Universitat Autònoma de Barcelona

Essays on cities, urban form and emissions

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Content

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Summary

In this thesis we study how local and global emissions emerge in cities and which elements are critical to this. I examine the role of urban form on such emissions, through infrastructure and land use, and associated passenger and freight transport and stationary economic activities, which take place within city borders. Chapter 2 reviews the current literature on urban form in economics and geography. We contrast these two lines of literature and look at the application of the concept of urban form in urban economics, and how it interacts with that of environmental externalities. Policies, recommendations and ideas for further research are drawn and discussed. Chapter 3 explains the methodology used for the data collection on land use and transport in the Metropolitan Area of Barcelona. This serves as the empirical input for Chapter 4. Chapter 4 offers an ambitious, innovative model of local and global emissions, based on accounting economic activity, land uses and transport in a circular city. It identifies the best-performing urban form in terms of a set of formal evaluation criteria, as well as a long-term transition to it from the current form. This is done for distinct scenarios of combinations of car fleet composition and shares of renewable energy in electricity. The model is applied to the city of Barcelona. Chapter 5 analyses a survey implemented in the Metropolitan Area of Barcelona to elicit consumer preferences concerning vehicle types. Multinomial logit regression was undertaken to assess important attributes for choosing among conventional, hybrid and electric vehicles are price and range. This produces estimates of the willingness to pay for an additional driving range, emission reduction, reduction in either refuel time or fuel cost. In addition, the presence of incentives such as free parking, toll-free highways or free tunnels access is assessed. Chapter 6 analyses the relationship between climate-related emission targets, mayoral powers and city attributes by combining data from the C40 cities-climate network with other data. This involves normalizing emission targets on a common baseline and performing correlation and multiple regression analyses. These results are still preliminary and can be improved. They show a weak link between mayoral powers and city emission targets. A final chapter summarizes and concludes.

CHAPTER I:

Introduction

1. Background

This introductory chapter expresses the motivation behind researching the role of cities in combating climate change. The thesis offers four types of studies in this respect: a) the environmental impact of the interaction of city's urban form with alternative sources of energy, b) introduction of incentives for change in composition of the car fleet and c) the determinants of emission targets. Following the UN estimates, world population is expected to grow from 7.7 billion in 2019 to 8.5 billion in 2030 and to 9.7 billion in 2050 (United Nations, 2019). Currently, 55% of the world's population resides in urban areas. Figure 1 depicts the trend of rural-urban population since the 1500s and projected until 2050. Furthermore, cities are estimated to be responsible for 70% of world's emissions, while using about 78% of the world's energy (UN Habitat, 2011).

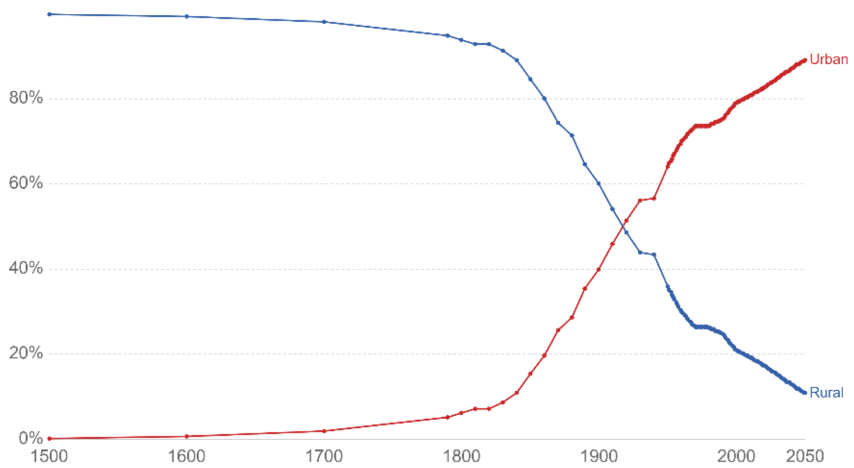

Figure 1: Past and predicted urban and rural population trends between 1500 and 2050. (Source: OWID, based on UN World Urbanization Prospects 2018 and historical sources)

According to the UN World Urbanization Prospects 2018, a settlement is considered urban if it is inhabited by 300000 and above. However, the definition of urban locality varies across countries, which in turn may result in inconsistent reporting and complications for comparing nations. For instance, in Denmark, Greenland, Iceland and Sweden a locality is considered urban if 200 or more inhabitants live there. Conversely, in Japan, a settlement is considered urban if the number of inhabitants exceeds 50000. The second highest threshold is set Mali with 30000 inhabitants and followed by a threshold of 20000 used in the Netherlands, Nigeria and Syria. This is summarized in Figure 2. The interaction of urban population, city zones and area of each zone in the city give rise to various urban forms. In this thesis we wish to establish which urban form performs best and under which circumstances. This deals with question such as: Do cities with dense concentration of population in certain zones create fewer greenhouse gas (GHG) emissions as opposed to low-density cities? Or to what extent do the long distances traveled within low-density areas in cities affect overall emissions? We also explore the plausible pathways of transformation of urban forms to those which generate fewer GHGs. Additionally, we discern how these transitions are influenced by car fleet composition and distribution of energy sources.

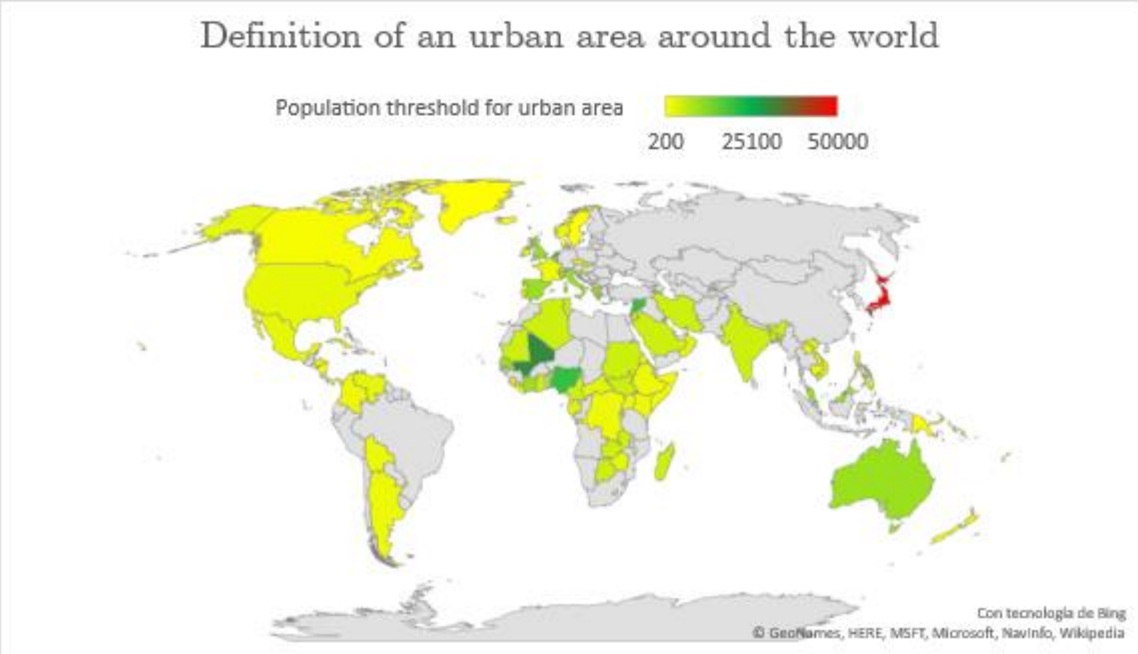

Figure 2: *Definition of a population threshold for an urban area (own figure; Data from UN World Urbanization Prospects 2018)*

In the remainder of this chapter we will look at how climate change has been addressed in the field of economics. Proposed solutions along with their advantages and challenges will be briefly discussed. A final section defines the goal of the thesis and elaborates research questions and approaches for each chapter in this thesis.

2. Climate policy studies and cities

To the threat of the climate change, many different disciplines have provided their own perspective, with a vast range of solutions. Economics considers climate change as a market failure. Stern (2008) has referred to climate change as "the greatest market failure the world has ever seen". The main challenge associated with solving climate change is that the climate is a public good, meaning one cannot escape its effects while a stable climate requires a moderate to low level of GHG emissions by all people and firms on the planet. Since a public good lacks property rights, there is no accountability nor direct consequences associated with its misuse or damage, contrary to private property. Moreover, the misuse of a global public good like the climate means that when one person or country emits greenhouse gases into the atmosphere, its consequences are felt globally. This gives rise to a free-rider problem at a global scale, that is emission reduction by one agent or country contributes only little to a global solution but implies a significant cost for them. To overcome free-riding, international coordination of policies is needed, as it is the only way to guarantee that they can become sufficiently strong and overall effective. Another restriction to fight climate change is that people assign low importance to the long-term impacts of climate change, as these will fall upon future generations. In other words, people highly discount the future, which translates through voter interest into high discounting by politicians and governments they make up. Perhaps some people's attitudes toward climate change have changed during the past 20 years, which might have translated into more attention for the future and distinct voting behavior, but one cannot be too optimistic about this. It is true, though, that policy makers give more attention to debate on environmental policies although this still awaits implementation of serious regulatory policies at local, national as well as supranational levels.

Social science has studied several solutions. One line of research suggests that technological progress is crucial to mitigate climate change by using low-carbon technologies. It has become common practice to include the expected future rate of technological change as deterministic in the estimates of total costs of adaptation of any climate policy (e.g. Clarke and Weyant, 2002; Carraro et al., 2003). In policy terms, incentives for adoption and innovation of relevant low-carbon technologies has been stressed. Economists have strongly argued argue that technological progress alone is not enough to mitigate climate change, but that technology support needs to be complemented by environmental regulation, with the latter being the focal point (Jaffe, et al., 2005). This would change choices by all agents towards low-car options and keep low-carbon innovation trajectories open that currently generate too expensive technologies but that offer great potential for the future. The reason for implementing serious environmental regulation is its capacity to alter behavior of the agents in both purchase (or adoption) and user phases, for both households and firms, which in turn will then affect choices by investors and innovators. Environmental regulation can be achieved through a variety of policy instruments, including taxes, quotas, technological standards and sanctions. Taxation enjoys perhaps most support as it is cost-effective for the economy (equalizes marginal costs of abatement among all emitters), simple (one uniform instrument), flexible (can be adapted quickly if circumstances require so) and cheap for the regulator (decentralizes the decision to emit or abate).

In recent years, partly because of failing international negotiations, the focus in climate policy has somewhat shifted from national to local governments. This has resulted in a new field of study concerned with multilevel governance which studies how the individual levels should be linked and what should each of them be responsible for. For instance, Bulkeley and Kern (2006) analyzed this shift in the case of the UK and contrasts it with the developments in Germany. Formally, Germany was in the lead in terms of environmental policy capabilities on municipal level. However, the differences between these two forms of governments have converged since the 1990. This was due to the EU encouraging service provision in the UK whilst liberalization and privatization took place in in Germany. Many studies highlight the importance of multilevel governance in achieving country's environmental goals. Multilevel governance hence requires higher levels of cooperation and integration among the different levels of governance in a country. Romero-Lankao (2012) recognizes the implicit difficulty to integrate and considers that it impedes governments from achieving ambitious environmental goals. This obstacle has henceforth given rise to considerable rhetoric rather than effective policies responding to the threat of climate change. Cities have increased the level of self-regulation and own initiative as well as joined various groups which promote cities to combat climate change, such as C40 or Covenant of Mayors (CoM). A survey reported by Technopolis Group (2013) listed a variety of reasons for cities to join the CoM. The main reasons were connected to gaining visibility at EU, national and regional levels. This is expected to increase the legitimacy of mitigation action by local governments and enable them to promote relevant changes in behavior among their citizens. Furthermore, the recognition of such efforts by national and supranational governments may enable easier access to funding and knowledge necessary for the implementation of mitigation policies.

3. Thesis aim and overview

In this thesis we contribute to the literatures on climate change solutions in the context of land use, urbanization and transport. Our study's purpose is to propose effective climate policies at the urban level and well as feasible pathways for their implementation. Specifically, we categorize this study into three distinct lines of research. The first discerns the impact of urban form on emissions and associated policies, to which we devote Chapters 2 and 4. A second line of research deals with cities' ambition in setting emission targets for the upcoming years in the context of mayoral powers, which is explored in Chapter 5. A third line of research is dedicated to studying consumer behavior by analyzing stated preferences about vehicles with low environmental impacts. This is explored in Chapter 6 of this thesis. Chapter 3 consists of data collection and methodology. We will address shortly each of the chapters in order to give an overview of the content of the thesis. Chapter 2 reviews the economic literature dealing with urban form with the aim to identify policies that reduce emissions through changes in urban structure and design. We contrast this notion as defined in geography with their economic counterparts. We also identify the most relevant issues associated with urban form, which fall into the categories of city's attributes, scope of the model, congestion and pollution externalities. We offer more detail on pollution externalities as they represent one of the most pressing concerns for the society today. Studies concerning pollution externalities include both empirical and theoretical studies, using either monocentric or polycentric urban forms in modelling the city. Some recent studies include Borck and Pflueger (2018), Regnier and Legras (2018), Schindlera, Carusoa, Picard (2017). We discuss in some detail the policies recommended to correct for environmental externalities as found in urban economics, and their divergence from the policies implemented in cities around the world. We conclude by outlining issues that merit further research.

In Chapter 3 we explain the process behind the collection of data for this thesis as well as the BREATHE project in the context of which this work was undertaken. The data collected pertains to the Metropolitan Area of Barcelona. The long-term goal of BREATHE was to implement comparable models for cities around Europe, notably Barcelona, Amsterdam, Istanbul and Gothenburg, and study relevant policies to reduce local and global emissions, with a focus on adapting urban form. In Chapter 4 we determine which urban form generates minimal global and local emissions. To this end, we develop a spatial accounting model of a circular city consisting of six zones. Activities comprise low- and high-density housing, offices and industry. Spatial interactions among activities give rise to freight and passenger transport. We assess global emissions of greenhouse gases due to the direct and indirect use of coal, oil and gas by economic activities and transport. In addition, we calculate local emissions which are zone-specific. Distribution and health effects of such emissions are also considered. The model analyses each urban form for various scenarios of distinct shares of electric vehicles in transport and of renewable energy in electricity production. Numerical exercises allow establishing a relationship between optimal urban form and shares of electric vehicles and renewable energy. We also derive transition paths to the most desirable urban form considering minimal transition effort. This may help urban planners to design a feasible time strategy for improving urban form in terms of emissions.

In Chapter 5 we evaluate the level of cities' ambition about setting emission targets and implementing policies, and factors explaining this. Our dataset consists of a subset of C40 cities, due to data limits, because these are supposedly at the forefront of mitigation action. They were also the first to disclose their self-imposed emission targets. First, we determine the targeted future emission levels based on the targeted reduction (%) from the baseline emissions. We calculate these for discrete 10 year periods:2020, 2030, 2040 and 2050. We contrast the resulting emission levels with those in the base year 2015. We further conduct a series of regressions of target emission levels on distinct explanatory variables, including mayoral powers, city characteristics and geographical location.

Chapter 6 deals with the adaptation of hybrid vehicles. This is motivated by the fact that the implementation of these alternative types of vehicle have become of interest to local policy makers because of their low GHG emissions and especially low local air pollutants. We estimate a multinomial logit model to analyse stated preferences of 500 candidates from a survey implemented in Metropolitan Area of Barcelona. Each car choice is characterised by a set of features, such as price, emission reduction, fuel cost reduction, etc. We calculate a willingness to pay (WTP) for each of these features. We also explore the impact of four scenarios with distinct governmental incentives on consumer's choice. These include free parking, toll-free roads, payment-free tunnels and no incentive scenario.

The thesis ends with a brief Chapter 7. This offers conclusions and summarizes the main findings of this thesis.

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CHAPTER II:

Policies to reduce emissions through changes in urban form

1. ***Introduction***

Why are cities organized, the way they are and why are no two cities alike? Does the design of one city make it superior to the rest? Urban morphology, the study of urban form, tries to provide an answer to these questions by studying cities and their organization in space. This field of research distinguishes two basic environments – natural and built environment. Natural environment, such as landform, geology, water, fauna y flora, is pre-ambulatory and often deterministic to any built environment constructed on it. The transition from one environment to another is achieved by transformation due to human activity, which results in streets, plots and buildings. These create patterns, which arise deliberately (by planning) or through individuals acting out on their own interests. Repetition of these patterns gives rise to extended urban form (Kropf, 2017). Findings from urban morphology have served as an ancillary scientific foundation for many sciences in addressing issues related to urban form. In this paper we will focus on the representation of urban form, together with its definitions, models and applications in urban economics and geography.

Formally, urban form was used in geography to refer to physical features only, such as urban layout and land use (e.g. Anderson et al., 1996, Williams et al., 2000). However, in more recent research, urban form has been defined on the basis of both physical and non-physical characteristics. Dempsey et al. (2009) defined urban form as a combination of the following five elements and their interplay:

- Density
- Land Use
- Accessibility and Transport Infrastructure
- Urban Layout
- Housing and Building Characteristics

Distinct research areas focus on studying, and endogenizing, only some of these elements at once. As a result, the recommendations for future policies that arise from one field may differ from, be complementary or be inconsistent with, those coming from others. For instance, the way urban form is modeled in economics tends to exclude urban layout, building characteristics and accessibility, while addressing features such as density, land use, transport and housing characteristics. On the contrary, geographers focus on adjustment of urban layout together with the associated land use. Hence, finding the optimal urban form that both geographers and economists both agree on, might be rather difficult as each emphasizes distinct aspects of urban form and thus is likely to arrive at distinct conclusions. In this article we review the economic literature dealing with urban form and recommended policies to correct for environmental externalities. This is contrasted with policies applied to cities today. In particular, we look at policies affecting pollution externalities through changes in urban form. Furthermore, we address gaps in the literature and suggest future research questions.

The paper is organized as follows. After reviewing basic terminology and models depicting urban form in Section 2, the application of these models to urban economics is discussed in Section 3. Here we examine the interaction between urban form and pollution externalities in greater detail. We assess the various policies proposed to correct for externalities in cities and their efficacy, efficiency and feasibility in Section 4. Section 5 outlines the links between urban form and specific factors that have received little attention so far in the literature. Section 6 concludes.

2. ***Representation of urban form in four abstract models***

There are many different models found in geography that define urban form. We review the ones that adopt a spatial-analytical approach to urban morphology (Korpf, 2017). This approach has its origins in geography. It considers urban form as a primary result of human activity and spatial interactions. They, moreover, provide a basis for analytical approaches in urban economics. Our review includes the monocentric model, the sector model, the urban village model and the multi-nuclei model.

2.1 The monocentric model

The monocentric model, also known as the Burgess model (Park and Burgess 1925, p.51), is one of the earliest theoretical models to explain urban social structures. The model depicts urban land use in concentric rings that are uniformly distributed as shown in Figure 1. Same model was used by von Thünen (1826) when modelling the agricultural land use.

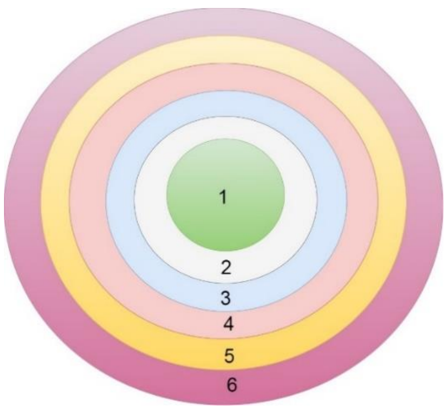

Figure 1: Urban structure of Park and Burgess (1925)

The general concept of monocentric city - a city with one single, central, dominant business district, does not entail symmetry directly, but in its simplest form, it is assumed. It was originally used as an explanation of distribution of social groups within urban areas with its first application to the city of Chicago.

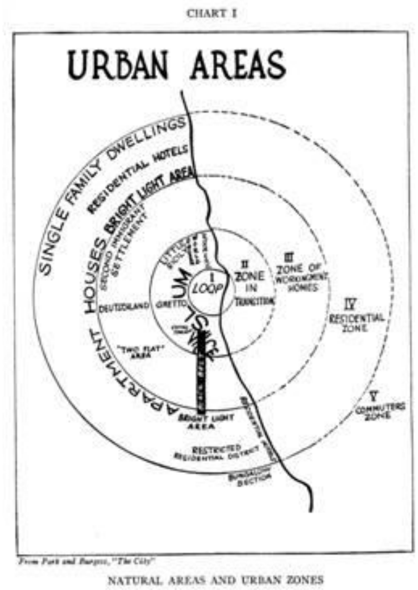

Figure 2: the application of the Park and Burgess 1925 model to the city of Chicago

As we may observe, the monocentric model used in geography entails various rings around the central business zone with distinct land uses, densities and building types. However, when using the term monocentric model in urban economics, often based on von Thünen (1826) or Alonso (1964), we tend to model it differently. Most common definition uses the CBD as a singular point with the highest land and/or job density allocated on a continuous plane, with boundary being determined by the cost of commuting in addition to rent. This is represented in Figure 3.

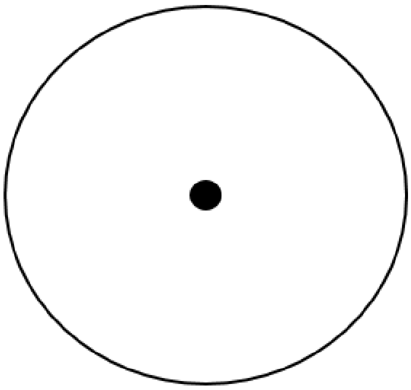

Figure 3: CBD within a city as found in Alonso (1964)

Some of the less common applications represent the CBD as a symmetric central zone surrounded by a singular zone with homogeneous characteristics (density, type of activity, land use, building type). This special case is represented in Figure 4.

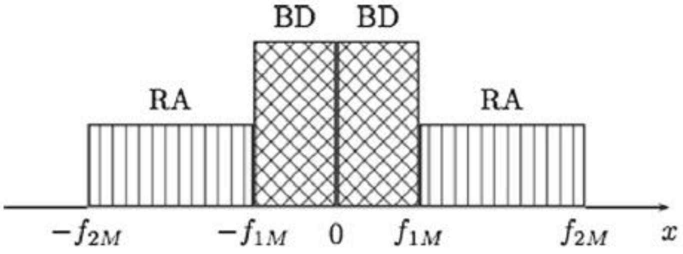

Figure 4: Monocentric urban configuration (Regnier and Legras, 2018)

As depicted above, the monocentric model is composed of circular zones, with a CBD in the center, where most of the economic activity takes place. This implies that most of the jobs are also concentrated in this area, which is in Figure 5 depicted with the color red. The movement of population hence follows a radial pattern and is from the periphery toward the center.

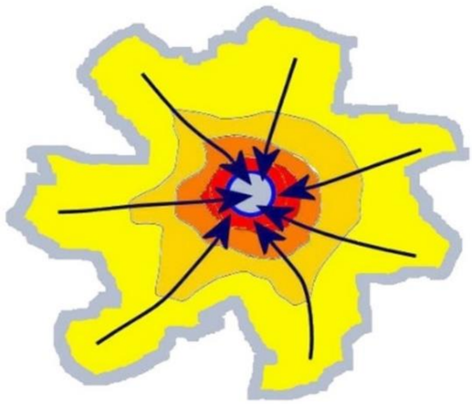

Figure 5: Movement pattern in monocentric city (Betraud, 2006)

Note: In Figures 5, 8 and 9 the areas with highest density are shaded darker (red/ orange in colour version) while the areas with the smallest density are displayed lighter (yellow in colour version).

2.2 Polycentric model

Over the years a shift from studying monocentric to more complex structures took place. Rather than a singular, dominant center, the polycentric urban form is characterized by various smaller centers, spread-out throughout the city. In geography, a polycentric model, known as multiple nuclei model (Figure 6), was proposed by Harris and Ullman (1945). It considers various city centres and industrial suburbs not necessary be adjacent to one another. This model can address both asymmetric and symmetric cities, but asymmetry is more common. In this section, the use of multi-nuclei model will represent the geographic model (Figure 6) and polycentric model will refer to the model of polycentric structures as used in economics (Figure 7).

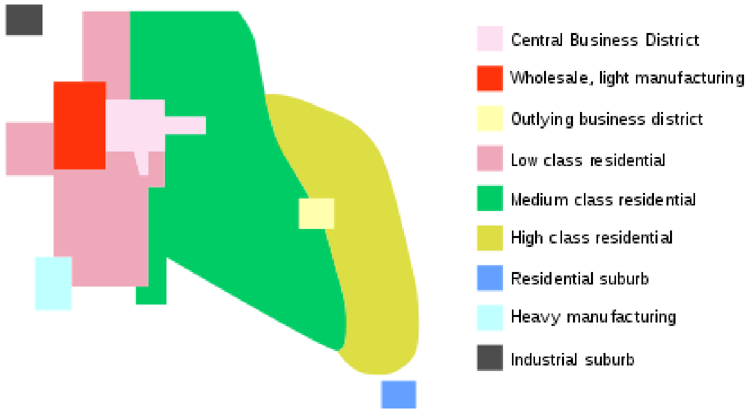

Figure 6: Multi-nuclei model from Harris and Ullman (1945)

Polycentric models in urban economics (Figure 7) were pioneered by Ogawa and Fujita (1980, 1982), Fujita (1985), Fujita (1989). Their models assume symmetry implicitly, and hence it does to a great extend resemble Burgess' model of monocentric city with distinct rings rather than Harris and Ullman (1945).

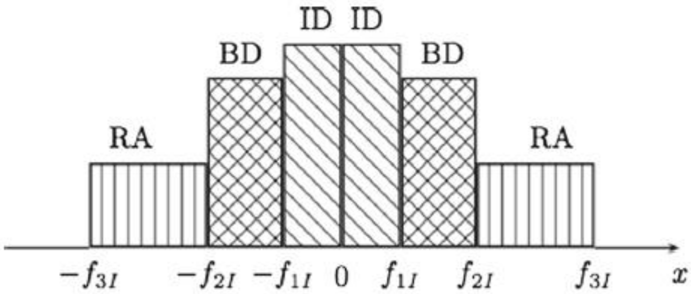

Figure 7: Polycentric urban configuration (Regnier and Legras, 2018)

The lower concentration of economic activities in a polycentric configuration results in a more uniform distribution of jobs, housing and resulting associated amenities. In addition, it generates a less dense movement of agents than in a monocentric setting. Due to the even distribution of zones, the amenities in these subcenters are also evenly distributed. This is found true for the polycentric models as used in urban economics (Figure 7). These models imply symmetry explicitly, as opposed to multi-nuclei's (Figure 6) asymmetric distribution. Amenities and associated activities in polycentric urban model in economics give rise to a movement pattern of agents, as depicted in Figure 8.

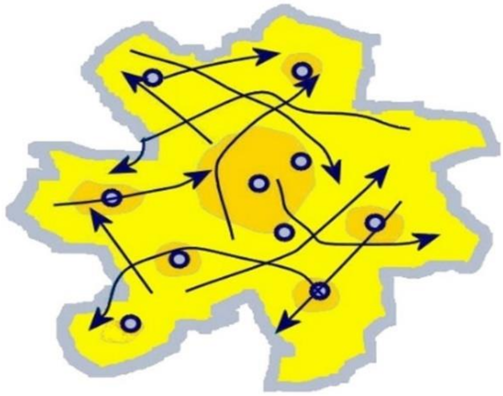

Figure 8: Movement of agents in Polycentric model (Bertraud, 2006)

2.3 Urban village model

The concept of urban village associated with works of Jacobs (1961), is defined as a city with medium-density housing, mixed use zoning and walking-distance amenities that promote emission-free transport (i.e. walking or biking). Figure (9) depicts Bertaud's (2006) interpretation of urban village.

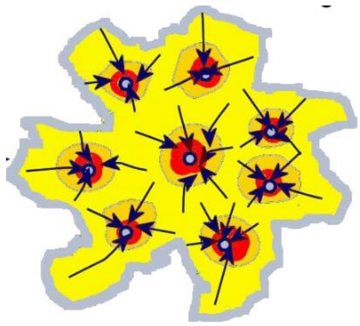

Figure 9: Urban village model (Bertraud, 2006)

In urban economics, urban village is modelled as mixed urban zones, modelling one of the possible urban villages allocated in the city (Figure 10).

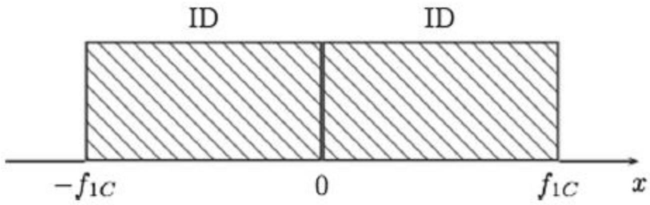

Figure 10: Completely mixed urban configuration (Regnier and Legras, 2018)

This model is hard to find in the real world and therefore not often used in the urban economic literature. Hence, we will not dedicate more time to it in the remainder of the paper.

2.4 Sector model

An extension of the monocentric model by Burgess (1925) is the 'Sector model' proposed by Hoyt in 1939. It retains the circular structure of Burgess model but has a spatial distribution of zones which allows for an outward growth of the city. This model has been used the dynamics of growth and spatial structure of Paris. Unfortunately, its economic counterpart is not found, even though asymmetric urban cities were modelled previously (e.g. Borck, and Tabuchi, 2016), however they do not specify the model used and the type of asymmetric assumed.

