, a 3D model and a street viewpoint is projected in real-time. A Deep Convolutional Generative Adversarial Network (DC-GAN) is used to project a street representation on a screen.

The PlacemakingAI is a tool that uses a Generative Adversarial Networks (GANs) to adapt street designs in real-time, according to features such as pedestrian counts, pavement size, tree counts and bench counts (Kim et al., 2022). The PlacemakingAI is still under development and not available to the public. The images generated from the algorithm in the examples are less realistic than an original photograph, suggesting the complexity of generating representations of urban spaces. However, the level of detail may be enough to promote collaborative designs and discussions of new street designs.

Although the DeepScope and PlacemakingAI are a step towards more participative urban designs, they are still the exception. The DeepScope is a participative urban design platform, but it may be complex to use it in a public session that has a moderator, since changing the configuration of the street according to insights of the public may be challenging. The PlacemakingAI uses an interface where users can increase or reduce the images' features to propose future street design scenarios. The PlacemakingAI may be more suitable for guiding, communicating ideas, and building up discussions in public sessions.

Our proposal is similar to the PlacemakingAI, but instead of having a user interface, we propose that the algorithm generates various scenarios according to specific features. For example, if we want to change the number of cars, the algorithm will generate multiple images with diverse possibilities. These images – some more realistic than others - can be used in a workshop to present different scenarios, build up discussions, and assist the dialogue between citizens, urban planners and policy makers. Our project proposes to use a Conditional Variational Autoencoder, since it can produce automatically many scenarios at once, with minor variations of the input image, according to specific features.

7.3 Generative modelling to guide public participation in street design projects

Recently, image generative AI softwares, most known as *deep fakes*, have been released for the general public such as DALL-E-2 and Midjourney. Both algorithms generate images from text and were trained with images following their descriptions. Although these softwares have an important role in the creativity process and generate high resolution images, it was not designed to guide public participation in workshops. A limitation of text-to-image generative AI softwares is the little control on the features of the generated images (e.g., change sidewalk width).

The lack of control over the features could generate street images with unrealistic scenarios. Our proposal of using generative AI to guide public participation in street design projects aims to change certain features of the image in different intensities. Differently from the workshop presented in Chapter 6, that already proposed solutions to be analyzed in certain streets, here, the logic follows the suggestion by one of the participants of the workshop. After selecting complex zones and characterizing the disputes of space, generative AI could be used as a tool to propose different solutions of reallocating road space. Thus, solutions could be proposed by adapting certain features within the latent space of the model.

We used Midjourney to create images that illustrate the objective of using AI for public participation in street design projects. The generated images are presented in Figure 29, when asked to the software in the text prompt to: "Using generative AI for visualizations to guide public participation in street design projects". Interestingly, the images generated on top right and left present an idea where participants of the workshop could select smaller screens with proposed street project scenarios. The generated images in the lower part present a different approach, which participants could have more control over certain features, such as planting trees (refer to colorful trees in generated image below right) or including digital or static signaling (refer to objects in blue in generated image below left). Thus, different tools could be created to speed up the planning process and include different stakeholders in the discussion.

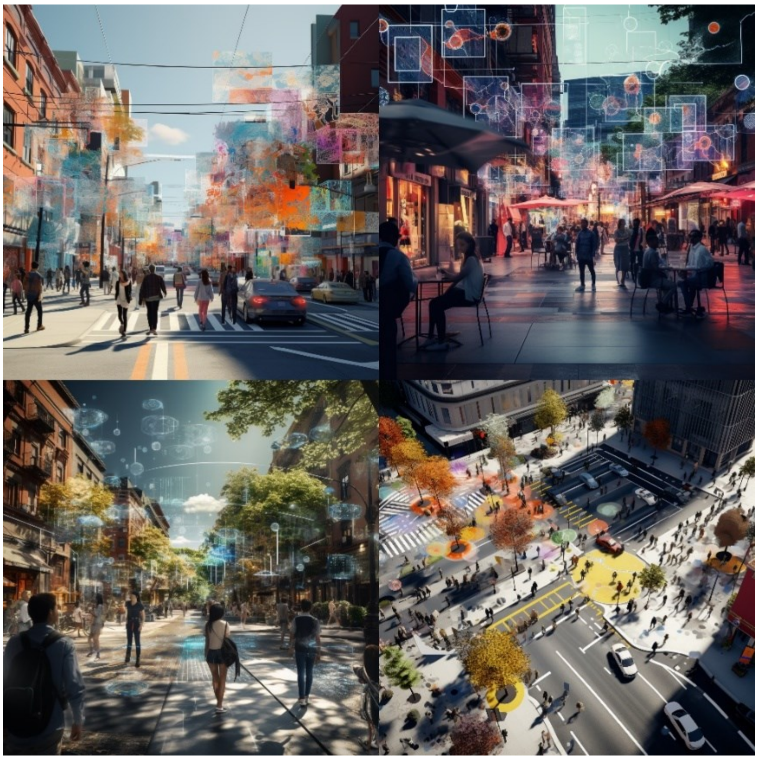

Figure 29: Generated images by text-to-image AI.
Source: Midjourney

7.4 Methodology

7.4.1 Methodological framework

Figure 30 presents the methodological framework of our proposal on using generative models to support decision-making in urban design. The methodology consists of three main tasks: i) data collection and preprocessing; ii) object detection/ segmentation; and iii) generative deep modelling. The following subsections explain in more detail each task. Note that the practical problems began to appear on the third task and will be discussed further ahead in the paper.

First, we collected images of urban streets located in the complex zones to reallocate road space identified in Chapter 5. This criterion was essential since most complex spaces tend to have less obvious solutions. More innovative and technological urban designs may arise in complex spaces with limited road space, that have to face the dilemma of allocating road space for conflictual urban functions, such as different transport modes and activities. Consequently, understanding urban design solutions that are not usually implemented may be challenging (e.g., allocating street space dynamically over time). Sequentially, we propose to filter only meaningful images and use image augmentation to increase the dataset and avoid overfitting. In the second task, we propose to perform object detection or image segmentation to extract features of the images. In our experiment, we used object detection to identify cars, trucks, buses, and pedestrians in images. The features are then treated in the format to be included in the model. The last task is to use the images and features as inputs for running a CVAE that generates new images based on the input images and conditioned by the features. Details regarding the algorithm used are presented in the Replication and Data Sharing section of this chapter.

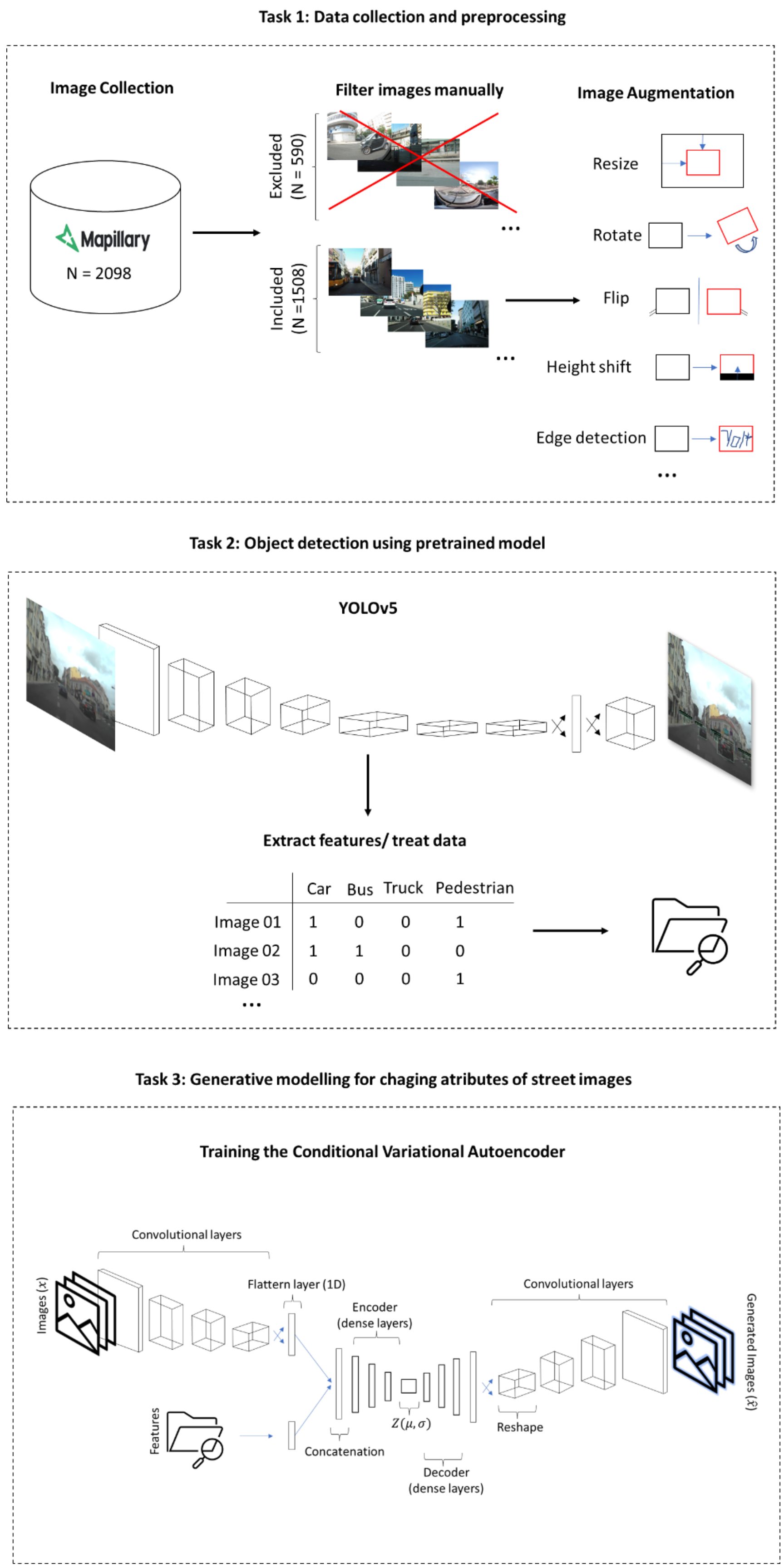

Figure 30: Methodological framework for generating images with different attributes. Source: Author.

7.4.2 Data collection and preprocessing (Task 1)

Images were extracted automatically based on random coordinates positioned within the complex zones to allocate road space that were identified in Chapter 5. We used QGIS to extract the coordinates. Initially, the software generated 213 coordinates within the twenty complex/very complex zones of 200x200m in Lisbon. We increased the number of coordinates (extracted images), by randomly extracting nine more images within the 100m radius of the coordinate. Note that some zones did not have images for 10 coordinates within a 100m radius, and thereby, fewer images were extracted. The images were extracted from the Mapillary database, which has more than one billion open-access street level images (*Mapillary*, n.d.). However, images from this database are taken by citizens. Many of them have low quality or are framed in a way that does not evidence the street cross-section from *façade to façade*. Therefore, the images were filtered manually to ensure that images presented the street layout. Figure 31 presents examples of included and excluded images from this filtering process. After selecting the images, we expanded the dataset by performing image augmentation techniques with R programming – essential step for increasing the size of the dataset and avoid overfitting -. Figure 32 presents an example of an image that passed through the process of augmentation. The decision sequentially to include the original dataset with one or more augmented images was based on the results of the loss function to avoid overfitting.

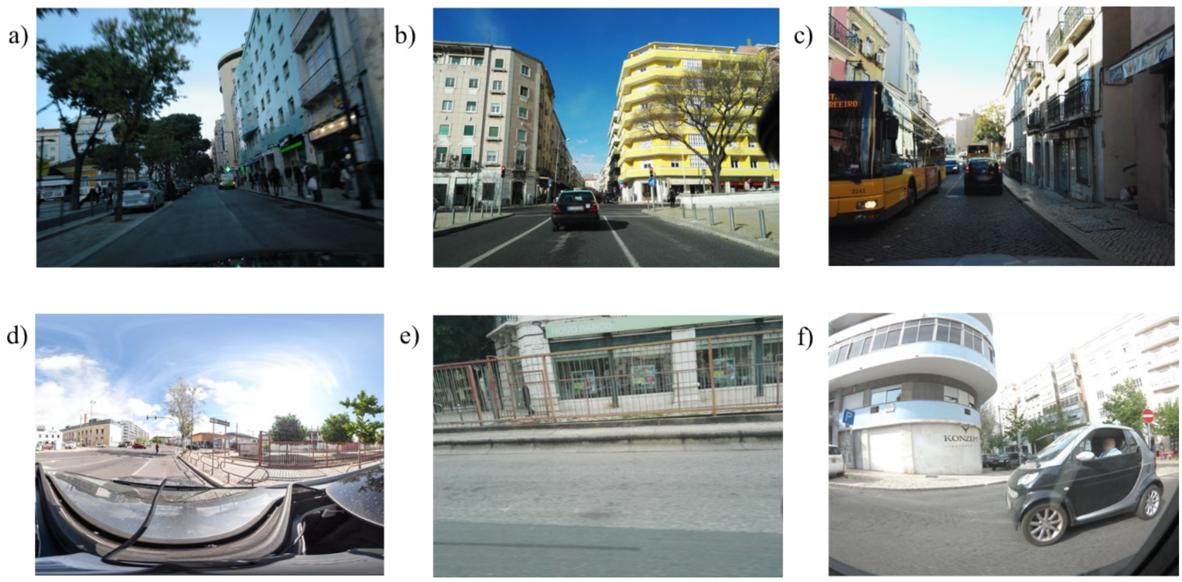

Figure 31: Examples of included (a, b, c) and excluded (d, e, f) images from the manual filtering process. Source: Author (images retrieved from Mapillary).

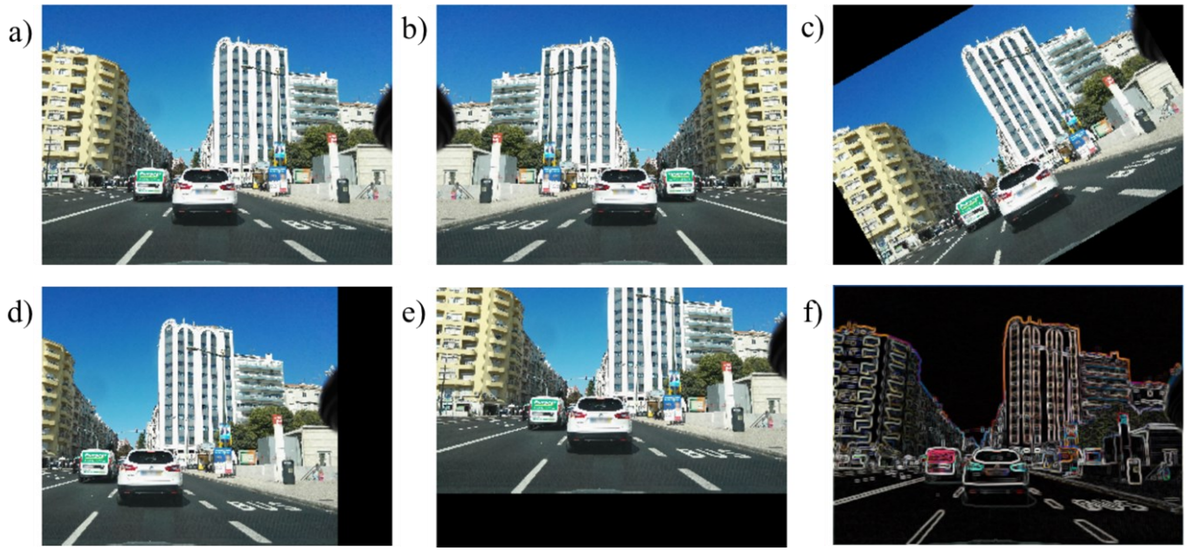

Figure 32: Example of results from Image augmentation of one image. a) original; b) flip; c) rotation; d) width shift; e) height shift; f) edge detection.
Source: Author.

7.4.3 Object detection (Task 2)

The objective of using generative models to adapt street images is to achieve some variation in the image. Nonetheless, the variation cannot be random, and some control over the output is required in order to have meaningful results. For this control, we propose a prior step of object detection or segmentation of the images. Ideally, if we want to increase the size of the lane or expand a sidewalk, the algorithm has to detect or segment the objects or pixels of the images, respectively. In our experiment, we used YOLOv3 (You Only Look Once), a pre-trained model using the COCO dataset (Common Objects in Context) for object detection (Redmon & Farhadi, 2018). We detected the following objects from the images: pedestrians, cars, trucks and buses. After the object detection, we adjusted the features of the images in two ways: i) having or not each object in the image; and ii) counting the number of each object present in the image. We used only the first one in our experiment. The second was not executed due to the poor results from the CVAE (Conditional Variational Autoencoder) and VAE (Variational Autoencoder) tested using the first case. However, we present the code for both data treatments. Figure 33 presents an example of an object detection in an image. Still, this method has limitations, as it could not identify the person behind a detected person in the example.

a) b)

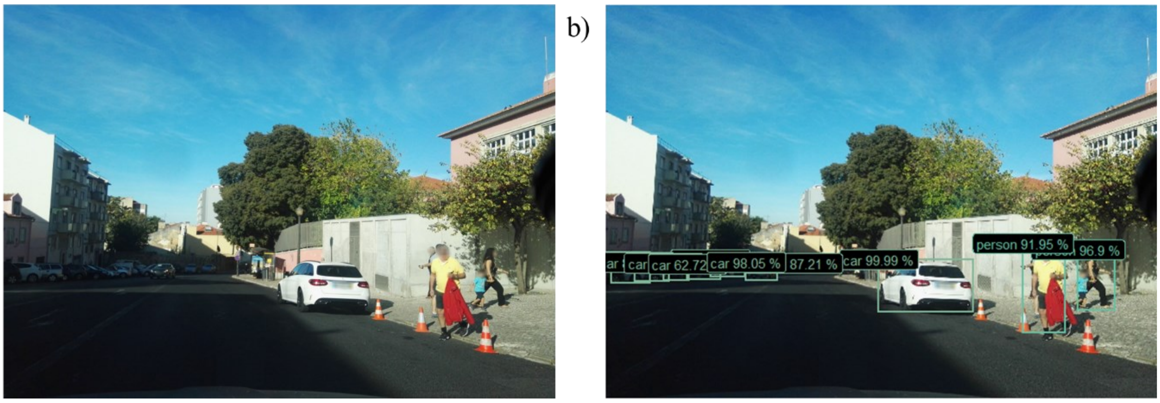

Figure 33: Object detection using YOLO. a) original image; b) image with objects detected.
Source: Author.