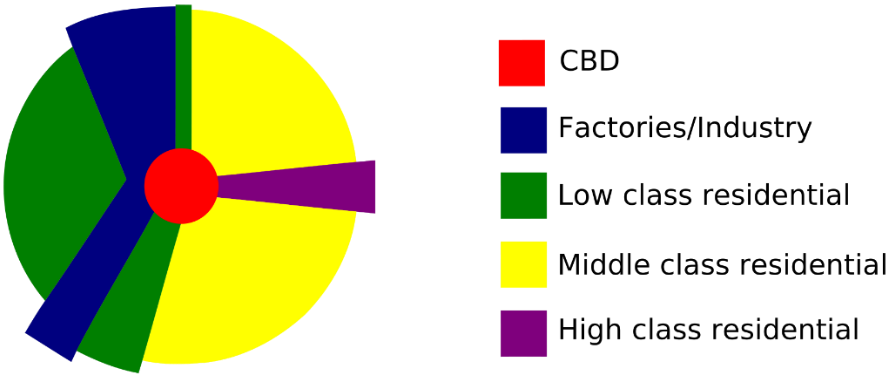

Figure 11: Sector model (Hoyt, 1939)

We do not include the movement patterns for this model as these resemble those of the monocentric model rather closely. This model has anyway not enjoyed great popularity among economics due to its lack of radial symmetry.

3. Urban economic models

In this section we analyze how the abstract models from Section 2 have influenced modelling in urban economics. One of the principal objectives of urban economics is to model the optimal allocation of agents and resources in space. Certainly, the evaluation of optimality depends solely on the criteria used, which vary depending on the objective of the study. For, the social welfare may be expressed in monetary terms or otherwise, e.g. health effects associated with environmental pollution. On top of modeling the spatial layout in which agents and resources operate; the interplay of the two gives rise to other factors such as density, land use, prices, transport and associated externalities. These are then modeled as either exo- or endogenous factors in urban economic models.

In Table 1 we list the studies in urban economics which developed important models of urban form. We sort these articles into categories depending on the focal point of the associated research. These categories include *city attributes*, *scope of the model*, *congestion or pollution externalities.* The first column of the table mentions the baseline studies, followed by a column indicating the type of urban form modelled. The third column entails a brief summary of articles' content. Recent papers built on these models are categorized by the type of extensions included within them, found in columns 4 through 7. The extension also follows the four categories enlisted above. We exclude from this table studies that have contributed to urban economic but do not model urban form explicitly.[1]

2.4 City attributes

City's attributes represent the spatial layout aspect of urban form. The most frequent city attributes modelled in the literature are the following

- City size
- City boundary
- Height limits
- Sub-centers and multiple centers
- Zoning
- Density

These attributes are modeled in the urban economic literature as either fixed spatial layout, set exogenously prior to calculations, or each of these individual aspects is used as a policy instrument. Ever since the paper of Alonso (1964), the analysis of land use within the field of economics has gained on popularity among academics and many lines of research developed. Alonso's model (1964) was based on the theory monocentric city of von Thünen (1826) and Park and Burgess (1925), discussed in the previous section. Alonso (1964) modelled household allocation by deriving bid rent prices. Solow (1973) arrived at the same result, but by using the approach of cost minimization. Fujita (1985) extended these models by developing bid-rent price curves. The studies by Solow and Vickrey (1971) find that land taxes are a poor policy instrument to guide land-use decisions. Depending on the urban form modelled - either monocentric or polycentric urban form- the outcomes and feasible policy instruments

[1] Examples of such studies are: Arrow and Debreu (1954) which laid down the basis for all GE Models as well as Dixit and Stiglitz (1977) for their contribution on monopolistic competition. *Econometric studies* of Glaeser, (1998; 1999, 2009): Glaeser and Kahn (2004, 2010), Kahn (2006), Kahn, Kok and Quigley (2014), Zheng and Kahn (2013), Costa and Kahn (2011), Kahn and Schwartz (2008), Watkiss et al. (2009), Nordhaus (2008, 2010), Fragkias et al. (2013), *Books* such as Duranton, G., Henderson, V. Strange, W. (2015) ; *Models* of Desmet and Rossi-Hansberg (2009, 2014, 2015), Farzin, (1996). Krugman (1991), Grossman and Krugman (1993) made another significant breakthrough in the field with the two region spatial model. This was later extended by Fujita, M; Krugman, P.; Venables, A.J. (1999) and Copeland and Taylor (2004), Calmette and Péchoux (2007), where the last two papers dealt with pollution.

differ a great deal.

After the exploitation of the monocentric model to the fullest, a shift toward polycentric cities has taken place. One of the first models including polycentric urban form was modeled Fujita (1989). Following his example, other famous extensions of this model have made an echo, including Regnier and Legras (2018) or Gaigné, Riou and Thisse (2012). Urban economists often use city size, density, height or even the distribution of land throughout the city in order find the "optimal city". Optimal city is as a term (almost) always accompanied by the attribute and a criterion which determines its optimality.

2.5 Scope of the model

On top of the extension of the spatial structure's aspect of the model, the newer literature adds an additional scope to the original. This includes various considerations, such as additional modes of transport, housing and labor markets, or even additional constraints, such as time and health. For instance, some models have extended the previous literature by the inclusion of a more elaborate labor market considerations (e.g. Zenou, 2009). Zenou (2009) builts in the urban search model based on Mortensen and Pissarides (1994) with spatial dimension. He models high skilled workers wiling to live closer to jobs whilst low skilled workers tend to commute longer distances. He finds that job destruction depends vastly on social benefits (of not working) in combination to commuting cost. High commuting costs lead to job destruction. Other papers have included externalities in their analysis, e.g. pollution (Arnott et al. 1994).

2.6 Congestion externalities

Externalities in cities may be either a) positive or b) negative. Positive externalities in urban economics may be represented by agglomeration, knowledge spillovers, smaller travel distances. On the other hand, negative externalities in spatial setting are represented by congestion, air pollution or noise. Due to the extensivity of the literature on externalities we have divided these by the congestion externalities and air pollution externalities.

Models dealing with transport and the associated externalities often build upon the papers by Muth (1969) and Mills (1967), summarized by Brueckner (1987). These authors develop a transportation model in the spatial setting, which was later enhanced by additional considerations for either time (DeSalvo, 1985) or environmental quality (Yamada, 1972).

Most recent papers based on Muth-Mills model include road congestion (Borck and Brueckner, 2018) and air pollution (Bertaud and Brueckner, 2005; Borck 2016).

Furthermore, one of the pioneers in terms of road congestion was the paper by Vickrey (1969), which is often basis (even if partial) to the analytical papers in urban economics dealing with this issue, such as van den Berg and Verhoef (2011, 2016).

Additional dimensions have gradually become of interest, including the various modes of transport, shortest route path calculation, individual time valuation, bottleneck congestion, as well as the relationship between bid-rent prices and transportation costs.

2.7 Pollution externalities

The study of urban pollution externalities was first introduced by Henderson (1977) through connecting urban form's to environmental externalities. He found that there is a trade-off between welfare and city size where production processes create output associated with pollution. The conclusion of his analysis was that cities are of optimal size to begin with and that the variation of city sizes is due to different specifications of distinct industries' characteristics. Pigouvian taxes, zoning and redistribution of population were suggested to be possible solutions to diffusing the impacts of pollution externalities in spatial setting. Papers that followed included some aspects from the previous three categories (city attributes, scope of the model and congestion externalities) and their relationship to pollution externalities; namely spatial allocation, consideration for additional markets (e.g. housing or labor) or constraints (e.g. time, travel model, environmental damage).

Recent works by Borck and Tabuchi (2016) built on the paper of Henderson (1977) by modelling optimal and equilibrium city size with spillovers of local environmental pollution. They try to determine, at which cut-off point are cities too big, too small "or just right" in terms of population size, available resources and associated pollution created by the interplay of the two. According to their findings, equilibrium cities tend to be too large and small cities undersized. Arnott et al. (1994) created a model which studied the role of available space as a control for environmental externalities in the presence of non-local pollution. It describes commuting of workers to factories and other types of trips which pollute in a spatial setting. The authors found that Pigouvian taxes were not sufficient as a policy instrument. They suggested an extended model which would include heterogenous pollutes as well as use two circle rings to model the city and zone's boundary. A study by Xepapadeas (2005) extended this and by modeling pollution as disutility. A follow-up study by Kyriakopoulou and Xepapadeas (2013), constructed by elements from Arnott et al. (1994), Lucas and Rossi-Hansberg (2002) and Rossi-Hansberg (2005) found that clustering and centrifugal forces of environmental damages result in an urban form that resembles a bicentric rather than a monocentric city. They also assessed that if environmental damage is accounted for, the advantages of agglomeration at a given location are lost. Verhoef and Nijkamp (2002, 2003) created a general spatial equilibrium model of a monocentric city with distinct types of externalities - pollution in the industrial center and agglomeration economies. In the Verhoef and Nijkamp (2002) study, a distinction is made between two types of industrial agglomeration – where one type becomes more efficient by the scale of production and the other by the scale of the labor force. They conclude that with the twofold objective of implementing policies to improve 1) environmental quality and 2) agglomeration efficiency, the two types of agglomerations yield different results. With the scale of labor agglomeration efficiency, even at equilibrium, these two policies are at odds since the one type of policy would require a further increase and the other a decrease in production. The same issue might also arise for the size-of the-production-scale agglomeration, although at smaller extent if substitution between energy and labor is allowed.

A study by Kyriakopoulou and Xepapadeas (2017) the trade-off between agglomeration and dispersion forces in the form of pollution from stationary forces, production externalities and commuting costs, determines the emergence of industrial and residential clusters across space. In contrast to Arnott et al. (1994), they examine explicitly how diffusion of pollution is the force behind spatial industrial concentration in clusters, such as the positive productivity spillovers.

A study by Borck and Pflueger (2018) examines whether or not urbanization is good for the environment in the presence of heterogeneous workers. It shows that total emissions exhibit an inversely U-shaped behavior in the agglomeration-deglomeration process. This is due to the finding that emissions from manufacturing, commuting and housing increase under agglomeration but decrease with re-dispersion. They found market forces alone may suffice to generate an urban Environmental Kuznets Curve, as defined by Copeland and Taylor (2003).

Another study by Schindlera et al. (2017) analyzed urban structure when localized pollution exposure arises from commuting traffic and investigates the feedback effect of endogenous pollution on residential choices. They found that the first-best structure is a less expanded city with higher densities at the center and lower densities at the fringe. Further, they concluded that when residents have incentives to relocate to less polluted urban areas, they may make longer commuting trips to their workplaces, thereby generating additional pollution and exposing other residents further. Schindlera et al. (2017) also established that aversion to pollution exposure reduced the urban population size and resulted in non-monotonic population density distributions: the population density in locations near the center is reduced while locations farther away from the center retain high population densities since households prefer to move outward to escape air pollution exposure. A study by Gaigné et al.

(2012) modelled density in polycentric cities in relation to greenhouse gas emissions by commuting. They extended their model with endogenous city size and form, following Cavailhès et al. (2007). They suggested that cities' authorities control the intra-urban distribution of firms and workers in order to decrease the average distance travelled by workers as means to decreasing environmental damage on global scale. The authors also argued that there are perverse effects associated with city's compactness as well as possible positive effects related to job decentralization.

Another approach to modeling pollution was carried out by Reilly and Richards, (1993), Reilly et al., (1999), Aaheim (1999) and Manne and Richels, (2000). These authors created models to deal with correlated, multiple pollutants. By "correlated", they mean multiple pollutants which are jointly produced by a single source but are differentiated by the level of impact - local or global externalities (e.g. smog vs. global warming). A paper by Kaplan and Silva (2005) examined joint tradable permit markets as a self-enforcing mechanism to control correlated externality problems. "Self-enforcing" refers to a mechanism that accounts for the endogeneity that exists between competing jurisdictions in the setting of environmental policy within a federation of regions. They found that joint domestic and international permit markets are Pareto efficient for a wide class of preferences.

In the literature dealing with multiple pollutants, Legras (2011) shows that the incomplete specification of an environmental model may lead policy makers to set suboptimal pollution targets in a multipollutant setting. The author concluded that time horizon of policy design matters in assessing the impact of incomplete model specification in multipollutant setting. A study by Yang (2006) set up an optimal control problem of negatively correlated local and global stock externality provision, where CO_2 is well-mixed in the atmosphere and has a global impact, regardless of emission locations, and the opposite apply for the cooling effects of SO_2. He assumed that global social planner's objectives and policies differ from those of a local social planner (e.g. local one should internalize all the local emissions). Schmieman et al. (2002) analyzed the interaction between stock pollutant and flow pollutant using a cost-benefit analysis for the European countries. Their model jointly analyzed acidification and ozone. They pointed out the lack of consideration by European countries of targets for reducing pollutants in a multi-pollutants setting. With this motivation in mind the authors have designed an appropriate control or policy instrument.

A recent study by Regnier and Legras (2018) was concerned with evaluating policy design for industrial and transport air pollution in a shared land market. Their objectives were threefold: (1) to identity the effect of industrial pollution on households' choice of localization when neither employment nor residential locations are specified a priori, (2) to assess the level of GHG emissions resulting from the equilibrium city structure, (3) and to find the optimal policy mix to manage polluting emissions from both the industrial and the transport sectors. To model these, they have used a closed city model where environmental quality is considered as a spatial attribute of housing, which affects the households' utility function directly but not its budget constraint. This created a trade-off between accessibility and environmental quality. They have explored various mixing patterns of the city zones. They found that in two-zone setting (non-mixed), the total distance travelled in a monocentric urban configuration increases with the population, residential and industrial lot sizes, and labor intensity. However, in completely mixed city, households cannot respond to the pollution damage by choosing a location farther from firms, so firms must offer a higher wage to provide an incentive for households to locate where environmental quality is low. They proposed two types of policies. A) The tax on commuting is a price-based instrument and creates direct incentives for households to limit their commuting distance several forms: an urban toll or kilometric tax. B) abatement norm on industrial emissions (quantity-based instrument) They found that A) impacts city structure and B) does not.

Table 1: Urban economic articles reviewed

Baseline model	**Urban form**	**Content of baseline model**	**Extension**			
			City attributes (size, boundary, height limits, zoning, etc.)	*Scope of the model* (transport, housing or labor market, constraints, etc.)	*Congestion externalities* (bottleneck congestion, network controls, tolls, etc.)	*Pollution externalities* (local and global pollution, multi-pollutants, correction policies, etc.)
Alonso (1964); von Thünen (1826), Solow (1973), Fujita (1985), Solow and Vickrey (1971)	Monocentric	Bid prices (Alonso, 1964; Solow, 1973), bid price curves (Fujita, 1985), Solow and Vickrey (1971) say that land prices may be a very poor guide to land-use decisions	Fujita, Krugman and Venables (1999)	Zenou and Smith (1995), Zenou (2009)		Arnott, et al (2008), Verhoef and Nijkamp (2002, 2003), Lucas and Rossi-Hansberg (2002) and Rossi-Hansberg (2005) Borck and Pflueger (2018), Kyriakopoulou and Xepapadeas (2013, 2017), Xepapadeas (2005)
Ogawa and Fujita (1980, 1982), Fujita (1985), Fujita (1989)	Polycentric	ALL: Polycentric city structures	Regnier and Legras (2018), Gaigné, Riou and Thisse (2012)	Zenou, Y. (2009)	Wu, JJ(2006)	Regnier and Legras (2018), Schindlera, Carusoa, Picard (2017), Gaigné, Riou and Thisse (2012)
Henderson (1974), Henderson (1977)	Both	ALL: Production output, city sizes and its associated pollution externalities.	Borck and Tabuchi (2016)	Henderson and Thisse (2004)	Arnott et al. (1994); Kyriakopoulou and Xepapadeas (2011, 2013)	Kaplan and Silva (2002, 2005) [2] Borck and Tabuchi (2016)
Muth (1969), Mills (1967, 1972a, 1972b, 1987), Evans (1973), Beckmann (1974), DeSalvo (1977, 1985), Yamada (1972), Schweizer et al (1976)	Both	ALL: Allocation and distance trade-off; commuting, time and policy, (Beckman, 1974) Environmental quality, leisure, accessibility and space (Yamada, 1972)	Bertaud and Brueckner (2005) Borck and Brueckner (2018)	Brueckner (1987), Anas et al., (1998); DeSalvo (1985), Anas and Moses (1979), Anas (1987), Anas et al (1998)	Borck and Brueckner (2018)	Bertaud and Brueckner (2005), Borck (2016)
Reilly and Richards, (1993); Reilly et al., (1999); Aaheim, (1999); Manne and Richels, (2000)	Both	ALL: Multiple, interrelated pollutants				Schmieman et al., (2002); Kaplan and Silva, (2005); Yang, (2006); Moslener and Requate, (2007, 2009), Legrass (2011)
Vickrey (1969), Chu (1995), Oron et al. (1973), Kanemoto (1976), Solow (1972)	Both	ALL: bottleneck congestion, network controls		Anas and Kim (1994, 1996), Anas and Rhee (2006), Anas and Xu (1999); Tscharaktschiew and Hirte (2010, 2012, 2013)	Verhoef and Nijkamp (2003), van den Berg and Verhoef (2011, 2016)	Verhoef and Nijkamp (2002)

[2] Kaplan and Silva (2005)* is a model not based on Henderson but it is important to keep in mind as it models different types of air pollutants

4. ***Policies implemented***

In theory, there is a myriad of options available to the policy makers. However, due to numerous restrictions – political, jurisdictional, ethical, budgetary, etc. - not all these options are feasible. Also, each city does entail its own set of characteristics due to its built and natural environment, which contribute to its uniqueness and cause for some policies to be very effective in one city and quite the opposite in another. In this section we discuss the distinct types of environmental policies which are being applied in cities right now but that have not been fully explored in the economic literature. There are a number of reasons for this, one of them being the complexity which entails modelling urban form and its impact on the agents, resources and space (as we have discussed in the introduction). This often results in a partial approach as it lacks one or more elements that make up urban form. The most neglected elements are urban layout and land use, as these are hard to model and hence the use of the over-simplified models of urban form.

We will distinguish between policies suggested by the economic model studies and how these have been applied (or not) – discussing successes, problems, barrier, etc.; and policies that are not studied with the models but have been applied for some reason, which needs explanation. Most popular policy instruments from the models include cordon tolls, permits, height or boundary limits, etc. All these accept the current urban form by maintaining it as is or limiting it from changing further rather than implying changes to it for the future. We will discuss these policy instruments in the order of relevance and popularity in application among cities.

One of the popular policy instruments to adjust land use in the cities is zoning. Zoning represents the reassignment of primary purpose/activity that takes place in a zone to another purpose or activity. This method is to some extent discussed by the models dealing with city's attributes in the economic literature. Zoning may combine the elements of urban layout together with housing and building characteristics. If these elements are altered, they may result to affect other elements of urban form such as layout and density. However, depending on the type of zoning policy, the impacts on urban form might differ. For instance, impact in zoning which deals with height limits may not necessary impact urban layout, rather it would make it remain unchanged. The same goes for density. The contrary applies for greening-of-cities types of zoning policies, which have clear impact on urban layout of the city. Whether zoning can or cannot improve the current urban form in terms of air pollution externalities, remains unanswered, as not all types of zoning policies have been studied. Furthermore, to what extent would air pollution be reduced if other aspects of urban form, such as access to transport infrastructure, would also change simultaneously? In addition, zoning may create some negative externalities, due to separation of residence and work zones that causes considerable transport and associated emissions.

Another popular policy instrument among urban economist is the cordon toll. This policy has been implemented in relatively few cities around the world, the best known cases being Singapore, London, Stockholm and New York Manhattan (Cost2Drive (2019). However, the main issue resulting from this instrument is ineffectiveness when other alternative routes are available. For instance, in the case of Stockholm, after the trial run in 2006 and initial voting, the toll was passed. Most of the votes supporting the toll's implementation came from the inner city of Stockholm, while the majority of road users in the surrounding areas voted against. Due to this polarization, this instrument may be often difficult to implement.

To reduce air pollution from cars in urban areas, cities opted for different policies and strategies. For example, Paris has issued a partial ban on cars in the city center during designated dates (Vidal, 2016), whereas a lot of German cities are restricting the entry to clean-fuel vehicles only, on top of stricter pollution standards for cars. Another popular policy implemented in Bogota and Delhi, is restricting car use depending on its licence plate number (Vidal, 2016: El espectador, 2018). None of these options have been analysed with an economic model. Other possible policies that are being currently considered (but have not been modelled) include subsidies for abstaining from car ownership. Freiburg tries to achieve this by providing cheaper housing while Curitiba in Brazil does it through offering improved public transport (Vidal, 2016). Additional alternatives to solving air pollution by restraining car usage in the urban areas include restricting parking spaces, changing urban infrastructure and pricing pollution.

5. ***Missing links***

In the urban economics models reviewed, we found a vast variety of connections between urban form, externalities and city's attributes. These results may serve as useful insights for future policy design. However, a significant gap in literature prevails. Here we discuss some of the relationships neglected by the literature.

Urban form as modeled in the urban economics is assumed to be constant over time and it is never considered to change over time. This is a serious concern when proposing a policy (Legras, 2011) given the fact that the long-run predictions of the model do not take into the account the possible change of the spatial structure within which the agents modelled will operate. And the change of the urban form itself may be due to an explicitly new design enforced by the policy maker or 'by accident', where agents act out in their best interests (Korpf, 2017). We believe that introducing dynamics in the urban structure of the city with various outcomes would provide for a more complex and precise analysis.

It is important to realize the possible inter-temporal steps and changes in the urban form's design. For, under different scenarios including share of electric vehicle use, green electricity, local pollution levels, different urban forms may be preferable. Moreover, in the case of green-private transport, the introduction of the electric vehicles may prove beneficial locally, yet if the car production processes and sources of clean energy do not catch up, the electric car will be a source of pollution indirectly. Another underplayed interaction in the literature is the relationship between urban form and pollution externalities. Even though this relationship has been explored, it has always been in a static setting. What we would like to ask is the following: Do emissions impact urban form and vice versa?

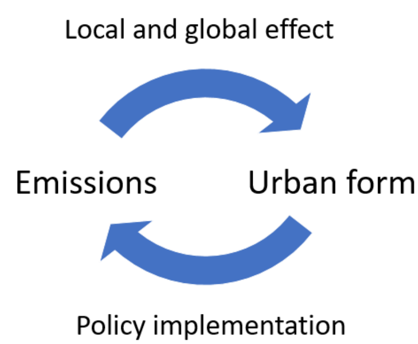

Figure 12: Urban form and emissions

Furthermore, is it a causal effect? What is the direction of this impact? Do people create emissions, use resources while polluting and thereby alter urban form? Another possible theory is that this interaction may change in the long-run, depending on the transformation of the urban form over time. Here we consider that the causal interaction between urban form and emissions might change as well due a variety of reasons, such as the levels of pollution the urban form will be at and the health impacts of these levels, the attitude toward environmental pollution, etc.

Another neglected relationship by the literature is that of urban form and technology. Even though this relationship was partly addressed by Anas (1989), many considerations remain unexplored. For instance, can we view technology as a both centrifugal and centripetal force (as has been studied in the case of environmental externalities and urban form)? How would be the results impacted? Furthermore, each city's industry type is distinct, and this determines whether further dispersion of the city will take place, e.g. due to natural environment's restrictions (Korpf, 2017). Moreover, can the impact of renewable energy in public transport create two extremes solutions; with trade-off between people working from home or long-distance commute.

6. ***Conclusions***

In this paper we have reviewed the literature on urban form and its applications to urban economics. We have first defined the term, explained its origins in geography and listed its core components. Next, a summary of main models of urban morphology was presented and their application in urban economics was discussed. We found that the biggest discrepancies when translating geographic models to urban economics related to the definition of the center and sub-centers as well as the presence of (a)symmetry in urban form. Furthermore, it was concluded that the movement of agents in urban economic models is often radial and organized.

Then we took a closer look at the economic literature dealing with urban form and various extensions, such as distinct markets considerations, city's attributes and externalities. Here we went into more detail on the interaction of urban form and environmental externalities, reviewing proposed solutions to dealing with pollution in an urban context. Subsequently, we discussed the applicability of these policy suggestions to cities and contrasted them with policies as implemented currently. A final section identified important missing links in the literature addressing urban form, such as time-dynamics and technology, notably in relation to emissions. We motivated why these deserve thoughtful attention in future research.

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CHAPTER III:

Methodology and data collection: The case of Barcelona for the Breathe project

1. Introduction

The research conducted in this thesis is part of an international project (BREATHE) covering four European cities – Amsterdam, Barcelona, Istanbul and Gothenburg. BREATHE is the acronym for Building Resilient Economic Agglomerations addressing Transportation and Health Effects. The focal point of this project was to study the interactions among urban form, economic welfare, energy use, location choice and local and global (greenhouse gas) emissions generated by households and firms. The project intended to provide policy makers with insights about land, energy and transport policies to improve local air quality and provide tools to help planning a smooth transition towards low-carbon cities. A specific objectives of the project was to develop a general-equilibrium model to numerically analyse the location choice of agents in a spatial setting with environmental externalities. This was on the plate of other partners in the project (notably Amsterdam). It is of the intention to apply the model to the city of Barcelona later, after the project has ended. For the moment it is being applied to Amsterdam only.

We have developed a model to study optimal urban form in terms of emissions and how to make a transition to a more efficient city in terms of emission production. Parameter values for applying this model to Barcelona are based on land use and transport data collected, as reported hereafter. The data presentation is organized as follows. We present data on land use, location choice, energy use and environmental quality, which is used for empirically founding the mentioned model. Sources used for data collection reported in Section 2 are listed in Table 1. The company Cylstat assisted with the data collection for the cadastre data.

Table 1: Sources of data

Description	***Name in dataset***	***Note***	***Source***
Public transport network nodes	Mapa03_point	trams, buses, trains and metro with buffers at 250m	AMB (2018a)
Public transport network nodes	Mapa03_polyline	trams, buses, trains and metro with buffers at 250m	
Daily car traffic intensity	A1CMXarxaViariaIMD_Polyline	Distinguished roads and highways	Generalitat de Catalunya (2018a)
Road network node	A1CMViesSegments_point	Distinguished roads and highways, buffer at 250m	
Road network lines	A1CMViesSegments_polyline	Distinguished roads and highways, buffer at 250m	
Grid	A1CMDistAgregCel2KmII_region	2x2 km	INE (2011)
Mobility	EnqMobilitat 2012	Survey 2012	IERM (2012)
Parks and gardens	A1CMCel2KmUsosParcsGardens_region		AMB (2018b)
EV Charging Stations	A1CMChargingEstations_point	Differentiated by type	Live Barcelona (2018)
Air quality at control stations	QualitatAire2	Different pollutants	Generalitat de Catalunya (2018b)
Control stations for air quality	A1CMXarxaAtmosferica_point		
Educational levels	A1CMDistAgregCel2KmNivellEstudis	Different types	IDESCAT (2011)
Land Use	A1CMCel2KmUsosCadastre_i_Viari_region	Includes roads and 7 different build environment categories	Sede Catastro (2018), Ministero de hacienda (2018)

2. Land use data

The data collected in this section was partly motivated by the specifications defined by the model of general equilibrium called MOLES from Tikoudis and Oueslat (2017) as it is the intention to apply this model in the future to Barcelona. The data is organized in sections grouped by the category in the model to which the it pertains– e.g. the land use, transport or policy questions. The data accessed from the cadastre was available freely to public and the questionnaire was implemented through a private company. For organizational purposes the data structured using themes. In the first section, the data is grouped by a category of use, e.g. land use, transport, policy questions, etc.

2.1 Built environment

Built environment in this study corresponds to commercial, industry, collective housing (apartments), single-family housing, offices and other purposes. For the calculation of the surface area by land use we used the Spanish Cadastre data from 2017, which comprises both level of census districts, municipalities and land uses.

The information collected from the cadastre is distributed in 96 census districts covering 18 municipalities which make up the metropolitan area analysed. It represents a total area of 256,131,285.00 m^2 of constructed area. It should be noted that because of incomplete data provided by cadastre, some areas could not be accounted for, which entails about 3% of total built area. Hence, the data presented here account for a total surface of 248,471,575 m^2 of constructed area. The way the cadastre units are recorded in our analysis is illustrated in Figure 2. The image on the left-hand side represents the municipalities with corresponding districts. In the image in the middle are displayed the same municipalities with grid overlay. The right image shows the selected region with grid overlay to demonstrate the losses in area which fall outside of municipalities boundaries but are covered by the 2x2 km grid.

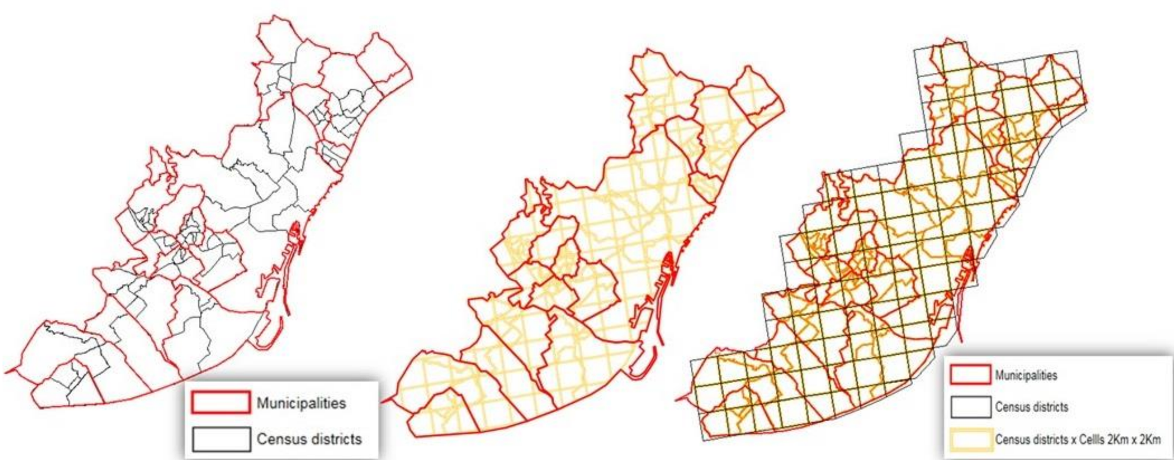

***Figure 2**: Constructed land: Commercial, industry, apartments, single-family households, office and other*

Additional losses of data occurred due to the deconstruction and the following assembly of data per grid cell. For example, a square in a grid is often comprised of various cadastral units; hence squares had to be broken down to smaller cadastral units (as illustrated in Figure 3) and then put back together in order to calculate the built environment per square. In this way, 377 polygons were generated with a total calculated coverage of 246.161.155,29 m^2 of built environment. Some of the data was thus lost (1%) as it did not fit within the square format, as shown in the right image of Figure 3.

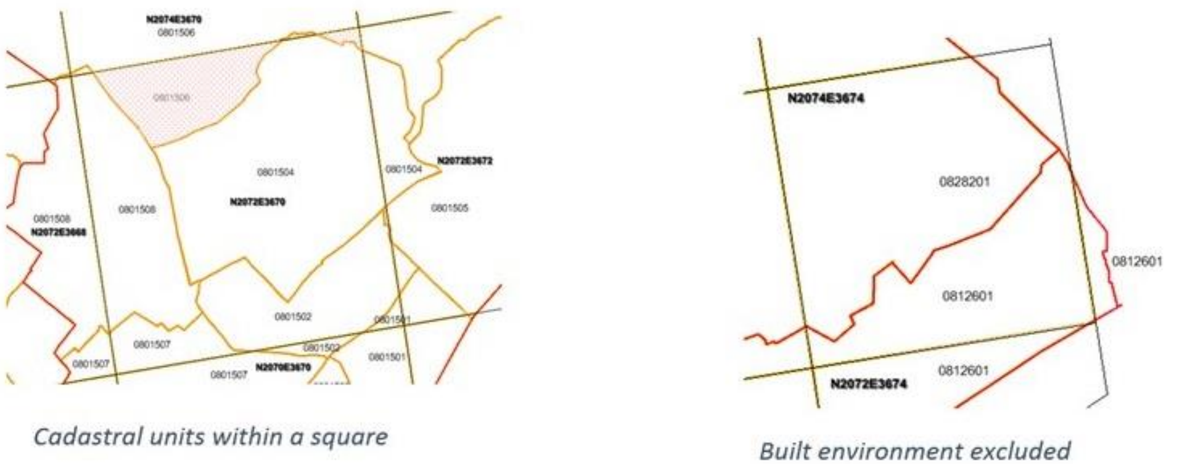

Figure 3: *Decomposition of squares into cadastral units (left) and loss of the surface area (right)*

The different types of built environmental used in our analysis are displayed in Figures 4 and 5.

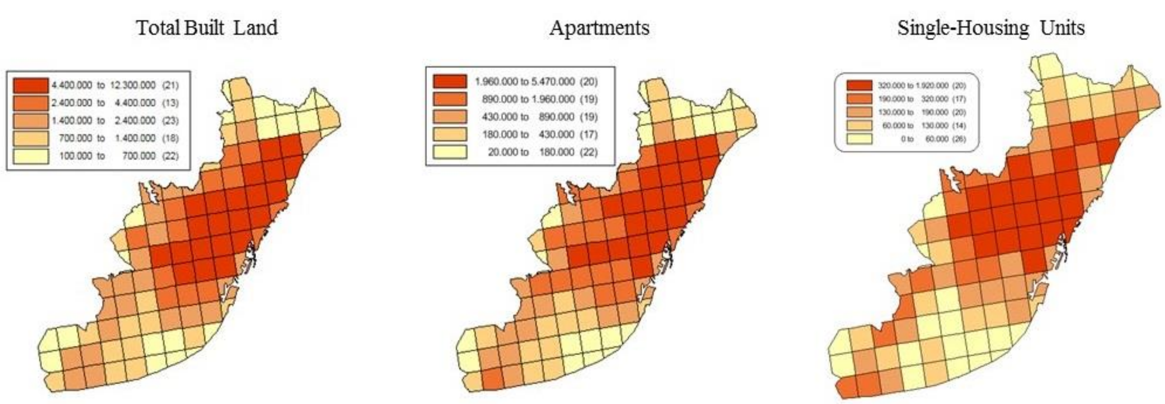

Figure 4: *Total, apartments and single-housing units: built land types and their corresponding densities.*

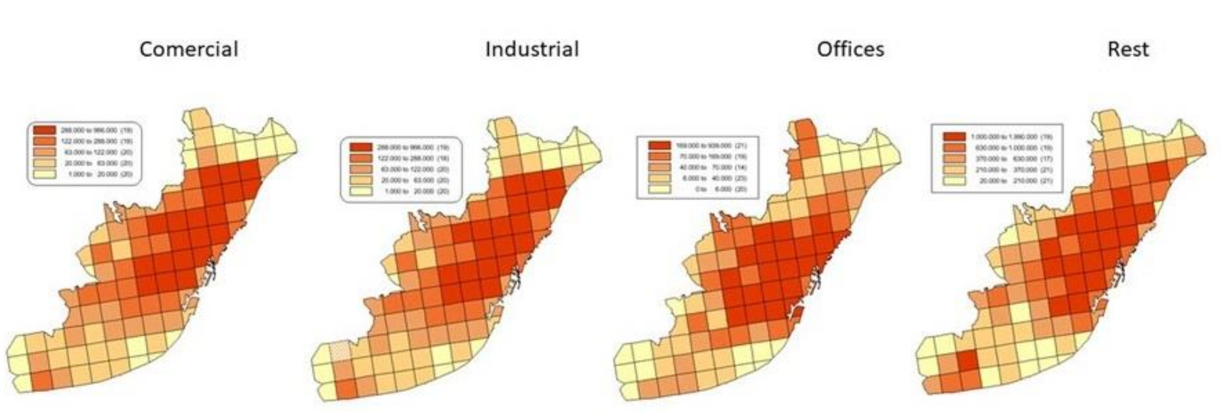

Figure 5: *Densities of commercial, industrial, office and other types of built land*

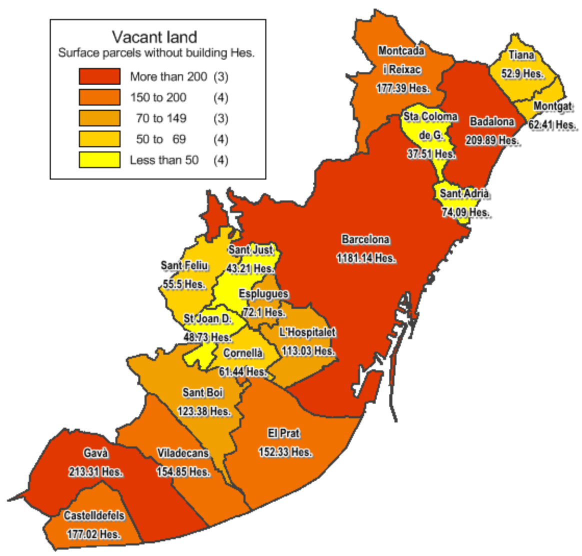

Figure 6: *Densities of vacant land available for construction in the region selected*

2.2 Parks

Parks, mountains and other green areas are displayed in Figure 7. These were not included in the cadastre's built environment but were extracted separately. Figure 6 displays the initial data collected where the grid had a parks' overlay. In order to meet the programming criteria, this has been converted into coverage ranges allocated in a single grid cell, as displayed in Figure 7 (on the right-hand side). Figure 7 further disaggregates the green areas (left).

Figure 6: *green areas and parks selected with a grid layover*

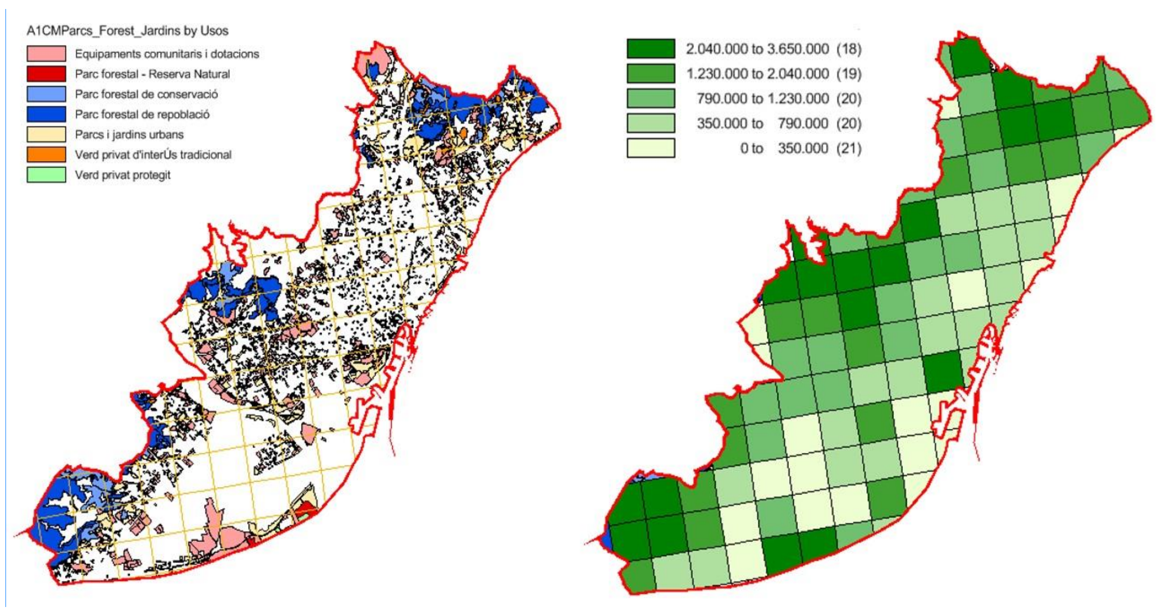

Figure 7: *Parks and other green areas in the Metropolitan Area of Barcelona, with further disaggregation of the green areas (left) and level of green area shares per grid cell (right)*

2.3 Centroids and grid

The centres of the districts within the municipalities, also known as centroids, are visually represented in Figure 8. These are to be used as a reference point in the model for determination of consumers' and firms' allocation or residence.

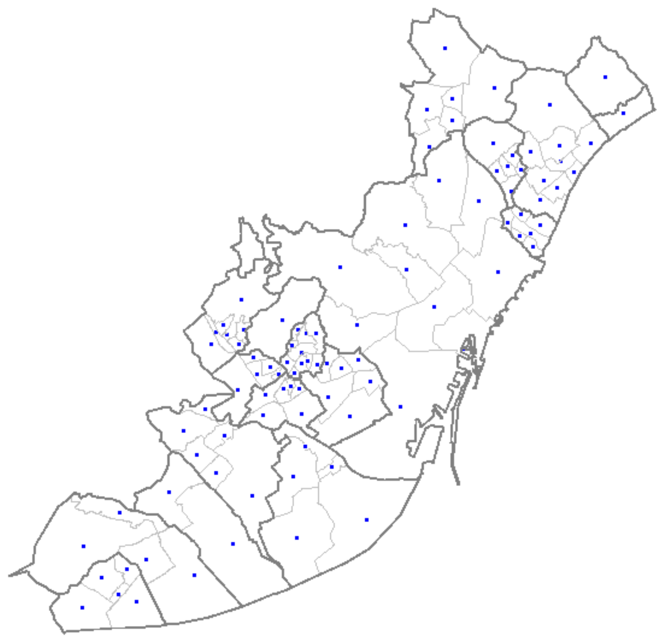

Figure 8: *Centroids*

A grid made of squares of 2 x 2 km has been superposed over the designated area. Each square includes its unique identification number by which it is recognized (see Figure 9). The area of interest comprises the following municipalities with corresponding postal codes from Spanish National Statistical Institute (INE): 08015 Badalona, 08019 Barcelona, 08056 Castelldefels, 08073 Cornellà de Llobregat, 08077 Esplugues de Llobregat, 08089 Gavà, 081101 Hospitalet de Llobregat (L'), 08125 Montcada i Reixac, 08126 Montgat, 08169 Prat de Llobregat (El), 08194 Sant Adrià de Besós, 08200 Sant Boi de Llobregat, 08211 Sant Feliu de Llobregat, 08217 Sant Joan Despí, 08221 Sant Just Desvern, 08245 Santa Coloma de Gramenet, 08282 Tiana and 08301 Viladecans.

Figure 9: *Grid with codes of each square over the Metropolitan Area of Barcelona*

Figure 10 depicts the aggregated version of land use data collected in this section for the city of Barcelona as used in Siskova and Jeroen (2019). The figure displays two types of residential density housing, both low and high; followed by low and high industry land uses and commercial activities. Additionally, vacant spaces represent parks and green areas. City center is the visual representation of the historical core of the municipality boarded by two main road axes. Transport system included in Figure 10 considers two types of transport within the city - railroads and roads used for both public and private transport alike.

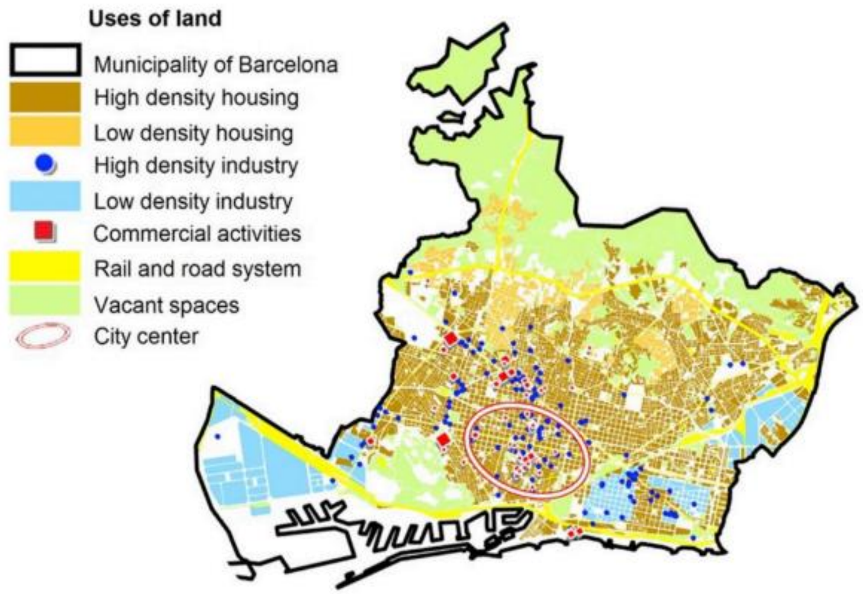

Figure 10: *Distribution of land uses in Barcelona*

3. Transport

3.1 Private Transport

The reason for choosing the selected municipalities over the functional area (FA) of Barcelona stemmed from the fact that the FA includes freight transport, which to a great extend alters the boarders of this region. Further, freight transport is excluded from the model by Tikoudis and Oueslat (2017) and hence will be exempt from this study. Hence, by not accounting for freight, and basing our analysis on passenger transport only, our region of interest shrinks. Figure 9 displays the data on passenger transport within the FA (the highlighted area).

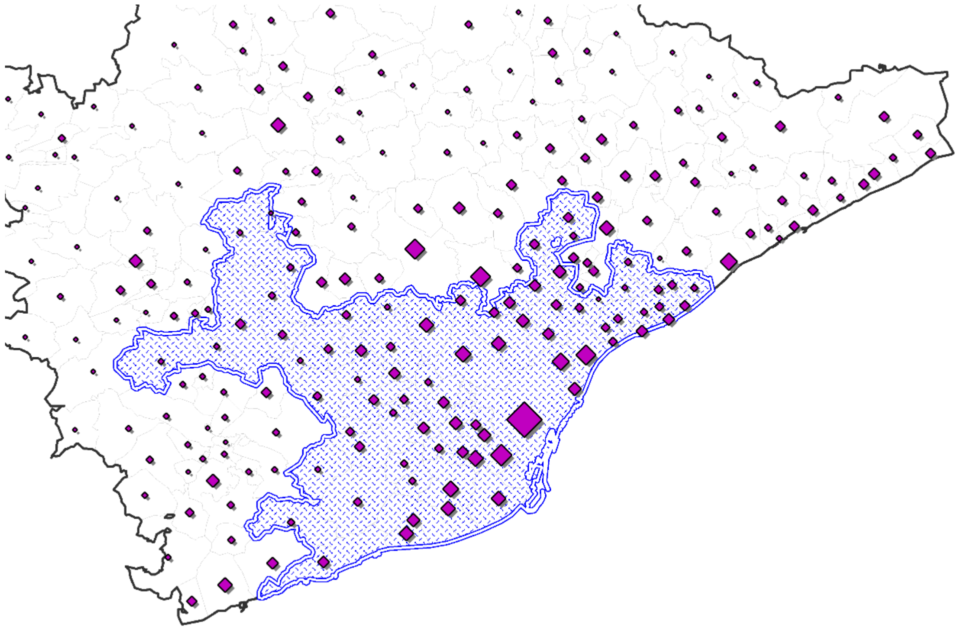

Figure 11: *Passenger transport in the Functional Area of Barcelona*

Passenger transport in our study includes two modes - public and private. Public transport accounts for buses, trains, tams and metro and any publicly provided form of transportation. Private transport in our study includes privately owned cars, motorbikes and possibly walking for short distances. For private transport we create a grid of road transport system and for public transport we also do the same, including all of the connections of the distinct modes used. For private transport we distinguish between two types of roads: highways and other roads, where the distinction was made based on their road capacity, width and traffic flow. Highways entail higher capacity and hence higher traffic flows. Apart from the roads officially categorized as highways, we have included the outer rings of Barcelona as highways as they have multiple lanes and dense traffic. We have applied a buffer of 250 meters on the network of roads and highways (this includes their crossings, hereafter nodes); resulting in the artificial network together with the share of roads per square (for land use purposes) as displayed in Figure 12.

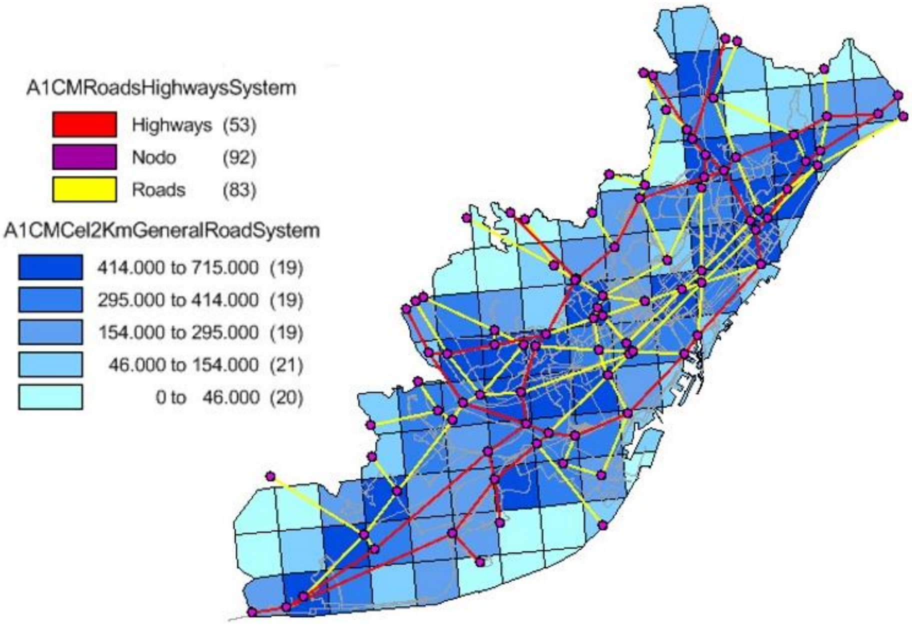

Figure 12: *Roads and highways*

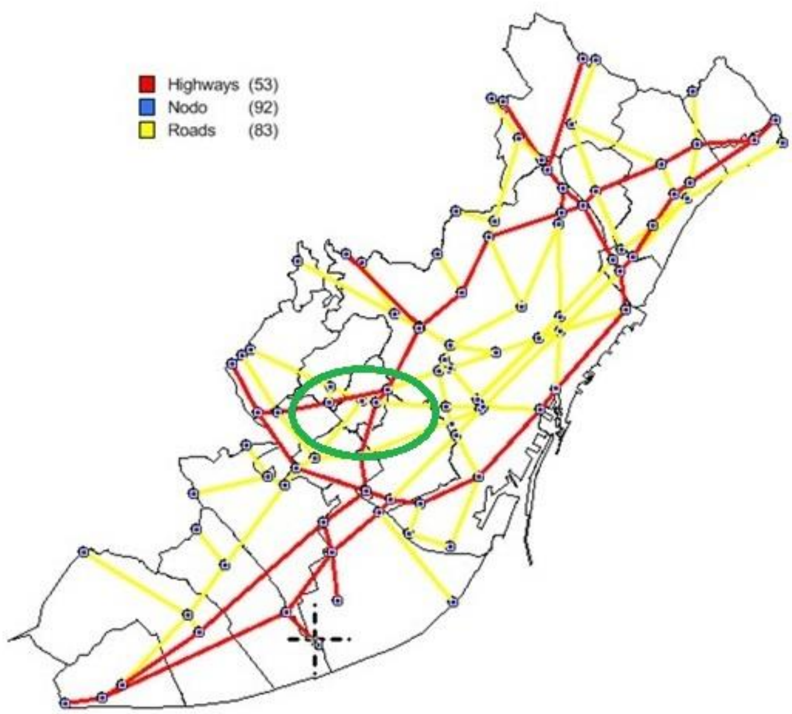

Figure 13: *Road crossing without a node*

Note: There is one instance (green oval) where the crossings of highways and roads do not result in a node, as there is no physical connection between the two.

3.2 Public Transport

In order to create a unified layer of public transport we have to aggregate distinct types of modes. This results in Figure 14, which represents public transport in Barcelona for train (14 left) and buses (right), aggregated at buffers of 250 m. The right image in the figure represents the system of bus stations outside of the city center for relatively less-well connected areas. Only the most representative bus stations are included. Figure 16 shows distinct aggregation choices of bus stations depending on the buffer adopted. For example, any buffer beyond 250 m would create one aggregate station covers most of the center of Barcelona, due to its high density of bus stations correlated with densely populated areas (Figure 16).

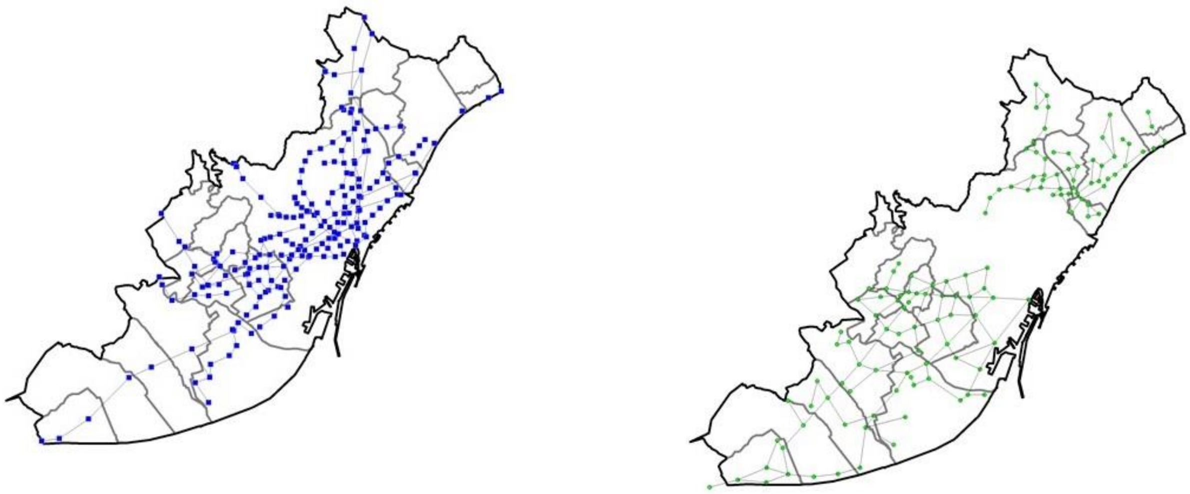

Figure 14: *Public transport: Train and metro (left) and buses (right)*

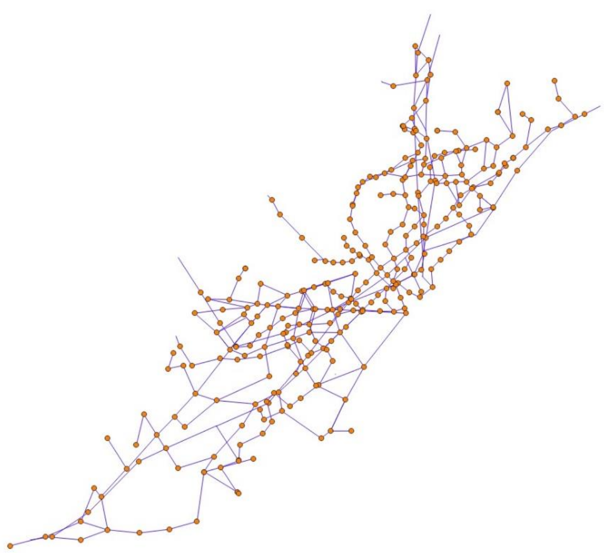

Figure 15: *Complete public transport network*

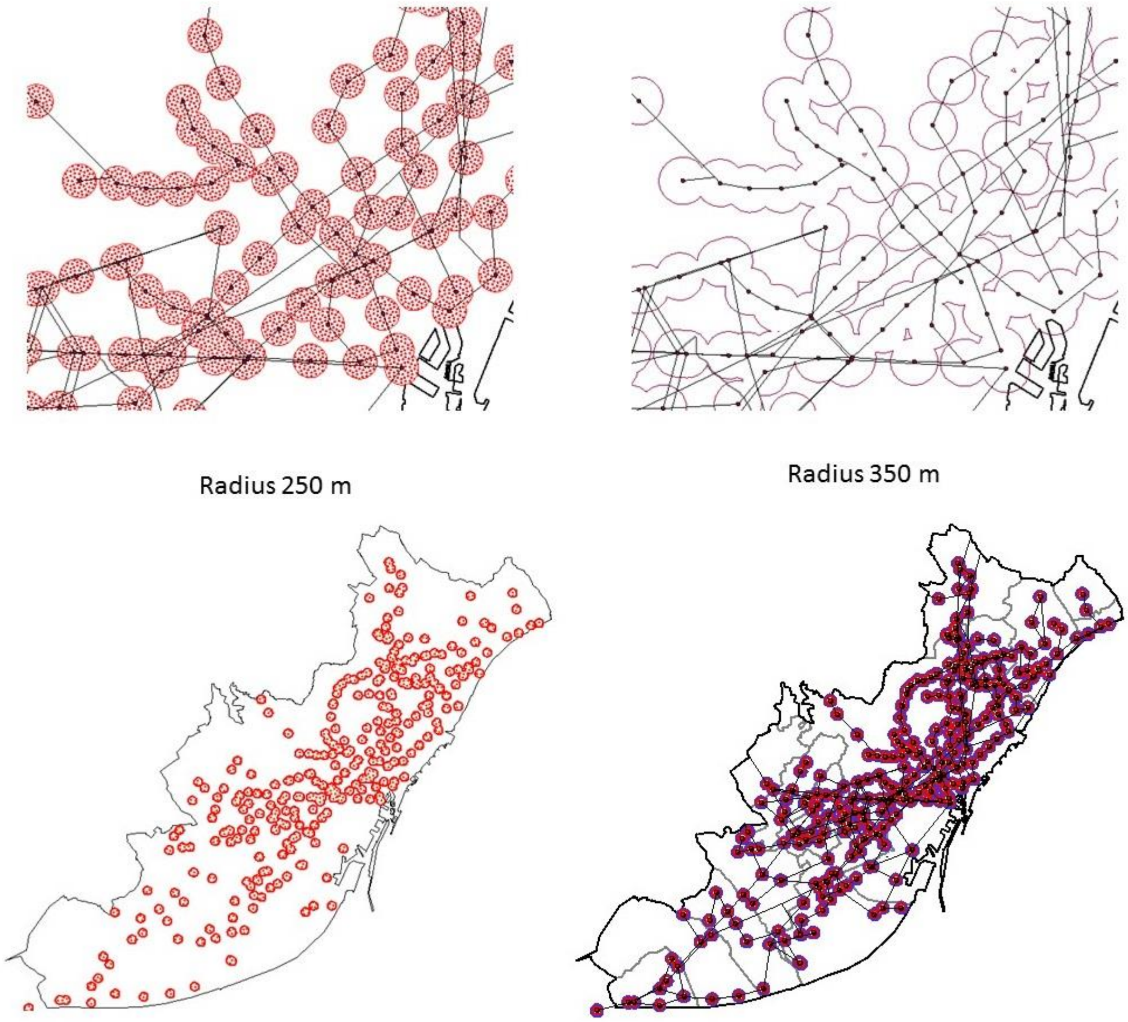

Figure 16: *Comparison of distinct buffers comparison: At 250 m (left) and 350 m (right)*

Traffic intensity

Figure 17 comprises the average daily road traffic density of highways (red) and roads (orange).