7.4.4 Conditional variational autoencoder on street images (Task 3)

The objective of using a CVAE in images is to generate images that are similar to the real ones while having a certain control of the output based on the extracted features. According to Noyman and Larson (2020), the outputs of variational autoencoders are more controllable than generative adversarial networks. In CVAE, image features vary along the latent space. For example, if we want to expand the sidewalk length, conceptually, CVAE could be used to vary the size of the feature ("sidewalk") within the latent space. In the simpler case tested in this chapter, the idea is to control the images based on the transportation modes (car, truck, pedestrian, and buses), by increasing or reducing the amount in the image. The CVAE is detailed below and illustrated in Figure 30.

The CVAE is an extension of the VAE proposed by Sohn et al. (2015). Both models have an encoder and decoder. However, the CVAE is conditioned by additional features, *c*. The encoder and decoder are neural networks that can be mathematically defined in the CVAE respectively as, $Q_\theta(z|x, c)$ and $P_\varphi(z|x, c)$. The input images x and the features *c* are passed through the encoder Q, into a latent space *z*, while the decoder P reconstructs fake images similar to the true images, conditioned by the features. The CVAE is optimized during training by a loss function which combines the decoder's reconstruction loss and the Kullback-Leibler (KL) divergence. The reconstruction loss is measured by the cross-entropy loss where *x* is the input images and $\hat{x}$ the generated images, as described below:

$$CE(x, \hat{x}) = -\sum_{i=1^n} [x_i \log \hat{x}_i + (1 - x_i) \log(1 - \hat{x}_i)]$$

(Equation 12)

Considering D_z as the dimensionality of the latent space, the KL divergence is described as:

$$D_{KL}[Q_\theta(z) \| P_\varphi(z)] = -\frac{1}{2}\sum_{k=1}^{D_z}(1 + \log \sigma_k - \mu_k^2 - \sigma_k)$$

(Equation 13)

The loss function is a minimization problem by joining the reconstruction loss and the KL divergence, where β is the hyperparameter that weights the KL divergence. The loss function is described as follows:

$$\min_{\theta,\varphi} L(\theta, \varphi) = CE(x, \hat{x}) + \beta D_{KL}[Q_\theta(z) \| P_\varphi(z)]$$

(Equation 14)

7.5 Results

7.5.1 Results from the experiment

This subsection presents the results of the many trials performed by the algorithm, based on the architecture and data used. As this was an experimentation of an emerging method, the results were not satisfactory. It is important to acknowledge that AI algorithms are complex and face the *black box problem*, resulting in a lack of control (to a certain a degree) of the results. Many practitioners perform AI experiments by trial and error. The success and failure of AI experiments are evaluated by the quality of the outputs reached by the algorithm (Merhi, 2023).

Table 10 describes in detail all the experiments performed in our case study and serves as a proposal for reporting AI experiments. Namely, the id of the trial; which algorithm was tested; the main question we wanted to answer with the trial; the main considerations, including data and parameters considered; main findings; and hypothesis and conclusions from each trial. Figure 34 presents examples of generated images from our procedure of the most relevant trials. The blurry character of the images generated are expected, based on the considerations that were made. Additionally, presenting all the steps (with successful outcomes or not) contributes to more transparency in science. Not only all the steps and conclusions are presented throughout the process, but also when and reasons why we decided to stop the experiment.

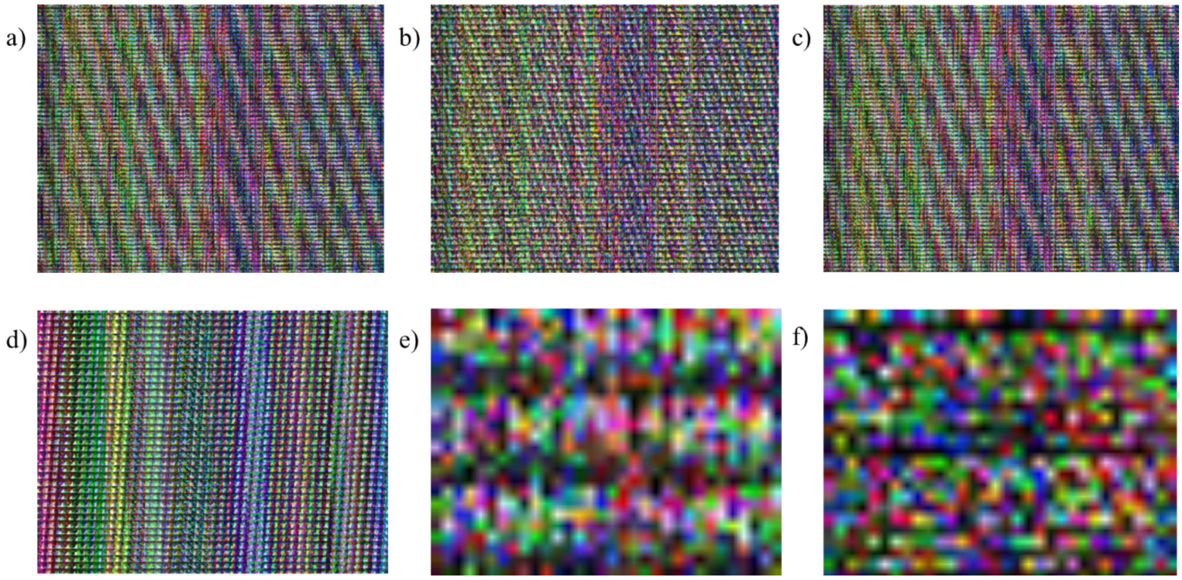

Figure 34: Examples of generated images ($\hat{x}$) from training. a) Trial 2; b) Trial 6; c) Trial 10; d) Trial 12; e) Trial 14; f) Trial 15.
Source: Author.

Insufficient data quality and computational power to train the model with a large database were the main reasons for stopping the experiment, and not performing more trials. Consequently, future research must account for computational power to train the model with a large quantity of data and have more quality in the images. We chose to use images from Mapillary due to its benefits of being open-source and having a large available database. Since photos are taken by citizens, some images are of low quality, while lacking quality and form standards. There is a challenge to find open-source databases of street cross-section images with high quality. To continue the work, more images from this source could be used requiring an intense work of image filtering. Ideally, images taken from the same angle in similar places can achieve better results, as concluded in our experiments. Also, separating street images with similar characteristics into different datasets may improve the model. An example, was the case of PlacemakingAI that seperated Google Street View images into two datasets: green spaces and pedestrian only commercial streets (Kim et al., 2022). Although Google Street View images are more standard and have higher quality than images from Mapillary, they require permission to be used.

In this experiment we used object detection as an initial approach to detect features in images to be an input in the generative deep model. However, image segmentation could be a step further to characterize every pixel of the image, even though there is a lack of packages of pretrained models in R programming. For image segmentation many codes, pre-trained models and developments using the Cityscapes[4] dataset (that identify urban objects) are available using Python, as for instance the work produced by: Breitenstein and Fingscheidt (2022); Liu et al. (2022); and Ye and Xu (2023).

While we used variational autoencoders to generate images, other generative deep models could also be tested such Generative Adversarial Networks (GANs). There has been recent research comparing the performance of both types of generative models for generating images. In some applications, images generated by VAE are more similar but blurrier than the ones generated by GANs (Diaz-Pinto et al., 2018; Larsen et al., 2016). Still, more tests have to be executed, since different types and applications of images can lead to different results.

[4] The Cityscapes Dataset. https://www.cityscapes-dataset.com/

Table 10: Proposal for reporting step-by-step the process of AI experiments, exemplified by our experiment. Source: Author.

Trial	Algorithm	Question	What was considered	Main Results	Main conclusions and hypothesis
1	CVAE	What are the first results with a small number of images?	The first model aimed to check if the algorithm worked and its first results. Only 114 images for training and 20 images for the test were used. Using labels of images as dummy variables for each transport mode (1: with transport mode; 0: without transport mode) Nº Train images = ***114***; Nº Test images = ***20***; Batch size = 2; Epochs = 50; Filters = 1L; Intermediate dim = 128; Latent dim = 2.	Images from training and testing are blurry and do not reproduce any meaningful result.	The number of images is too low to train the network.
2	CVAE	What are the results of increasing the sample of images?	The algorithm was executed with the original sample. Nº Train images = ***1265***; Nº Test images = ***243;*** Batch size = 2; Epochs = 50; Filters = 1L; Intermediate dim = 128; Latent dim = 2.	Generated images from training and testing continued to be blurry. However, they started to have higher neatness.	The batch size and epochs may be too low.
3	CVAE	What are the results when we increase the batch size and the number of epochs?	Nº Train images = 1265; Nº Test images = 243. Batch size = ***25***; Epochs = ***100***; Filters = 1L; Intermediate dim = 128; Latent dim = 2.	Generated images from training and testing continued to be blurry, having a very similar aspect to the previous results.	We began to hesitate if adding the labels was the problem. We tried to simplify the problem by executing the VAE.
4	***VAE***	Does the algorithm work in a simpler form? What if we run the model without the labels (Only the VAE)?	Nº Train images = 1265; Nº Test images = 243. Batch size = 25; Epochs = ***100***; Filters = 1L; Intermediate dim = 128; Latent dim = 2.	Generated images continued to have the same blurry aspect, suggesting that the labels were not the problem in the CVAE.	The number of images may still be very short since the results did not differ from the last trial.
5	VAE	What are the results of increasing the number of images?	In this early stage we did not perform image augmentation. To test the algorithm, we simply duplicated the number of images to check what would happen. Nº Train images = ***2530***; Nº Test images = ***486***. Batch size = 25; Epochs = 100; Filters = 1L; Intermediate dim = 128; Latent dim = 2.	The generated images were slightly more nitid but did not change much. The loss function indicated overfitting, which is expected due to image duplication.	Still the number of images may be too small to train the network.
6	VAE	What are the results of increasing, even more, the number of images?	We triplicated the number of images by copying once more the images into the database.	Generated training and test images are still blurry but appear more nitid. Overfitting continues to happen.	At this point we raised several hypotheses about why the results were unexpected. a) The number of images remains too low to train the network.

Trial	Algorithm	Question	What was considered	Main Results	Main conclusions and hypothesis
6			Nº Train images = ***3795***; Nº Test images = ***729***. Batch size = 25; Epochs = 100; Filters = 1L; Intermediate dim = 128; Latent dim = 2.		b) Image augmentation may help achieve better results and avoid overfitting. b) Hyperparameters and layers of the network require adjustments. c) Intermediate and latent dimensions are too low, not capturing sufficient information. d) Street cross sections images are too complex.
7	VAE	What happens if we increase filters, intermediate dimension, and latent dimension of the model?	Nº Train images = ***1265***; Nº Test images = ***243***. Batch size = 25; Epochs = 100; Filters = ***10L***; Intermediate dim = ***10000***; Latent dim = ***1000***.	The computer did not support running the model.	At this point we began to doubt if we had the computational power required to train the model.
8	VAE	Does the model continue not to run, if we increase the batch size and epochs?	Nº Train images = 1265; Nº Test images = 243. Batch size = ***100***; Epochs = ***500***; Filters = 10L; Intermediate dim = 10000; Latent dim = 1000.	The computer continued to not to be able to run the model.	As expected, the increase in the dimensions of the model's dimensions resulted in more complex models that our computer could not support.
9	VAE	Does the model continue not to run if we substantially reduce the number of images?	Nº Train images = ***200***; Nº Test images = ***50***. Batch size = 100; Epoch = 500; Filters = 10L; Intermediate dim = 10000; Latent dim = 1000.	The computer continued to not run the model; when intermediate and latent dimensions were very high.	The intermediate and latent dimensions need to be smaller.
10	VAE	What are the results if we reduce the intermediate dimension and latent dimension?	Nº Train images = ***1265***; Nº Test images = ***243***. Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = ***1000***; latent dim = ***100***.	Reducing the size of the intermediate and latent dimensions worked for running the model. Still the results were not satisfactory. Compared to Trial 4, which had smaller intermediate dimension, latent dimension, epochs and batch size, the generated images were very similar.	Increasing the dimensionality may not be a critical factor for having better results, although very small dimensionalities can limit the information received.
11	VAE	Did the increase in dimensionality not result in meaningful results because the number of images was too low?	We used the same database as trial 6. Therefore, copying the original database two more times. Nº Train images = ***3795***; Nº Test images = ***729;*** Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = 1000; Latent dim = 100.	The generated images were very similar to the results of Trial 6, which used the same database, but with smaller intermediate and latent dimensions, epochs and batch size.	At this point, we concluded that adjustments in the dimensionality did not make a difference in the results. Instead, increasing the dataset size has more influence in more nitid images. However, the complexity of urban streets and the lack of standard patterns in images, may negatively influence the results.
12	VAE	What are the generated images if we use more similar street images?	To test if the results would improve with more similar images, we created a ***new database*** with 62 images taken from the ***same street*** of the original database. As the number is too low, we replicated the database eleven times, obtaining a total of 682 images for training. We maintained the same images for testing.	Making images more similar resulted in generating images with more vivid and nitid colors, representing an improvement in the model, although overfitting was present. Even with a smaller number of images than Trial 11 for example, the results seem better due to more similarity between images.	From this trial, we concluded that two main issues may be resulting in bad results: a) The number of images is still very low to train the network.

Trial	Algorithm	Question	What was considered	Main Results	Main conclusions and hypothesis
12			Nº Train images = ***682***; Nº Test images = ***243***; Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = 1000; Latent dim = 100.		b) Urban street images are complex due to the lack of patterns in shapes, colors, and form. Training a network for urban streets would require filtering only images that are very similar to each other.
13	VAE	What are the results when we increase the size of the database with image augmentation?	We used the ***original dataset*** and added the augmented images by ***rotation, flip, height shift*** and ***edge detection*** to the training database. Nº Train images = ***6325***; Nº Test images = 243; Batch size = 100; Epochs = 500; filters = 10L; Intermediate dim = 1000; latent dim = 100.	The computer did not support to run the model with 6325 training images.	This was a critical point in the project, making us be certain that we did not have sufficient technological resources to continue the trials for long.
14	VAE	Does the model work if we reduce the size of the images?	All trials used images with size 240x320x3. We reduced the images to ***24x32x3***. Nº Train images = 6325. Nº Test images = 243. Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = 1000; Latent dim = 100.	Reducing the size of the image made the algorithm work. Still no meaningful result was generated. However, some appearance of what looked like a pattern of colors began to appear.	Our hypothesis is that reducing the complexity (size) of images resulted in better results. Making the neural network denser may result in detecting more patterns in the images.
15	VAE	Does the model improve when adding one more layer to the network?	We increased ***one convolutional layer*** of the model. Nº Train images = 6325. Nº Test images = 243. Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = 1000; Latent dim = 100.	The results did not change much from the last trial.	Increasing the number of layers in the network may result in better results.
16	VAE	Does the model improve by adding more layers to the network?	We added ***more layers to the network***, but the computer did not run the models. We tried varying the parameters of the layers, but this also did not work. Nº Train images = 6325. Nº Test images = 243. Batch size = 100; Epochs = 500; Filters = 10L; Intermediate dim = 1000; Latent dim = 100.	Adding more layers to the network made the model heavier. We did not have the computational power to run more complex models.	This was a stopping point for our trials. The limitations of computational power to run models with dense networks and large datasets was in our view the main reason for not achieving satisfactory results.

7.5.2 Lessons from the experiment

We examine in this section the main reasons why the outcomes of the algorithm did not achieve an urban form and the practical challenges faced in developing the model. It is essential to understand the factors that influence the success of AI implementation (Duan et al., 2019; Dwivedi et al., 2021), especially because AI has been a trending topic in many interdisciplinary research projects. Reiter et al. (2003) argue that negative as well as positive examples in AI are essential for theory formation and learning processes.

Starting from scratch

The philosopher Karl Popper believes that experimental science should focus on efforts to disprove theories, rather than proving them (K. Popper, 1959). The author claims that it is impractical to prove theories by experimental research, since researchers cannot check all predictions in all possible contexts. Disproving theories is more likely to happen by experimental science because it is possible to evaluate if a theory is applied in specific contexts. For example, if all swans are claimed to be white, this assertion can be refuted by the appearance of a black swan (K. Popper, 1959; Taleb, 2007). In our experiment, the architecture of the CVAE was based on the literature of other research using different types of data and applications, since there were not a lot of examples in urban design to take on. Since the results of generative models are usually unpredictable, and constrained by their architecture and training data (Noyman & Larson, 2020), it was very difficult to detect if the hyperparameters and layers of the network were ideal for the problem. As we tried to prove a theory by building a new architecture, instead of disproving one, it was not practical to detect if the architecture chosen was ideal, even though many trials with different possibilities were executed. On the contrary, for the object detection of the images, we used a previously trained model, resulting in meaningful results.

Many AI projects are based on trial and error due to the high level of complexity and lack of transparency of many algorithms, facing the *black box problem* (Yavar Bathaee, 2018). This is one of reasons why starting from scratch is usually not recommended. As stated by Lenat and Feigenbaum (1991), artificial intelligence models should not learn from scratch, but instead expand from previously trained models. Using pre-trained networks, combining them and adapting to the problem could have been better practice.

Data complexity and technological infrastructure

Merhi (2023) claims that key technological resources such as data quality and quantity, integration complexity, and IT infrastructure is the most critical factor for successful AI implementation. Westenberger et al. (2021) also believes that the key resources are a leading factor for successful AI implementation, relating specially to data availability, quality, and quantity. In our case, even though a large quantity of street cross-section images was available, the computational capabilities available only allowed us to train a certain number of images. At some point, the experiment did not continue since we could not add more images to the model.