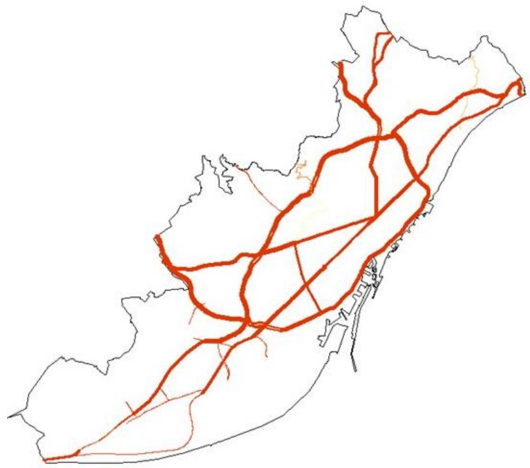

***Figure 17**: Traffic intensity*

The traffic intensity will serve for model's fine-tuning of the travel times and length of the alternative route for the consumer's choice set. This may further affect consumer's residence allocation and work choices.

4. Data motivated by policy questions

Charging stations

For the purpose of answering various policy questions, different data was collected. We analyse both global and local emissions and aim to test for the impact of electric vehicles on changing the level of global emissions generated in the Barcelona region. On the other hand, we wanted to monitor the impact of density and transit intensity on the local air quality. Hence, the policy issue of interest was introducing incentives for using electric vehicles. In this context, a relevant question was whether the propensity of a charging station is an important factor of passenger's decisions regarding purchase of an electric vehicle.

The charging stations for electric vehicles and their typology – fast and slow-charging – is displayed in Figure 18. For modelling impacts on local air quality we used information from the sensory monitoring stations placed throughout the region, which capture various air particles, such as NO_2, PM10, SO_2. The air quality monitoring stations for various air pollutants (see QualitatAire2 file for details) are displayed in Figure 19.

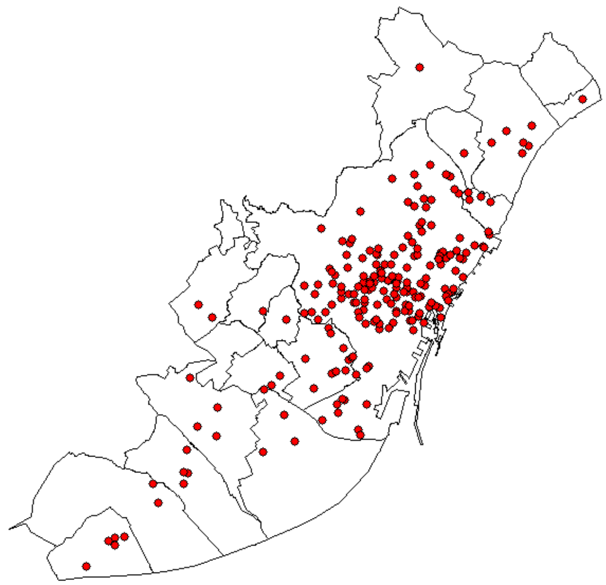

Figure 18: *Charging stations in designated region*

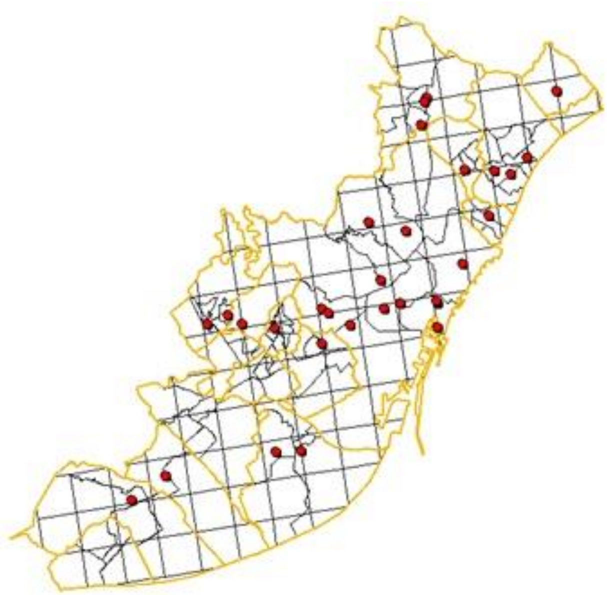

Figure 19: *Air quality monitoring stations*

Education

Levels of education and illiteracy are shown in Figures 20 and 21, respectively. The left-hand side of both Figures 20 and 21 represents the levels of education and illiteracy per municipality or district, which is then aggregated and averaged per 2x2km cell (as explained in section 2.1) in the righ-hand images. The reason to account for education and illiteracy levels is to model heterogenous workers with low and high skills, where education or illiteracy are used proxies.

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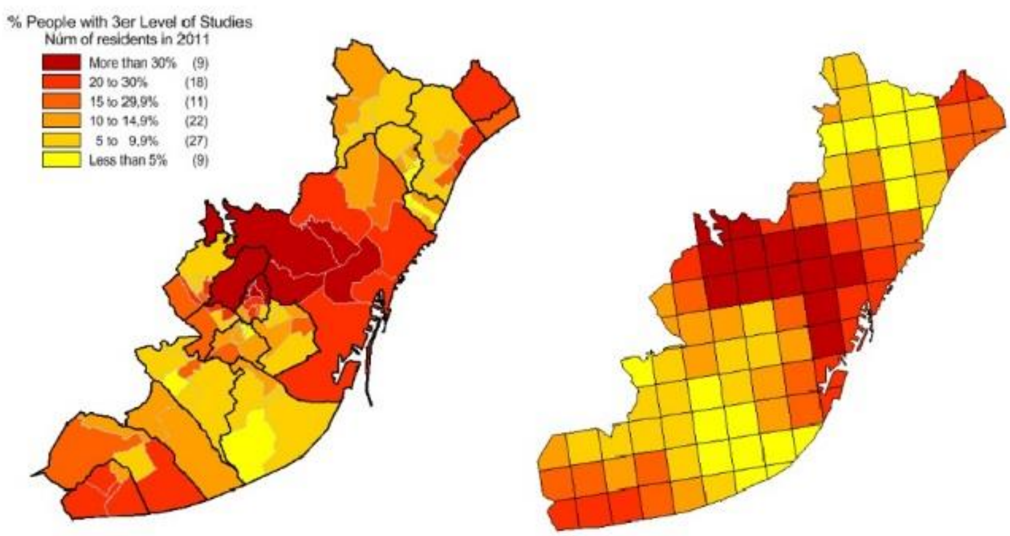

Figure 20: *Education levels: Tertiary education*

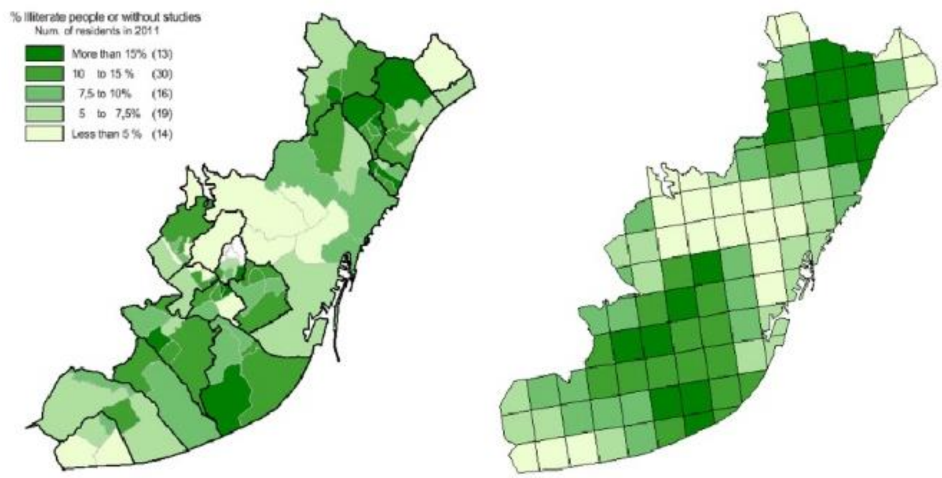

Figure 21: *Education levels: Illiterates*

In addition, to further fine-tune traffic flows described in the model, we included the mobility matrix in the municipalities in Barcelona Metropolitan area. This matrix is displayed in Table 2.

Table 2: **Mobility in the municipalities of the first metropolitan ring of Barcelona. Mobility Survey 2011**

ORIGIN (columns) / **DESTINATION** (rows)

		Besos						BCN	Baix Llobregat Nord							Baix Llobregat Sud			
		Badalona	Montcada i Reixac	S. Adrià del Besòs	Sta Col. de Gramenet	Tiana	Montgat	Barcelona	L'Hospitalet de Llob.	El Prat de Llob.	Cornellà de Llob.	Sant Joan Despi	Sant Just Desvern	Esplugues de Llob.	Sant Feliu de Llob.	Sant Boi de Llob.	Viladecans	Gavà	Castell- defels
Besòs	Badalona	493.146	1.113	7.760	30.401	4.978	7.053		4.592	489	858	699	246	653	460	621	704	615	669
	Montcada i R.	1.545	66.111	513	3.244	43	630												
	S. Adrià del B.	24.866	541	52.776	6.079	130													
	Sta Col. de G.	21.590	513	1.890	273.917	499													
	Tiana	1.687	155	77	1.174	6.576	1.382												
	Montgat	3.846				3.019	17.895												
BCN	Barcelona	107.262	17.613	35.751	68.809	3.495	5.270	9.983.542	210.488	28.318	44.060	20.453	13.879	31.599	19.750	28.138	19.949	17.902	31.587
B. Llob. Nord	L'Hospitalet de Ll.	4.394	1.719	2549	5.737	562	506		507.620	10.515	15.607	2.510	1.461	12.011	3.632	5.509	3.437	3.313	4.606
	El Prat de Ll.	5.238							5.727	153.538	2.542	578	257	1.419	1.173	3.847	2.553	2.158	2.876
	Cornellà de Ll.								18.629	1.725	164.075	7.190	1.155	8.099	2.800	4.267	2.412	1.591	2.473
	Sant Joan Despi								17.928	729	11.878	49.868	1.426	2.124	5.221	2.398	3.558		
	Sant Just Desvern								2.229	85	1.918	1.741	22.424	4.219	1.615	3.521			
	Esplugues de Ll.								2.725	1.719	7.530	4.718	5.004	71.130	1.446				
	Sant Feliu de Ll.								4.059	365	1.298	1.668	1.294	1.280	83.517				
B. Llob. Sud	Sant Boi de Ll.	2.097							5.104	1.983	3.484	2.149	534	1.614	1.325	213.201	6.364	1.901	2.192
	Viladecans								2.598	3.015	2.673					3.208	138.665	10.363	5.420
	Gavà								4.368							1.703	5.149	93.076	11.913
	Castelldefels															2.486	18.234	6.526	119.081
	Exterior 1ª Cor. Met.	39.669	16.647	4.236	22.668	2.421	3.054		30.660	6.925	11.165	4.695	2.554	6.513	11.861	17.086	8.548	5.999	9.062
	Interns i de conexió	705.340	104.412	105.552	412.029	21.723	35.790		816.727	209.406	267.088	96.269	50.234	140.661	132.800	285.985	209.573	143.444	189.879
	Externs	21.124	3.314	4.858	9.846	1.738	1.690		32.642	3.654	6.588	6.531	2.507	7.054	6.043	6.358	6.939	4.228	6.737
	Total desplaçaments	726.464	107.726	110.410	421.875	23.461	37.480		849.369	213.060	273.676	102.800	52.741	147.715	138.843	292.343	216.512	147.672	196.616
Σ	Interns	493.146	66.111	52.776	273.917	6.576	17.895		507.620	153.538	164.075	49.868	22.424	71.130	83.517	213.201	138.665	93.076	119.081
%		67,9%	61,4%	48,1%	64,9%	28,0%	55,1%		59,8%	72,1%	60,0%	48,5%	42,5%	48,2%	60,2%	72,9%	64,0%	63,0%	60,6%
Σ	Connexió	212.196	38.301	52.166	138.112	15.147	12.918		309.107	55.868	103.013	46.401	27.810	69.531	49.283	72.784	70.908	50.368	70.798
%		29,2%	35,6%	47,5%	32,7%	64,6%	39,7%		36,4%	26,2%	37,6%	45,1%	52,7%	47,1%	35,5%	24,9%	32,8%	34,1%	36,0%
Σ	Externs	21.124	3.314	4.858	9.846	1.738	1.690		32.642	3.654	6.588	6.531	2.507	7.054	6.043	6.358	6.939	4.228	6.737
%		2,9%	3,1%	4,4%	2,3%	7,4%	5,2%		3,8%	1,7%	2,4%	6,4%	4,8%	4,8%	4,4%	2,2%	3,2%	2,9%	3,4%
Total desplaçaments		**726.466**	**107.726**	**109.800**	**421.875**	**23.461**	**32.503**		**849.369**	**213.060**	**273.676**	**102.800**	**52.741**	**147.715**	**138.843**	**292.343**	**216.512**	**147.672**	**196.616**

Source: Own elaboration based on Àrea Metropolitana de Barcelona http://www.amb.cat/web/mobilitat/planificacio/estudis-de-mobilitat

6. Conclusions

Part of the results were used in constructing Chapter 4. In the future we will utilize the data in a model for the study consumer behaviour, movement and environmental damage created in the Barcelona Metropolitan Area. We have also adapted a questionnaire, which is analysed in Chapter 6 of this thesis. The results from the survey analysis estimate consumer preferences for electric vehicles as well as policies which create incentives for such transition. These findings will in turn serve for calibration of the general equilibrium model. allowed us to.

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CHAPTER IV:

Optimal urban form for global and local emissions under electric vehicle and renewable energy scenarios

1. Introduction

During the past decades, economists, environmental scientists and urban planners have studied a sustainable design of cities in terms of location and distribution of activities, such as housing, shopping, industries and offices. How can this issue be resolved and which objectives should be guiding it? There may be a trade-off between agglomeration effects and pollutive emissions due to density. Indeed, the higher the proximity among industry, offices and housing, the more productive may be the resulting urban economy. Agglomeration can, however, cause considerable local emissions of air pollutants with associated negative consequences for human health. In this article we analyze distinct urban forms in order to determine which performs best in terms of global or local emissions, including a fair distribution and minimal overall health effects of local emissions.

As a main innovation, we explore the impact of usage of electric vehicles in combination with different sources of electricity. To this end, we define scenarios with distinct shares of electric and gasoline-based vehicles in passenger transport, and with variable shares of renewables in electricity production. We then examine global and local emissions for each scenario under distinct urban forms. To operationalize this, a spatial model of the city is developed consisting of multiple zones, with zone-specific activities, such as low and high density housing or industry. Spatial interactions give rise to freight and passenger transport in and between zones. We assess global emissions of greenhouse gases (GHGs) due to the use of coal, oil and gas by housing, production activities and transport. In addition, we assess local emissions that are zone-specific. The model further includes policy variables to influence private motorized transport and associated emissions.

We use the term urban form rather than spatial structure, as the latter only represents one element that makes up urban form (Dempsey et al, 2009). The scope of our analysis includes additional characteristics such as density, housing and industry attributes as well as transport. We used the monocentric urban form model, containing urban social structures developed by Park and Burgess (1925). It depicts urban land in concentric rings that are uniformly distributed with activities. It was originally used as an explanation of distribution of social groups within cities. Its first application concerned the city of Chicago. Many extensions of this model have been developed since, such as the 'Sector model' by Hoyt (1939). This retains the circular structure, while allowing outward growth of the city. This model has intended to depict the dynamics of growth and spatial structure of Paris (Clerc and Garel, 1988). Another, more complex version, was later proposed by Harris and Ullman (1945), known as the multiple nuclei model. It considered multiple city centers and industrial suburbs, positioned not necessary adjacent to one another. This has been applied to cities in Latin America (Griffin and Ford 1980), Sub-Saharan Africa (Blij 1964) and Southeast Asia (McGee 1967).

Some of the earliest studies of land use in economics were conducted by Ricardo

(1817) and Von Thünen (1826). Von Thünen looked at how land should be used throughout the city, focusing on various agricultural processes. Ricardo analysed the revenue from landownership and prices of land. Both found that population increases forces land rent to rise.[3] A wave of applications of urban form in economics in the 1960s was marked by the works by Alonso (1960a, 1960b) and Muth (1961a, 1961b). They showed that there is a trade-off between access to a central business district (i.e. the center of a city) and housing prices. Their use of a circular monocentric structure goes back to Park and Burgess (1925). Another stream of studies of urban form in combination with transportation economics was undertaken by Anas (1979, 1981). It expanded the literature by including transportation cost, modes of transport and time. In this vein, Oueslati et al. (2015) analyze urban sprawl in EU Cities and apply the monocentric model incorporating extensions, such as geographical, socio-cultural and climatic factors.

The more recent literature offers a variety of studies dealing with urban form and emissions. A comprehensive review is offered by Duranton et al. (2015), while analysis by Kahn and co-authors of urban form and sustainability are of interest to us. Kahn (2003) looked at how various eastern European cities improved their environmental quality after the transition away from a communistic regime (see also Kahn, 2006). Similar studies were undertaken for coastal cities in China by Zheng and Kahn (2013) and Zheng et al. (2014), while Kahn and Schwartz (2008) studied how air quality in California developed under the influence of income and population growth as well as sprawl of large cities. Makido et al. (2012) analyzed the relationship between urban form and CO_2 emissions for Japan. Dense and monocentric cities are found to have higher per capita emissions from residential and passengers transport. The authors concluded that striving for a compact city is not always desirable, given its high emission production.

A study by Grazi et al (2008) assesses how urban form affects transportation distances and consequential production of GHGs. They find that urban location with high density produces reduced emissions, given the distances travelled and travel mode. A study by Gaigne et al. (2012) analyses whether areas with higher population density perform better in environmental terms. The authors find that monocentric cities may cause more pollution than polycentric ones as a high share of commuters does not take advantage of public transport opportunities. Kim (2012) considers urban form as a determinant of transport modes. By manipulating the price of commuting, residents in areas with lower density are drawn closer to the center which reduces urban sprawl. Wiedenhofer et al. (2013) analyze household energy consumption contrasting urban, suburban and rural areas in Australia. They find an effect of urban form, income and demographics, while noting that improvements in the energy efficiency of vehicles may leak away through rebound effects to other, indirect energy uses.

We recognize the challenges associated with changing urban form (Williams, 2010). According to Dawson (2014), cities should strive to become more sustainable within their

[3] The work of Von Thünen was not translated into English until 1966 and hence the Park and Burgess model of almost a century later is considered pioneering in the field.

context and current urban form before trying to shift to another. Constraints other than current urban form should also be reviewed when choosing the future urban form, such as economic activities, their location, necessary space and economic interactions within and outside of the city boundary (Dawson, 2014; Caparros-Midwood et al, 2017). The broader the number of factors included in the analysis, the higher the possibility of prevention of unwanted negative trade-offs (Bai et al 2016).

To examine environmentally desirable urban forms, in this article we develop a spatial accounting model of urban economic activities that cause local and global emissions. We take the basic concepts found in the literature - including the monocentric city structure (Park and Burgess, 1925) and the method of accounting for emissions (Kahn, 1999) and develop an original model which has no overlaps with other articles in the literature. We use the model to study a variety of urban forms and test how they perform under distinct scenarios of car fleet composition and electricity sources. The urban forms considered include spatial configurations ranging from compact to spread-out cities. In our study, population density and agglomeration receive attention in various ways: proximity of residential zones to working, shopping, as well as leisure activities, and distinct densities of housing and economic activity, such as low- and high-density housing, land-intensive industry and land-extensive office buildings.

Based on our results we recommend a feasible time paths of transformation of the urban form for Barcelona into a more desirable urban forms in terms of emissions. We base our recommendation on the similiarity indicator that we propose. This indicator represents the degree to which extent urban forms are similiar in terms of spatial structure represented by the order of zones from the center. We assume that those urban forms that are more similiar will imply smaller efforts to transition into.

We apply the model to Barcelona, Spain. A number of studies have been conducted for this city, e.g. Garcia-Lopez (2012), Garcia-Lopez and Muniz (2013), and Garcia-Sierra and van den Bergh (2014). A study by Garcia-Lopez (2012) estimates the relationship between the growth of population, location patterns and highway and railroad improvements in the Barcelona Metropolitan Region (BMR). It finds that highway and railroad construction causes suburbanization and fosters population growth in suburban areas. Garcia-Lopez and Muniz (2013) analyze the impact of urban spatial structure on local economic growth in BMR. They find that certain intra-metropolitan urban structures (central business district and sub-centres) foster economic growth. Garcia-Sierra and van den Bergh (2014) analysed the impact of built environment characteristics, transportation factors, market factors, socio-economic factors and behavioural factors on commuting patterns in BMR and suggest a policy mixes that discourages car usage. Baldasano et al. (1999) assess the contribution to CO_2 emissions within the city of Barcelona by private transport.

The remainder of this article is organized as follows. Section 2 presents the theoretical model. Section 3 defines scenarios covering three dimensions: urban form, electricity generation and composition of transport vehicles. In addition, this section presents the evaluation criteria. Numerical simulation results are reported and interpreted in Section 4. A final section summarizes and concludes.

2. The Model

2.1 Urban form and emissions

The model consists of a set of accounting equations defining the placement of activities in each zone of the space available to the city. Based on the activities in each zone, passenger and freight transport flows between zones are derived. In turn, global and local emissions due to all fixed and transport activities can be calculated. Each zone is assumed to contain only one activity which is uniformly spread throughout. Figure 1 offers a visual representation of the urban form layout employed, namely a circular structure consisting of six zones.

The city is composed of the following activities:

- Shopping in city center.
- Leisure or recreation on vacant land, including parks and semi-nature.
- Low density housing (LDH).
- High density housing (HDH).
- Low density economic activity (LDI), notably industry.
- High density economic activity (HDI), including offices and warehouses.

While the center with shops is assumed to be located in zone 1 (see Figure 1), the other activities can be located in any of the zones 2 through 6, giving rise to distinct urban forms. The majority of the population resides in HDH and the rest in the LDH. One can perceive the offices and storage in HDI as the steering wheel of the industrial processes that take place in the LDI, whose primary purpose is manufacturing. As a result, transportation of intermediate goods occurs between LDI and HDI. On the other hand, transport of final goods goes from the zone with LDI to central zone with shops. Passenger transport goes from both housing zones (LDH and HDH) to work zones (LDI and HDI), to the city center for shopping, and to the vacant land for leisure.

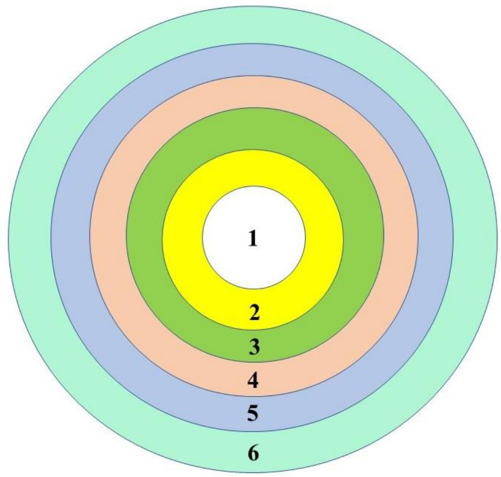


Figure 1: *City structure with six zones*

The model describes both local and global emissions. Local pollutants worsen air quality in respective zones, affecting the health of the population. Local air pollutants may include particles, ground-level ozone, carbon monoxide, sulphur oxides, nitrogen oxides and lead. In terms of global pollutants, we focus on greenhouse gases (GHG) such as carbon dioxide, methane and nitrous oxide. They cause enhanced global warming and subsequent physical, biological, social, economic and health impacts worldwide. Emissions of CO_2 serve as a proxy of GHGs in the model, given that they are the most important GHG and easily quantifiable. As a proxy for local pollutants serves NOx. Figure 2 depicts the connection between the various types of elements in the model, showing the cause-effect chain from the exogenous population size and urban form to emissions.

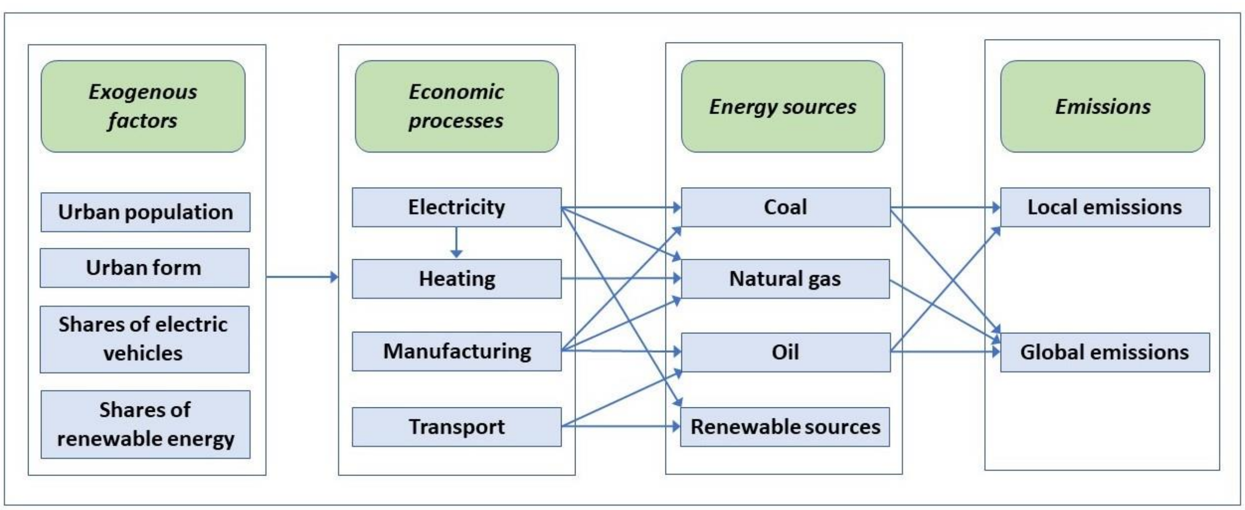


Figure 2: *Process flows from exogenous factors to emissions*

Global emissions of GHGs derive from the use of fossil fuels *coal, oil and gas* for electricity, heating or other (notably industrial) uses of energy. In addition, we consider renewables like solar PV and wind energy as possible sources of electricity. Each energy source has unique global and local emission intensities. Local emissions are the sum of emissions derived from fossil fuels with distinct emission intensities. With regard to global emissions, we consider gas to be a rather clean pollutant in terms of local air quality impacts. We assume that renewable resources create no emissions.

2.2 Demographics and activities

Demographics and distribution of the population over distinct activities is displayed in Figure 3. The population is allocated into two zones of residence (LDH and HDH) defined by an allocation factor γ. The population is further divided into workers and non-workers, captured by allocation factor α. Workers' commuting trips from origin (HDH or LDH) to destination (HDI or LDI) are represented by μ. Share of the population that participates in shopping trips is captured by β.