In terms of data quality, images lacked a certain pattern in terms of angle and clarity due to the database being constituted of pictures taken by citizens. Also, streets and visualizations of streets are complex in terms of aesthetics, urban form, arborization, number and variety of transport modes, size, color, and shape of buildings, etc. Consequently, generative models for street-cross section applications tend to be more complex due to high dimensionality than other applications such as generating building shapes or façades which have similar shapes and patterns. Additionally, training data is a lot of times unavailable and expensive, requiring high quantity and quality of data and computational power (Westenberger et al., 2021). As experienced in practice, the quality and quantity of the data and computational power required for generating images with an urban form is often only possible to recognize and evaluate during the execution of the algorithm (Baier & Seebacher, 2019).

Understanding how much data, how similar they must be to each other, and which type of data the algorithm requires for generating high quality images are essential factors for success. There is still a huge challenge to train high dimensional datasets (J. Cai et al., 2018; Domingos, 2012), large amounts of data (Baier & Seebacher, 2019; Merhi, 2023), and in a reasonable time (Lopes & Ribeiro, 2017).

Programming language

The experiment presented in this chapter was executed using R programming, which is mostly a statistical and graphical tool. Although the tasks were completed using R, it is not widely used in machine learning which led to many difficulties, although it is possible to perform almost the same tasks as in Python (Rhys, 2020). Python is by far the most popular language used in machine learning and deep learning (Nguyen et al., 2019), having packages first developed in Python to then implemented in R later (Rhys, 2020). Consequently, most developments in deep learning are being held in Python having way more available information than R programming related to open codes, coding questions and answers in public platforms, tips, and guidelines. The most used packages for implementing machine learning are *Keras* and *TensorFlow*, that were first developed in Python and then adapted to R. More examples and developments in R are required to guide researchers and practitioners in machine learning, in order to promote more interdisciplinary research and practice in AI. Also, some pre-trained models are only developed in Python, although the coding is possible in R. We contribute to improving the knowledge on R programming in machine learning by sharing the codes used as well as giving guidelines and reproducing the results of the paper in Rmarkdown. Also, Baier and Seebacher (2019) propose that more user-friendly tools are required for non-experts to use AI technology.

7.6 Discussion

7.6.1 Challenges and risks

Our proposal of using generative AI to create street images to guide workshops and public discussions is not absent from challenges and risks. It is important to mention, that *deep fakes* and generative technologies being developed should not infringe the existent law regarding the fundamental rights, which determines that every human being has the right to live, to have integrity, freedom, personal security, and privacy protected. In fact, a draft of the Artificial Intelligence Act was proposed by the European Union in 2021 to regulate AI (European Commission, 2021). The regulation proposes to establish a unique definition of AI and regulate AI technology based on risks of infringing the fundamental rights and safety principles. AI systems are classified in four categories based on their risk, having different levels of transparency requirements. AI systems classified as having unacceptable risk are prohibited in the market; high risk AI systems are regulated upon new legislation; limited risk AI systems have transparency obligations; and low or minimal risk AI systems can be used freely. Still, the impacts of AI may have to society are not clear, and there is a discussion on whether the proposal of the AI Act adequately protects the fundamental rights, rule of law and democracy (Smuha et al., 2021).

Generative AI systems are classified as limited risk AI systems in the proposal, requiring three main principles of transparency. First, all contents generated by AI must be evident that were developed by the machine and not by humans. Developers and users have to disclose that the images generated were made by AI. Still, it is not required to present the limitations, biases and possible applications of the AI system. In the case of using generative AI in workshops for street design, it is essential to provide information to participants of whether the AI system can or not produce some solutions. In fact, it must be clear for the participants the accuracy and detail level that the *deep fake* algorithm can generate. Being transparent in the process will allow participants to know the limitations and use the generated images as a tool for enhancing creativity and discussion, rather than relying strictly on the AI results.

Second, generative AI systems have to be designed to prevent from generating illegal content. The second transparency requirement for generative AI models can be accommodated in using this technology for street design projects, since generated images will only contain urban elements. A risk of this application could be infringing privacy issues, when facial recognition can be detected in street images (e.g., pedestrians and cyclists) which are used in the workshop. Importantly, defining which content is illegal may not be that evident for other applications, since some content may face moral dilemmas that are dependent on cultural, social, and regional aspects (Awad et al., 2018).

Last, generative AI systems have to disclose copyright information of the data used for training, and guidelines for users to comply with their obligations regarding the AI Act. Besides giving credit to the copyrights, it is also important for users to understand which type of data was used to train the generative AI. For example, the results of using Google Street View, Mapillary, or 3D street projects to train the model may lead to different perceptions of the results. There is a discussion whether generative AI models are infringing copyrights of artists, musicians, and authors, since these algorithms generate images, videos or text based on the information from training data.

7.6.2 Limitations and future research direction on using AI for street visualizations.

Public acceptance and trust in the solutions proposed by the AI may be a risk. People will only rely on results from AI to make important decisions when they trust the system (Baier & Seebacher, 2019). Dealing with the lack of transparency of generative deep models is a challenge that has to be assessed. Even though it is not possible to be totally transparent of the generated street design solutions, we recommend that the moderator of the workshop session is clear in stating the algorithm is a tool and that the images generated are to be used for promoting discussion. Consequently, other solutions may arise from the discussion, or even some of the solutions generated by the algorithm may not be coherent or applicable due to local characteristics, technical and political challenges. The "bad results" are also important to promote discussion and enable policy makers and local community to rise up reasons and characteristics that may be barriers for implementing certain types of solutions, especially more innovative ones such as allocating space dynamically over time.

Although there is an assumption that visualizations help the communication of designs, still the psychological and mental responses are poorly understood (Wergles & Muhar, 2009). Also, most research has focused on making images from generative deep models more realistic, rather than focusing on how people understand the images, and their role. Our hypothesis is that images that are too realistic may remove the creativity, potentially have a "Wow-Effect" of the technology in the audience (McQuillan, 1998) – the power of the tool reduces the critical assessment of the content -, and may lead to misinterpretations associated to the prediction of the solution. Also, a higher degree of detail does not imply better comprehension (Pietsch, 2000). Having a level of noise in the generated images may positively contribute to innovation, making participants understand the proposed solutions at the same time as stimulating discussions on the subject. We suggest that future investigations assess the mental and psychological responses on different levels of detail of generative deep models.

Furthermore, both experts and local community can be included in the workshop. Even though public participation has been acknowledged as essential by the scientific and practitioner communities, how this participation should be done is not well stablished (Gordon et al., 2011). It is important that AI applications in public participation does not only give room for local communities, but also promotes higher understanding of innovative solutions, and engagement with policy makers of diverse backgrounds.

7.6.3 Implications for practice

Experiments that lack ideal outcomes are common in science. However, in AI, reporting unsatisfactory results is not common, as in other fields such as medicine and physics (Reiter et al., 2003; Rychtyckyj & Turski, 2008). It is essential to understand the factors that influence the success of AI implementation (Duan et al., 2019; Dwivedi et al., 2021).

Westenberger et al. (2021) apply semi-structured interviews with 6 experts to discover the key factors that influence not achieving the goals of Artificial Intelligence projects. The authors conclude that there are 12 main factors for unsuccessful projects, within 5 major categories: unrealistic expectations, use case-related issues, organizational constraints, lack of key resources, and technological issues. Baier and Seebacher (2019) also use semi-structured interviews with 11 AI practitioners to discover the main challenges in implementing machine learning algorithms. The authors compare the challenges to the literature findings, concluding that challenges appear in the project's pre-implementation, implementation and management. Jöhnk et al., (2021) perform interviews with 25 experts to investigate the readiness of adopting AI in organizations, resulting in 5 main categories: strategic alignment, resources, knowledge, culture, and data. Although studies based on interviews have demonstrated the challenges and factors that influence the unsuccessful AI project expectations, few have actually presented their unsatisfactory results.

Reporting the experiment process in an organized approach and making conclusions out of it has major contributions to practice, as it allows practitioners to anticipate practices that can be avoided, and eventually continue the work that has begun. Also, providing open codes, data, guidelines as well as reporting the main findings, considerations and hypothesis of each experiment leads to more transparency and reproducible science. Real case studies are also important for policy makers to understand more specific factors for the success AI projects since it may be easier to learn from experience of other practitioners than from findings from interviews that have a higher scale assessment of the problem. As stated by Merhi (2023), practitioners require practical solutions, rather than theoretical ones to guide them for implementing AI solutions.

7.7 Conclusions

In this chapter we propose the use of generative deep models for guiding public meetings and workshops on street design and street space allocation projects. While visualizations are still used for public discussions, using generative deep models to generate various scenarios of street images by modifying characteristics of the images in real-time, can be used as a tool to promote discussions on possible solutions. These models may have higher importance when explaining and proposing innovative solutions to the street that are not straightforward to have a *mental map* by the public, such as allocating road space dynamically for different uses, or using technology to manage the space. Generating various scenarios of a specific street is important because more than one solution could be applied to the street. Consequently, public managers may choose one solution for reallocating the space permanently, or more than one solution, that could be used for changing the space at different times of the day, week, or season.

Besides promoting the idea, we performed an initial experiment with a restricted dataset and computational infrastructure, as a first conceptual experience. In order to produce meaningful results, a higher quality and number of images, as well as sufficient computational power would be required. We explore and use R programming to perform computer vision tasks, which is not very common. We share the code, dataset and reproduce the paper's results in R, guiding other researchers to replicate the expected and unexpected results and eventually continue the research.

As AI is a trending topic, it has become more common for researchers of different engineering backgrounds to explore and apply AI in multidisciplinary tasks (Baier & Seebacher, 2019). Consequently, what are common practices and knowledge for computer science engineers may not be for researchers of different backgrounds. We hope that this experimental chapter, can also encourage other researchers to share their experiences. Also, as we shared transparently and in detail the whole process of experiments, codes and data used, this can guide other researchers to continue our work, and possibly achieve more satisfactory results.

7.8 Replication and data sharing

The code, dataset, and guidelines for replicating the results of this paper are found at: https://github.com/valenca13/CVAE_StreetDesign

Chapter 8

8 Conclusions

The objective of the thesis is to evaluate the coherence of allocating road space dynamically over time in complex urban areas. We characterize complex urban areas as those facing the challenge of accommodating multiple transport modes and various urban functions within limited available space. Thus, road space allocation in complex areas often requires trade-offs and the amount of space that should be allocated for a certain transport mode or urban function may not be evident. The hypothesis of this work is that road space could be allocated dynamically for using space more efficiently and changing the use of spaces according to demands and policy goals. The next sub-section reviews the main findings regarding each research question. Sequentially, there is a sub-section on limitations and future studies.

8.1 Review of main findings

The research questions are proposed to obtain a clear insight into the potentialities and challenges of allocating road space dynamically. In sum, the research questions that are answered throughout the thesis analyze respectively: i) the differences between emerging concepts and the importance of allocating space dynamically in complex areas; ii) the existing and future technologies that can be used; iii) the locations and periods that are coherent to reallocate space dynamically; iv) and the use of artificial intelligence to enhance public participation in street design projects of *dynamic road space allocation*.

RQ1: **<u>What</u> are the differences between emerging road space allocation solutions and their relationship with new sensing, management, and control technologies?**

In Chapter 2, a literature review was performed on the most relevant journals in Transportation and Urban Studies to detect the historical context and differentiate the emerging practices in road space allocation. Three main types of emerging solutions regarding road space allocation were found in the main literature: i) temporary; ii) intermittent; and iii) dynamic. First, temporary practices, such as pop-up bike lanes, are characterized by "try-and-test" practices. They are often cheap, quick and modify spaces with simple practices such as remarking the streets. As it is already mentioned in the name, temporary solutions are not permanent, but can eventually become in successful cases. In terms of adapting to demands, temporary solutions are often static as they do not consider traffic and urban dynamics, not adapting in real-time or in hourly periods according to different demands. Temporary solutions have an unpredictable life cycle or are planned to be executed during a specific period of time (e.g., street markets are open only during the summer). Temporary solutions, if planned for a certain life cycle, may have a "dynamic" character of adapting space in less complex periods such as seasons or weekdays (refer to the examples of Figure 1 in the Introduction).

On the other hand, the use of smart technology in sensing, demand management, and control is found to be relevant in the literature of "intermittent" and "dynamic" practices of road space allocation. The Intermittent Bus Lane was the first proposal that integrated these technologies to adapt road space reactively to the position of the bus, even before the trend of smart cities and big data arose in the literature. Intermittent Bus Lanes were proposed as a solution for the underutilization of dedicated bus lanes when bus frequency is low. They are designed to give priority to the bus by informing other vehicles not to enter the lane when the bus is approaching and allow vehicles to use the lane otherwise. Vehicle detectors are used to identify the position of the bus, communicating with a control system that provides transit signal priority and informs users of the status of the bus lane. A similar approach was proposed later, named Bus Lane with Intermittent Priority. The main difference between the two is that the Intermittent Bus Lane does not consider vehicles that are already in the lane. On the other hand, Bus Lanes with Intermittent Priority gives priority to the bus by informing users also to leave the lane, not depending on transit signal priority.

Intermittent practices in road space allocation adapt the use of space in real-time according to the position of a priority vehicle (e.g., buses), being dependent on technology for sensing, management, and control. Consequently, if spaces are being adapted in real-time, communication between priority vehicles and the infrastructure controller is required. This technological dependence indicates that intermittent practices are permanent, although there are few practical cases. In Chapter 4 we propose a smartness classification of road space allocation that ranges from level 0 (No use of technology) to Level 5 (Full connectivity). Intermittent Bus Lanes and Bus Lanes with Intermittent Priority are within Level 3 (Infrastructure and vehicle technology), where demand management and control technologies are used to adapt the space according to the position of a priority vehicle that communicates with the infrastructure (V2I). It is important to mention that buses do not communicate between themselves or with other vehicles.

A limitation of these types of practices is the lack of consideration of public transport frequency and traffic dynamics over time. In periods with heavy traffic such as peak hours, it may be unpractical or even cause conflicts between vehicles, to give priority to the bus since the adjacent lane may be saturated. Thus, adaptations in real-time in traffic lanes may only be possible in less complex and conflicting times.

To fulfill the limitation of intermittent practices, dynamic lane allocation is proposed. While intermittent practices adapt the infrastructure in real-time, dynamic lane allocation adapts the use in periods (e.g., peak and non-peak). Consequently, dynamic applications can consider public transport frequencies and traffic dynamics, by dedicating the lanes exclusively for buses during peak hours and being mixed with traffic or intermittent in non-peak hours, for example. Therefore, dynamic lane allocation adapts the use of space according to fluctuations of demands in defined periods. Real-time or historical data could be used for decision-making. As mentioned, temporary solutions could also be dynamic, but in cases where smart technology is adopted, these solutions may require to be permanent.

One of the conclusions from Chapters 2, 3, and 4 is that, while the literature on temporary practices is held in more local areas, the literature on intermittent and dynamic practices is focused on highways and arterials. Thus, complex urban environments are not analyzed in these practices, where there is a conflict between urban functions and uses and there exists a dilemma to allocate road space. In Chapter 3, we propose the concept of *dynamic road space allocation* that aims to reallocate spaces dynamically in complex urban areas, that have limited spaces. The main motivation of this proposal is to use spaces more efficiently by adapting uses according to different demands and policy goals. The main differences between dynamic lane allocation and *dynamic road space allocation* are related to where it is implemented, its priorities, and architecture. On the one hand, dynamic lane allocation is implemented in arterials and highways, prioritizes the mobility function, and only considers the interactions of users in the traffic lanes. On the other hand, *dynamic road space allocation* aims to be implemented in complex urban streets (usually classified as main and local distributors), adapts space for both mobility and access/place functions, and considers both traffic lanes and adjacent space in its design.

Technology can be used for dynamic adaptations of space, but these solutions are not reliant on it. The level of complexity of allocating space dynamically also includes the technological level adopted, that can vary within all levels of technology adoption. Allocating space dynamically can be adopted with traditional vertical and horizontal signaling informing the transitions between uses (as experienced in practice – refer to Figure 2 for examples), to a context where AVs require communication between vehicles and vehicles to infrastructure (Level 4 – Communication between Vehicles and Infrastructure) or in a futuristic context where all the infrastructure and users (not only vehicles) are connected (Level 5 – Full Connectivity).

RQ2: **<u>How</u> can we allocate road space dynamically in complex urban streets?**

Chapter 3 presents the concept of *dynamic road space allocation* and suggests some technologies for sensing transport modes and activities and managing urban space. Emerging crowdsource big data (e.g., Google Maps, Waze, GPS, video analytics) have made it possible to characterize urban space dynamics in real-time. In the past, heavy data collection in road space relied on loops, radars, or manual counts, often being held during peak hours. Besides the costs relative to these practices, they often only characterized traffic flows, disregarding pedestrians, cyclists or activities. Recently, big data has not only allowed a broader characterization of urban space, but also enabled short-term planning to rely on data-driven decision making. Thus, big data could characterize traffic and urban dynamics over time in order to reallocate road space dynamically based on demand-driven decisions.

In terms of transport demand management, low-level technologies such as LEDs in-pavement lighting and flexible bollards that are already commonly used in urban areas, could be tools for adapting the use of space over time. Variable message signs could inform users of the uses of space over time. In spaces where it is very evident that it is underutilized (not requiring sensing), a simple vertical sign could inform the dynamic transitions. On the other hand, higher levels of technologies could also be adopted depending on the transport modes involved, local context and policy goals. Control technologies such as adaptive signal controls can be used in cases where vehicles are communicated with the infrastructure (V2I) and with each other (V2V) in order to reallocate space dynamically according to these demands.

Using technology for sensing and control, and adapting road space dynamically are not absent from challenges and the decision to use them should be context-oriented. First, the level of technology used for managing and controlling urban space should not exclude some segments of society (e.g., the elderly, people with disabilities), or be adopted in front of more urgent social needs such as basic sanitation, shelters, etc. Technology should be seen as tool, rather than the solution *per se*. The use of technology should also consider built environment restrictions or vulnerabilities such as fragile old buildings, and architectural and environmental protection areas. Enforcement challenges may also be present in the implementation of high technological solutions, including low qualification and readiness levels of municipal technical and decision makers, time-consuming bureaucracy, and complexity of decision-making chains. There are still technological limitations for sensing urban space that require caution such as storing, managing and analyzing large databases and video camera limitations to detect objects in diverse weather and illumination conditions. Sensing urban space should not infringe data privacy regulations, requiring clear legislation on data ownership and usage. Finally, the level of technology used should take into account behavioral aspects and public acceptance.