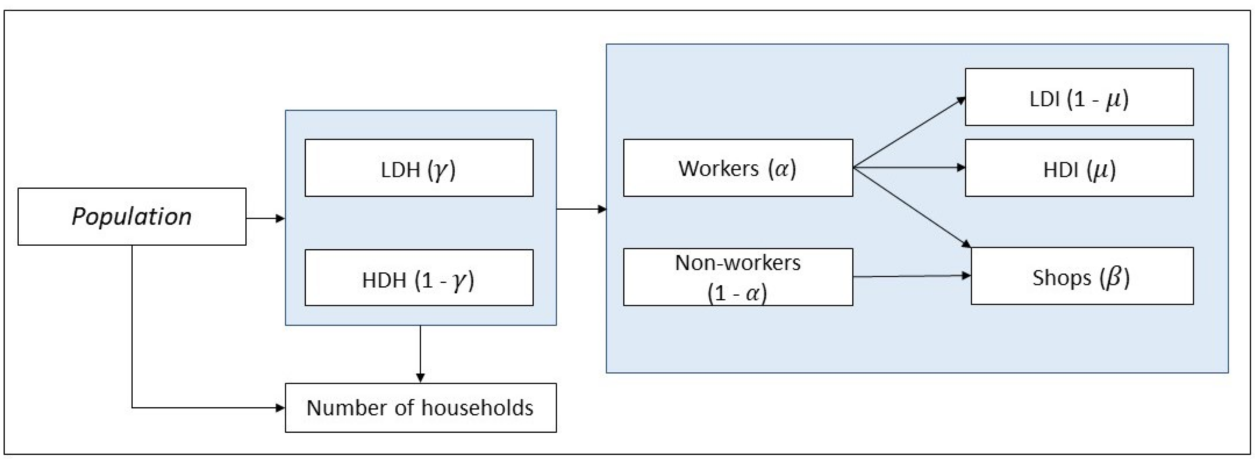


Figure 3: *Demographics and implications for activities*

To illustrate some of the demographics' relations, the total population residing in LDH (P_{LDH}) is defined as:

$$P_{LDH} = \gamma * P_{total} \tag{1}$$

Population that resides in HDH may be defined as follows:

$$P_{HDH} = (1 - \gamma) * P_{total} \tag{2}$$

Workers are divided by the place of work (HDI or LDI). The following equation refers to workers from either LDH or HDH that work in HDI.

$$P_{work_{z,HDI}} = \alpha * \mu * P_z \quad z = LDH, HDH \tag{3}$$

We describe the share of population that takes part in shopping trips with parameter β as we assume that both workers and non-workers participate in them. This may be defined for both LDH or HDH residents in this fashion:

$$P_{shop_z} = \beta * P_z \quad z = LDH, HDH \tag{4}$$

To approximate the number of families residing in either of the residential zones, the total population in each district is divided by average family size. This variable is relevant to determining the number of leisure trips we assume these families participate as a whole.

$$F_z = \frac{P_z}{F_{size}} \quad z = LDH, HDH \tag{5}$$

2.3 Electricity use in transport, housing, shopping and manufacturing

Electricity is used for household activities, in manufacturing processes and by electric vehicles in transport. Electricity can be produced by gas, coal or renewable resources. We only consider global emissions from electricity production, as it is assumed to take place outside the city. Hence, any local pollutants emitted would not affect health of those living in the city. We use a straightforward accounting approach to estimate emissions, following Kahn (1999).[4]

We assume that there are various possible sources of electricity. The $E_{Elc}^{\mathcal{G}}$ are the total emissions caused by electricity production where $e_{Elc,i}^{\mathcal{G}}$ is the corresponding emission coefficient of electricity production from gas, coal or renewable resources. The $\sum_{s=V,R,S,M} D_s$ represents the total electricity demanded in various zones. We sum over the different types of electricity demands $\sum_{s=V,R,S,M} D_s$, where D_V represents the demand for electricity by electric and gasoline vehicles in passenger transport, D_R is the demand made in residence areas and D_S by shops and D_M manufacturing processes. ω_i represents the share of the total electricity produced from a specific resource i. Since the renewable sources do not produce local nor global emissions, their emission coefficient is zero.

[4] The model excludes any consideration of private or public costs. This would require an entirely different model. We agree that the cost of a transition to electric vehicles (EV) and renewable energy (RE) is a relevant issue, but it should be derived from other studies. The metier of our model is that it can address order effects, that is, which sequence of EV and RE transitions performs better in terms of global and local emissions, or associated health effects. We could add an ad-hoc consideration of costs, but we feel it rather weakens than strengthens our analysis.

$$E_{Elc}^{\mathcal{G}} = \sum_{s=V,R,S,M} \sum_{i=c,g,r} e_{Elc,i}^{\mathcal{G}} * \omega_i * D_s \quad \mathcal{G} = Global \tag{6}$$

The following are the weights ω_i corresponding to each of the respective sources of electricity production:

$$\omega_c + \omega_g + \omega_r = 1 \tag{7}$$

We assume that all demand for electricity will be met by supply, so that:

$$\sum_{s=V,R,S,M} D_s = \sum_{i=c,g,r} S_i \tag{8}$$

The demand for electricity created by the usage of electric vehicles is calculated as the sum of two parts, namely electricity consumed during usage and production phases. The first is obtained by multiplying the total length travelled L_{TP} by the electricity (kWh) required per kilometer expressed by ${e_{TP_e}}^{\mathcal{G}}$. The second part consists of the sum of electricity use to manufacture a vehicle and battery. Electricity consumption in battery manufacturing is obtained by consumption coefficient ($e_{bev}^{\mathcal{G}}$) expressed in kWh, which is multiplied by the number of cars in the system N_{cars}. The amount of electricity needed for a production of an average car (excluding the electric battery) is captured by the coefficient ${e_{car,prod}}^{\mathcal{G}}$ also in kWh, which is then multiplied by the number of cars in the system. This is depicted in the following equation:

$$D_V = \delta * ({e_{TP_e}}^{\mathcal{G}} * L_{TP} + e_{bev}^{\mathcal{G}} * N_{cars}) + {e_{car,prod}}^{\mathcal{G}} * N_{cars} \tag{9}$$

P_{work} is used as a proxy for estimating the number of cars N_{cars} in the system. Moreover, the difference between life cycle emissions between electric vehicle and gasoline vehicle is the energy consumption needed during the production of the electric vehicle's battery. This consumption varies depending on the electricity mix. In other words, the fixed part is the energy required for battery's production; however, the variable part are the emissions produced by these processes which depend on the energy source. The rest of the car's production in both electric vehicles and gasoline-based vehicles exhibits the same energy demand. Note that the last part of eq.(9) which deals with production of a car includes both gasoline and electric vehicles.

The second type of electricity demand is by residents in low (LDH) and high-density households (HDH) is calculated in the following manner:

$$D_R = Elc_{avg} * (F_{LDH} + A_{HDH} * F_{HDH}) \tag{10}$$

Here Elc_{avg} represents the average consumption per household, F_{LDH} and F_{HDH} represent the number of households in each of the respective residential zones. A_{HDH} is the efficiency improvement in energy use in HDH in relative to LDH. We attribute A_{HDH}

to shared walls and isolation in both electricity consumption and heating by gas, which was exogenously extracted from the data.

2.4 Heating and manufacturing

An important share of total heating is based on usage of natural gas where we calculate its global emissions by gas demands families in each of the residential zones represented by the number of families in each (F_z). These demands are multiplied by the emission coefficient for gas $e_g^{\mathcal{G}}$. An efficiency improvement is included for HDH (A_{HDH}) relative to LDH, which is same as in previous section.

$$E_h^{\mathcal{G}} = e_g^{\mathcal{G}} * G_h * (F_{LDH} + A_{HDH} * F_{HDH}) \quad \mathcal{G} = Global \tag{11}$$

Emissions by manufacturing activities are calculated based on their consumption of oil, coal and gas multiplied by their respective fuel emission intensities. This excludes electricity production in order to avoid double-accounting. Global emissions from manufacturing activities are as follows:

$$E_m^{\mathcal{G}} = e_c^{\mathcal{G}} * C_{m,z} + e_o^{\mathcal{G}} * O_{m,z} + e_g^{\mathcal{G}} * G_{m,z} \quad \mathcal{G} = Global \tag{12}$$

where consumptions of coal ($C_{m,z}$), oil ($O_{m,z}$) and gas ($G_{m,z}$) are multiplied by corresponding emission coefficients.

In addition, manufacturing processes have local air-polluting impacts, which exclude natural gas; represented in eq. (13).

$$E_{m,z}^{\mathcal{L}} = e_c^{\mathcal{L}} * C_{m,z} + e_o^{\mathcal{L}} * O_{m,z} \quad \mathcal{L} = Local \tag{13}$$

2.5 Passenger transport

Passenger transport in our model represents transport from private electric or gasoline-based vehicles. Different trip purposes call for distinct frequency of travel and length. For instance, for commuting the number of trips is derived from the number of working days in a year. The length of trips depends on the origin of commuting (LDH or HDH) and destination (LDI or HDI) and urban form. Number of trips created for leisure and shopping in the model are exogenously given.

We calculate the distance travelled within each of the respective zones in the following manner:

$$l_z = \begin{cases} \frac{1}{2}u & if \quad z = o \quad or \quad z = d \\ u & if \quad o < z < d \end{cases} \tag{14}$$

Here u is the unit distance between zones, which follows a uniform distribution. Transport in origin (o) and destination (d) zones representing internal travels within a zone passes through half of the unit distance $(\frac{1}{2}u)$ creating half of the emissions as we assume that traffic will not necessarily pass through the entire zone. Half a unit of distance represents the average distance if original and destination locations are uniformly distributed within each zone. The remaining zones bare the full emission share (u).

The total number of trips within a city is the sum all trips across zones for all activities (k). The activities k include shopping $(k = 1)$, commuting $(k = 2)$, leisure activities $(k = 3)$, inter-industry $(k = 4)$ and final goods $(k = 5)$ transport.

The length travelled per year within a zone $L_{TP,z}$ in a year equals the lengths made in the different of trips made multiplied the number of trips $T_{trips(k,z)}$ per activity k, multiplied by the number of people that made that trips $P_{k,z}$. Distances are further multiplied by the number of 2, representing a return trip.

$$L_{TP,z} = 2 \sum_{k=1}^{3} l_z * T_{trips(k,z)} * P_{k,z} \tag{15}$$

The total length of all trips made within the city equals the sum of distances travelled in each zone, given the origin-destination $(o - d)$ pair:

$$L_{TP} = \sum_{z=o}^{d} L_{TP,z} \tag{16}$$

Global emissions express the total traffic caused by passenger transport with global emission coefficient. δ represents the total traffic created by electric vehicles and $(1 - \delta)$ is created by gasoline-based cars. The transport created by electric vehicles is accounted for in the demand for electricity (D_V).

$$E_{TP}^{\mathcal{G}} = (1 - \delta) * e_{TP_o}^{\mathcal{G}} * L_{TP} \quad \mathcal{G} = Global \tag{17}$$

Similarly, local emissions at zone level are calculated using a local emission coefficient.

$$E_{TP,z}^{\mathcal{L}} = (1 - \delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z} \quad \mathcal{L} = Local \tag{18}$$

2.6 Freight transport

Freight transport includes trips made by trucks and vans to move goods between zones. The traffic flows include include movement of inter-industry goods and final goods, which take place between LDH, HDH and Center. Similarly to passenger transport, a distinction between global and local transport is made by including a designated emission coefficient.

Distance travelled by trucks for inter-industry ($k = 4$) and final goods transport($k = 5$) in in each zone is calculated by multiplying the distance travelled in an individual trip by the associated number of trips made by each type of freight transport ($T_{trips(k,z)}$). Number of trips is exogenously given. This is calculated in the following manner:

$$L_{TF,z} = 2\sum_{k=4,5} l_z * T_{trips(k,z)} \tag{19}$$

Moreover, the total length travelled across the city is defined as sum of the different trips' lengths across zones in eq.(20).

$$L_{TF} = \sum_{z=o}^{d} L_{TF,z} \tag{20}$$

Freight transport is undertaken with gasoline-based vehicles. Global emissions are calculated using corresponding emission coefficient.

$$E_{TF}^{\mathcal{G}} = e_{TF}^{\mathcal{G}} * L_{TF} \quad \mathcal{G} = Global \tag{21}$$

Similarly, local emissions are calculated.

$$E_{TF}^{\mathcal{L}} = e_{TF}^{\mathcal{L}} * L_{TF,z} \quad \mathcal{L} = Local \tag{22}$$

3. Scenarios and evaluation criteria

3.1 Scenarios for electric vehicles, renewable electricity and urban form

The model is run for a variety of scenarios. These cover three dimensions: urban form, electricity generation and composition of transport vehicles. Table 1 shows the different combinations of the latter. The electricity produced by gas and coal have equiproportionate shares of the electricity which not produced by renewable resources (see eq.(7)).

Table 1: *Scenarios for shares of electric vehicles (EV) and renewable energy (RE) with consequences for gasoline vehicles (GV), global emissions (GE) and local emissions (LE)*

Scenario	EV share (δ)	RE share (ω_r)	EV emissions	GV emissions
1	0	0	No emissions	GE+LE
2	0	0.5	No emissions	GE+LE
3	0	1	No emissions	GE+LE
4	0.5	0	High GE	GE+LE
5	0.5	0.5	Moderate GE	GE+LE
6	0.5	1	No emissions	GE+LE
7	1	0	High GE	No emissions
8	1	0.5	Moderate GE	No emissions
9	1	1	No emissions	No emissions

If the electric vehicle share δ takes a value greater than zero, passenger transport consists of both electric and gasoline vehicles. In Table 1, for all of the scenarios where gasoline vehicles are present ($\delta < 1$), global and local emissions are produced. On the contrary, electric vehicles produce global emissions only if renewable electricity (ω_r) is lower than 1.

We have defined eleven city structures reflecting distinct organizations of activities among zones - including city center (shopping), vacant land (leisure), LDH, HDH, LDI and HDI. The eleven urban forms selected fall into four categories: compact city, intermediate city, spread-out city and green city. Their individual acronyms each entail an extra letter indicating compact (C), intermediate (I) spread out (S) and green (G) urban forms. They are depicted in Table 2.

Compact city scenarios refer to urban forms where residents live within a close proximity to their work and shops. Spread-out city scenarios include larger distances to be travelled as the resident or work zones with the highest density are at greater distance. Intermediate cities fall in between. Green city denotes a structure where allocation of vacant, green land is near housing districts.

We propose an indicator of differences between two urban forms which allows us to quantify the distance between distinct urban forms. This helps to assess a time sequence of feasible transitions from a current to a more desirable urban form. In other words, we assume that the easiest (and least costly) transition would happen between urban forms with smallest differences based on this indicator. The indicator is constructed by summing terms that indicate the distance between identical zone uses in two distinct urban forms; this distance is calculated by taking the difference between the positions of the same zone (LDH, HDH, LDI, etc.). In formal terms, the indicator is then as follows:

$$\Delta_{A,B} = \sum_{z=1}^{6} |i_z^A - i_z^B| \qquad i = 1, \dots, 6 \tag{23}$$

Here A and B represent the urban forms compared. For instance, comparing UFC1 and UFS3™s leads to a value for this indicator of: 4+2+1+3+2=12. Table 3 presents a matrix with values of this indicator for all possible combinations of urban forms. In discussing the results in Table 10 (on the likely time sequence of scenarios and optimal of urban form) we now also use the values of this indicator to identify which order of urban forms make up a feasible transition trajectory. The results of this indicator for urban forms proposed are displayed in Table 3.

Table 2: *Urban forms considered*

Zones	Urban Form										
	Compact City				Intermediate City			Spread-out City			Green City
	UFC 1	UFC 2	UFC 3	UFC 4	UFI 1	UFI 2	UFI 3	UFS 1	UFS 2	UFS 3	UFG
1	Center	Center	Center	Center	Center	Center	Center	Center	Center	Center	Center
2	HDI (Offices)	HDI (Offices)	HDH (Flats)	HDH (Flats)	LDH (Houses)	HDH (Flats)	LDH (Houses)	LDH (Houses)	LDH (Houses)	LDH (Houses)	LDH (Houses)
3	HDH (Flats)	HDH (Flats)	HDI (Offices)	HDI (Offices)	HDH (Flats)	LDH (Houses)	HDH (Flats)	LDI (Industry)	LDI (Industry)	LDI (Industry)	Vacant
4	LDI (Industry)	LDH (Houses)	LDI (Industry)	LDH (Houses)	HDI (Offices)	LDI (Industry)	LDI (Industry)	Vacant	HDH (Flats)	HDH (Flats)	HDH (Flats)
5	LDH (Houses)	LDI (Industry)	LDH (Houses)	LDI (Industry)	LDI (Industry)	HDI (Offices)	HDI (Offices)	HDH (Flats)	Vacant	HDI (Offices)	HDI (Offices)
6	Vacant	Vacant	Vacant	Vacant	Vacant	Vacant	Vacant	HDI (Offices)	HDI (Offices)	Vacant	LDI (Industry)

Table 3: *Matrix of quantified differences between urban forms*

Indicator values											
	UFC1	UFC2	UFC3	UFC4	UFI1	UFI2	UFI3	UFS1	UFS2	UFS3	UFG
UFC1	0	2	2	4	6	6	6	12	10	8	12
UFC2	2	0	4	2	4	6	6	12	10	8	10
UFC3	2	4	0	2	6	4	6	12	10	8	12
UFC4	4	2	2	0	4	4	6	12	10	8	10
UFI1	6	4	6	4	0	4	2	8	6	4	6
UFI2	6	6	4	4	4	0	2	8	6	4	8
UFI3	6	6	6	6	2	2	0	6	4	2	6
UFS1	12	12	12	12	8	8	6	0	2	4	6
UFS2	10	10	10	10	6	6	4	2	0	2	6
UFS3	8	8	8	8	4	4	2	4	2	0	6
UFG	12	10	12	10	6	8	6	6	6	6	0

Figures 4 -7 show the traffic flows arising from the respective city structures, where compact are presented in Figure 4, intermediate cities in Figure 5, spread out cities are in Figure 6, followed by green city in Figure 7.

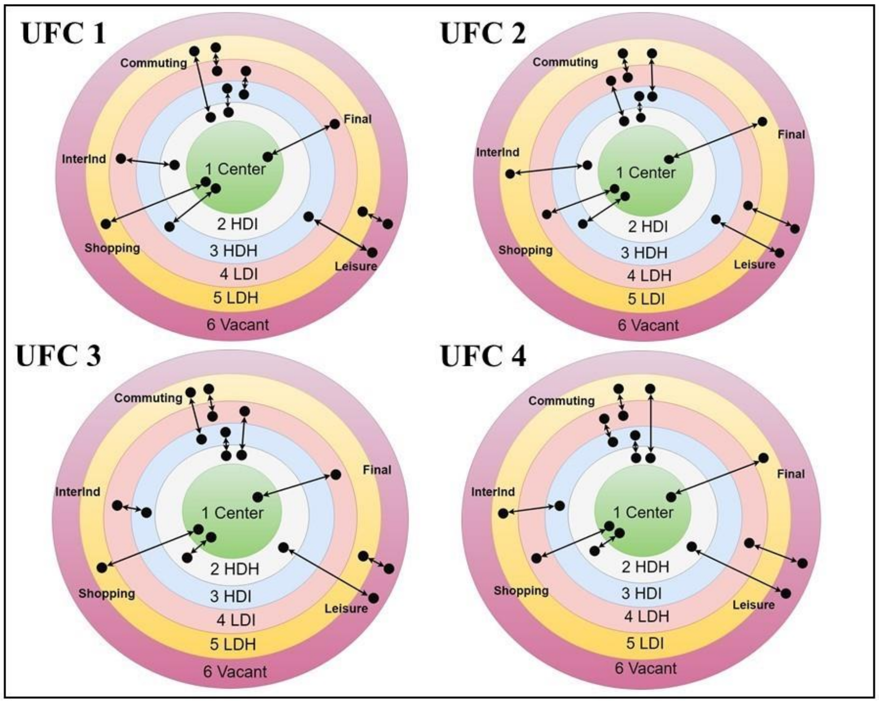
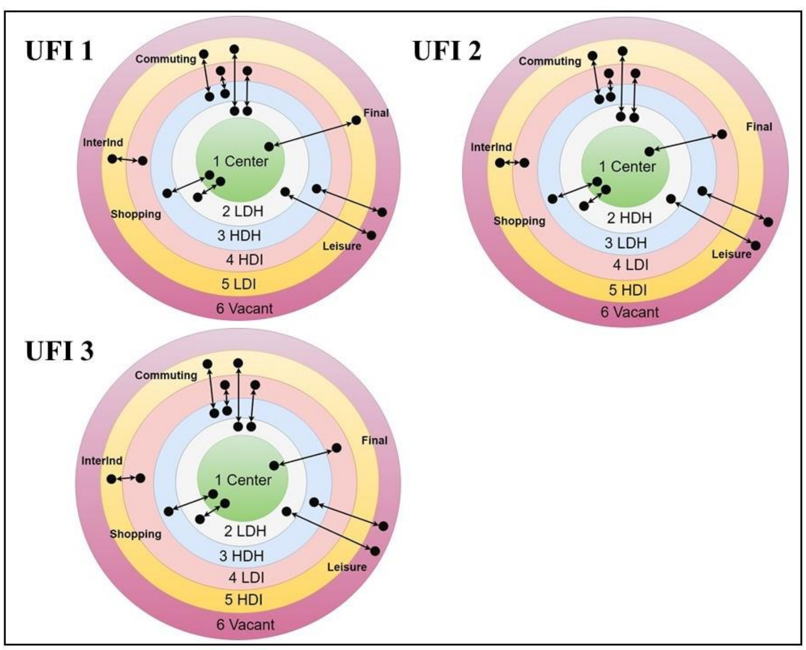


Figure 4: *Urban forms with passenger and freight transport flows: compact cities*

Notes: The traffic flows from passenger and freight transport are represented by straight lines between dots in zones, representing the origin and destination. In the zone with the dot only half of the distance is travelled on average; whereas in the remaining zones the full distance u is crossed. ***InterInd*** represents inter-industry freight transport of goods and ***Final*** the freight transport of final goods.



Fi gure 5: *Urban forms with passenger and freight transport flows: intermediate cities*

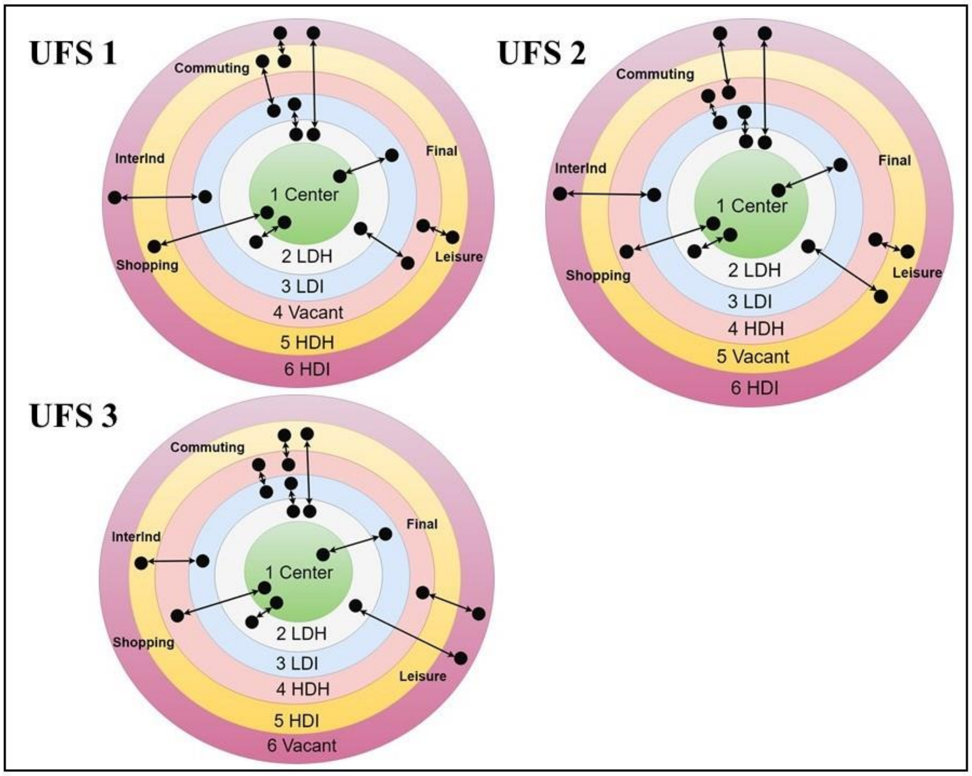


Figure 6: *Urban forms with passenger and freight transport flows: spread-out cities*

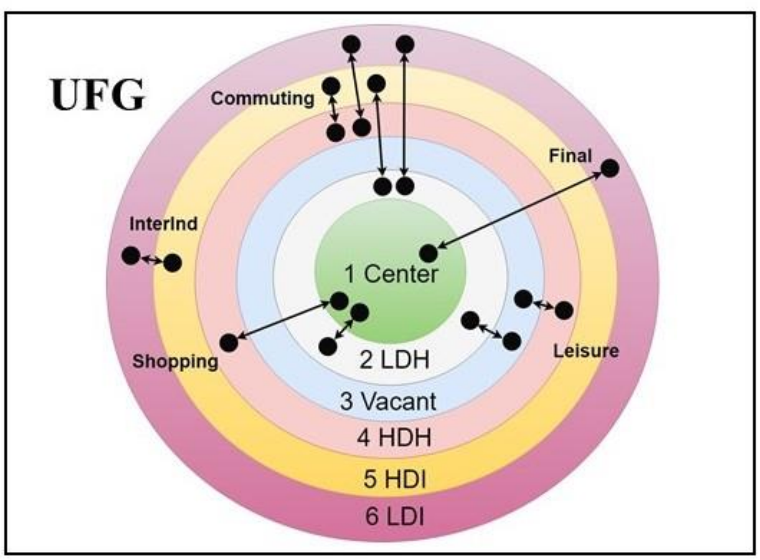


Figure 7: *Urban forms with passenger and freight transport flows: green city*

3.2 Evaluation criteria

In our analysis we use three categories of criteria in order to evaluate performance of an urban form. These fall into:

1. *Global emissions*

   (a) Total global emissions.
   (b) The share of transport in global emissions.

2. *Local emissions*

   (a) Total local emissions.
   (b) Gini index of local emissions across zones.
   (c) Average local emissions.

2. *Health indexes*

(a) Average health, which captures the impact on people in zone of emissions generated in that zone.
(b) Average extended health, which also includes the impact on people of emissions from adjacent zones.

Global emissions are the sum of emissions by each activity.

$$E^{\mathcal{G}} = E^{\mathcal{G}}_{Elc} + E^{\mathcal{G}}_{h} + E^{\mathcal{G}}_{m} + E^{\mathcal{G}}_{TP} + E^{\mathcal{G}}_{TF} \tag{24}$$

The share of transport in global emissions is calculated as:

$$E^{\mathcal{G}}_{T} = \frac{E^{\mathcal{G}}_{TP} + E^{\mathcal{G}}_{TF}}{E^{\mathcal{G}}} \tag{25}$$

Total local emissions summed over all zones in the city equals

$$E^{\mathcal{L}}_{total} = \sum_{z=o}^{d} E^{\mathcal{L}}_{z} \tag{26}$$

The calculation of local emissions is more complicated. We illustrate this for urban form UFI3 in Table 4.

Table 4: *Local emissions in individual zones calculated for urban form UFI3*

Zone	**Local emissions ($E_z^{\mathcal{L}}$)**
1	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=1} + e_{TF}^{\mathcal{L}} * L_{TF,z=1}$
2	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=2} + e_{TF}^{\mathcal{L}} * L_{TF,z=2}$
3	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=3} + e_{TF}^{\mathcal{L}} * L_{TF,z=3}$
4	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=4} + e_{TF}^{\mathcal{L}} * L_{TF,z=4} + e_C^{\mathcal{L}} * C_{m,z}^{\mathcal{L}} + e_O^{\mathcal{L}} * O_{m,z}^{\mathcal{L}}$
5	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=5} + e_{TF}^{\mathcal{L}} * L_{TF,z=5}$
6	$(1-\delta) * e_{TP_o}^{\mathcal{L}} * L_{TP,z=6}$

We report an average of local emissions over all zones, calculated as:

$$E_{avg}^{\mathcal{L}} = \frac{1}{n}\sum_z E_z^{\mathcal{L}} \tag{27}$$

A health index HI measures the level of zone-specific pollution weighted by how many people are affected by it in the particular zone. It takes into consideration the time spent by people in the various activities k, which includes commuting, leisure, shopping, freight transport and other housing and manufacturing activities:

$$HI_z = \frac{E_z^{\mathcal{L}} * P_{k,z} * \theta_{k,z}}{P_{total}} \qquad z = o, \dots, d \tag{28}$$

Note that we do not need to sum the term in equation 29 over k, as the activity k is zone-specific and there is exactly one activity in each zone for a designated time span. Henceforth, summing over z is sufficient. Here $\theta_{k,z}$ represents the time share of individual activities (k) in different zones (z). Total time available consists of $\theta_{k,z}$ plus time devoted to travelling (θ_{TP}), such that:

$$\theta_{TP} + \sum_k \theta_{k,z} = 1 \qquad \theta_k \equiv \theta_{k,z} \tag{29}$$

We report an average health index over all zones, calculated as:

$$HI = \frac{1}{n}\sum_z HI_z \tag{30}$$

HI is calculated for each of the relevant zones. We demonstrate this by applying HI to urban form UFI3 (Figure 5). The health indexes HI for each zones are summed in Table 5. $HI_{z=1}$ expresses the impact of emissions produced in zone 1 on people that participate in shopping activities. $HI_{z=2}$ and $HI_{z=3}$ represent how the emissions produced in residential zones affect residents during the time they spend in their houses. Furthermore, we calculate how emissions in work zones affect workers in $HI_{z=4,5}$. $HI_{z=6}$

captures emissions due to transport through vacant land affecting families, originating from residential zones F_X, recreating here.

Table 5: *Health Index HI_z for each zone under urban form UFI3*

Zone	**Health Index HI_z**
1	$E_1^{£} * P_{shop} * \theta_{shop}/P_{total}$
2	$E_2^{£} * F_{LDH} * \theta_{res,LDH}/P_{total}$
3	$E_3^{£} * F_{HDH} * \theta_{res,HDH}/P_{total}$
4	$E_4^{£} * P_{work,X} * \theta_{work}/P_{total}$
5	$E_5^{£} * P_{work,X} * \theta_{work}/P_{total}$
6	$E_6^{£} * F_X * \theta_{leissure}/P_{total}$

The second type of health index (HIE) is extended by assuming that pollution produced in one zone affects adjacent zones as well; however, the effect weakens (a form of spatial discounting) the further it is. This is captured by the following equation:

$$HIE_z = \frac{P_{k,z} * \theta_{k,z} * (\sum_{z=o}^{z=d} E_z^{£} * \rho^{|o-d|})}{P_{total}} \qquad z = o, \dots, d \tag{31}$$

where $0 < \rho < 1$.