Besides the challenges, in Chapter 4, we conclude that allocating road space dynamically is not dependent on technology but that may be required depending on the transport modes involved, the local context and policy goals. For example, if spaces need to adapt dynamically according to autonomous and connected vehicles, a higher smartness level is required due to the need of having V2V and V2I communications. The smartness levels of road space allocation proposed in Chapter 4 presents a framework where decision makers can choose the types of sensing, control and transport demand management technologies required for each case. While the urgency of implementing the solution may require lower-smartness levels, conceptualizing these levels allows the policy makers to develop more sophisticated solutions addressing ethical, safety and acceptability concerns in the medium to long term. As mentioned previously, allocating road space dynamically can vary from no use of technology to a fully connected system.

One of the main concerns that appeared in the debates of the workshop (Chapter 6) is that although existent and emerging technologies can be used for allocating road space dynamically, the acceptability of users, and the risks of people not understanding or adapting well to dynamic transitions should be taken into account. Solutions that require less technology can expect higher social acceptance. However, as mentioned previously, solutions may have different smartness levels, that also are related to having a high number of dynamic transitions or are in short periods of time (e.g., minutes or hours). Thus, dynamic solutions should aim to be as parsimonious as possible, using technology as a tool, and when needed, having the right balance between the number of transitions, technology use and social acceptability.

RQ3: <u>Where</u> and <u>when</u> can we allocate road space dynamically over time?

In Chapter 3 we discuss the conceptual assumptions of reallocating road space dynamically over time in complex environments. Complex streets have limited space to fulfill all uses and functions. However, many of these spaces are still used inefficiently, having spaces oversupplied and undersupplied at certain times. Reallocating road space dynamically in complex zones can more efficiently use spaces that are underutilized at certain times, giving it another use. In Chapter 5, we propose a methodology for identifying complex zones that have the highest potential for reallocating road space dynamically. In sum, complex zones are characterized by having: i) a dilemma between allocating space for mobility or access functions (mostly in main and local distributors); ii) high network connectivity being a main hub of trips; iii) high volumes of traffic at least at one period of the day; iv) high density influencing the number of trips and mode choice; and v) high diversity of land use which influences the fluctuations of different demands during the day. Furthermore, in spaces where public transport operates in a high frequency at least a period of the day, it becomes even more complex to reallocate space due to the dispute for space between traffic and public transport and the adjacent space occupied to the traffic lane for the bus stop. The site selection methodology of complex zones proposed in this thesis can guide policy makers, at an initial stage, to comprehend which areas in the city require a deeper evaluation to reallocate road space.

Nonetheless, the site selection methodology is applied on a municipality scale, not going into details on the local context and street segment characteristics. Also, different solutions require different selection criteria on a local scale. From the discussions in the workshop with experts (Chapter 6), after selecting zones that are complex, it is important to characterize the disputes and complementary uses and functions over time in complex streets. This is a prior step of intense data collection, to fully understand the street's urban dynamics. One of the main conclusions from the workshop is that street-level criteria for reallocating road space dynamically are specific for each solution. Even the criteria that are similar within solutions, have distinct importance levels. Three main types of local criteria were defined for selecting where to reallocate road space dynamically: i) geometric characteristics referring to the street dimensions; ii) functional characteristics related to the use of the street; and iii) layout characteristics related to the space organization. It is important to mention that some of the criteria proposed by the experts are not used for evaluating static road space allocation, requiring new indicators for evaluating urban space. Therefore, the street of intervention for reallocating space dynamically can vary across solutions, depending on the characterization of the conflicts and uses and local criteria within the complex urban zone.

From the characterization of the dynamics, road space can be allocated dynamically when demands are complementary or disputed. Complementary demands happen when a certain use or function is underused, while another lacks sufficient space to accommodate its demand. In this case, road space could be allocated dynamically from one to another. When demands are disputed (e.g., peak hours), the decision to reallocate space dynamically requires trade-offs by restricting one mode or function to the detriment of the other. Municipalities more inclined to challenge the space of the car will tend to have more options of solutions. In this case, the goal is to increase the level of service and use of sustainable transport or place making activities, even if there is an impact (to some extent) on the level of service of the car. *Dynamic road space allocation* must be seen as fair and reasonable by the public and promote minor and gradual behavioural changes, in order to challenge car space.

Zones with low complexity are characterized by low traffic volumes and demands, being vacant most of the time. Consequently, in these zones it is not recommended to reallocate space dynamically, since the current demands are very low. Reclaiming spaces statically for sustainable modes or place making activities are more indicated in this case.

Furthermore, key points from the discussions in the workshop also suggest that: i) it is more complex to change urban functions dynamically in small periods of time; ii) there is a higher need for technology when spaces are allocated dynamically in small periods of time; iii) there is a higher challenge to reallocate space dynamically when the road changes its geometry and use along the segment; iv) other policies besides reallocating road space dynamically may be necessary to change behaviours such as surveillance and fines for illegal parking.

It is important to mention that some *dynamic road space allocation* solutions are less complex to implement than others. As mentioned by a member in the workshop, it is plausible to believe dynamic bus lanes can be implemented in complex areas due to its controlled environment. Bus drivers are trained and can adapt to the transitions between uses, and car drivers are accustomed to sharing the space with the bus. On the contrary, solutions such as reallocating a traffic lane to a cycle lane dynamically may lead to confusion among users and create an unsafe environment due to the differences in speeds if not implemented properly. In this case, dynamic cycle lanes could be used when traffic is very low such as Sundays. Consequently, the dynamic cycle lane would serve a recreational purpose, instead of commuting. The social acceptance and the success of allocating road space dynamically is dependent on the type of solution being implemented, the time interval of the dynamic application (e.g., hours, days, seasons) and the smartness level of the solution. *Dynamic road space allocation* should not make disruptive changes to the built environment, maintaining most of the street's characteristics in a logical orientation.

RQ4: Can <u>technology</u> be a tool to guide <u>decision-making</u> processes and enable interdisciplinary comprehension of allocating road space dynamically?

The decision-making process of reallocating road space dynamically in complex areas may not be evident for industry and municipality technical staff of different backgrounds. Promoting the participation of different stakeholders is essential for discussing trade-offs of the intervention and having an interdisciplinary and broader view on the impacts and acceptability of innovative processes. Visualizations of future scenarios of how the street can look like can help stakeholders understand concepts that are not well established, such as *dynamic road space allocation*, and also evaluate many scenarios at the same time. Still, many street reallocation projects that rely on visualizations of scenarios take a significant time and effort. Visualizations using CAD softwares in workshops have many limitations since they do not generate visualizations in real-time, are not developed for multiple users to collaborate, and require arduous work in complex projects. Consequently, these softwares are usually only used in the final phases of decision making.

Nonetheless, visualizations can have an important role in initial stages of decision making, making the concept of *dynamic road space allocation* more easily understood and stimulating discussions. In this context, Chapter 7 presents an experiment of using a generative deep model (artificial intelligence) to generate future scenarios of a street. The main purpose of this idea is to generate many visualizations for a street by modifying some characteristics of the images. In a workshop, stakeholders would have many scenarios of a street that could promote discussion on the ideal solutions for reallocating road space (statically or dynamically). Thus, policy makers could choose only one or many generated images, depending on if they evaluate that the space should be allocated statically or dynamically, respectively.

A challenge for using AI in workshops of road space allocation projects is in how people may trust the results of the algorithm. Here, the moderator has to be clear on the capabilities and limitations of the images generated and also state that eventually some scenarios may not be applicable. However, presenting many solutions, even if some are more applicable than others, can generate discussions and better understanding of the concept. This idea is very likely not to contain illegal content, unless the images contain people that could be identified. Also, the type of data used for training such as Google Street View or Mappilary images may lead to different perceptions of the solutions, and may result in different scenarios. It is important in the workshop that limitations and capabilities of the type of data used are disclosed.

In terms of regulation, the transparency of generative models is a main concern. The proposed AI Act in Europe establishes that generative models require three main transparency principles: i) it has to be clear that all contents were generated by AI; ii) they cannot generate illegal content; and iii) they have to disclose the copyright information of the data used for training. Although these are steps towards more transparency in AI, they fail to disclose the biases, limitations, and capabilities of the algorithm and the type of data used for training. Additionally, it may not always be evident when contents are illegal, especially if they face the *trolley problem*.

Most developments in AI image generation are trying to make images more realistic, rather than focusing on the emotional responses, and comprehension of the message being delivered. Images too realistic may reduce creativity and lead to misinterpretations of the limitations of the algorithm. A higher level of detail does not result necessarily in better understanding. A certain level of "noise" in the generated images could actually enhance creativity and promote discussions, besides being evident that the image was generated by AI.

One of the main conclusions of the experiment is that generative deep models are dependent on a huge amount and quality of data and computational power in order to obtain meaningful results. Consequently, research and innovations of image generation may only be possible with a very high monetary investment, limiting the developments to more powerful institutions. In practice, private companies such as OpenAI, Microsoft and Google are the ones leading the way on the developments of generative artificial intelligence, both for image generation (e.g., DALL-E, Midjourney) and text generation (e.g., CHAT-GPT). There is a risk that these developments go in line with *surveillance capitalism*, being mainly developed for obtaining profit and market control, then actually contributing to people's better understanding of concepts and ideas. Therefore, the society impacts of generative models and how people perceive and eventually change behaviours from its results is still not clear.

8.2 Limitations and future research directions

This thesis has explored many methods to determine where, when and how can road space be allocated dynamically over time. We established criteria for selecting the most appropriate sites and periods of time for reallocating road space dynamically. Also, a discussion on the use of artificial intelligence to improve the decision-making process of road space allocation solutions was held. The main conclusion of the work is that different solutions of allocating road space dynamically in complex urban areas vary from implementation complexity, technological requirements and social acceptance depending on the local context. The work developed in this thesis has been discussed in well-known international and national conferences, and three chapters are currently published or accepted for publication in Q1 journals (Chapters 2, 5, and 6) while one chapter is published in an important journal, but that does not currently have an Impact Factor due to its novelty (Chapter 3). Currently, one chapter has been submitted to a Q1 journal (Chapter 4), remaining only Chapter 7 to be submitted in the future. Although this work has made major contributions to the literature, it still requires future research to address topics such as the impacts in diverse spheres (e.g., traffic performance and accessibility) and social acceptance of such solutions.

In Chapter 3 (refer to Figure 11), a framework is presented for evaluating the traffic performance impacts of different *dynamic road space allocation* solutions. From the site selection process in Chapters 5 and 6, it is possible to select a street with high potential for reallocating road space dynamically. Sequentially, there is a need to collect data in this street to evaluate the urban dynamics. A suggestion is to film a street for 24 hours during a whole week. It is important that the video camera does not infringe data privacy of users such as facial recognition. To calibrate and evaluate the spillover effects such as traffic evaporation, it is necessary to also have data on the surroundings of the street being evaluated. In this case, manual traffic counts in surrounding intersections during peak hours, when demands are typically higher, is sufficient.

After exporting and treating the data from the videos, an object detection algorithm could be used to identify and count the number of different transport modes that pass every 15 minutes. Consequently, it is possible to evaluate the intensities and fluctuations of various demands, and define if they are complementary, disputed, or even if the space is vacant. From the local criteria established in the workshop (Chapter 6), it is also possible to choose which solutions are more probable to be implemented in certain situations. Also, the use of artificial intelligence to generate solutions, as referred to in Chapter 7, can help in building the scenarios for impact evaluation. After the decision of the scenarios, and analysis of urban dynamics, it is possible to evaluate its impacts through microsimulation.

On one hand, when the demands are complementary, it is expected that the demands of the transport mode being allocated the space increases, without jeopardizing the one that lost temporarily the space. On the other hand, when the demands are disputed it is expected that the demands of the transport mode being allocated the space also increases, but there is an impact on the level of service of the other transport mode. In this case, there must be a criterion of how much the policy makers are willing to compromise one mode for another.

Another interesting topic of study is how *dynamic road space allocation* influences the accessibility of different users to main services and contributes to the concept of the *15-minute city*. Solá and Vilhelmson (2019) developed the "flowers of proximity" to visualize the distances of different activities. More recently, this concept has been applied to evaluate the accessibility of different cities (Büttner et al., 2022). The "flowers of proximity" puts activities in different ranges of travel times (e.g., 5, 15, and 30 minutes), where each "petal of the flower" represents a type of activity (e.g., healthcare, education, entertainment, commerce, working and living). Consequently, there are petals that are wider depending on the number of activities per category and larger depending on their accessibility in travel time. If we consider the accessibility to activities over time, each "flower petal" would increase and/or decrease its size (travel times to activities) depending on how the infrastructure supports the demands. Allocating road space dynamically could potentially increase the accessibility to essential activities, but also reduce to others. It is important to evaluate the performance of *dynamic road space allocation* not only in terms of level of services and traffic performance, but also if it increases the accessibility to essential activities. The latter policy goal can be used as an important argument to implement these solutions in public meetings.

Furthermore, it is necessary to evaluate the emotional responses to adapting road space dynamically, evaluating what are the main factors that influence people to accept and adapt easily to changes in urban environments. In Chapter 3 and Chapter 6, we discussed that there are many challenges in terms user acceptability, especially during the transitions from one use to another. It is important to emphasize that different solutions and technological adoption will have different levels of acceptance. Some methodologies could be used for evaluating public acceptance.

First, if it is possible to implement in practice a pilot project that allocates space dynamically, then it would be interesting to perform surveys on users and workers of surrounding commerce and services. If it is not possible to put in practice a case study, then virtual reality or videos of different scenarios that present the dynamic transitions to possible users could be used as visualizations of how the environment would become. While evaluating a pilot project, the surveys would rely on revealed preferences from the experience of using the space, virtual reality and video rely on declared preferences, having its limitations of possibly having socially wanted responses.

References

Al-Dweik, A. J., Mayhew, M., Muresan, R., Ali, S. M., & Shami, A. (2017). Using Technology to Make Roads Safer: Adaptive Speed Limits for an Intelligent Transportation System. *IEEE Vehicular Technology Magazine*, *12*(1), 39–47. https://doi.org/10.1109/MVT.2016.2634462

Al-Kodmany, K. (2001). Supporting imageability on the World Wide Web: Lynch's five elements of the city in community planning. *Environment and Planning B: Planning and Design*, *28*(6), 805–832. https://doi.org/10.1068/b2746t

Albino, V., Berardi, U., & Dangelico, R. M. (2015). Smart Cities: Definitions, Dimensions, Performance, and Initiatives. *Journal of Urban Technology*, *22*(1), 3–21. https://doi.org/10.1080/10630732.2014.942092

Alhajyaseen, W. K. M., Najjar, M., Ratrout, N. T., & Assi, K. (2017). The effectiveness of applying dynamic lane assignment at all approaches of signalized intersection. *Case Studies on Transport Policy*, *5*(2), 224–232. https://doi.org/10.1016/j.cstp.2017.01.008

Alhajyaseen, W. K. M., Ratrout, N. T., Assi, K. J., & Hassan, A. A. (2017). The Integration of Dynamic Lane Grouping Technique and Signal Timing Optimization for Improving the Mobility of Isolated Intersections. *Arabian Journal for Science and Engineering*, *42*(3), 1013–1024. https://doi.org/10.1007/s13369-016-2274-4

Aliyu, A., Abdullah, A. H., Kaiwartya, O., Cao, Y., Lloret, J., Aslam, N., & Mohammed, U. (2018). Towards video streaming in IoT Environments : Vehicular communication perspective. *Computer Communications*, *118*(March), 93–119. https://doi.org/10.1016/j.comcom.2017.10.003

Amoh-Gyimah, R., Saberi, M., & Sarvi, M. (2016). Macroscopic modeling of pedestrian and bicycle crashes: A cross-comparison of estimation methods. *Accident Analysis and Prevention*, *93*(August), 147–159. https://doi.org/10.1016/j.aap.2016.05.001

Anderson, P., & Geroliminis, N. (2020). Dynamic lane restrictions on congested arterials. *Transportation Research Part A: Policy and Practice*, *135*(March), 224–243. https://doi.org/10.1016/j.tra.2020.03.009

Anvari, B., Bell, M. G. H., Sivakumar, A., & Ochieng, W. Y. (2015). Modelling shared space users via rule-based social force model. *Transportation Research Part C: Emerging Technologies*, *51*(February), 83–103. https://doi.org/10.1016/j.trc.2014.10.012

Assi, K. J., & Ratrout, N. T. (2018). Proposed quick method for applying dynamic lane assignment at signalized intersections. *IATSS Research*, *42*(1), 1–7. https://doi.org/10.1016/j.iatssr.2017.03.004

Austroads. (1988). *Guide to Traffic Engineering Practice*.

Austroads. (2015). *Guide to Traffic Management Part 1: Introduction to Traffic Management* (3rd ed.). Austroads Lrd. https://doi.org/978-1-925294-38-5

Awad, E., Dsouza, S., Kim, R., Schulz, J., Henrich, J., Shariff, A., Bonnefon, J. F., & Rahwan, I. (2018). The Moral Machine experiment. *Nature*, *563*(7729), 59–64. https://doi.org/10.1038/s41586-018-0637-6

Baier, L., & Seebacher, S. (2019). Challenges in the deployment and operation of machine learning in practice. *27th European Conference on Information Systems*, *May*, 1–15. https://aisel.aisnet.org/ecis2019_rp/163/

Banister, D. (2008). The sustainable mobility paradigm. *Transport Policy*, *15*(2), 73–80. https://doi.org/10.1016/j.tranpol.2007.10.005

Banister, D. (2011). Cities, mobility and climate change. *Journal of Transport Geography*, *19*(1), 1538–1546. https://doi.org/10.1016/j.jtrangeo.2011.03.009

Barbeau, S. J., & Antrim, A. (2013). The Many Uses of GTFS Data – Opening the Door to Transit and Multimodal Applications. *Location-Aware Information Systems Laboratory at the University of South Florida*, *4*. http://prezi.com/-69luw8sfabp/the-many-uses-of-gtfs-data-its-america-april-2013/

Barrero, G. A., & Rodriguez-Valencia, A. (2022). Asking the user: a perceptional approach for bicycle infrastructure design. *International Journal of Sustainable Transportation*, *16*(3), 246–257. https://doi.org/10.1080/15568318.2020.1871127

Barthelemy, M. (2017). From paths to blocks: New measures for street patterns. *Environment and Planning B: Planning and Design*, *44*(2), 256–271. https://doi.org/10.1177/0265813515599982

Bastani, K., Namavari, H., & Shaffer, J. (2019). Latent Dirichlet allocation (LDA) for topic modeling of the CFPB consumer complaints. *Expert Systems with Applications*, *127*(August), 256–271. https://doi.org/10.1016/j.eswa.2019.03.001

Batty, M. (2013). Big data, smart cities and city planning. *Dialogues in Human Geography*, *3*(3), 274–279. https://doi.org/10.1177/2043820613513390

Batty, M., Chapman, D., Evans, S., Haklay, M., Kueppers, S., Shiode, N., Smith, A., & Torrens, P. M. (2001). *Visualizing the city: communicating urban design to planners and decision-makers*.