The average extended health index is reported, which takes the following form:

$$HIE = \frac{1}{n} \sum_z HIE_z \tag{32}$$

The HIE $_z$ are illustrated in Table 6 for urban form UFI3:

Table 6: *Health Index HIE for urban form UFI3 calculated for all six zones*

Zones	**Health Index HIE_z**
1	$(E_1^{£} * \rho^0 + E_2^{£} * \rho^1 + E_3^{£} * \rho^2 + E_4^{£} * \rho^3 + E_5^{£} * \rho^4 + E_6^{£} * \rho^5) * P_{shop} * \theta_{shop}/P_{total}$
2	$(E_2^{£} * \rho^0 + E_1^{£} * \rho^1 + E_3^{£} * \rho^1 + E_4^{£} * \rho^2 + E_5^{£} * \rho^3 + E_6^{£} * \rho^4) * F_{LDH} * \theta_{res,LDH}/P_{total}$
3	$(E_3^{£} * \rho^0 + E_2^{£} * \rho^1 + E_4^{£} * \rho^1 + E_1^{£} * \rho^2 + E_5^{£} * \rho^2 + E_6^{£} * \rho^3) * F_{HDH} * \theta_{res,HDH}/P_{total}$
4	$(E_4^{£} * \rho^0 + E_3^{£} * \rho^1 + E_5^{£} * \rho^1 + E_2^{£} * \rho^2 + E_6^{£} * \rho^2 + E_1^{£} * \rho^3) * P_{work,X} * \theta_{work}/P_{total}$
5	$(E_5^{£} * \rho^0 + E_4^{£} * \rho^1 + E_6^{£} * \rho^1 + E_3^{£} * \rho^2 + E_2^{£} * \rho^3 + E_1^{£} * \rho^4) * P_{work,X} * \theta_{work}/P_{total}$
6	$(E_6^{£} * \rho^0 + E_5^{£} * \rho^1 + E_4^{£} * \rho^2 + E_3^{£} * \rho^3 + E_2^{£} * \rho^4 + E_1^{£} * \rho^5) * F_X * \theta_{leissure}/P_{total}$

4. Numerical excercises

4.1 Data sources

Using the model from Section 2 and scenarios of Section 3, we study the city of Barcelona. A map of it is shown in Figure 8. We have used data which include demographics and distribution of population, emissions coefficients and standards, consumption and commuting patterns from various sources. All sources for each parameter in the model are listed in Table 7.

In addition, according to IDAE (2017), the total demand for electricity in Spain in households (D_R) is approximately about the same as in shops (D_S) and manufacturing (D_M). Total electricity consumption of battery production (${e_{bev}}^{\mathcal{G}}$) was calculated by multiplying average battery size by average electricity consumption per kWh of battery output. Consumption of electricity to produce an average vehicle (both gasoline and electric) originates from Sullivan et al (2010, pg 18). The emission coefficient for passenger vehicles represents an average of diesel and gasoline emission coefficients since about 52% of all cars used are diesel-based and the remainder is gasoline-based (EEA 2016).

The number of commuting and leisure trips was adjusted by a factor of 3 in order to compensate for the share of commuters that reside outside of the city borders and tourists. The number of shopping trips was also adjusted by a factor of 6. This data was deducted by type of parked vehicles (rental, residence or not) within the borders of Barcelona (Ajuntament de Barcelona, 2017).

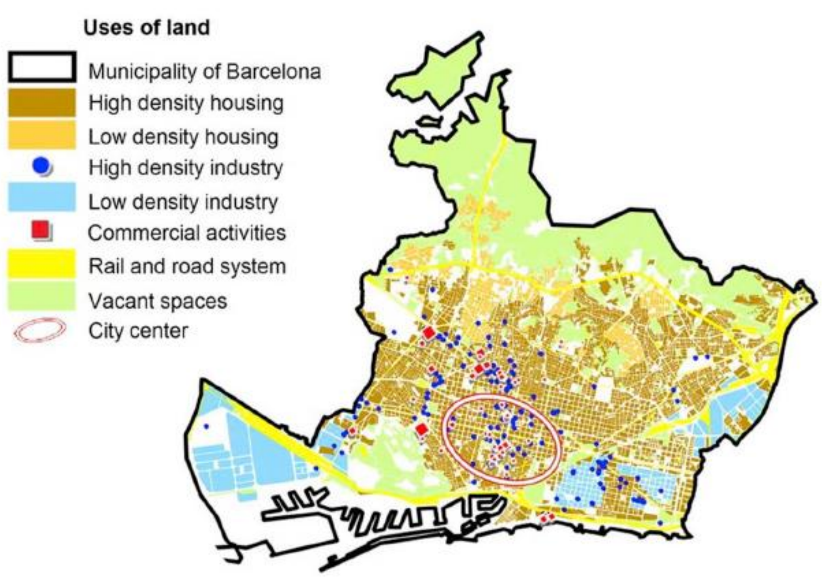


Figure 8: Land uses in Barcelona with corresponding land uses

Table 7: Data sources for each parameter

Parameter	***Value***	***Description***	***Source***
		Demographics	
P_{total}	1604555	total population of Barcelona	Ajuntament de Barcelona (2017)
	0.55	share of population that are workers	
	0.21	the share of the population that participates in shopping	
	0.35	share of population that resides in LDH	
	0.62	the share of workers that work in HDI	
F_{size}	2.59	average family size	Compara tarifas energia (2016)
		Electricity	
$e_{Elc;C}$	318.2814	emission coefficient from electricity production by coal [kg/MWh]	SEI (2017)
$e_{Elc;G}$	198.69102	emission coefficient from electricity production by natural gas [kg/MWh]	
e_{TPe}	0.21875	EV electricity demand per km (kwH)	US Department of Energy (2013)
Elc_{avg}	2500	electricity demand per household (kWh)	Compara tarifas energia (2016)
A_{HDH}	0.486506747	energy efficiency improvement of HDH in respect to LDH	IDAE (2017)
		Heating	
$e_g{}^G$	204.84	emission coeffi cient from natural gas produced by heating [kg/MWh] = g/kWh	SEI (2017)
G_h	4600	natural gas demand per household in LDH (in kWh)	Compara tarifas energia (2016)
		Manufacturing	
$e_c{}^L$	0.269709544	emission coefficient of coal used in manufacturing (excludes electricity production)	Access to European Union Law (2015)
$e_o{}^L$	0.082987552	emission coefficient of oil used in manufacturing (excludes electricity production)	
$e_c{}^G$	2100.82	emission coefficient of coal used in manufacturing (excludes electricity production)	EIA, 2017
$e_o{}^G$	8.89	emission coefficient of oil used in manufacturing (excludes electricity production)	
$e_g{}^G$	53.12	emission coefficient of natural gas used in manufacturing (excludes electricity production)	
${}^{C}m;z$	3.132071696	demand for coal in manufacturing (equal supply) in in thousands TOE	IDESCAT (2017), Informa (2017) and Ajuntament de Barcelona (2017)
${}^{O}m;z$	14099.64238	demand for oil in manufacturing (equal supply) in in thousands TOE	
${}^{G}m;z$	5.174197862	demand for natural gas in manufacturing (equal supply) in thousands TOE	
		Passenger transport	
u	4.5	distance travelled across a district in km	Ajuntament de Barcelona (2017)
$T_{trips(shop)}$	1	number of shopping trips	
$T_{trips(work)}$	0.412	number of work trips	
$T_{trips(leisure)}$	0.47	number of leisure trips	
$e_T{}^L{}_{Po}$	0.07	local emission coefficient of passenger cars (NOx) - on road 2017 g/km	ICCT (2017), EEA (2017)
$e_T{}^G{}_{Po}$	121.3	global emission coefficient of passenger cars (CO2) g/km	
		Freight Transport	
$e_T{}^L{}_F$	0.261	local emission coefficient of gasoline trucks (Nox) g/km	ICCT (2017), EEA (2017)
$e_T{}^G{}_F$	168	global emission coefficient for trucks (CO2) g/km	
$T_{trips(k=4;5)}$	58991.5	number of trips made by trucks	Ajuntament de Barcelona (2017)
$T_{trips\ (final;z)}$	29495.75	number of trips made to by trucks between LDH and center (50%)	
$T_{trips(interind;z)}$	29495.75	number of trips made to by trucks between LDH and HDH (50%)	
		Time allocation	
Total	1	normalized total disposable amount of hours (yearly)	
k;z	1/3 or 1/6	time allocation by activity: 1/3 for work, 1/3 to stay at the place of residence, 1/6 for shopping and 1/6 for leisure of the Total	
	1/2	slope in the linear function for emissions (see Eq. 30)	

4.2 Results

We have simulated the model for the nine scenarios in Table 1 and the eleven urban forms in Table 2, giving a total of 9 x 11 = 99 cases. Tables 8 to 10 show results for three scenarios with distinct shares renewable energy and electric vehicles for group of urban forms.

Table 8 depicts the performance of compact cities in scenarios 1, 5 and 9; representing two extreme cases (1 and 9) and one intermediate option (5). For a complete table including all of the scenarios for all urban forms, see Appendix B. In table 9 are displayed the results from intermediate cities in the above mentioned scenarios. Table 8 contains results for both spread-out and green cities and their performances under scenarios 1, 5 and 9. Sensitivity analysis has been preformed for these extreme case scenarios. We found that the emission coefficient for passenger vehicles when compared to the rest of the parameters has the greatest impact on the model as a whole for both local and global emissions. Another coefficient which seems to be determinant is truck's emission's coefficient impact for local emissions only. This can also be explained by the structure of our model, which is focused on the calculation of emissions from transport. The remaining coefficients seemed to have a lesser impact on the model and their impact was very systematic. Detailed results of this are in Appendix.

Table 8: *Results for three scenarios with distinct shares of renewable electricity and electric vehicles, for compact cities (UFC1-UFC4).*

Scenario	***Criteria***	***UFC1***	***UFC2***	***UFC3***	***UFC4***
1	Total GE	***3,782,178,262,422***	4,097,678,668,089	4,028,410,391,410	4,077,190,530,978
	Traffic GE	15.28%	15.30%	13.84%	14.87%
	Total LE	1,959.41	2,326.92	1,847.88	2,174.00
	Gini Index LE	0.35	0.33	0.34	0.32
	Avg LE	326.57	387.82	307.98	362.33
	Avg HI	22.72	27.76	19.05	23.23
	Avg HIE	55.55	67.67	***50.16***	60.01
5	Total GE	***2,896,175,636,974***	3,034,566,500,443	2,961,288,443,182	3,003,360,079,182
	Traffic GE	11.94%	12.95%	10.95%	12.36%
	Total LE	1,376.92	1,719.33	1,241.83	1,563.54
	Gini Index LE	0.39	0.34	0.37	0.33
	Avg LE	229.49	286.55	206.97	260.59
	Avg HI	16.20	20.51	12.71	16.59
	Avg HIE	39.24	50.11	33.80	43.12
9	Total GE	634,580,226,243	679,967,321,283	***611,886,678,723***	657,273,773,763
	Traffic GE	17.88%	0.23	***14.84%***	20.72%
	Total LE	794.43	1,111.74	***635.78***	953.08
	Gini Index LE	0.50	0.36	0.46	0.36
	Avg LE	132.41	185.29	***105.96***	158.85
	Avg HI	9.69	13.26	6.37	9.94
	Avg HIE	22.93	32.55	17.45	26.22

Note: Bold numbers represent the top performing urban form/(-s) in a given criteria.

Table 9: *Results for three scenarios with distinct shares of renewable electricity and electric vehicles, for intermediate cities (UFI1-UFI3).*

Scenario	***Criteria***	***UFI1***	***UFI2***	***UFI3***
1	Total GE	4,091,890,836,759	4,154,024,773,141	4,107,426,230,582
	Traffic GE	15.18%	16.45%	15.50%
	Total LE	2,112.45	2,174.08	2,053.07
	Gini Index LE	0.33	0.33	0.33
	Avg LE	352.08	362.35	342.18
	Avg HI	23.68	22.97	22.97
	Avg HIE	60.52	59.05	57.80
5	Total GE	3,001,479,628,196	3,024,616,973,734	3,000,746,117,750
	Traffic GE	12.24%	12.79%	12.12%
	Total LE	1,453.44	1,404.93	1,344.43
	Gini Index LE	0.32	0.32	0.32
	Avg LE	242.24	234.16	224.07
	Avg HI	15.92	15.01	15.01
	Avg HIE	41.35	38.23	37.75
9	Total GE	634,580,226,243	***611,886,678,723***	***611,886,678,723***
	Traffic GE	17.88%	***14.84%***	***14.84%***
	Total LE	794.43	***635.78***	***635.78***
	Gini Index LE	0.30	0.29	0.29
	Avg LE	132.41	***105.96***	***105.96***
	Avg HI	8.15	7.05	7.05
	Avg HIE	22.19	17.40	17.69

Note: Bold numbers represent the top performing urban form/(-s) in a given criteria

Table 10: *Results for three scenarios with distinct shares of renewable electricity and electric vehicles, for spread-out cities (UFS1-UFS3) and green city (UFG).*

Scenario	***Criteria***	***UFS1***	***UFS2***	***UFS3***	***UFG***
1	Total GE	4,092,235,479,704	4,100,984,499,812	***4,024,621,468,842***	4,061,692,150,999
	Traffic GE	15.18%	15.36%	***13.76%***	14.55%
	Total LE	2,075.14	2,097.86	***1,799.83***	2,223.51
	Gini Index LE	***0.21***	***0.21***	0.28	0.21
	Avg LE	345.86	349.64	***299.97***	370.59
	Avg HI	23.64	23.69	***16.93***	25.60
	Avg HIE	56.28	58.23	***50.23***	63.04
5	Total GE	2,998,905,990,544	3,011,687,703,450	***2,957,641,621,169***	2,996,961,014,621
	Traffic GE	12.25%	12.34%	***10.90%***	12.13%
	Total LE	1,434.78	1,446.14	***1,217.81***	1,588.30
	Gini Index LE	***0.19***	***0.19***	0.29	0.19
	Avg LE	239.13	241.02	***202.97***	264.72
	Avg HI	16.20	16.22	***11.16***	18.56
	Avg HIE	38.62	39.82	***33.74***	44.33
9	Total GE	634,580,226,243	634,580,226,243	***611,886,678,723***	657,273,773,763
	Traffic GE	17.88%	17.88%	***14.84%***	20.72%
	Total LE	794.43	794.43	***635.78***	953.08
	Gini Index LE	***0.13***	***0.13***	0.29	0.14
	Avg LE	132.41	132.41	***105.96***	158.85
	Avg HI	8.75	8.75	***5.39***	11.51
	Avg HIE	20.96	21.41	***17.24***	25.62

Note: Bold numbers represent the top performing urban form/(-s) in a given criteria.

We find global emissions in all three tables for scenario 1 to be approximately six time higher than in scenario 9. A much smaller reduction is found in scenario 5. The global emissions in scenarios 1, 5 and 9 follow a ratio pattern of 4:3:0.6 across the different urban forms. This is a robust result given that it is present in all of the results for all urban forms. Additionally, the share of global emissions created from traffic in scenario 9 is higher than those in scenario 1 for all results. However, absolute emissions from traffic are smaller due to a decrease in global emissions in scenario 9 in comparison with scenario 1.

The interpretation of this is that if electric cars are implemented, even if partially, the emissions from traffic and overall emissions will fall. However, emissions reduction is much higher if electric vehicle use is combined with 100 percent renewable electricity. On the other hand, the benefits of using electric vehicles are offset if electricity is created from polluting sources. We find a reduction in global emissions with factor 6 and in local emissions with a factor 3 versus a scenario with only gasoline vehicles and all electricity coming from non-renewable sources. If the benefits of the electric vehicles are to be fully exploited, the shift to renewable electricity production should precede or run parallel to the usage of electric vehicles.

Table 11 offers a qualitative interpretation of the (many) results. It categorizes the results in four main categories: (1) best performance (++), (2) good performance (+), (3) bad performance (-) and (4) worst performance (- -). For each criteria a rank was assigned and then the ranked results were categorized. Category 1 contains the top three results in terms of majority of criteria; the next 2 best results, and so on. A complete qualitative assessment of results can be found in Appendix C, while Table 11 gives an overview of the results by aggregating the distinct categories. In Table 11 we may observe how cities UFS3, UFC3, UFI2 and UFI3 perform well across all of the different scenarios. On the contrary, urban forms UFC2, UFG and UFI1 score the worst across all evaluation criteria in all 9 scenarios.

Table 11: *Qualitative assessment of the results for urban forms and different shares of electric car and of electricity sources*

Scenario	***UFC1***	***UFC2***	***UFC3***	***UFC4***	***UFI1***	***UFI2***	***UFI3***	***UFS1***	***UFS2***	***UFS3***	***UFG***
1	++	- -	++	+	-	- -	-	+	-	++	- -
2	++	- -	++	+	-	- -	-	+	-	++	-
3	++	- -	++	+	-	- -	+	+	-	++	- -
4	+	- -	++	- -	-	-	++	+	-	++	- -
5	+	- -	++	- -	-	-	++	+	-	++	- -
6	+	- -	++	- -	-	-	++	+	-	++	- -
7	-	- -	+	- -	-	++	++	+	-	++	- -
8	-	- -	+	- -	-	++	++	+	-	++	- -
9	-	- -	+	- -	-	++	++	+	-	++	- -

Table 12 summarizes the results by indicating which urban forms perform best under each scenario in terms of the various criteria. Associated tables with complete results are presented in Appendix *B*.

Table 12: *Optimal urban form (UF) under each of the proposed scenarios for distinct shares of renewable energy (RE) and electric vehicles (EV)*

Scenario	***EV share***	***RE share***	***1st Best UF***	***2nd Best UF***	***3rd Best UF***
1	0	0	UFS3	UFC3	UFC1
2	0	0.5	UFS3	UFC3	UFC1
3	0	1	UFS3	UFC3	UFC1
4	0.5	0	UFS3	UFC3	UFI3
5	0.5	0.5	UFS3	UFC3	UFI3
6	0.5	1	UFS3	UFC3	UFI3
7	1	0	UFS3	UFI2	UFI3
8	1	0.5	UFS3	UFI2	UFI3
9	1	1	UFS3	UFI2	UFI3

We find that UFS3 consistently performs the best for all electricity and vehicle scenarios. We attribute this to the high-density residence district being adjacent to both work districts, whilst maintaining low-density residences adjacent to one of the work districts. This implies that zones with a higher share of working population are in close proximity to zones that employ the majority of workers, which reduces the average length of commuting trips. Moreover, the location of the HDH and HDI is roughly in the middle of the circular structure, further reducing distances travelled for commuting, shopping and leisure activities.

The second best-performing urban forms are UFC2 and UFI3, followed by urban forms UFC3 and UFC1. Both urban form UFC1 and UFC3 maintain HDH and HDI adjacent and but close to the city center rather than next to the vacant land as the urban form UFS3. Urban forms UFI2 and UFI3 conserve some of traits of urban forms UFC1 and UFC3 by maintaining HDH close to the center, limiting passenger transport.

These insights can be used for planning the appropriate time pattern of adjusting the city's urban form. In Table 13 we consider the different urban forms and corresponding time horizons at which cities transition into these best performing urban forms, given the expected shift towards renewable electricity and electric vehicle usage. Planners should opt for the urban form that is well-performing but is also feasible given the current urban form of the city. Table 13 shows six feasible transition paths to first-, second- or third-best urban forms given likely scenarios for the shares of electric vehicles and renewable energy and distances between urban forms as quantified in Table 3. We anticipate that the shift towards electric cars will go faster than the transition to renewable energy. We consider Barcelona to be closest in its current state to urban form UFC4.

We calculate an indicator TTE, total transition effort, as the sum of the differences between the urban forms that are part of the transition path. The lower the TTE, the more desirable in principle is the associated transition path. The ultimate choice would depend on assessing the combination of final urban form (first- to third-best) and the value of the TTE (low to high). The ideal option would combine the first-best urban form with the lowest TTE. As Table 13 shows, this ideal does not exist, hence the choice depends on the subjective trade-off between transition path 1 (best final outcome) and 2 (lowest TTE), which would require political debate.

Table 13: *Likely time sequence in scenarios and feasible transition pattern of urban forms (UF).*

		Present	10 years	20 years	30 years	40 years	TTE
Scenarios	EV share	0	0.5	0.5	1	1	
	RE share	0	0	0.5	0.5	1	
Ranking of UFs	First best UF	UFS3	UFS3	UFS3	UFS3	UFS3	
	Second best UF	UFC3	UFC3	UFC3	UFI2	UFI2	
	Third best UF	UFC1	UFI3	UFI3	UFI3	UFI3	
Transition	1	UFC4	UFS3	–	–	–	8
	2	UFC4	–	–	UFI2	–	4
	3	UFC4	UFI3	–	–	–	6
	4	UFC4	UFC3	–	UFI2	–	2+4=6
	5	UFC4	UFC1	–	UFI2	–	4+6=10
	6	UFC4	UFC1	UFI3	–	–	4+6=10

Notes: TTE denotes the total transition effort calculated as the sum of the distances between UFs making up the transition path; "–" indicates that the urban form is the same as in the previous period.

5. Conclusions

We have developed a model to assess the impact of different spatial forms of a city on global and local emissions. This allows identifying a sustainable design of a city in terms of location and distribution of activities, including housing, shopping, working in industry and offices. In line with the theoretical literature, urban form is conceptualized as a spatial structure consisting of circular zones with associated density, housing and industry attributes as well as transport. Eleven distinct urban forms were analyzed, each with a unique spatial organization of activities into zones. In addition, we defined nine scenarios with particular electric vehicle shares in passenger transport and shares of renewable energy in electricity generation. The combination of these scenarios and the urban forms creates particular outcomes in terms of local and global emissions. We evaluated such outcomes by creating a number of indicators: total global emissions, share of transport in global emissions, total local emissions, local emissions in each zone, distribution of local emissions across zones (Gini index), average local emissions and two indexes for health. The objective of this study was to identify the best-performing urban form in terms of the evaluation criteria and the long-term transition to a more sustainable urban form.

In the numerical exercise we found the urban form UFS3 to consistently produce minimal local and global pollution and scoring among the top 10 percent for all nine scenarios and most of the evaluation criteria. We attribute this to the fact that the most populated zone (HDH) and the zone with greater share of workers (HDI) are adjacent, which minimizes the commuting distances. Moreover, both HDH and HDI are placed in the middle of surrounding zones, causing minimal travel distances to recreation and shopping zones. Other well-performing urban forms are UFC1 and UFC3, which have zones HDH and HDI allocated next to the city center and in this way minimize the distances travelled between the residence zone with highest population density and the zone that the employs majority of the labor force. Urban forms UFI2 and UFI3 both maintain HDH next to the city center as well. However, the impact of the scenarios where a higher portion of electricity sources are renewable and a higher share of vehicles are electric is much smaller in urban forms UFI2 and UFI3 when compared with the other urban forms, due to their remoteness of HDI zone.

When all vehicles are electric and all electricity is renewable, global (local) emissions are a factor of six (three) smaller than in the scenario where all vehicles are gasoline-fuelled and all electricity is fossil-fuel based. The reduction of global and local emissions emitted diminishes when the electricity is produced from polluting sources. Hence, if the benefits in terms of global and local emissions reduction that comes from the usage of electric vehicles is to be fully exploited, the shift to renewable electricity should precede or run parallel to the increase in usage of electric vehicles.

We considered Barcelona to be closest in its current state to urban form UFC4 and analyzed potential transitions to the three most desirable final urban forms. We found that a transition to UFI2 involves the lowest effort, while a transition to UFS3 requires double the effort while achieving the most desirable outcome.

Further research could make a distinction between a small, central shopping center and a large shopping mall in the city outskirts, as this characterizes many large cities nowadays. Further, this model could be extended to other urban structures, such as polycentric and multi-nuclei city. However, depending on how asymmetric these city structures would be, the calculation of travel distances may become very complex. Another challenge would be the introduction of congestion and the distinction of particular transportation modes (bikes, public transport and cars) to capture that compact cities face distinct levels of, and solutions to, congestion compared to spread-out ones. Finally, introduction of prices together with scarcity of land would permit the assessment of social welfare impacts and analysis of optimal pricing policies, such as carbon and congestion pricing.

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Appendix A: Complete model and variable notation

Table A1 presents the complete version of the model used.

Table A1
Complete model.

Eq. no.	Equation
1	$P_{LDH} = \gamma * P_{total}$
2	$P_{HDH} = (1 - \gamma) * P_{total}$
3	$P_{work_{z,\ HDI}} = \alpha * \mu * P_z \quad z = LDH, HDH$
4	$P_{shop_z} = \beta * P_z \quad z = LDH, HDH$
5	$F_z = \frac{P_z}{F_{size}} \quad z = LDH, HDH$
6	$E^{\mathscr{G}}_{Elc} = \sum_{s=V,R,S,M} \sum_{i=c,g,r} e^{\mathscr{G}}_{Elc,i} * \omega_i * D_s \quad \mathscr{G} = Global$
7	$\omega_c + \omega_g + \omega_r = 1$
8	$\Sigma_{s=V,\ R,\ S,\ M} D_s = \Sigma_{i=c,\ g,\ r} S_i$
9	$D_V = \delta * (e_{TPe}{}^{\mathscr{G}} * L_{TP} + e^{\mathscr{G}}_{bev} * N_{cars}) + e_{car,prod}{}^{\mathscr{G}} * N_{cars}$
10	$D_R = Elc_{avg} * (F_{LDH} + A_{HDH} * F_{HDH})$
11	$E^{\mathscr{G}}_h = e^{\mathscr{G}}_g * G_h * (F_{LDH} + A_{HDH} * F_{HDH}) \quad \mathscr{G} = Global$
12	$E^{\mathscr{G}}_m = e^{\mathscr{G}}_c * C_{m,z} + e^{\mathscr{G}}_o * O_{m,z} + e^{\mathscr{G}}_g * G_{m,z} \quad \mathscr{G} = Global$
13	$E_{m,\ z}{}^{\mathscr{L}} = e_c{}^{\mathscr{L}} * C_{m,\ z} + e_o{}^{\mathscr{L}} * O_{m,\ z} \quad \mathscr{L} = Local$
14	$l_z = \begin{cases} \frac{1}{2}u & if \quad z = 0 \quad or \quad z = d \\ u & if \quad o < z < d \end{cases}$
15	$L_{TP,\ z} = 2\Sigma_{k=1}{}^{3} l_z * T_{trips(k,z)} * P_{k,\ z}$
16	$L_{TP} = \Sigma_{z=o}{}^{d} L_{TP,\ z}$
17	$E^{\mathscr{G}}_{TP} = (1 - \delta) * e^{\mathscr{G}}_{TP_0} * L_{TP} \quad \mathscr{G} = Global$
18	$E_{TP,\ z}{}^{\mathscr{L}} = (1 - \delta) * e_{TP_o}{}^{\mathscr{L}} * L_{TP,\ z} \quad \mathscr{L} = Local$
19	$L_{TF,\ z} = 2\Sigma_{k=4,\ 5} l_z * T_{trips(k,z)}$
20	$L_{TF} = \Sigma_{z=o}{}^{d} L_{TF,\ z}$
21	$E^{\mathscr{G}}_{TF} = e^{\mathscr{G}}_{TF} * L_{TF} \quad \mathscr{G} = Global$
22	$E_{TF}{}^{\mathscr{L}} = e_{TF}{}^{\mathscr{L}} * L_{TF,\ z} \quad \mathscr{L} = Local$

Table A2 presents the formal expressions of the evaluation criteria.

Table A2
Evaluation criteria.

Eq. no.	Equation
23	$\Delta_{A,\ B} = \Sigma_{z=1}{}^{6} \lvert i_z{}^{A} - i_z{}^{B} \rvert \qquad i = 1,\ \ldots,\ 6$
24	$E^{\mathscr{G}} = E^{\mathscr{G}}_{Elc} + E^{\mathscr{G}}_{h} + E^{\mathscr{G}}_{m} + E^{\mathscr{G}}_{TP} + E^{\mathscr{G}}_{TF}$
25	$E^{\mathscr{G}}_{T} = \frac{E^{\mathscr{G}}_{TP} + E^{\mathscr{G}}_{TF}}{E^{\mathscr{G}}}$
26	$E_{total}{}^{\mathscr{L}} = \Sigma_{z=o}{}^{d} E_z{}^{\mathscr{L}}$
27	$E^{\mathcal{L}}_{avg} = \frac{1}{n} \sum_z E^{\mathcal{L}}_z$
28	$HI_z = \frac{E^{\mathcal{L}}_z * P_{k,z} * \theta_{k,z}}{P_{total}} \qquad z = o,\ \ldots, d$
29	$\theta_{TP} + \Sigma_k \theta_{k,\ z} = 1 \qquad \theta_k \equiv \theta_{k,\ z}$
30	$HI = \frac{1}{n} \sum_z HI_z$
31	$HIE_z = \frac{P_{k,z} * \theta_{k,z} * \left(\sum_{z=o}^{z=d} E^{\mathcal{L}}_z * \rho^{\lvert o-d \rvert} \right)}{P_{total}} \qquad z = o,\ \ldots, d$
32	$HIE = \frac{1}{n} \sum_z HIE_z$

Zones.

Center	Represents the shopping zone allocated in the city center
LDH	Low density housing
LDI	Low density economic activity, notably industry
HDH	High density housing
HDI	High density economic activity, including offices and warehouses.
Vacant	Land represents zone where leisure activities take place, including parks and semi-nature

Parameters.