Berghauser Pont, M., Stavroulaki, G., & Marcus, L. (2019). Development of urban types based on network centrality, built density and their impact on pedestrian movement. *Environment and Planning B: Urban Analytics and City Science*, *46*(8), 1549–1564. https://doi.org/10.1177/2399808319852632

Berglund, E. Z., Monroe, J. G., Ahmed, I., Noghabaei, M., Do, J., Pesantez, J. E., Khaksar Fasaee, M. A., Bardaka, E., Han, K., Proestos, G. T., & Levis, J. (2020). Smart Infrastructure: A Vision for the Role of the Civil Engineering Profession in Smart Cities. *Journal of Infrastructure Systems*, *26*(2), 03120001. https://doi.org/10.1061/(asce)is.1943-555x.0000549

Bertolini, L. (2020). From "streets for traffic" to "streets for people": can street experiments transform urban mobility? *Transport Reviews*, *40*(6), 734–753. https://doi.org/10.1080/01441647.2020.1761907

Bibri, S. E., & Krogstie, J. (2017). On the social shaping dimensions of smart sustainable cities: A study in science, technology, and society. *Sustainable Cities and Society*, *29*(February), 219–246. https://doi.org/10.1016/j.scs.2016.11.004

Bivand, R., Krug, R., Neteler, M., Jeworutzki, S., & Vanderhaeghe, F. (2021). *rgrass7: Interface Between GRASS 7 Geographical Information System and R* (0.2-5). https://cran.r-project.org/package=rgrass7

Blei, D. M., Ng, A. Y., & Jordan, M. I. (2003). Latent Dirichlet Allocation. *Journal of Machine Learning Research*, *3*, 993–1022.

Bozovic, T., Hinckson, E., Stewart, T., & Smith, M. (2021). How to improve the walking realm in a car-oriented city? (Dis)agreements between professionals. *Transportation Research Part F: Traffic Psychology and Behaviour*, *81*(July), 490–507. https://doi.org/10.1016/j.trf.2021.06.011

Brandão, A., & Brandão, P. (2019). *O lugar de todos: Interpretar o espaço público urbano* (A. Brandão & P. Brandão (eds.); IST-ID, As). Rainho & Neves, Lda.

Breitenstein, J., & Fingscheidt, T. (2022). Amodal Cityscapes: A New Dataset, its Generation, and an Amodal Semantic Segmentation Challenge Baseline. *IEEE Intelligent Vehicles Symposium, Proceedings*, *2022-June*, 1018–1025. https://doi.org/10.1109/IV51971.2022.9827342

Bremner, L. (2000). Reinventing the Johannesburg inner city. *Cities*, *17*(3), 185–193.

Büttner, B., Seisenberger, S., Larriva, M. T. B., De Gante, A. G. R., Haxhija, S., Ramirez, A., &

McCormick, B. (2022). *Urban Mobility Next 9: ±15-Minute City: Human-centred planning in action* (Issue November). https://doi.org/10.13140/RG.2.2.10482.79041

Cai, J., Luo, J., Wang, S., & Yang, S. (2018). Feature selection in machine learning: A new perspective. *Neurocomputing*, *300*, 70–79. https://doi.org/10.1016/j.neucom.2017.11.077

Cai, L., Xu, J., Liu, J., Ma, T., Pei, T., & Zhou, C. (2019). Sensing multiple semantics of urban space from crowdsourcing positioning data. *Cities*, *93*(October), 31–42. https://doi.org/10.1016/j.cities.2019.04.011

Calabrese, F., Diao, M., Di Lorenzo, G., Ferreira, J., & Ratti, C. (2013). Understanding individual mobility patterns from urban sensing data: A mobile phone trace example. *Transportation Research Part C: Emerging Technologies*, *26*(January), 301–313. https://doi.org/10.1016/j.trc.2012.09.009

Cambra, P., & Moura, F. (2020). How does walkability change relate to walking behavior change? Effects of a street improvement in pedestrian volumes and walking experience. *Journal of Transport and Health*, *16*(November), 100797. https://doi.org/10.1016/j.jth.2019.100797

Candelo, C., Ortiz, G. A., & Unger, B. (2003). *Organising and Running Workshops: A practical guide for trainers*. WWF Colombia.

Carr, J., & Dionisio, M. R. (2017). Flexible spaces as a "third way" forward for planning urban shared spaces. *Cities*, *70*(July), 73–82. https://doi.org/10.1016/j.cities.2017.06.009

Cervero, R. (1996). Mixed land-uses and commuting: Evidence from the American housing survey. *Transportation Research Part A: Policy and Practice*, *30*(5), 361–377. https://doi.org/10.1016/0965-8564(95)00033-X

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment*, *2*(3), 199–219. https://doi.org/10.1016/S1361-9209(97)00009-6

Chauhan, S., Agarwal, N., & Kar, A. K. (2016). Addressing big data challenges in smart cities: a systematic literature review. *Info*, *18*(4), 73–90. https://doi.org/10.1108/info-03-2016-0012

Chen, P. (2015). Built environment factors in explaining the automobile-involved bicycle crash frequencies: A spatial statistic approach. *Safety Science*, *79*(November), 336–343. https://doi.org/10.1016/j.ssci.2015.06.016

Chen, S., Wang, H., & Meng, Q. (2022). An Optimal Dynamic Lane Reversal and Traffic Control Strategy for Autonomous Vehicles. *IEEE Transactions on Intelligent Transportation Systems*, *23*(4), 3804–3815. https://doi.org/10.1109/TITS.2021.3074011

Chiabaut, N., Xie, X., & Leclercq, L. (2014). Performance analysis for different designs of a multimodal urban arterial. *Transportmetrica B: Transport Dynamics*, *2*(3), 229–245. https://doi.org/10.1080/21680566.2014.939245

Choosumrong, S., Raghavan, V., Delucchi, L., Yoshida, D., & Vinayaraj, P. (2014). Implementation of Dynamic Routing as a Web Service for Emergency Routing Decision Planning. *International Journal of Geoinformatics*, *10*(2).

Chu, K. F., Lam, A. Y. S., & Li, V. O. K. (2020). Dynamic Lane Reversal Routing and Scheduling for Connected and Autonomous Vehicles: Formulation and Distributed Algorithm. *IEEE Transactions on Intelligent Transportation Systems*, *21*(6), 2557–2570. https://doi.org/10.1109/TITS.2019.2920674

Cocola-Gant, A., & Gago, A. (2021). Airbnb, buy-to-let investment and tourism-driven displacement: A case study in Lisbon. *Environment and Planning A: Economy and Space*, *53*(7), 1671–1688. https://doi.org/10.1177/0308518X19869012

Couch, C., & Dennemann, A. (2000). Urban regeneration and sustainable development in Britain: The example of the Liverpool Ropewalks Partnership. *Cities*, *17*(2), 137–147.

Cresswell, A. M., & Pardo, T. A. (2001). Implications of legal and organizational issues for urban digital government development. *Government Information Quarterly*, *18*(4), 269–278. https://doi.org/10.1016/S0740-624X(01)00086-7

Currie, G., & Lai, H. (2008). Intermittent and dynamic transit lanes Melbourne, Australia, experience. *Transportation Research Record*, *2072*, 49–56. https://doi.org/10.3141/2072-06

Currie, G., Sarvi, M., & Young, B. (2007). A new approach to evaluating on-road public transport priority projects: Balancing the demand for limited road-space. *Transportation*, *34*(4), 413–428. https://doi.org/10.1007/s11116-006-9107-3

Daniels, T. (2010). Smart Growth: A New American Approach to Regional Planning. *Planning Practice and Research*, *16*(3–4), 271–279. https://doi.org/10.1080/02697450120107880

Datta, A. (2015). A 100 smart cities, a 100 utopias. *Dialogues in Human Geography*, *5*(1), 49–53. https://doi.org/10.1177/2043820614565750

De Fabritiis, C., Ragona, R., & Valenti, G. (2008). Traffic estimation and prediction based on real time floating car data. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 197–203. https://doi.org/10.1109/ITSC.2008.4732534

De Gruyter, C., Zahraee, S. M., & Young, W. (2022). Understanding the allocation and use of street space in areas of high people activity. *Journal of Transport Geography*, *101*(April), 103339. https://doi.org/10.1016/j.jtrangeo.2022.103339

Demsar, U., Spatenkova, O., & Virrantaus, K. (2008). Identifying Critical Locations in a Spatial Network with Graph Theory. *Transactions in GIS*, *12*(1), 61–82.

Diaz-Pinto, A., Colomer, A., Naranjo, V., Morales, S., Xu, Y., & Frangi, A. F. (2018). Retinal image synthesis for glaucoma assessment using DCGAN and VAE models. *International Conference on Intelligent Data Engineering and Automated Learning*, 224–232.

Domingos, P. (2012). A few useful things to know about machine learning. *Communications of the ACM*, *55*(10), 78–87. https://doi.org/10.1145/2347736.2347755

Duan, Y., Edwards, J. S., & Dwivedi, Y. K. (2019). Artificial intelligence for decision making in the era of Big Data – evolution, challenges and research agenda. *International Journal of Information Management*, *48*(January), 63–71. https://doi.org/10.1016/j.ijinfomgt.2019.01.021

Duell, M., Levin, M. W., Boyles, S. D., & Waller, S. T. (2016). Impact of autonomous vehicles on traffic management: Case of dynamic lane reversal. *Transportation Research Record: Journal of the Transportation Research Board*, *2567*, 87–94. https://doi.org/10.3141/2567-10

Dwivedi, Y. K., Hughes, L., Ismagilova, E., Aarts, G., Coombs, C., Crick, T., Duan, Y., Dwivedi, R., Edwards, J., Eirug, A., Galanos, V., Ilavarasan, P. V., Janssen, M., Jones, P., Kar, A. K., Kizgin, H., Kronemann, B., Lal, B., Lucini, B., … Williams, M. D. (2021). Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management*, *57*(101994). https://doi.org/10.1016/j.ijinfomgt.2019.08.002

Eichler, M. D. (2005). *Bus Lanes with Intermittent Priority: Assessment and Design* [University of California]. https://nacto.org/docs/usdg/bus_lanes_with_intermittent_priority_eichler.pdf

Eichler, M. D., & Daganzo, C. F. (2006). Bus lanes with intermittent priority: Strategy formulae and an evaluation. *Transportation Research Part B*, *40*(9), 731–744. https://doi.org/10.1016/j.trb.2005.10.001

Essa, M., Hussein, M., & Sayed, T. (2018). Road users' behavior and safety analysis of pedestrian–bike shared space: case study of Robson Street in Vancouver. *Canadian Journal of Civil Engineering*, *45*(12). https://doi.org/https://doi.org/10.1139/cjce-2017-0683

European Commission. (2011). White paper on transport: Roadmap to a single European transport area - towards a competitive and resource-efficient transport system. In *European Commission*. https://doi.org/10.2832/30955

European Commission. (2013). Together towards competitive and resource-efficient urban mobility. In *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Vol. 913 final* (Issue COM(2013)).

European Commission. (2021). *Proposal for a Regulation of the European Parliament and of the Council Laying Down Harmonised Rules on Artificial Intelligence (Artificial Intelligence Act) and Amending Certain Union Legislative Acts*.

Fatiguso, F., De Fino, M., Cantatore, E., & Caponio, V. (2017). Resilience of Historic Built Environments: Inherent Qualities and Potential Strategies. *Procedia Engineering*, *180*, 1024–1033. https://doi.org/10.1016/j.proeng.2017.04.262

Feinerer, I., Hornik, K., & Meyer, D. (2008). Text mining infrastructure in R. *Journal of Statistical Software*, *25*(5), 1–54. https://doi.org/10.18637/jss.v025.i05

Ferreri, M. (2019). Learning from temporary use and the making of on-demand communities in London's Olympic "fringes." *Urban Geography*. https://doi.org/10.1080/02723638.2019.1679527

Freeman, L. C. (1977). A Set of Measures of Centrality Based on Betweenness. *Sociometry*, *40*(1), 35–41. https://doi.org/10.2307/3033543

Freeman, L. C. (1979). Centrality in social networks: Conceptual Clarification. *Social Networks*, *1*(3), 215–239. https://doi.org/10.1016/0378-8733(78)90021-7

Fu, Q., Tian, Y., & Sun, J. (2021). Modeling and simulation of dynamic lane reversal using a cell transmission model. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, *26*(6), 1–13. https://doi.org/10.1080/15472450.2021.1973898

Galdini, R. (2020). Temporary uses in contemporary spaces. A European project in Rome. *Cities*, *96*, 102445. https://doi.org/10.1016/j.cities.2019.102445

Gehl, J. (2013). *Cities for people*. Island Press.

Geurs, K. (2018). Planning With Accessibility Indices in the Netherlands: Discussion Paper. *International Transport Forum*. www.itf-oecd.org

Gomez, M. V. (1998). Reflective Images : The Case of Urban Regeneration in Glasgow and Bilbao. *International Journal of Urban and Regional Planning*, *22*(1), 106–121. https://doi.org/https://doi.org/10.1111/1468-2427.00126

Gonzales, E. J., Geroliminis, N., Cassidy, M. J., & Daganzo, C. F. (2010). On the allocation of city space to multiple transport modes. *Transportation Planning and Technology*, *33*(8), 643–656. https://doi.org/10.1080/03081060.2010.527171

Gordon, E., Schirra, S., & Hollander, J. (2011). Immersive planning: A conceptual model for designing public participation with new technologies. *Environment and Planning B: Planning and Design*, *38*(3), 505–519. https://doi.org/10.1068/b37013

Gössling, S. (2016). Urban transport justice. *Journal of Transport Geography*, *54*(June), 1–9. https://doi.org/10.1016/j.jtrangeo.2016.05.002

Gössling, S., Schröder, M., Späth, P., & Freytag, T. (2016). Urban Space Distribution and Sustainable Transport. *Transport Reviews*, *36*(5), 659–679. https://doi.org/10.1080/01441647.2016.1147101

Gouda, M., Fan, J., Luc, K., Ibrahim, S., & El-Basyouny, K. (2021). Effect of Redesigning Public Shared Space Amid the COVID-19 Pandemic on Physical Distancing and Traffic Safety. *Journal of Transportation Engineering, Part A: Systems*, *147*(11), 04021077. https://doi.org/10.1061/jtepbs.0000596

Griffiths, R. (1995). Cultural strategies and new modes of urban intervention. *Cities*, *12*(4), 253–265. https://doi.org/10.1016/0264-2751(95)00042-K

Griffiths, T. L., & Steyvers, M. (2004). Finding scientific topics. *Proceedings of the National Academy of Sciences*, *101*(suppl 1), 5228–5235.

Grün, B., & Hornik, K. (2011). topicmodels: An R Package for Fitting Topic Models. *Journal of Statistical Software*, *40*(13). https://doi.org/10.18637/jss.v040.i13

Haans, A., & de Kort, Y. A. W. (2012). Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety, prospect, concealment, and escape. *Journal of Environmental Psychology*, *32*(4), 342–352. https://doi.org/10.1016/j.jenvp.2012.05.006

Hamilton-Baillie, B. (2008a). Shared Space: Reconciling people, places and traffic. *Built Environment*, *34*(2), 161–181. https://doi.org/https://doi.org/10.2148/benv.34.2.161

Hamilton-Baillie, B. (2008b). Towards shared space. *Urban Design International*, *13*(2), 130–138. https://doi.org/10.1057/udi.2008.13

Handy, S. (2020). Is accessibility an idea whose time has finally come? *Transportation Research Part D: Transport and Environment*, *83*(June), 102319. https://doi.org/10.1016/j.trd.2020.102319

Hass-klau, C. (1990). *The pedestrian and city traffic*. Belhaven Press.

Hass-klau, C. (1992). *Civilised streets: A guide to traffic calming*. Environmental and Transport Planning.

Hausknecht, M., Au, T. C., Stone, P., Fajardo, D., & Waller, T. (2011). Dynamic lane reversal in traffic management. *14th IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, *2*, 1929–1934. https://doi.org/10.1109/ITSC.2011.6082932

Havârneanu, G. M., & Havârneanu, C. E. (2012). When norms turn perverse: Contextual irrationality vs. rational traffic violations. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(2), 144–151. https://doi.org/10.1016/j.trf.2011.12.003

Hebbert, M. (2005). Engineering, urbanism and the struggle for street design. *Journal of Urban Design*, *10*(1), 39–59. https://doi.org/10.1080/13574800500062361

Herath, H. M. K. K. M. B., & Mittal, M. (2022). Adoption of artificial intelligence in smart cities: A comprehensive review. *International Journal of Information Management Data Insights*, *2*(1), 100076. https://doi.org/10.1016/j.jjimei.2022.100076

Herrschel, T. (2013). Competitiveness AND Sustainability : Can "Smart City Regionalism" Square the Circle ? *Urban Studies*, *50*(11), 2332–2348. https://doi.org/10.1177/0042098013478240

Herszenhut, D., Pereira, R., Andrade, P., Bazzo, J., Padgham, M., & Saraiva, M. (2022). *gtfstools: General Transit Feed Specification (GTFS) Editing and Analysing Tools*. 1.2.0. https://ipeagit.github.io/gtfstools/, https://github.com/ipeaGIT/gtfstools

Hickman, R., Hall, P., & Banister, D. (2013). Planning more for sustainable mobility. *Journal of Transport Geography*, *33*(1), 210–219. https://doi.org/10.1016/j.jtrangeo.2013.07.004

Hillier, B. (1996). *Space Is the Machine. A Configurational Theory of Architecture*. Cambridge University Press.

Hillier, B., & Iida, S. (2005). Network and Psychological Effects in Urban Movement. In A. G. Cohn & D. M. Mark (Eds.), *Spatial Information Theory* (Lecture no, pp. 475–490). Springer, Berlin, Heidelberg. https://doi.org/https://doi.org/10.1007/11556114_30

Hogan, T., Bunnell, T., Pow, C. P., Permanasari, E., & Morshidi, S. (2012). Asian urbanisms and the privatization of cities. *Cities*, *29*(1), 59–63. https://doi.org/10.1016/j.cities.2011.01.001

Hui, E. C. M., Li, X., Chen, T., & Lang, W. (2020). Deciphering the spatial structure of China's megacity region : A new bay area — The Guangdong-Hong Kong-Macao Greater Bay Area in the making. *Cities*, *105*(October), 102168. https://doi.org/10.1016/j.cities.2018.10.011

Hui, N., Saxe, S., Roorda, M., Hess, P., & Miller, E. J. (2018). Measuring the completeness of complete streets. *Transport Reviews*, *38*(1), 73–95. https://doi.org/10.1080/01441647.2017.1299815

Hussein, M., Popescu, B., Sayed, T., & Kim, L. (2016). Analysis of road user behavior and safety during New York City's Summer Streets Program. *Transportation Research Record*, *2586*, 120–130. https://doi.org/10.3141/2586-14

Hysing, E., Frändberg, L., & Vilhelmson, B. (2015). Compromising sustainable mobility? The case of Gothenburg congestion tax. *Journal of Environmental Planning and Management*, *58*(6), 1058–1075.

İmre, Ş., Çelebi, D., & Koca, F. (2021). Understanding barriers and enablers of electric vehicles in urban freight transport: Addressing stakeholder needs in Turkey. *Sustainable Cities and Society*, *68*(May), 102794. https://doi.org/10.1016/j.scs.2021.102794

InCites Journal Citation Reports. (2018). *2018 Journal Rankings*. https://jcr.clarivate.com/JCRHomePageAction.action?#

Instituto Nacional de Estatística. (2011). *Censos 2011: Resultados Definitivos - Portugal*.

Jazeel, T. (2015). Utopian urbanism and representational city-ness: On the Dholera before Dholera smart city. *Dialogues in Human Geography*, *5*(1), 27–30. https://doi.org/10.1177/2043820614565866

Jelodar, H., Wang, Y., Yuan, C., Feng, X., Jiang, X., & Li, Y. (2019). Latent Dirichlet allocation (LDA) and topic modeling: models, applications, a survey. *Multimedia Tools and Applications*, *78*(15169–15211). https://doi.org/10.1007/s11042-018-6894-4

Jöhnk, J., Weißert, M., & Wyrtki, K. (2021). Ready or Not, AI Comes— An Interview Study of Organizational AI Readiness Factors. *Business and Information Systems Engineering*, *63*(1), 5–20. https://doi.org/10.1007/s12599-020-00676-7

Johnsen, M., Brandt, O., Garrido, S., & Pereira, F. (2022). Population synthesis for urban resident modeling using deep generative models. *Neural Computing and Applications*, *34*(6), 4677–4692. https://doi.org/10.1007/s00521-021-06622-2

Jones, I. H. (2014). *Road space allocation: The intersection of transport planning, governance and infrastructure* (Issue November) [RMIT University]. https://researchbank.rmit.edu.au/view/rmit:160985

Jones, P. (2018). *MORE: Multimodal Optimisation of Roadspace in Europe*. Horizon 2020. https://www.roadspace.eu/

Jones, P. (2016). A comprehensive basis for determining the allocation of urban street space. *14th World Conference on Transport Research*, *July*. http://discovery.ucl.ac.uk/1502401/1/WCTR A comprehensive basis for determining the allocation of urban street space.pdf

Jones, P., Boujenko, N., & Marshall, S. (2007). *Link & Place-A guide to street planning and design*. Landor Publishing.

Junghans, L., Kreft, S., & Welp, M. (2018). Inclusive Visions for Urban Transitions: Lessons from stakeholder dialogues in Asian medium sized cities. *Sustainable Cities and Society*, *42*(October), 512–520. https://doi.org/10.1016/j.scs.2018.08.003

K. Popper. (1959). *The Logic of Scientific Discovery*. Hutchinson and Co.

Kampouri, A., Politis, I., & Georgiadis, G. (2022). A system-optimum approach for bus lanes dynamically activated by road traffic. *Research in Transportation Economics*, *92*(101075). https://doi.org/10.1016/j.retrec.2021.101075

Kang, C., Ma, X., Tong, D., & Liu, Y. (2012). Intra-urban human mobility patterns: An urban morphology perspective. *Physica A*, *391*, 1702–1717. https://doi.org/10.1016/j.physa.2011.11.005

Kaparias, I., Bell, M. G. H., Miri, A., Chan, C., & Mount, B. (2012). Analysing the perceptions of pedestrians and drivers to shared space. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(3), 297–310. https://doi.org/10.1016/j.trf.2012.02.001

Kaparias, I., & Li, P. (2021). Behaviour and perceptions of powered two-wheeler users in street designs with elements of shared space. *Transportation Research Part F: Traffic Psychology and Behaviour*, *80*(July), 368–380. https://doi.org/10.1016/j.trf.2021.05.007

Kapousizis, G., Ulak, M. B., Geurs, K., & Havinga, P. J. M. (2023). A review of state-of-the-art bicycle technologies affecting cycling safety: level of smartness and technology readiness. *Transport Reviews*, *43*(3), 430–452. https://doi.org/10.1080/01441647.2022.2122625

Kar, A. K., & Dwivedi, Y. K. (2020). Theory building with big data-driven research – Moving away from the "What" towards the "Why." *International Journal of Information Management*, *54*(June), 102205. https://doi.org/10.1016/j.ijinfomgt.2020.102205

Kar, A. K., Ilavarasan, V., Gupta, M. P., Janssen, M., & Kothari, R. (2019). Moving beyond Smart Cities: Digital Nations for Social Innovation & Sustainability. *Information Systems Frontiers*, *21*(3), 495–501. https://doi.org/10.1007/s10796-019-09930-0

Karami, A., Bookstaver, B., Nolan, M., & Bozorgi, P. (2021). Investigating diseases and chemicals in COVID-19 literature with text mining. *International Journal of Information Management Data Insights*, *1*(2), 100016. https://doi.org/10.1016/j.jjimei.2021.100016

Kesselring, S., & Freudendal-Pedersen, M. (2021). Searching for urban mobilities futures. Methodological innovation in the light of COVID-19. *Sustainable Cities and Society*, *75*(December), 103138. https://doi.org/10.1016/j.scs.2021.103138

Kidando, E., Moses, R., Sando, T., & Ozguven, E. E. (2019). An application of Bayesian multilevel model to evaluate variations in stochastic and dynamic transition of traffic conditions. *Journal of Modern Transportation*, *27*(4), 235–249. https://doi.org/10.1007/s40534-019-00199-2

Kim, D., Guida, G., & López, J. L. G. del C. (2022). PLACEMAKINGAI: Participatory Urban Design with Generative Adversarial Networks. *Proceedings of the 27th International Conference of the Association for Computer- Aided Architectural Design Research in Asia (CAADRIA)*, *2*, 485–494.

Krueger, R., & Casey, M. A. (2015). *Focus Groups: A Practical Guide for Applied Research* (5th ed.). SAGE Publications Lta.

Kumar, S., Kar, A. K., & Ilavarasan, P. V. (2021). Applications of text mining in services management: A systematic literature review. *International Journal of Information Management Data Insights*, *1*(1), 100008. https://doi.org/10.1016/j.jjimei.2021.100008

Kummitha, R. K. R., & Crutzen, N. (2017). How do we understand smart cities? An evolutionary perspective. *Cities*, *67*(July), 43–52. https://doi.org/10.1016/j.cities.2017.04.010

Kushwaha, A. K., Kar, A. K., & Dwivedi, Y. K. (2021). Applications of big data in emerging management disciplines: A literature review using text mining. *International Journal of Information Management Data Insights*, *1*(2), 100017. https://doi.org/10.1016/j.jjimei.2021.100017

Larsen, A. B. L., Sønderby, S. K., Larochelle, H., & Winther, O. (2016). Autoencoding beyond pixels using a learned similarity metric. *33rd International Conference on Machine Learning, ICML 2016*, *4*, 2341–2349.

Lauttamäki, V. (2014). *Practical Guide for Facilitating a Futures Workshop* (Issue October). Finland Futures Research Centre.

Lee, C., & Abdel-Aty, M. (2005). Comprehensive analysis of vehicle-pedestrian crashes at intersections in Florida. *Accident Analysis and Prevention*, *37*(4), 775–786. https://doi.org/10.1016/j.aap.2005.03.019

Lee, H., & Kim, S. (2021). Perceived Safety and Pedestrian Performance in Pedestrian Priority Streets (PPSs) in Seoul, Korea: A Virtual Reality Experiment and Trace Mapping. *International*

Journal of Environmental Research and Public Health, *18*(2501). https://doi.org/doi.org/10.3390/ijerph18052501

Lee, H., & Kim, S. N. (2019). Shared space and pedestrian safety: Empirical evidence from Pedestrian Priority Street projects in Seoul, Korea. *Sustainability (Switzerland)*, *11*(17). https://doi.org/10.3390/su11174645

Lenat, D. B., & Feigenbaum, E. A. (1991). On the thresholds of knowledge. *Artificial Intelligence*, *47*(1–3), 185–250. https://doi.org/10.1109/aiia.1988.13308

Levin, M. W., & Boyles, S. D. (2016). A cell transmission model for dynamic lane reversal with autonomous vehicles. *Transportation Research Part C: Emerging Technologies*, *68*(July), 126–143. https://doi.org/10.1016/j.trc.2016.03.007

Levin, M. W., Rey, D., & Schwartz, A. (2019). Max-pressure control of dynamic lane reversal and autonomous intersection management. *Transportmetrica B*, *7*(1), 1693–1718. https://doi.org/10.1080/21680566.2019.1691675

Li, L., Su, X., Wang, Y., Lin, Y., Li, Z., & Li, Y. (2015). Robust causal dependence mining in big data network and its application to traffic flow predictions. *Transportation Research Part C: Emerging Technologies*, *58*(Part B), 292–307. https://doi.org/10.1016/j.trc.2015.03.003

Li, S., Lyu, D., Liu, X., Tan, Z., Gao, F., & Huang, G. (2020). The varying patterns of rail transit ridership and their relationships with fine-scale built environment factors : Big data analytics from Guangzhou. *Cities*, *99*(April), 102580. https://doi.org/10.1016/j.cities.2019.102580

Li, Y., Li, K., Tao, S., Wan, X., & Chen, K. (2014). Optimization of the design of pre-signal system using improved cellular automaton. *Comput Intell Neurosc*, *2014*(926371). https://doi.org/0.1155/2014/926371

Li, Yingcheng, Xiong, W., & Wang, X. (2019). Does polycentric and compact development alleviate urban traffic congestion? A case study of 98 Chinese cities. *Cities*, *88*(May), 100–111. https://doi.org/10.1016/j.cities.2019.01.017

Liu, H., Liu, F., Fan, X., & Huang, D. (2022). Polarized self-attention: Towards high-quality pixel-wise mapping. *Neurocomputing*, *506*(September), 158–167. https://doi.org/10.1016/j.neucom.2022.07.054

Liu, W., Wu, W., Thakuriah, P., & Wang, J. (2020). The geography of human activity and land use: A big data approach. *Cities*, *97*(February), 102523. https://doi.org/10.1016/j.cities.2019.102523

Lopes, N., & Ribeiro, B. (2017). Novel trends in scaling up machine learning algorithms. *Proceedings - 16th IEEE International Conference on Machine Learning and Applications, ICMLA 2017*, 632–636. https://doi.org/10.1109/ICMLA.2017.00-90

Luo, S., Nie, Y., & Zhu, L. (2019). Intersection Operation with Non-Traditional Dynamic Lane Scheme through Vehicle-to-Signal Connection. *Transportation Research Record*, *2673*(8), 322–332. https://doi.org/10.1177/0361198119844970

Lynch, K. (1960). *The Image of the City*. MIT Press.

Lytras, M. D., Visvizi, A., Chopdar, P. K., Sarirete, A., & Alhalabi, W. (2021). Information Management in Smart Cities: Turning end users' views into multi-item scale development, validation, and policy-making recommendations. *International Journal of Information Management*, *56*(May 2020), 102146. https://doi.org/10.1016/j.ijinfomgt.2020.102146

Ma, C., & Xu, X. (2020). Providing Spatial-Temporal Priority Control Strategy for BRT Lanes: A Simulation Approach. *Journal of Transportation Engineering, Part A: Systems*, *146*(7), 1–7. https://doi.org/10.1061/jtepbs.0000385

Mahizhnan, A. (1999). Smart cities: The Singapore case. *Cities*, *16*(1), 13–18. https://doi.org/10.1016/S0264-2751(98)00050-X

Maia, G., Villas, L. A., Viana, A. C., Aquino, A. L. L., Boukerche, A., & Loureiro, A. A. F. (2015). A rate control video dissemination solution for extremely dynamic vehicular ad hoc networks. *Performance Evaluation*, *87*, 3–18. https://doi.org/10.1016/j.peva.2015.01.006

Mapillary. (n.d.). https://www.mapillary.com

Marques da Costa, E. (2016). Atlas Digital AML: Socio-Economia. *Atlas Digital - Área Metropolitana de Lisboa*, 1–28.

Martín, A., Julián, A., & Cos-gayón, F. (2019). Analysis of Twitter messages using big data tools to evaluate and locate the activity in the city of Valencia (Spain). *Cities*, *86*(March), 37–50. https://doi.org/10.1016/j.cities.2018.12.014

Martinelli, D. D. (2022). Evolution of Alzheimer's disease research from a health-tech perspective: Insights from text mining. *International Journal of Information Management Data Insights*, *2*(2), 100089. https://doi.org/10.1016/j.jjimei.2022.100089

Marty, R. (2023). *googletraffic: Google Traffic* (0.1.3). https://dime-worldbank.github.io/googletraffic/

McCann, B. (2005). Complete the streets! *Planning*, *71*(5), 18–23.

Mcfarland, D. A., Ramage, D., Chuang, J., Heer, J., Manning, C. D., & Jurafsky, D. (2013). Differentiating language usage through topic models. *Poetics*, *41*(6), 607–625. https://doi.org/10.1016/j.poetic.2013.06.004

McQuillan, A. G. (1998). Honesty and Foresight in Computer Visualizations. *Journal of Forestry*, *96*(6), 15–16. https://doi.org/10.1093/jof/96.6.15

Mehran, B., & Nakamura, H. (2009). Considering Travel Time Reliability and Safety for Evaluation of Congestion Relief Schemes on Expressway Segments. *IATSS Research*, *33*(1), 55–70. https://doi.org/10.1016/s0386-1112(14)60237-5

Mehta, V. (2015). The street as Ecology. In *Incomplete Streets: Processes, Practices, and Possibilities* (1st ed., p. 346). Routledge.

Merat, N., Louw, T., Madigan, R., Wilbrink, M., & Schieben, A. (2018). What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space? *Accident Analysis and Prevention*, *118*(September), 244–252. https://doi.org/10.1016/j.aap.2018.03.018

Merhi, M. I. (2023). An evaluation of the critical success factors impacting artificial intelligence implementation. *International Journal of Information Management*, *69*(April), 102545. https://doi.org/10.1016/j.ijinfomgt.2022.102545

Meyer, P. B., & Lyons, T. S. (2000). Lessons from Private Sector Brownfield Redevelopers. *Journal of the American Planning Association*, *66*(1), 46–57. https://doi.org/10.1080/01944360008976083

Miller, E. J. (2018). Accessibility: measurement and application in transportation planning. *Transport Reviews*, *38*(5), 551–555. https://doi.org/10.1080/01441647.2018.1492778

Mittal, P., Singh, Y., & Sharma, Y. (2015). Macroscopic Traffic Flow Model based Dynamic Road Traffic Lights Management Framework. *Indian Journal of Science and Technology*, *8*(1), 1–6. https://doi.org/10.17485/ijst/2015/v8i30/75970

Montgomery, J. (1998). Making a city: urbanity, vitality and urban design. *Journal of Urban Design*, *3*(1), 93–116. https://doi.org/10.1080/13574809808724418

Morris, B. T., & Trivedi, M. M. (2008). A survey of vision-based trajectory learning and analysis for surveillance. *IEEE Transactions on Circuits and Systems for Video Technology*, *18*(8), 1114–1127. https://doi.org/10.1109/TCSVT.2008.927109

Moura, F., & Antunes, A. (2022). *Streets4All*. Fundação para a Ciência e a Technologia.

https://streets4all.tecnico.ulisboa.pt/

Moura, F., & De Abreu E Silva, J. (2019). Smart Cities: Definitions, Evolution of the Concept and Examples of Initiatives. In W. Leal Filho, A. Azul, L. Brandli, P. Özuyar, & T. Wall (Eds.), *Industry, Innovation and Infrastructure. Encyclopedia of the UN Sustainable Development Goals*. Springer, Cham.

Nagy, D., Villaggi, L., & Benjamin, D. (2018). Generative urban design: Integrating financial and energy goals for automated neighborhood layout. *SimAUD*, 190–197. https://doi.org/10.22360/simaud.2018.simaud.025

Nannicini, G., Baptiste, P., Barbier, G., Krob, D., & Liberti, L. (2010). Fast paths in large-scale dynamic road networks. *Comput Optim Appl*, *45*(January), 143–158. https://doi.org/10.1007/s10589-008-9172-y

National Association of City Transportation Officials. (2016). *Transit Street Design Guide*. Island Press.