α	Share of the total population that represents the workers
β	Share of the population that takes part in shopping trips
γ	Share of the population residing in LDH
δ	Distortion parameter representing the usage of electric vehicles out of the total population with cars
μ	Share of the working population that works in HDI
ω_c	Share of the electricity that has been produced by coal
ω_g	Share of the electricity that has been produced by renewable resources
ρ	Share of the electricity that has been produced by natural gas
	Value of the decreasing function of the impacts of local emissions in adjacent zones

Emission coefficients.

e_c	Emission coefficient of coal in manufacturing processes
e_{bev}	Consumption of energy in manufacturing of electric vehicle battery expressed in kWh
$e_{car,\ prod}$	Consumption of energy in manufacturing of an average vehicle vehicle (electric or gasoline) which excludes the electric battery, expressed in kWh
$e_{Elc,\ i}$	Various emission coefficients in electricity production including coal, gas and renewable resources
e_{TF}	Emission coefficient from freight transport
e_g	Emission coefficient for gas
e_o	Emission coefficient of oil in manufacturing processes
e_{TP_e}	Coefficient that represents the electricity needed for an electric car to run one kilometer in kWh (1 km/kWh)
e_{TP_o}	Emission coefficient produced by oil-based (petroleum) cars

Subscripts and superscripts.

c	Coal
d	Destination zone
$\mathscr{G}$	Connotation for global emissions
g	Gas
h	Heating
i	The index for three different electricity sources
k	Activity type including work, leisure, shopping or residing at home that different shares of population participate during a determined time of the day throughout the year
$\mathscr{L}$	Connotation for local emissions
m/M	Manufacturing
o	Origin zone
r	Renewable sources
R	Residential buildings
s	Types of electricity demands
S	Shops
u	Unit of distance
V	Vehicle
z	Zone

Variables.

A_{HDH}	An energy consumption improvement of HDH in respect to LDH for both heating and electricity consumption
$C_{m,\ z}$	Consumption of gas in manufacturing in zone z
D_s	Different types of electricity demands
E_{Elc}	Emissions produced by electricity production outside of city
E_{TP}	Emissions produced by passenger transport
E_{TF}	Emissions produced by freight transport
F_z	Number of families residing in a zone
F_{size}	Average family size
G_h	Consumption of gas in heating
G_m	Consumption of gas in manufacturing in zone z
l_z	Distance travelled on a singular trip within a zone z
$L_{TF,\ z}$	Distance travelled within a zone by freight transport during a year
L_{TF}	Total distance travelled within a city by freight transport during a year
$L_{TP,\ z}$	Distance travelled within a zone by passenger transport during a year
L_{TP}	Total distance travelled within a city by passenger transport during a year
N_{cars}	Total number of cars circulating in the system
O_m	Consumption of oil in manufacturing in zone z
P_{total}	Total population
P_z	Population allocated in determined zone z
P_{kz}	Population participating in activity k allocated in determined zone z
S_i	Electricity supply from different sources
$T_{trips(k,z)}$	Number of trips made by passenger transport by different activities in zone z in a year

Appendix B: Complete results

Scenario	Criteria	Urban Form										
		Compact City				Intermediate City			Spread-out City			Green City
		UFC1	UFC2	UFC3	UFC4	UFI1	UFI2	UFI3	UFS1	UFS2	UFS3	UFG
1	Total GE	3,782,178, 262,422	4,097,678, 668,089	4,028,410, 391,410	4,077,190, 530,978	4,091,890, 836,759	4,154,024, 773,141	4,107,426, 230,582	4,092,235, 479,704	4,100,984, 499,812	4,024,621, 468,842	4,061,692, 150,999
	Traffic GE	15.28%	15.30%	13.84%	14.87%	15.18%	16.45%	15.50%	15.18%	15.36%	13.76%	14.55%
	Total LE	1959.41	2326.92	1847.88	2174.00	2112.45	2174.08	2053.07	2075.14	2097.86	1799.83	2223.51
	Gini Index LE	0.35	0.33	0.34	0.32	0.33	0.33	0.33	0.21	0.21	0.28	0.21
	Avg LE	326.57	387.82	307.98	362.33	352.08	362.35	342.18	345.86	349.64	299.97	370.59
	Avg HI	22.72	27.76	19.05	23.23	23.68	22.97	22.97	23.64	23.69	16.93	25.60
	Avg HIE	55.55	67.67	50.16	60.01	60.52	59.05	57.80	56.28	58.23	50.23	63.04
2	Total GE	2,440,654, 097,681	2,622,794, 370,299	2,553,526, 093,619	2,602, 306,233,187	2,617,006, 538,968	2,679,140, 475,350	2,632,541, 932,791	2,617,351, 181,913	2,626,100, 202,021	2,549,737, 171,051	2,586,807, 853,209
	Traffic GE	23.68%	23.90%	21.83%	23.30%	23.73%	25.50%	24.18%	23.74%	23.99%	21.72%	22.84%
	Total LE	1959.41	2326.92	1847.88	2174.00	2112.45	2174.08	2053.07	2075.14	2097.86	1799.83	2223.51
	Gini Index LE	0.35	0.33	0.34	0.32	0.33	0.33	0.33	0.21	0.21	0.28	0.21
	Avg LE	326.57	387.82	307.98	362.33	352.08	362.35	342.18	345.86	349.64	299.97	370.59
	Avg HI	22.72	27.76	19.05	23.23	23.68	22.97	22.97	23.64	23.69	16.93	25.60
	Avg HIE	55.55	67.67	50.16	60.01	60.52	59.05	57.80	56.28	58.23	50.23	63.04
3	Total GE	1,099,129, 932,940	1,147,910, 072,508	1,078,641, 795,828	1,127,421, 935,397	1,142,122, 241,177	1,204,256, 177,559	1,157,657, 635,000	1,142,466, 884,122	1,151,215, 904,230	1,074,852, 873,260	1111,923, 555,418
	Traffic GE	52.59%	54.60%	51.69%	53.78%	54.37%	56.73%	54.99%	54.39%	54.73%	51.52%	53.13%
	Total LE	1959.41	2326.92	1847.88	2174.00	2112.45	2174.08	2053.07	2075.14	2097.86	1799.83	2223.51
	Gini Index LE	0.35	0.33	0.34	0.32	0.33	0.33	0.33	0.21	0.21	0.28	0.21
	Avg LE	326.57	387.82	307.98	362.33	352.08	362.35	342.18	345.86	349.64	299.97	370.59
	Avg HI	22.72	27.76	19.05	23.23	23.68	22.97	22.97	23.64	23.69	16.93	25.60
	Avg HIE	55.55	67.67	50.16	60.01	60.52	59.05	57.80	56.28	58.23	50.23	63.04
4	Total GE	4,925,496, 194,356	5,155,194, 303,991	5,077,312, 649,087	5,114,372, 303,785	5,114,608, 022,682	5,141,162, 519,326	5,116,720, 078,639	5,109,288, 425,906	5,130,477, 341,664	5,071,913, 466,347	5,109,323, 364,652
	Traffic GE	7.02%	7.62%	6.38%	7.26%	7.18%	7.53%	7.11%	7.19%	7.25%	6.35%	7.11%
	Total LE	1376.92	1719.33	1241.83	1563.54	1453.44	1404.93	1344.43	1434.78	1446.14	1217.81	1588.30
	Gini Index LE	0.39	0.34	0.37	0.33	0.32	0.32	0.32	0.19	0.19	0.29	0.19
	Avg LE	229.49	286.55	206.97	260.59	242.24	234.16	224.07	239.13	241.02	202.97	264.72
	Avg HI	16.20	20.51	12.71	16.59	15.92	15.01	15.01	16.20	16.22	11.16	18.56
	Avg HIE	39.24	50.11	33.80	43.12	41.35	38.23	37.75	38.62	39.82	33.74	44.33
5	Total GE	2,896,175, 636,974	3,034,566, 500,443	2,961,288, 443,182	3,003, 360, 079,182	3,001,479, 628,196	3,024, 616,973,734	3,000,746, 117,750	2,998,905, 990,544	3,011,687, 703,450	2,957,641, 621,169	2,996,961, 014,621

					079,182							
	Traffic GE	11.94%	12.95%	10.95%	12.36%	12.24%	12.79%	12.12%	12.25%	12.34%	10.90%	12.13%
	Total LE	1376.92	1719.33	1241.83	1563.54	1453.44	1404.93	1344.43	1434.78	1446.14	1217.81	1588.30
	Gini Index LE	0.39	0.34	0.37	0.33	0.32	0.32	0.32	0.19	0.19	0.29	0.19
	Avg LE	229.49	286.55	206.97	260.59	242.24	234.16	224.07	239.13	241.02	202.97	264.72
	Avg HI	16.20	20.51	12.71	16.59	15.92	15.01	15.01	16.20	16.22	11.16	18.56
	Avg HIE	39.24	50.11	33.80	43.12	41.35	38.23	37.75	38.62	39.82	33.74	44.33
6	Total GE	866,855, 079,591	913,938, 696,895	845,264, 237,276	892,347, 854,580	888,351, 233,710	908,071, 428,141	884,772, 156,861	888,523, 555,182	892,898, 065,236	843,369, 775,991	884,598, 664,590
	Traffic GE	39.88%	42.98%	38.35%	41.60%	41.34%	42.61%	41.10%	41.35%	41.64%	38.21%	41.09%
	Total LE	1376.92	1719.33	1241.83	1563.54	1453.44	1404.93	1344.43	1434.78	1446.14	1217.81	1588.30
	Gini Index LE	0.39	0.34	0.37	0.33	0.32	0.32	0.32	0.19	0.19	0.29	0.19
	Avg LE	229.49	286.55	206.97	260.59	242.24	234.16	224.07	239.13	241.02	202.97	264.72
	Avg HI	16.20	20.51	12.71	16.59	15.92	15.01	15.01	16.20	16.22	11.16	18.56
	Avg HIE	39.24	50.11	33.80	43.12	41.35	38.23	37.75	38.62	39.82	33.74	44.33
7	Total GE	6,068,814, 126,290	6,212,709, 939,892	6,126, 214,906,765	6,151,554, 076,591	6,137,325, 208,606	6,128,300, 265,512	6,126,013, 926,696	6,126,341, 372,109	6,159,970, 183,516	6,119,205, 463,851	6,156,954, 578,306
	Traffic GE	1.87%	2.56%	1.48%	2.21%	1.85%	1.48%	1.48%	1.85%	1.84%	1.48%	2.21%
	Total LE	794.43	1111.74	635.78	953.08	794.43	635.78	635.78	794.43	794.43	635.78	953.08
	Gini Index LE	0.50	0.36	0.46	0.36	0.30	0.29	0.29	0.13	0.13	0.29	0.14
	Avg LE	132.41	185.29	105.96	158.85	132.41	105.96	105.96	132.41	132.41	105.96	158.85
	Avg HI	9.69	13.26	6.37	9.94	8.15	7.05	7.05	8.75	8.75	5.39	11.51
	Avg HIE	22.93	32.55	17.45	26.22	22.19	17.40	17.69	20.96	21.41	17.24	25.62
8	Total GE	3,351,697, 176,267	3,446,338, 630,587	3,369,050, 792,744	3,404,413, 925,177	3,385, 952,717,424	3,370,093, 472,117	3,368,950, 302,709	3,380,460, 799,176	3,397, 275,204,879	3,365,546, 071,287	3,407,114, 176,034
	Traffic GE	3.39%	4.61%	2.69%	4.00%	3.35%	2.69%	2.69%	3.36%	3.34%	2.70%	4.00%
	Total LE	794.43	1111.74	635.78	953.08	794.43	635.78	635.78	794.43	794.43	635.78	953.08
	Gini Index LE	0.50	0.36	0.46	0.36	0.30	0.29	0.29	0.13	0.13	0.29	0.14
	Avg LE	132.41	185.29	105.96	158.85	132.41	105.96	105.96	132.41	132.41	105.96	158.85
	Avg HI	9.69	13.26	6.37	9.94	8.15	7.05	7.05	8.75	8.75	5.39	11.51
	Avg HIE	22.93	32.55	17.45	26.22	22.19	17.40	17.69	20.96	21.41	17.24	25.62
9	Total GE	634,580, 226,243	679,967, 321,283	611,886, 678,723	657,273, 773,763	634,580, 226,243	611,886, 678,723	611,886, 678,723	634,580, 226,243	634,580, 226,243	611,886, 678,723	657,273, 773,763
	Traffic GE	17.88%	0.23	14.84%	20.72%	17.88%	14.84%	14.84%	17.88%	17.88%	14.84%	20.72%
	Total LE	794.43	1111.74	635.78	953.08	794.43	635.78	635.78	794.43	794.43	635.78	953.08
	Gini Index LE	0.50	0.36	0.46	0.36	0.30	0.29	0.29	0.13	0.13	0.29	0.14
	Avg LE	132.41	185.29	105.96	158.85	132.41	105.96	105.96	132.41	132.41	105.96	158.85
	Avg HI	9.69	13.26	6.37	9.94	8.15	7.05	7.05	8.75	8.75	5.39	11.51
	Avg HIE	22.93	32.55	17.45	26.22	22.19	17.40	17.69	20.96	21.41	17.24	25.62

Appendix C: Ranking of urban forms

In table C1 we present a complete qualitative ranking of the results reported in Appendix B. Urban forms are ranked from 1 to 11, where categories include best performance (1,2,3), good performance (4,5), bad performance (6,7,8) and worst performance (9,10,11).

Table 16: *Qualitative assessment of all urban forms under all 9 scenarios.*

Scenario	Criteria	UFC1	UFC2	UFC3	UFC4	UFI1	UFI2	UFI3	UFS1	UFS2	UFS3	UFG
	Total GE	1	8	3	5	6	11	10	7	9	2	4
	Traffic GE	7	8	2	4	5	11	10	6	9	1	3
1	**Total LE**	3	11	2	8	7	9	4	5	6	1	10
	Gini Index LE	11	6	10	5	7	9	8	1	2	4	3
	Avg LE	3	11	2	8	7	9	4	5	6	1	10
	Avg HI	3	11	2	6	8	4	4	7	9	1	10
	Avg HIE	3	11	1	8	9	7	5	4	6	2	10
	Total GE	1	8	3	5	6	11	10	7	9	2	4
	Traffic GE	5	8	2	4	6	11	10	7	9	1	3
2	**Total LE**	3	11	2	8	7	9	4	5	6	1	10
	Gini Index LE	11	6	10	5	7	9	8	1	2	4	3
	Avg LE	3	11	2	8	7	9	4	5	6	1	10
	Avg HI	3	11	2	6	8	4	4	7	9	1	10
	Avg HIE	3	11	1	8	9	7	5	4	6	2	10
	Total GE	3	8	2	5	6	11	10	7	9	1	4
	Traffic GE	3	8	2	5	6	11	10	7	9	1	4
3	**Total LE**	3	11	2	8	7	9	4	5	6	1	10
	Gini Index LE	11	6	10	5	7	9	8	1	2	4	3
	Avg LE	3	11	2	8	7	9	4	5	6	1	10
	Avg HI	3	11	2	6	8	4	4	7	9	1	10
	Avg HIE	3	11	1	8	9	7	5	4	6	2	10
	Total GE	1	11	3	6	7	10	8	4	9	2	5
	Traffic GE	3	11	2	9	6	10	4	7	8	1	5
4	**Total LE**	4	11	2	9	8	5	3	6	7	1	10
	Gini Index LE	11	9	10	8	6	7	5	1	2	4	3
	Avg LE	4	11	2	9	8	5	3	6	7	1	10
	Avg HI	7	11	2	9	5	3	3	6	8	1	10
	Avg HIE	6	11	2	9	8	4	3	5	7	1	10
	Total GE	1	11	3	8	7	10	6	5	9	2	4
	Traffic GE	3	11	2	9	6	10	4	7	8	1	5
5	**Total LE**	4	11	2	9	8	5	3	6	7	1	10
	Gini Index LE	11	9	10	8	6	7	5	1	2	4	3
	Avg LE	4	11	2	9	8	5	3	6	7	1	10
	Avg HI	7	11	2	9	5	3	3	6	8	1	10
	Avg HIE	6	11	2	9	8	4	3	5	7	1	10
	Total GE	3	11	2	8	6	10	5	7	9	1	4
	Traffic GE	3	11	2	8	6	10	5	7	9	1	4
6	**Total LE**	4	11	2	9	8	5	3	6	7	1	10
	Gini Index LE	11	9	10	8	6	7	5	1	2	4	3
	Avg LE	4	11	2	9	8	5	3	6	7	1	10
	Avg HI	7	11	2	9	5	3	3	6	8	1	10
	Avg HIE	6	11	2	9	8	4	3	5	7	1	10
	Total GE	1	11	4	8	7	6	3	5	10	2	9
	Traffic GE	8	11	2	10	6	1	3	7	5	4	9
7	**Total LE**	6	11	1	9	5	1	1	6	6	1	9
	Gini Index LE	11	8	10	9	7	4	4	1	1	4	3
	Avg LE	5	11	1	9	5	1	1	5	5	1	9
	Avg HI	8	11	2	9	5	3	3	6	6	1	10
	Avg HIE	8	11	3	10	7	2	4	5	6	1	9
	Total GE	1	11	4	9	7	5	3	6	8	2	10
	Traffic GE	8	11	2	10	6	1	3	7	5	4	9
8	**Total LE**	5	11	1	9	5	1	1	7	7	1	9
	Gini Index LE	11	8	10	9	7	4	4	1	1	4	3
	Avg LE	5	11	1	9	5	1	1	5	5	1	9
	Avg HI	8	11	2	9	5	3	3	6	6	1	10
	Avg HIE	8	11	3	10	7	2	4	5	6	1	9
	Total GE	5	11	1	9	5	1	1	5	5	1	9
	Traffic GE	4	1	8	2	4	8	8	4	4	8	2
9	**Total LE**	5	11	1	9	5	1	1	7	7	1	9
	Gini Index LE	11	8	10	9	7	4	4	1	1	4	3
	Avg LE	5	11	1	9	5	1	1	5	5	1	9
	Avg HI	8	11	2	9	5	3	3	6	6	1	10
	Avg HIE	8	11	3	10	7	2	4	5	6	1	9

Appendix D: Sensitivity analysis

Tables D1-D6 show results of sensitivity analyses for relevant parameters tested under different renewable electricity (ω_r = 0; 0.5; 1) and electric vehicles (δ =0; 0.5; 1) shares in the extreme case scenarios (1, 5, 9) used in Figures 8 to 10. The parameters include the emission coefficient factors for passenger and freight transport, due to the performance differences in on-road and in-lab emissions. We also assessed the variation of the coefficients α (workers), β (shoppers), γ (residents in LDH) and μ (workers in HDI), in order to control for the impact of distributional effects of the population. Each of these coefficients is tested separately and each bar in the tables represents how much global and local emissions are affected.

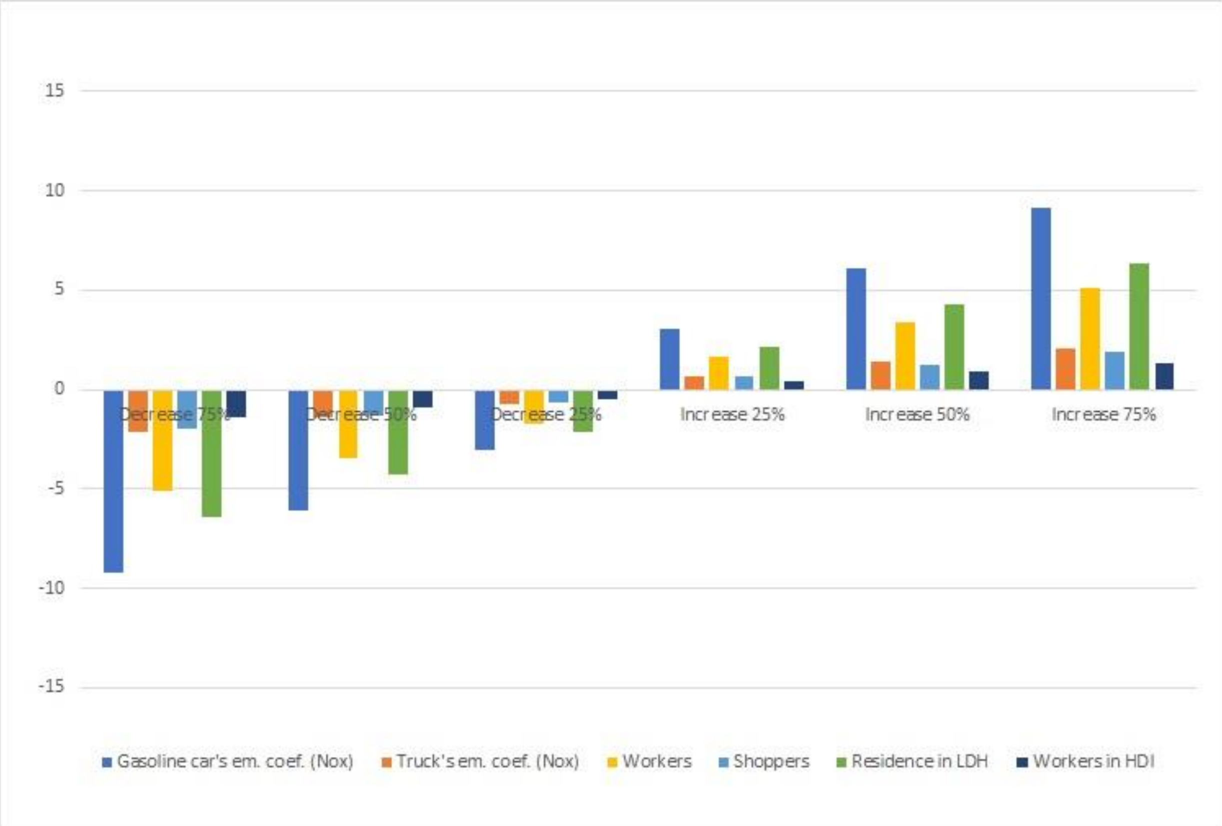

Figure 9: *Sensitivity analyses for global emissions, performed under δ=0 and ω_r=0.*

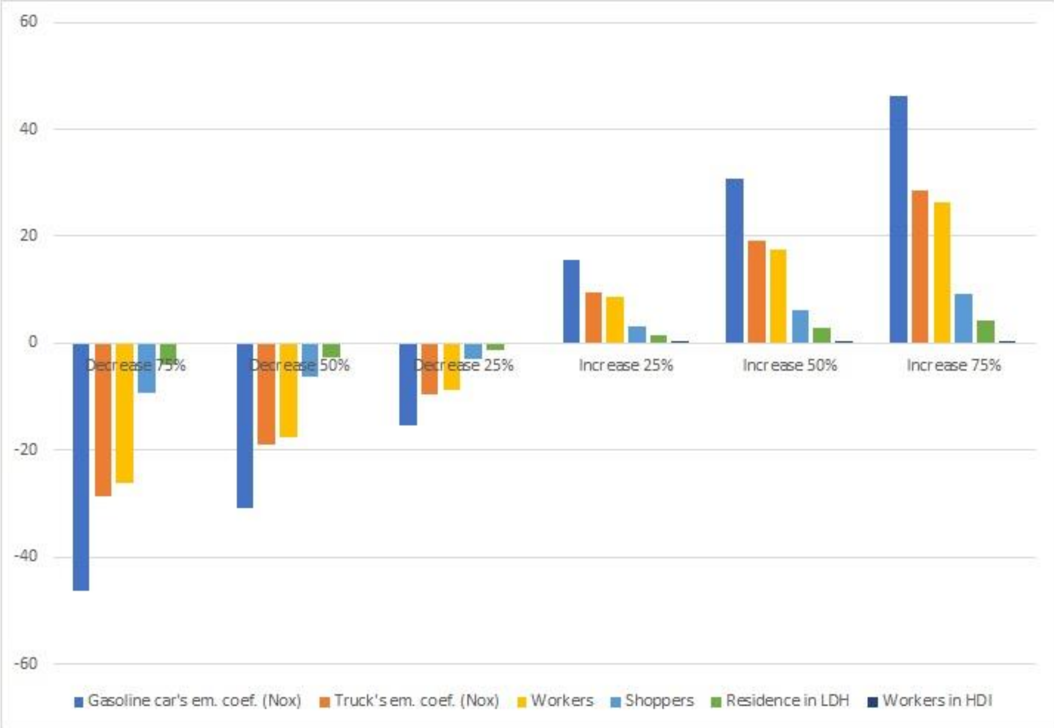

Figure 10: *Sensitivity analyses for local emissions, performed under* $\delta = 0$ *and* $\omega_r = 0$.

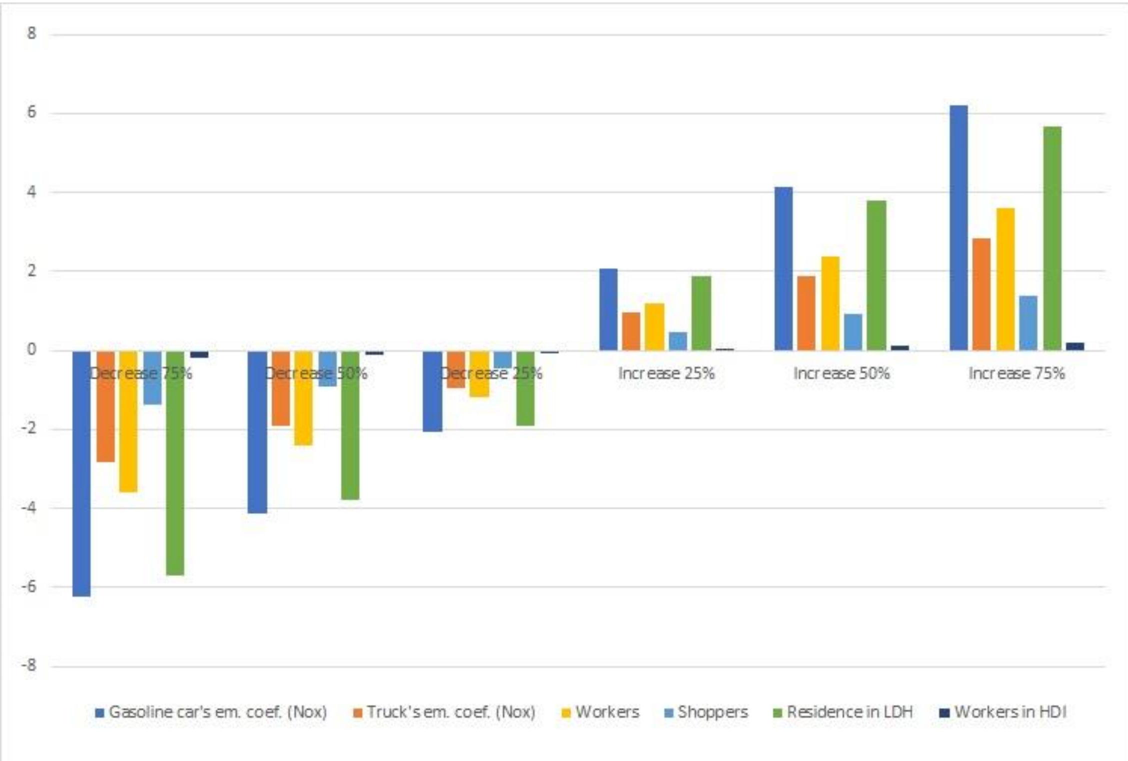

Figure 11: *Sensitivity analyses for global emissions, performed under* $\delta = 0.5$ *and* $\omega_r = 0.5$.