Nello-Deakin, S. (2019). Is there such a thing as a 'fair' distribution of road space? *Journal of Urban Design*, *24*(5), 698–714. https://doi.org/10.1080/13574809.2019.1592664

Nguyen, G., Dlugolinsky, S., Bobák, M., Tran, V., López García, Á., Heredia, I., Malík, P., & Hluchý, L. (2019). Machine Learning and Deep Learning frameworks and libraries for large-scale data mining: a survey. *Artificial Intelligence Review*, *52*(1), 77–124. https://doi.org/10.1007/s10462-018-09679-z

Noyman, A., & Larson, K. (2020). A Deep Image of the City: Generative Urban-Design Visualization. *SimAUD 2020: Symposium on Simulation in Architecture , Urban Design*, 161–168. http://simaud.org/2020/preprints/35.pdf

Open Mobility Data. (2022). *CARRIS GTFS*. https://transitfeeds.com/p/carris/1000

Orellana, D., & Guerrero, M. L. (2019). Exploring the influence of road network structure on the spatial behaviour of cyclists using crowdsourced data. *Environment and Planning B: Urban Analytics and City Science*, *46*(7), 1314–1330. https://doi.org/https://doi.org/10.1177/2399808319863810

Ortúzar, J. de D., & Willumsen, L. G. (2011). *Modelling Transport* (4th ed.). John Wiley & Sons, Ltd.

Osorio-arjona, J., & García-palomares, J. C. (2019). Social media and urban mobility : Using twitter to calculate home-work travel matrices. *Cities*, *89*(June), 268–280. https://doi.org/10.1016/j.cities.2019.03.006

Ozbil, A., Peponis, J., & Stone, B. (2011). Understanding the link between street connectivity, land use and pedestrian flows. *Urban Design International*, *16*(2), 125–141. https://doi.org/10.1057/udi.2011.2

Para, W., Guerrero, P., Kelly, T., Guibas, L., & Wonka, P. (2021). Generative Layout Modeling using Constraint Graphs. *International Journal of Computer Vision*, 6670–6680. https://doi.org/10.1109/iccv48922.2021.00662

Park, J., & Kim, J. (2019). Economic impacts of a linear urban park on local businesses: The case of Gyeongui Line Forest Park in Seoul. *Landscape and Urban Planning*, *181*(January), 139–147. https://doi.org/10.1016/j.landurbplan.2018.10.001

Park, Y., & Garcia, M. (2020). Pedestrian safety perception and urban street settings. *International Journal of Sustainable Transportation*, *14*(11), 860–871. https://doi.org/10.1080/15568318.2019.1641577

Pashkevich, A., Burghardt, T. E., Puławska-Obiedowska, S., & Šucha, M. (2022). Visual attention and speeds of pedestrians, cyclists, and electric scooter riders when using shared road – a field eye tracker experiment. *Case Studies on Transport Policy*, *10*(1), 549–558. https://doi.org/10.1016/j.cstp.2022.01.015

Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1), 439–446. https://doi.org/10.32614/RJ-2018-009

Pedersen, T. (2020). *A Tidy API for Graph Manipulation* (1.2.0). https://tidygraph.data-imaginist.com

Penn, A., Hillier, B., Banister, D., & Xu, J. (1998). Configurational modelling of urban movement networks. *Environment and Planing B: Planning and Design*, *25*(1), 59–84.

Pietsch, S. M. (2000). Computer visualisation in the design control of urban environments: A literature review. *Environment and Planning B: Planning and Design*, *27*(4), 521–536. https://doi.org/10.1068/b2634

Pinterest. (n.d.). *Lane Control Signs*. Retrieved April 21, 2021, from https://in.pinterest.com/vmsmaster/lane-control-signs/

POLIS. (2022). *Flexcurb*. EIT Urban Mobility. https://www.polisnetwork.eu/

Pulugurtha, S. S., & Sambhara, V. R. (2011). Pedestrian crash estimation models for signalized intersections. *Accident Analysis and Prevention*, *43*(1), 439–446. https://doi.org/10.1016/j.aap.2010.09.014

QGIS Development Team. (2021). *QGIS Geographic Information System* (3.18 (Zürich)). Open Source

Geospatial Foundation Project. https://qgis.org

Qin, H., Chen, W., Chen, W., Li, N., Zeng, M., & Peng, Y. (2021). A collision-aware mobile tag reading algorithm for RFID-based vehicle localization. *Computer Networks*, *199*(November), 108422. https://doi.org/10.1016/j.comnet.2021.108422

Quan, S. J. (2022). Urban-GAN: An artificial intelligence-aided computation system for plural urban design. *Environment and Planning B: Urban Analytics and City Science*, *49*(9), 2500–2515. https://doi.org/10.1177/23998083221100550

Quan, S. J., Park, J., Economou, A., & Lee, S. (2019). Artificial intelligence-aided design: Smart Design for sustainable city development. *Environment and Planning B: Urban Analytics and City Science*, *46*(8), 1581–1599. https://doi.org/10.1177/2399808319867946

Rahmani, M., Jenelius, E., & Koutsopoulos, H. N. (2015). Non-parametric estimation of route travel time distributions from low-frequency floating car data. *Transportation Research Part C: Emerging Technologies*, *58*(Part B), 343–362. https://doi.org/10.1016/j.trc.2015.01.015

Ratti, C. (2019). *Carlo Ratti Associati*. The Dynamic Street. https://carloratti.com/project/the-dynamic-street/

Redmon, J., & Farhadi, A. (2018). YOLOv3: An incremental improvement. *ArXiv Preprint ArXiv:1804.02767*.

Reiter, E., Robertson, R., & Osman, L. M. (2003). Lessons from a failure: Generating tailored smoking cessation letters. *Artificial Intelligence*, *144*(1–2), 41–58. https://doi.org/10.1016/S0004-3702(02)00370-3

Ren, M., Lin, Y., Jin, M., Duan, Z., & Gong, Y. (2020). Examining the effect of land - use function complementarity on intra-urban spatial interactions using metro smart card records. *Transportation*, *47*(August), 1607–1629. https://doi.org/10.1007/s11116-019-09977-7

Rhys, H. I. (2020). *Machine Learning with R, the tidyverse and mlr*. Manning.

Roque, C., Lourenço, J., Connell, T., Schermers, G., & Weber, R. (2019). Topic analysis of Road safety inspections using latent dirichlet allocation: A case study of roadside safety in Irish main roads. *Accident Analysis and Prevention*, *131*(April), 336–349. https://doi.org/10.1016/j.aap.2019.07.021

Ruiz-Apilánez, B., Karimi, K., García-Camacha, I., & Martín, R. (2017). Shared space streets: design, user perception and performance. *Urban Design International*, *22*(3), 267–284. https://doi.org/10.1057/s41289-016-0036-2

Rychtyckyj, N., & Turski, A. (2008). Reasons for success (and failure) in the development and deployment of AI systems. In *AAAI 2008 workshop on What Went Wrong and Why: Vol. WS-08-14* (Issue February, pp. 25–31).

Salton, G., & McGill, M. J. (1983). *Introduction to modern information retrieval*. McGraw-Hill Book Co., New York.

Sarkar, C., Webster, C., & Kumari, S. (2018). Street morphology and severity of road casualties: A 5-year study of Greater London. *International Journal of Sustainable Transportation*, *12*(7), 510–525. https://doi.org/10.1080/15568318.2017.1402972

Sayarshad, H. R., & Gao, H. O. (2018). A scalable non-myopic dynamic dial-a-ride and pricing problem for competitive on-demand mobility systems. *Transportation Research Part C: Emerging Technologies*, *91*(April), 192–208. https://doi.org/10.1016/j.trc.2018.04.007

Schönauer, R., Stubenschrott, M., Huang, W., Rudloff, C., & Fellendorf, M. (2012). Modeling concepts for mixed traffic. *Transportation Research Record*, *2316*, 114–121. https://doi.org/10.3141/2316-13

Seco, A. J. da M., Antunes, A. J. P., Costa, A. H. P., & Silva, A. M. B. (2008). Princípios Básicos de Organização de redes viárias. In *Manual de Planejamento das Acessibilidades e da Gestão Viária* (Vol. 4).

Sequera, J., & Nofre, J. (2020). Touristification, transnational gentrification and urban change in Lisbon: The neighbourhood of Alfama. *Urban Studies*, *57*(15), 3169–3189. https://doi.org/10.1177/0042098019883734

Serok, N., Levy, O., Havlin, S., & Blumenfeld-lieberthal, E. (2019). Unveiling the inter-relations between the urban streets network and its dynamic traffic flows: Planning implication. *Environment and Planning B: Urban Analytics and City Science*, *46*(7), 1362–1376. https://doi.org/https://doi.org/10.1177/2399808319837982

Shannon, C. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*(3), 379–423.

Shearmur, R. (2012). Are cities the font of innovation? A critical review of the literature on cities and innovation. *Cities*, *29*(SUPPL.2), S9–S18. https://doi.org/10.1016/j.cities.2012.06.008

Sidewalk Labs. (2019a). *Toronto Tomorrow: A new approach for inclusive growth - Volume 1, Chapter 1 - The Quayside Plan*. https://storage.googleapis.com/sidewalk-toronto-ca/wp-content/uploads/2019/06/23142019/MIDP_Vol.1_Chap.1_TheQuaysidePlan.pdf

Sidewalk Labs. (2019b). *Toronto Tomorrow: A new approach for inclusive growth - Volume 2 - The Urban Innovations*.

Sidewalk Labs. (2020). *Announcing Delve: Discovering radically better urban designs*. https://www.sidewalklabs.com/blog/announcing-delve-discovering-radically-better-urban-designs

Sidewalk Labs. (2023). *Sidewalk Toronto*. https://www.sidewalklabs.com/toronto

Smart City Streets. (n.d.). *Pedestrian Safety Solutions*. Retrieved April 21, 2021, from https://smartcitystreets.com/pedestrian-safety/

Smuha, N. A., Ahmed-Rengers, E., Harkens, A., Li, W., MacLaren, J., Piselli, R., & Yeung, K. (2021). How the EU Can Achieve Legally Trustworthy AI: A Response to the European Commission's Proposal for an Artificial Intelligence Act. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3899991

Society of Automotive Engineers. (2019). *SAE levels of driving automation, refined for clarity and international audience*. https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic

Sohn, K., Yan, X., & Lee, H. (2015). Learning structured output representation using deep conditional generative models. *Advances in Neural Information Processing Systems*, *28*. https://proceedings.neurips.cc/paper_files/paper/2015/file/8d55a249e6baa5c06772297520da2051-Paper.pdf

Solá, A. G., & Vilhelmson, B. (2019). Negotiating proximity in sustainable urban planning: A Swedish case. *Sustainability (Switzerland)*, *11*(1), 31. https://doi.org/10.3390/su11010031

Song, J., Fan, Y., Song, H., & Zhao, H. (2022). Target Tracking and 3D Trajectory Reconstruction Based on Multicamera Calibration. *Journal of Advanced Transportation*, *2022*(5006347), 8. https://doi.org/10.1155/2022/5006347

Sun, C., Zhou, Y., & Han, Y. (2022). Automatic generation of architecture facade for historical urban renovation using generative adversarial network. *Building and Environment*, *212*(January), 108781. https://doi.org/10.1016/j.buildenv.2022.108781

Sun, L., & Yin, Y. (2017). Discovering themes and trends in transportation research using topic modeling. *Transportation Research Part C: Emerging Technologies*, *77*(April), 49–66. https://doi.org/10.1016/j.trc.2017.01.013

Sun, W., Zheng, J., & Liu, H. X. (2018). A capacity maximization scheme for intersection management with automated vehicles. *Transportation Research Part C: Emerging Technologies*, *94*(February), 19–31. https://doi.org/10.1016/j.trc.2017.12.006

Talavera-Garcia, R., & Soria-Lara, J. A. (2015). Q-PLOS, developing an alternative walking index. A method based on urban design quality. *Cities*, *45*(June), 7–17. https://doi.org/10.1016/j.cities.2015.03.003

Taleb, N. N. (2007). *The Black Swan: The impact of the highly improbable*. Random House.

Toole, J. L., Colak, S., Sturt, B., Alexander, L. P., Evsukoff, A., & González, M. C. (2015). The path most traveled: Travel demand estimation using big data resources. *Transportation Research Part C: Emerging Technologies*, *58*(September), 162–177. https://doi.org/10.1016/j.trc.2015.04.022

Tsigdinos, S., Tzouras, P. G., Bakogiannis, E., Kepaptsoglou, K., & Nikitas, A. (2022). The future urban road: A systematic literature review-enhanced Q-method study with experts. *Transportation Research Part D: Transport and Environment*, *102*(January), 103158. https://doi.org/10.1016/j.trd.2021.103158

Tu, W., Cao, J., Yue, Y., Shaw, S., Zhou, M., Wang, Z., Chang, X., Xu, Y., & Li, Q. (2017). Coupling mobile phone and social media data: a new approach to understanding urban functions and diurnal patterns. *International Journal of Geographical Information Science*, *31*(12), 2331–2358.

Tzamourani, E., Tzouras, P. G., Tsigdinos, S., Kosmidis, I., & Kepaptsoglou, K. (2022). Exploring the social acceptance of transforming urban arterials to multimodal corridors. The case of Panepistimiou Avenue in Athens. *International Journal of Sustainable Transportation*, *0*(0), 1–15. https://doi.org/10.1080/15568318.2022.2037793

Ukkusuri, S., Miranda-Moreno, L. F., Ramadurai, G., & Isa-Tavarez, J. (2012). The role of built environment on pedestrian crash frequency. *Safety Science*, *50*(4), 1141–1151. https://doi.org/10.1016/j.ssci.2011.09.012

Umbrellium. (2017). *Make Roads Safer, more Responsive and Dynamic*. https://umbrellium.co.uk/case-studies/south-london-starling-cv/

United Nations. (1976). Report of Habitat: United Nations Conference on Human Set. In *Habitat I*.

United Nations. (1992). *Agenda 21: United Nations conference on Environment and Development*.

United Nations. (1996). *United Nations Conference on Human Settlements (Habitat II)*.

United Nations. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development*.

United Nations. (2016). *The United Nations Conference on Housing and Sustainable Urban Development (Habitat III)*.

United Nations. (2019). *World Urbanization Prospects: The 2018 Revision*.

United Nations World Commission on Environment and Development (WCED). (1987). *Report of the World Commission on Environment and Development: Our Common Future*.

Valença, G., Moura, F., & Morais de Sá, A. (2021). Main challenges and opportunities to dynamic road space allocation: From static to dynamic urban designs. *Journal of Urban Mobility*, *1*(December), 100008. https://doi.org/10.1016/j.urbmob.2021.100008

Valença, G., & Santos, E. (2020). A relação entre o conceito de ruas completas e a Política Nacional de Mobilidade Urbana: Aplicação a um projeto viário em Natal-RN, Brasil. *Eure*, *46*(139), 73–89. https://doi.org/10.4067/S0250-71612020000300073

van Paridon, K. N., Leivers, H. K., Robertson, P. J., & Timmis, M. A. (2019). Visual search behaviour in young cyclists: A naturalistic experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *67*, 217–229. https://doi.org/10.1016/j.trf.2019.10.014

van Zoonen, L. (2016). Privacy concerns in smart cities. *Government Information Quarterly*, *33*(3), 472–480. https://doi.org/10.1016/j.giq.2016.06.004

Vansteenkiste, P., Zeuwts, L., Cardon, G., Philippaerts, R., & Lenoir, M. (2014). The implications of low quality bicycle paths on gaze behavior of cyclists: A field test. *Transportation Research Part F: Traffic Psychology and Behaviour*, *23*(March), 81–87. https://doi.org/10.1016/j.trf.2013.12.019

Viegas, J., & Lu, B. (2001). Widening the scope for bus priority with intermittent bus lanes. *Transportation Planning and Technology*, *24*(2), 87–110. https://doi.org/10.1080/03081060108717662

Viegas, J., & Lu, B. (2004). The Intermittent Bus Lane signals setting within an area. *Transportation Research Part C*, *12*(December), 453–469. https://doi.org/10.1016/j.trc.2004.07.005

von Schönfeld, K. C., & Bertolini, L. (2017). Urban streets: Epitomes of planning challenges and opportunities at the interface of public space and mobility. *Cities*, *68*(August), 48–55. https://doi.org/10.1016/j.cities.2017.04.012

Wang, C., David, B., Chalon, R., & Yin, C. (2016). Dynamic road lane management study: A Smart City application. *Transportation Research Part E: Logistics and Transportation Review*, *89*(May), 272–287. https://doi.org/10.1016/j.tre.2015.06.003

Wang, D., Fu, Y., Liu, K., Chen, F., Wang, P., & Lu, C.-T. (2022). Automated Urban Planning for Reimagining City Configuration via Adversarial Learning: Quantification, Generation, and Evaluation. *ACM Transactions on Spatial Algorithms and Systems*, 1–23. https://doi.org/10.1145/3524302

Wang, D., Liu, K., Johnson, P., Sun, L., Du, B., & Fu, Y. (2021). Deep Human-guided Conditional Variational Generative Modeling for Automated Urban Planning. *Proceedings - IEEE International Conference on Data Mining, ICDM*, *2021-Decem*(Icdm), 679–688. https://doi.org/10.1109/ICDM51629.2021.00079

Wang, F., Antipova, A., & Porta, S. (2011). Street centrality and land use intensity in Baton Rouge, Louisiana. *Journal of Transport Geography*, *19*(2), 285–293. https://doi.org/10.1016/j.jtrangeo.2010.01.004

Wang, J., Huang, H., & Zeng, Q. (2017). The effect of zonal factors in estimating crash risks by transportation modes: Motor vehicle, bicycle and pedestrian. *Accident Analysis and Prevention*, *98*(January), 223–231. https://doi.org/10.1016/j.aap.2016.10.018

Wang, Z., He, S. Y., & Leung, Y. (2018). Applying mobile phone data to travel behaviour research: A literature review. *Travel Behaviour and Society*, *11*(April), 141–155. https://doi.org/10.1016/j.tbs.2017.02.005

Wasserman, S., & Faust, K. (1994). *Social Network Analysis: Methods and Applications*. Cambridge University Press.

Wergles, N., & Muhar, A. (2009). The role of computer visualization in the communication of urban design-A comparison of viewer responses to visualizations versus on-site visits. *Landscape and Urban Planning*, *91*(4), 171–182. https://doi.org/10.1016/j.landurbplan.2008.12.010

Westenberger, J., Schuler, K., & Schlegel, D. (2021). Failure of AI projects: Understanding the critical factors. *Procedia Computer Science*, *196*(2022), 69–76. https://doi.org/10.1016/j.procs.2021.11.074

Wey, W., & Huang, J. (2018). Urban sustainable transportation planning strategies for livable City's quality of life. *Habitat International*, *82*(February), 9–27. https://doi.org/10.1016/j.habitatint.2018.10.002

Wu, D., Deng, W., Song, Y., Wang, J., & Kong, D. (2017). Evaluating Operational Effects of Bus Lane with Intermittent Priority under Connected Vehicle Environments. *Discrete Dynamics in Nature and Society*, *2017*(1659176). https://doi.org/10.1155/2017/1659176

Wu, W., Head, L., Yan, S., & Ma, W. (2018). Development and evaluation of bus lanes with intermittent and dynamic priority in connected vehicle environment. *Journal of Intelligent Transportation Systems*, *22*(4). https://doi.org/10.1080/15472450.2017.1313704

Xie, X., Chiabaut, N., & Leclercq, L. (2012). Improving Bus Transit in Cities with Appropriate Dynamic Lane Allocating Strategies. *Procedia - Social and Behavioral Sciences*, *48*, 1472–1481. https://doi.org/10.1016/j.sbspro.2012.06.1123

Yang, Z., & Pun-cheng, L. S. C. (2018). Vehicle detection in intelligent transportation systems and its applications under varying environments : A review. *Image and Vision Computing*, *69*, 143–154. https://doi.org/10.1016/j.imavis.2017.09.008

Yavar Bathaee. (2018). The artificial intelligence black box and the failure of intent and causation. *Harvard Journal of Law & Technology*, *31*(2), 890–938. https://jolt.law.harvard.edu/assets/articlePDFs/v31/The-Artificial-Intelligence-Black-Box-and-the-Failure-of-Intent-and-Causation-Yavar-Bathaee.pdf

Ye, H., & Xu, D. (2023). *Joint 2D-3D Multi-Task Learning on Cityscapes-3D: 3D Detection, Segmentation, and Depth Estimation*. 1–7. http://arxiv.org/abs/2304.00971

Zarindast, A., Sharma, A., & Wood, J. (2021). Application of text mining in smart lighting literature - an analysis of existing literature and a research agenda. *International Journal of Information Management Data Insights*, *1*(2), 100032. https://doi.org/10.1016/j.jjimei.2021.100032

Zavestoski, S., & Agyeman, J. (2015). *Incomplete streets : processes, practices and possibilities* (S. Zavestoski & J. Agyeman (Eds.); 1st Ed.). Routledge.

Zhang, F., Zheng, N., Yang, H., & Geroliminis, N. (2018). A systematic analysis of multimodal transport systems with road space distribution and responsive bus service. *Transportation Research Part C: Emerging Technologies*, *96*(August), 208–230. https://doi.org/10.1016/j.trc.2018.09.009

Zhang, K., & Batterman, S. (2013). Air pollution and health risks due to vehicle traffic. *Science of the Total Environment*, *450–451*, 307–316. https://doi.org/10.1016/j.scitotenv.2013.01.074

Zhao, J., Liu, Y., & Yang, X. (2015). Operation of signalized diamond interchanges with frontage roads using dynamic reversible lane control. *Transportation Research Part C*, *51*(February), 196–209. https://doi.org/10.1016/j.trc.2014.11.010

Zhao, J., Yao, J., He, S., & Han, Y. (2017). Operational efficiency evaluation of intersections with dynamic lane assignment using field data. *Journal of Advanced Transportation*, *2017*(2130385).

https://doi.org/10.1155/2017/2130385

Zhao, J., Yun, M., Zhang, H. M., & Yang, X. (2015). Driving simulator evaluation of drivers' response to intersections with dynamic use of exit-lanes for left-turn. *Accident Analysis & Prevention*, *81*(August), 107–119. https://doi.org/https://doi.org/10.1016/j.aap.2015.04.028

Zhao, Y., Zhang, H., An, L., & Liu, Q. (2018). Improving the approaches of traffic demand forecasting in the big data era. *Cities*, *82*(December), 19–26. https://doi.org/10.1016/j.cities.2018.04.015

Zheng, H., & Yuan, P. F. (2021). A generative architectural and urban design method through artificial neural networks. *Building and Environment*, *205*(November), 108178. https://doi.org/10.1016/j.buildenv.2021.108178

Zheng, N., & Geroliminis, N. (2013). On the distribution of urban road space for multimodal congested networks. *Transportation Research Part B: Methodological*, *57*(November), 326–341. https://doi.org/10.1016/j.trb.2013.06.003

Zheng, Y., Hua, X., Wang, W., Xiao, J., & Li, D. (2020). Analysis of a signalized intersection with dynamic use of the left-turn lane for opposite through traffic. *Sustainability (Switzerland)*, *12*(18). https://doi.org/10.3390/su12187530

Zhi, L., Zhou, X., & Zhao, J. (2020). Vehicle routing for dynamic road network based on travel time reliability. *IEEE Access*, *8*, 190596–190604. https://doi.org/10.1109/ACCESS.2020.3030654

Zhong, C., Arisona, S. M., Huang, X., Batty, M., Schmitt, G., Zhong, C., Arisona, S. M., Huang, X., & Batty, M. (2014). Detecting the dynamics of urban structure through spatial network analysis. *International Journal of Geographical Information Science*, *28*(11), 2178–2199. https://doi.org/10.1080/13658816.2014.914521

Zhu, H., Liu, J., Liu, H., Wang, X., & Ma, Y. (2017). Recreational Business District boundary identifying and spatial structure influence in historic area development: A case study of Qianmen area, China. *Habitat International*, *63*(May), 11–20. https://doi.org/10.1016/j.habitatint.2017.03.003

Zuboff, S. (2015). Big other: surveillance capitalism and the prospects of an information civilization. *Journal of Information Technology*, *30*(1), 75–89. https://doi.org/10.1057/jit.2015.5

Supplementary Materials[5]

- **Supplementary Material 1**

This supplementary material presents examples of the material used in the workshop with experts (Chapter 6).

In Task 2 of the workshop, participants were presented with three *dynamic road space allocation* solutions:

Solution 1: Allocating a traffic lane to a bus lane dynamically in a certain period of the day;

Solution 2: Allocating a traffic lane to a cycle lane dynamically in a certain period of the day;

Solution 3: Allocating a traffic lane or parking space to expand sidewalks dynamically in a certain period of the day.

To each solution, the groups had to choose one street within pre-determined zones (Selected in Chapter 5), that they considered the most appropriate to reallocate road space dynamically. From the 20 zones that were considered possible for reallocating road space dynamically detected in Chapter 5, each group selected randomly 4 zones to work on. Sequentially, each group received a group of cards containing photos of all the streets that intersected the 200 x 200 meters zones. For example, one of the zones analyzed by the green group was Zone 8. Figure 35[6] presents the back of every card of this zone. Figure 36 to Figure 40 present the front of the cards of all the streets within Zone 8. Thus, after the group analyzed all the cards, they selected the following streets as the most appropriate to implement *dynamic road space allocation* solutions:

Solution 1: Rua Morais Soares
Solution 2: Rua Morais Soares
Solution 3: Rua Jacinto Nunes

---

[5] The codes and data for reproducing the results of Chapter 2 and Chapter 7 are presented in the Replication and Data Sharing sections of each Chapter.
[6] "Zona" is the Portuguese translation of "Zone".

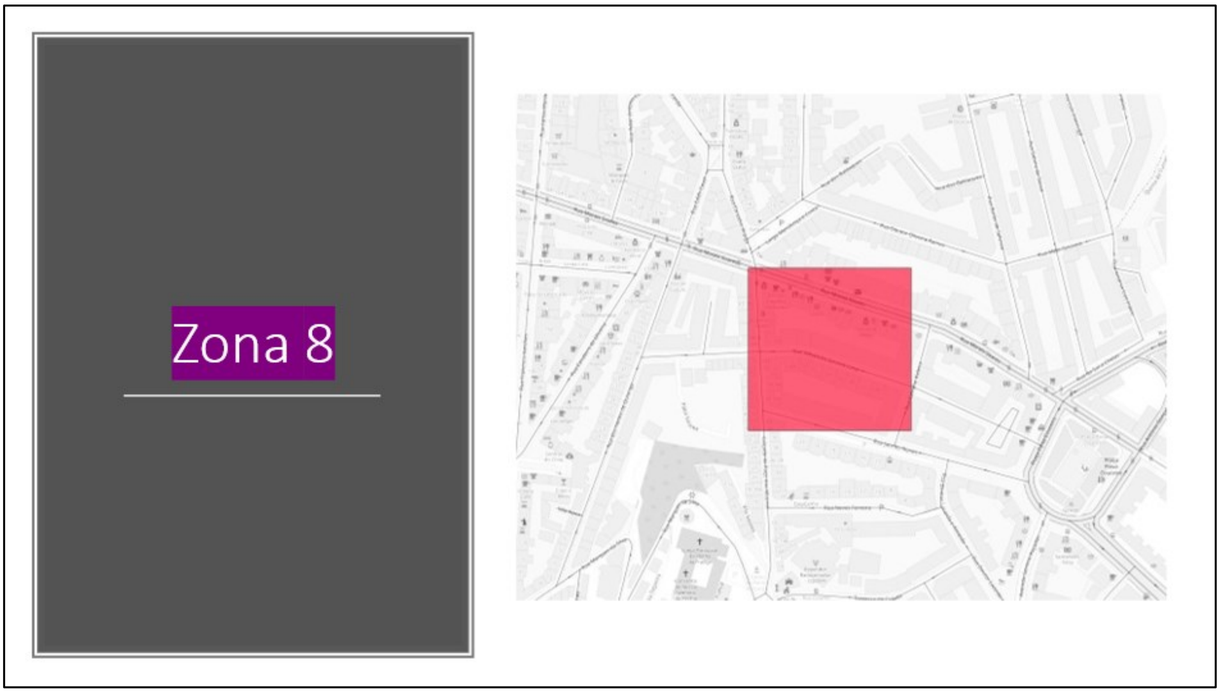

Figure 35: Back of cards from the workshop of Zone 8.
Source: Author.

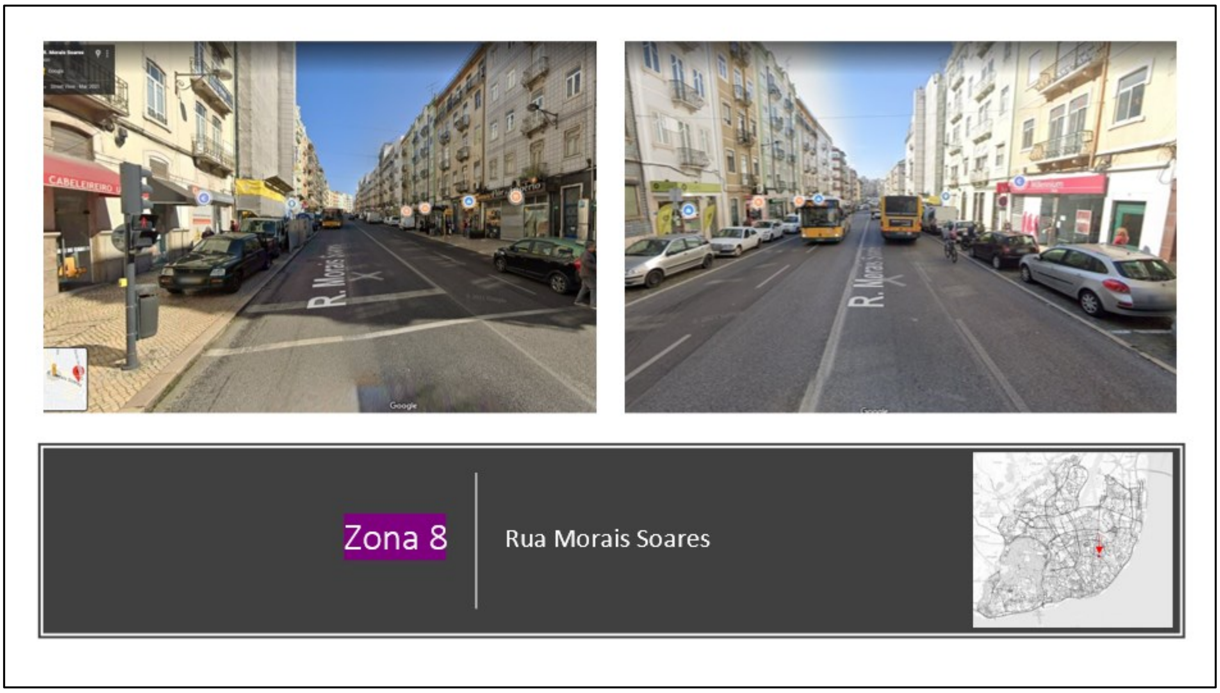

Figure 36: Front of the card of Rua Morais Soares.
Source: Author.

Figure 37: Front of the card of Calçada Poço dos Mouros.
Source: Author.

Figure 38: Front of the card of Rua Sebastião Saraiva Lima.
Source: Author.

Figure 39: Front of the card of Rua Jacinto Nunes.
Source: Author.

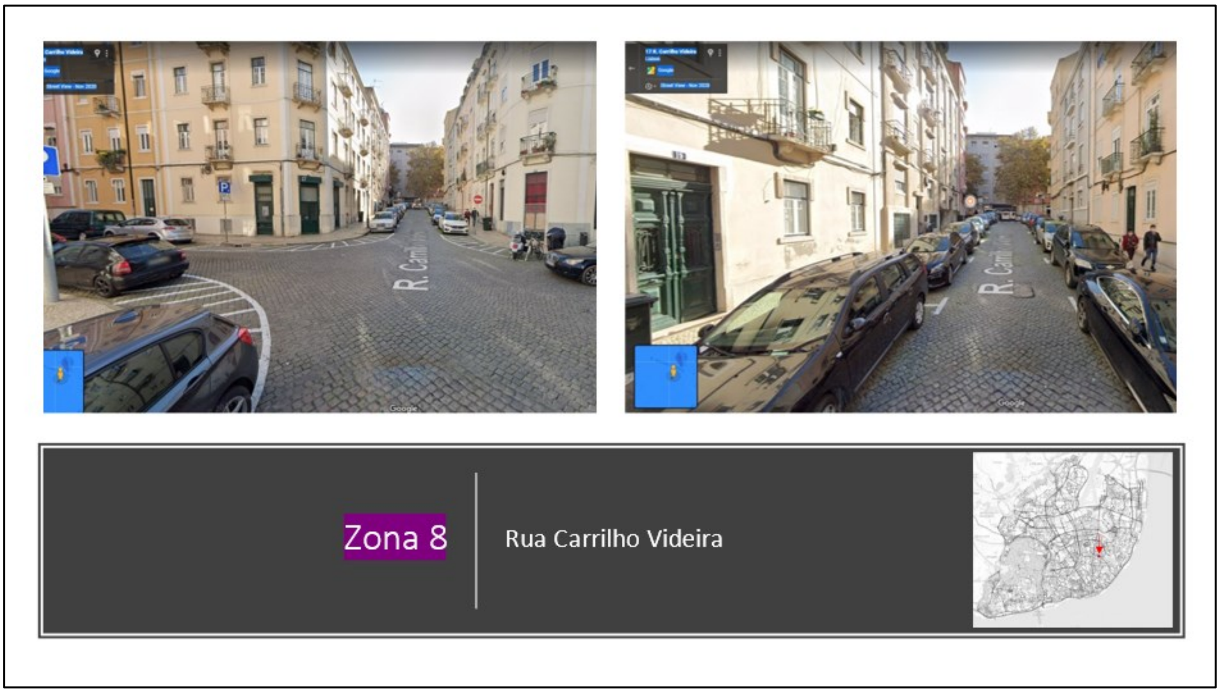

Figure 40: Front of the card of Rua Carrilho Videira.
Source: Author.

- **Supplementary Material 2**

In Task 3 of the workshop (Chapter 6), experts had to select and rank local criteria for selecting streets of intervention of three different *dynamic road space allocation* solutions. Every group received a sheet presenting some criteria that they could use to guide the discussion and decision, presented in Figure 41. This sheet contained urban qualities and physical characteristics of streets that have been known to influence active transportation and place making activity. Specifically, criterias related to the street cross section, adjacent space to the road, and barriers for implementing *dynamic road space allocation* were presented. It is important to mention that the groups could choose criteria that were not present in the sheet. Thus, the sheet had only the role to influence the discussion within the groups.

Possíveis critérios a serem considerados para a seleção das ruas e implementação da alocação dinâmica do espaço rodoviário

Características do perfil transversal	Características do espaço urbano adjacente à via	Possíveis barreiras para implementação de soluções DRSA
Mobiliário urbano	Diversidade social no local	Número de ruas a atravessar na viagem
Arborização	Atratividade do espaço público	Níveis de criminalidade
Atravessamento formal dos peões	Escala humana	Presença de lixo
Iluminação pública	Proximidade a espaços de permanência	Declives
Estacionamento público	Proximidade a paragens de transporte público	Ruído urbano
Distância do estacionamento a entrada dos edifícios	Espaços verdes	Volume de tráfego intenso
Largura bruta do passeio	Transparência das fachadas dos edifícios	Sinistralidade rodoviária elevada
Largura útil do passeio	Número de pontos de interesse	Vandalismo do espaço público
Largura da rua (fachada a fachada)	Esplanadas	
Altura dos edifícios	Número de edifícios com fachadas e cores atrativas	
Número de estabelecimentos comerciais	Extensão da frente do quarteirão	
Pavimento do passeio	Volume de pessoas	
Medidas acessibilidade universal	Diversidade dos usos em diferentes horários	
Sinalização vertical e horizontal	Diversidade das idades dos edifícios	
Número de casas de banho públicas	Presença de arte urbana	
Muros entre a edificação e a rua		

TÉCNICO LISBOA | U LISBOA | UNIVERSIDADE DE LISBOA

Figure 41: Sheet with many physical characteristics of streets and urban design qualities selected from the literature to guide the selection of criteria in Task 3 of the workshop.
Source: Author.