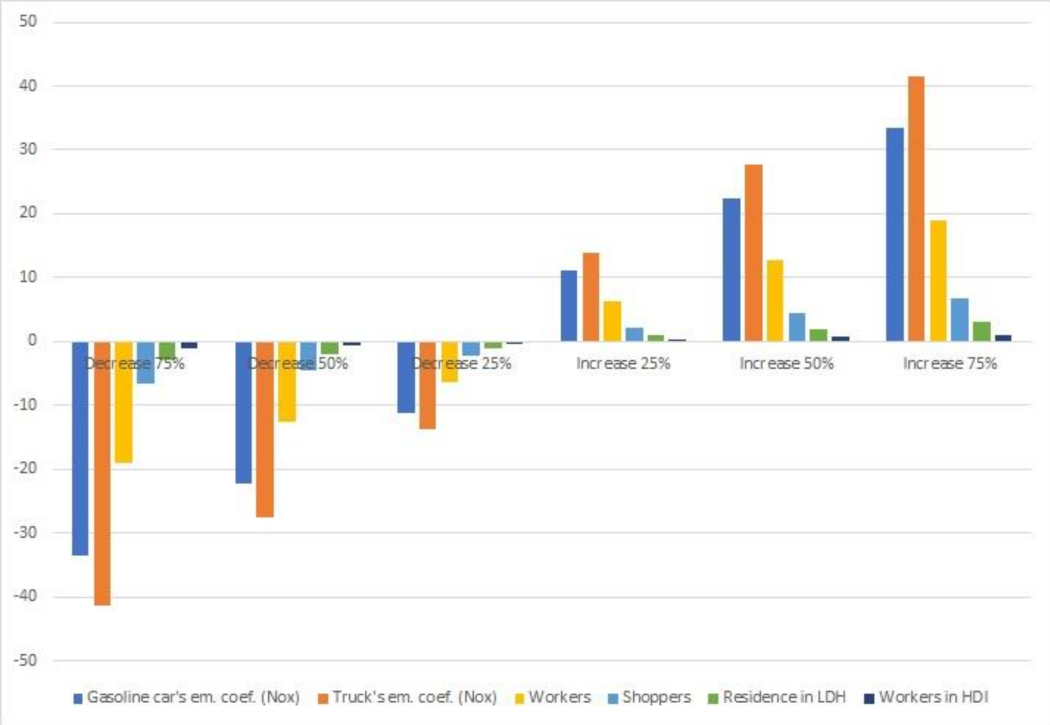

Figure 12: *Sensitivity analyses for total local emissions, performed under* δ *=0.5 and* ω_r *=0.5.*

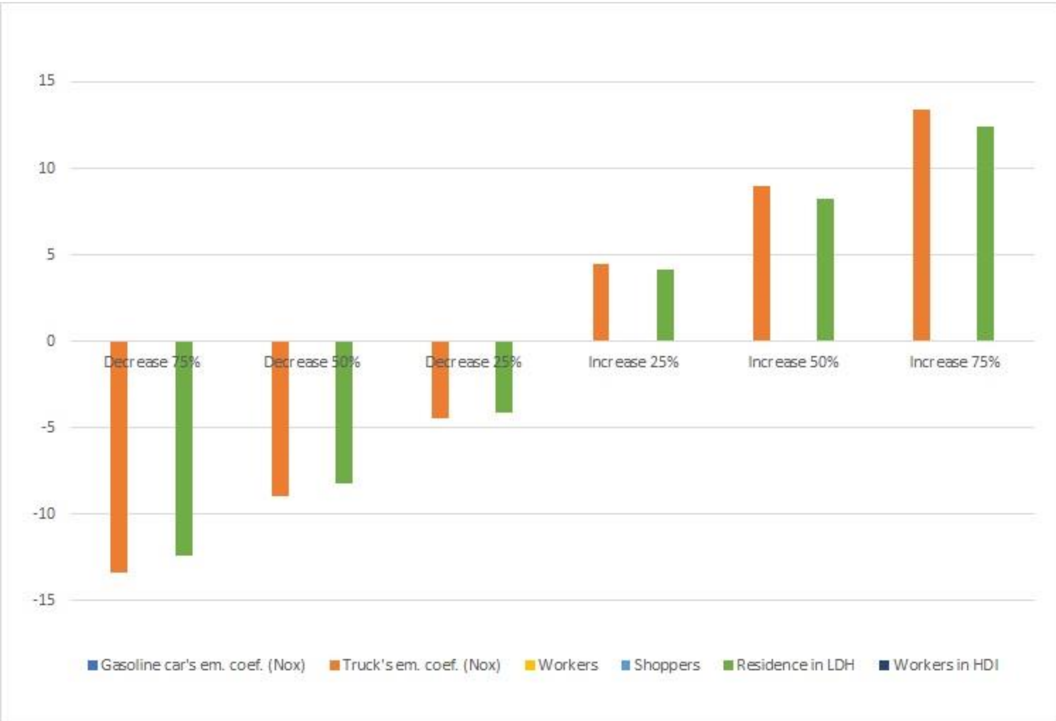

Figure 13: *Sensitivity analyses for global emissions, performed under* δ *=1 and* ω_r *=1.*

Note: The reason for a lack of variation in the results for varying values of the parameters for passenger vehicle emissions, α, β, μ is that they do not affect emissions when all electricity is renewable and all passenger vehicles are electric, as is the case here.

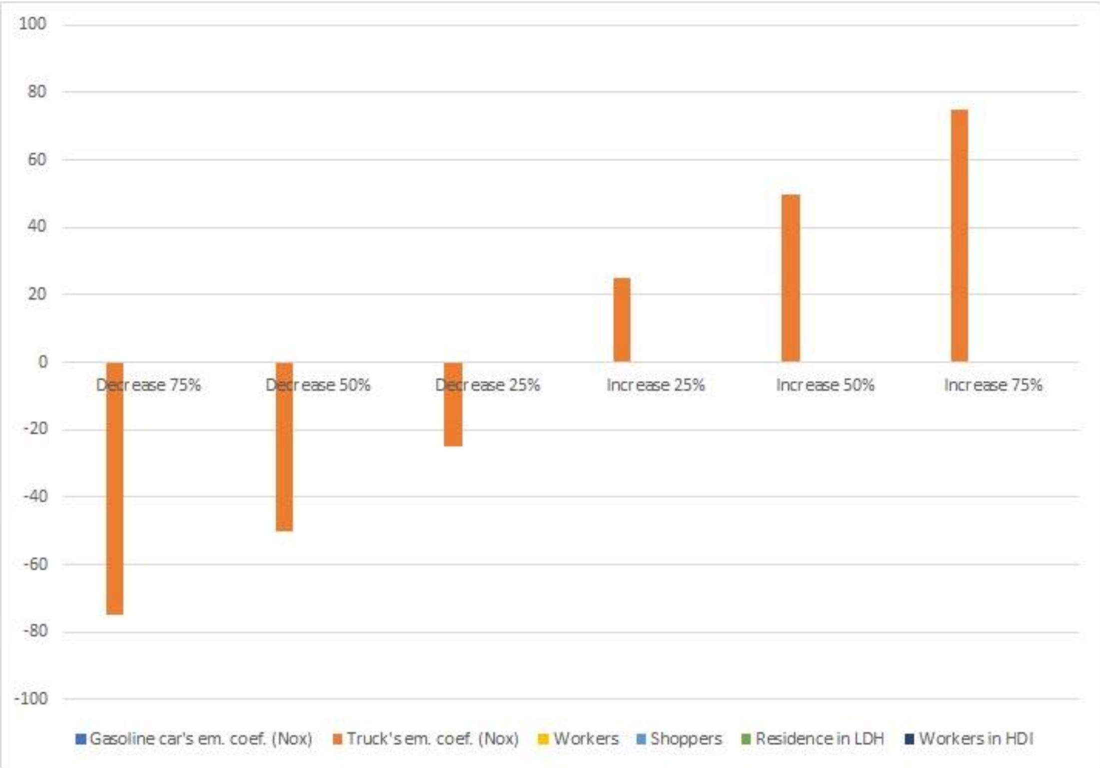

Figure 14: *Sensitivity analyses for total local emissions, performed under $\delta = 1$ and $\omega_r = 1$.*

Note: The reason for parameters for passenger vehicle emissions, α, β, μ not being displayed in table above is that their variation does not impact the model, due to all electricity being renewable and all passenger vehicles electric.

CHAPTER V:

Are emission targets of C40 cities realistic in view of their mayoral powers?

1. Introduction

In the last decade, cities have moved to the forefront of policy debates about effectively combating climate change through reducing greenhouse gas emissions. Currently, about 4.2 billion of the world's population (55%) resides in urban areas, compared to 0.75 (29%) in 1950 (UN World Urbanization Prospects 2018). It has been repeatedly stated that activities and households within city boundaries, though not necessarily controlled by urban climate policies, account for about 70% of global CO_2 emissions. This is expected to rise with future urbanization. In order to mitigate climate change, many cities have set emission targets for the future. In addition, some cities have joined networks and coalitions, such as C40, ARUP, ICLEI or the Covenant of Mayors, in order to share experiences and learn from each other.

Only few studies have been devoted to studying emission targets at city level. For instance, Liu et al., (2017) study the efficient distribution of carbon emissions reduction targets of Chinese cities. They suggest that emission targets which are being allocated to individual cities should not be assigned according to the cities' GDP as is the current practice, but instead more ambitious emission targets should be assigned to cities with greater emission abatement and financial capacities. Zhang et al. (2019) model the time of peak CO_2 emissions for Baoding – a city which is designated to be a pilot for Chinese low-carbon cities and associate sectoral transitions. They find that the emission structure of this city's emissions is composed primarily of industrial emissions (80%) which have been driven by the consistent economic growth and energy intensity. Population growth was concluded to have little contributions to emission increase. According to their estimates, the city's peak emissions (54 million tons of CO_2) will be reached in 2024 and the estimated emissions for 2040 was 80.18 million tons of CO_2. A study by Kuramochi et al. (2017) analyzes the impact of US sub-national and non-state actions and on national GHGs. The authors show that by following the sub-national and non-state commitments, GHG emissions can be reduced to 12-14% below 2005 level by 2025. However, in their estimates they assume all of the commitments to be implemented and fully exercised, which is a rather strong assumption given that they are voluntary. ICLEI (2015) discusses the policies and results of actions which were implemented in four US cities – Atlanta, Cincinnati, Minneapolis and Portland. Though the actions here are relevant, the common issue in all was how to integrate their efforts and policies with other governmental bodies as the powers of municipalities to reduce GHG emissions is limited.

In this paper we assess emission targets and how these relate to city features and mayoral powers. Prior to the actual analysis we normalize future emission targets by expressing them as percentages of change relative to a common baseline for each city. Despite numerous reports on emission targets, exact levels often remain unclear. This is due to discrepancies among cities' baselines. It is difficult to immediately associate the emission targets based on past emissions with current emissions since they might differ greatly. For instance, a 40% reduction from 1990 levels may represent only 10% in 2015 levels. These discrepancies in baseline settings are partly summarized in UNEP (2018) and Bansard et al. (2017).

Furthermore, in order for national and subnational governments to combat climate change, it is vital that their emission targets are set below the estimated business-as-usual (BAU) levels. BAU emissions are by definition insufficient to offset climate change, as BAU represents the scenario without climate mitigation policies being implemented. The relevance of BAU, New policies and The Sustainable Development scenarios is depicted in WEO (2019) under the ''World primary energy demand and energy-related CO_2 emissions by scenario''. According to these estimates, ''New Policies'', representing the policies that are implemented, leading to fewer emissions in comparison to BAU. However, ''New Policies'' far exceed the emissions from the desirable ''Sustainable Development'' scenario.

Henceforth, we wish to explore why some cities are more ambitious in their future emission targets than others. We focus on cities from the C40 group, which are considered to be at the forefront among cities in terms of climate change policies. We investigate whether cities adapt their emission targets for the future according to their mayoral powers (ARUP, 2015). In other words, we want to assess if the two are consistent. If not, then the targets may be unrealistic and impossible to achieve. The reason for us to focus on emission targets rather than current levels of emissions is that we expect the impact of current policies to be reflected with some time lag. Our hypothesis is that levels of mayoral powers today are reflected in level of ambition regarding future emission targets.

2. Stylized facts

In this section we aim to provide insight about how emission targets relate to city attributes and mayoral powers. Our database consists of 32 C40 cities that have defined emission targets for coming decades. The data on variables such as emission targets, current emission levels, population and GDP was accessed through the CDP database on C40 cities (CDP, 2019a,b,c,d,e,f) and complemented by data on cities' emission targets from Yokohama (2019) and Buenos Aires (2019). Data on mayoral powers was accessed through the official C40 website (C40, 2019). The complete table with descriptive statistics of the data is included in the Appendix A as Table A2.

Mayoral powers explained

In this paper we use the term mayoral powers, used by C40 cities, to denote the jurisdictional opportunities of a city to enforce environmental actions in distinct sectors. The data originate from a survey among C40 cities on Mayoral Powers (ARUP, 2015). Here cities stated the type and extent of their power over various climate policies. The survey categorized these into the following four dimensions: a) own or operate, b) set or enforce policy/regulations, c) control budget, and d) set vision. Each of these dimensions covers nine distinct sectors within every city, where discrete performance scores range from 0 to 3. A score of 0 implies no power, 1 implies very limited power; 1 to 2 represents partial power; and a score of 2 to 3 is an innuendo of strong power over the respective emission-producing sector. In our estimates we use the average values of each of the mayoral power categories over all sectors. The emission-producing sectors included in the analysis are the following nine:

Private Buildings	Finance & Economy	Urban Land Use
Public Buildings	Public Transport	Waste
Energy Supply	City Roads	Water

Here we first examine whether emission targets depend on the mayoral powers. If mayoral powers were to have no impact on the emission targets, then this would imply that cities' targets could be decoupled from actual policies. In this case targets could easily be too ambitious given the policies in place. We normalize the mayoral powers in our sample using a logarithmic transformation, which will also be used in our regressions. Among the cities included, Melbourne was the smallest with a value of 0.48, as depicted in Figure 1. On the contrary, Heidelberg has the highest average mayoral power with value of 1.01, followed by Los Angeles (0.97) and New York (0.94).

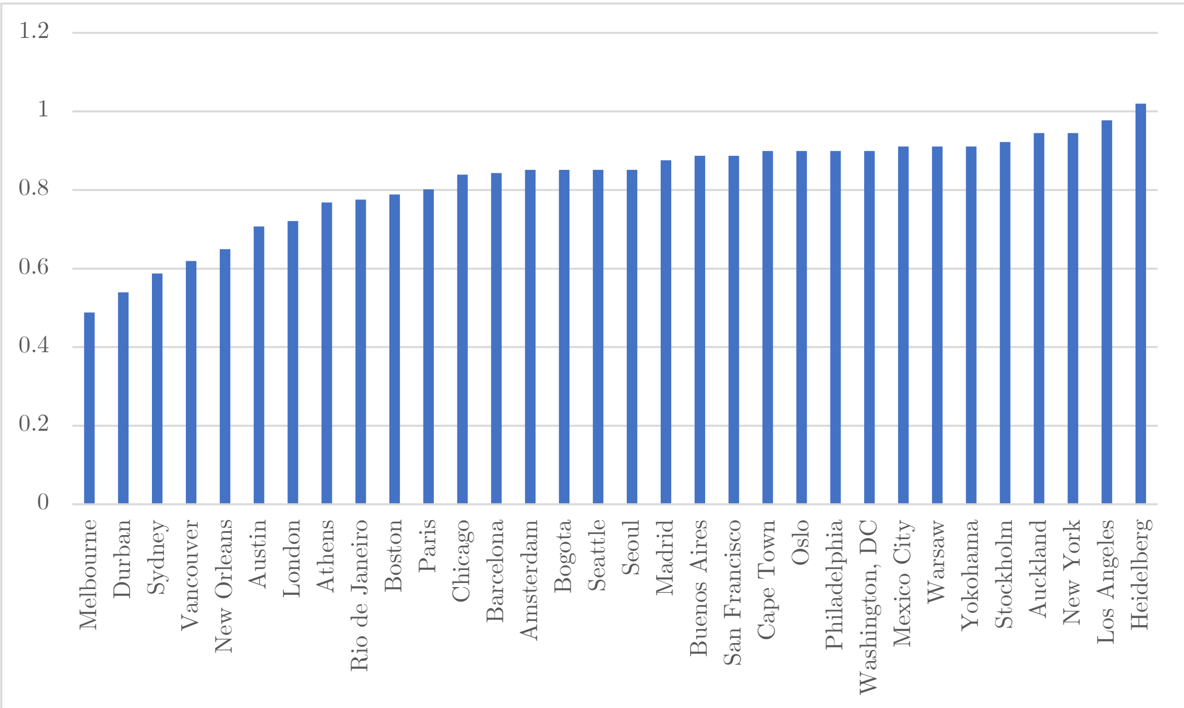

Figure 1: *Average mayoral powers normalized by the mean and ranked*

Correlations of emission targets with city features

In terms of population size, cities in our paper fall into three categories: below 2 million, 2-4 million and above 4 million inhabitants. The cities included represent all different continents. This is displayed in Figure 2. The smallest city included is Melbourne and the largest is Seoul.

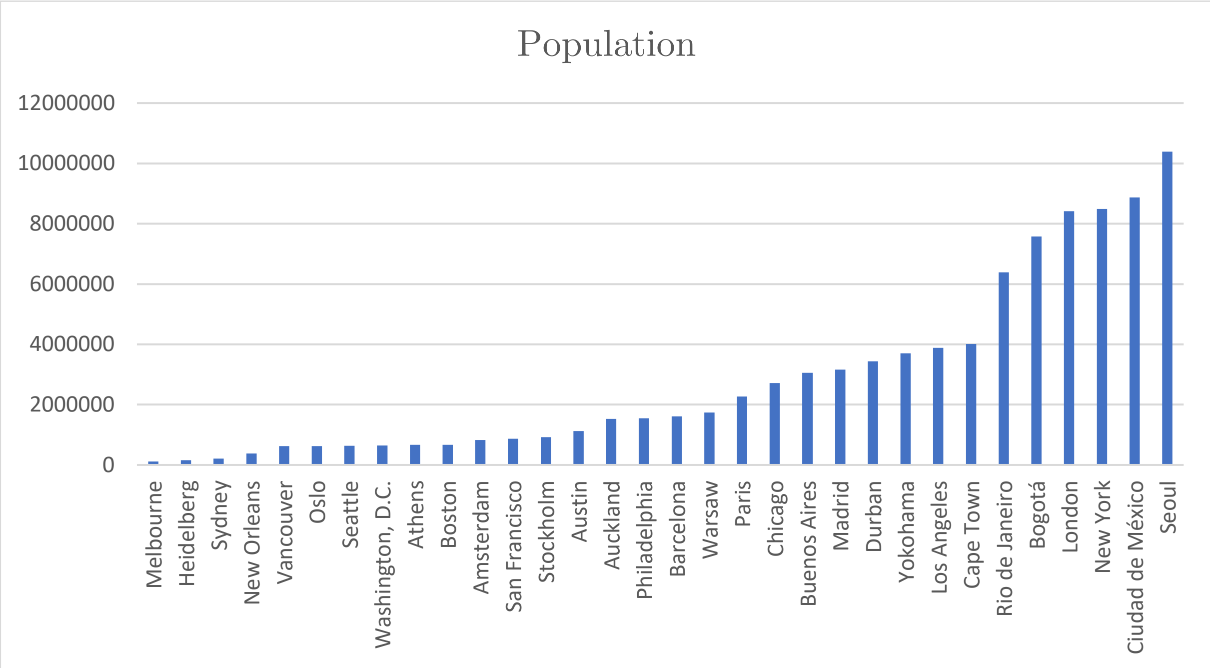

Figure 2: *Cities included in our study ordered by population size for the year 2015*

We calculated the emissions targets for years 2020, 2030, 2040 and 2050, for which these cities reported (fully or partly) their commitments. Given the inconsistency of target years in the reports, we estimate emissions directly or by proxies. Direct approach refers to a calculation based on an emission reduction from a given baseline. Proxies represent data estimated by emission targets in previous or following years together with associated baseline[5]. Given the gaps in the sample, we had to calculate the missing values. This results in normalized emission targets that are comparable among all cities. They are depicted in Table 1. Emissions calculated directly from targets are highlighted in grey. The remaining estimates were based on proxies, assuming a linear relationship between baseline emissions and target emissions. Zero values in the table represent a city's ambition to become a city with zero net emissions by that year (e.g. Melbourne). On the other hand, some cities are far less ambitious with their targets, setting them very close to their expected business-as-usual values, such as Mexico City. Furthermore, some cities increase the ambition of their emission

[5] In Appendix A, Table A1 presents the complete data used to obtain these estimates.

target over time, such as Heidelberg, while others remain close to their 2020 levels even in 2050, such as Buenos Aires.

Table 1: Target emission levels for years 2020, 2030, 2040 and 2050 based on emission targets (grey) with baseline year 2015.

City	2015	2020	2030	2040	2050
Amsterdam	4471000	3100500	1860300	1033500	206700
Athens	4711576	4147141.33	3041424	1935706.67	829989.333
Auckland	11309000	8002800	6669000	5335200	4446000
Austin	15200000	13057859.5	9173578.63	5289297.71	1405016.8
Barcelona	3433000	3323460	2608859	1894258	1179657
Bogotá	13217521	15465314.1	12372251.3	9279188.46	6186125.64
Boston	6900000	5512701	3675134	1837567	0
Buenos Aires	19667128	13230000	12,742,478	12,254,956	11,767,434
Cape Town	22683041	18,798,711	14893569	13282888.1	11672207.2
Chicago	33500000	24225000	18303333.3	12381666.7	6460000
Durban	22587081	16167499	11364696.7	7988640.15	5615492.69
Heidelberg	806000	697392.857	480178.571	262964.286	45750
London	40750490	29510000	16218000	12614000	9010000
Los Angeles	29024807	29350000	25650000	18000000	10800000
Madrid	10257048	8885900	7771800	6797384.08	5945138.89
Melbourne	5805437	0	0	0	0
Mexico City	24084942	29409567	36038443	44161458.5	54115390.5
New Orleans	4600000	3201549.75	1803099.5	1015498.14	571924.326
New York	50692754	46212000	36636000	24424000	12212000
Oslo	1298000	600000	60000	30000	0
Paris	5195663	4694571.75	3755657.4	2660257.33	1564857.25
Philadelphia	19212870	17084200.6	12977410	8595427.39	4213444.8
Rio de Janeiro	20268045	9121744	4160310.68	1897464.45	865409.248
San Francisco	4574578	4418888.5	3225013.6	2232702	1240389.8
Seattle	3171000	2652453.33	1557360	778680	0
Seoul	48550952	42555666.7	29667000	20681872.9	14418035.7
Stockholm	2511000	2000000	1500000	0	0
Sydney	5052256	3992000	1776000	790124.248	351518.203
Vancouver	2625609	1879350	1358444.78	981920.459	709758.544
Warsaw	12706696	10362387.2	8259928.34	6584044.29	5248185.87
Washington DC	8204579	3367298.33	2244865.56	1122432.78	0
Yokohama	21000000	16413600	14850400	9379200	3908000

Note: The highlighted (grey) values represent the stated emission targets set by cities and the non-highlighted numbers are estimates for based on stated targets and baseline emissions.

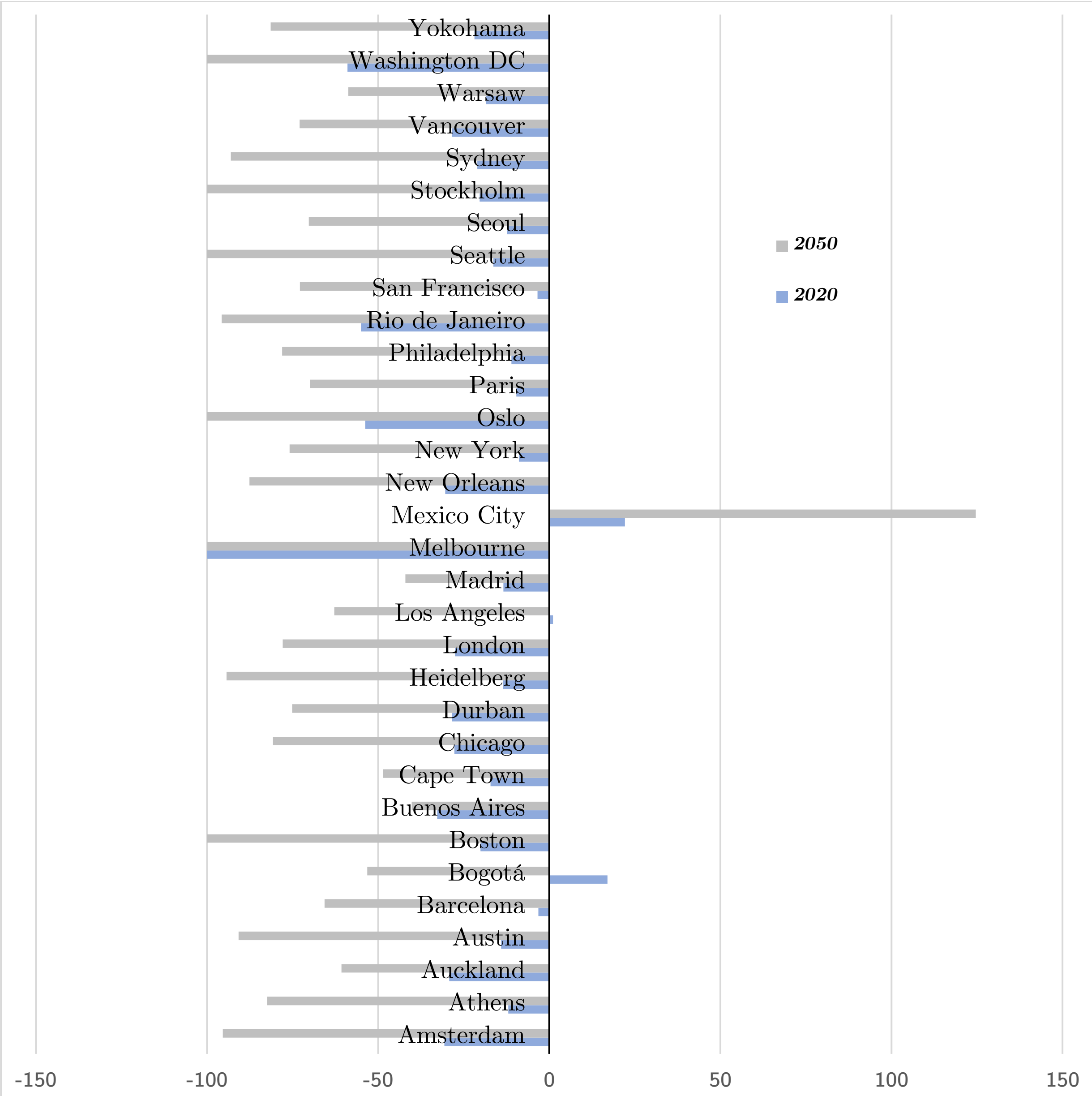

Figure 3: *Emission targets for years 2020 (blue) and 2050 (grey) compared to 2015 (baseline) emissions*

Figure 3 depicts the emission targets (%) for 2020 (blue) and 2050 (grey) in contrast to the 2015 baseline. In both, Mexico City has the highest emission targets, which is consistent with the fact that only a small deviation from its BAU scenario is expected. Bogota is also not very ambitious. On the other hand, cities such as Boston, Oslo, Seattle and Stockholm are ambitious and intend to reduce emissions by 100% by the year of 2050. Melbourne wants to accomplish this goal by 2020 already. Figure 4 depicts the correlation between emission targets (%) and logarithmic transformation of population size. The relationship's trend is upward sloping, implying that with the increase in population size, the emission targets become less ambitious (due to higher emission targets)

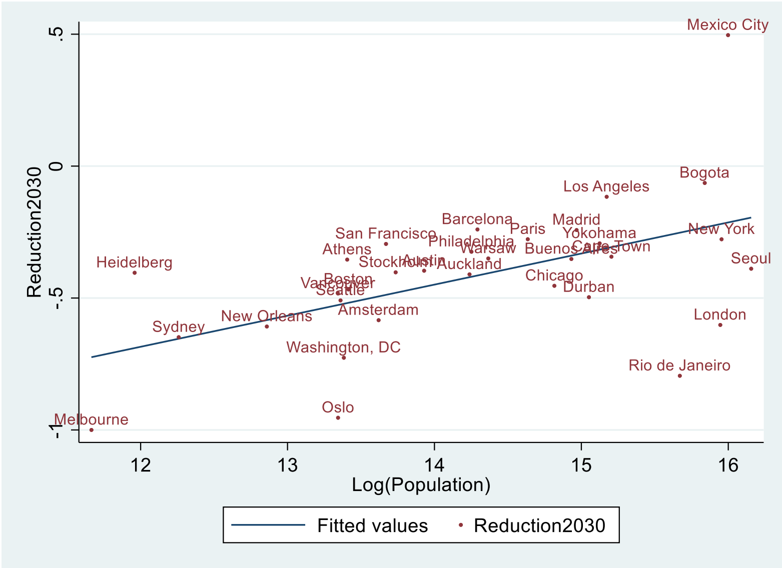

Figure 4: *Correlations between population size and emission targets for 2030*

In Figure 5 is displayed the relationship between the logarithmic transformation of GDP per capita and emission targets (%) for 2030. The downward sloping trend indicates that the greater the per capita GDP is, the higher is the reduction of emissions (%) which are being targeted. Henceforth, cities which are more ambitious in their targets tend to have a higher per capita GDP.

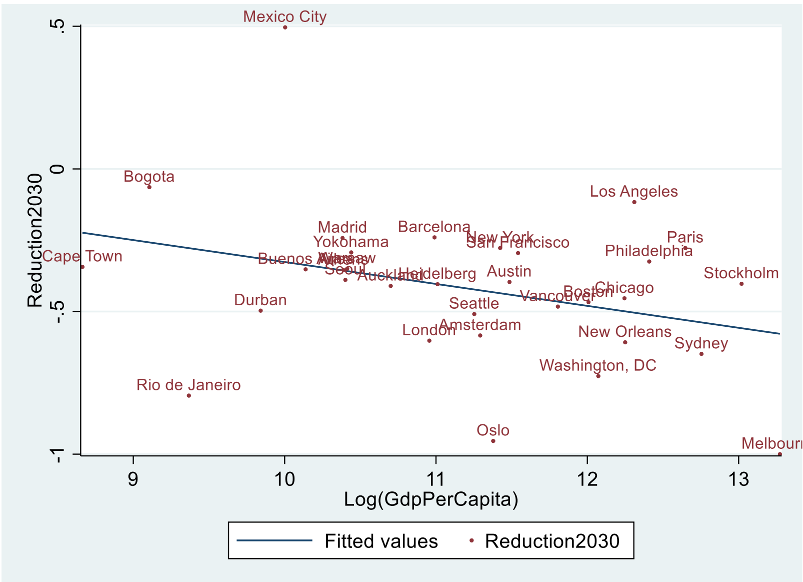

Figure 5: *Correlation between GDP per capita and emission targets for 2030*

Figure 6 is the visual representation of the average mayoral powers and emission targets (%) for 2030. As we may observe, the relationship demonstrates that the greater the average mayoral power, the greater the emission targets and hence the lower the city ambition.

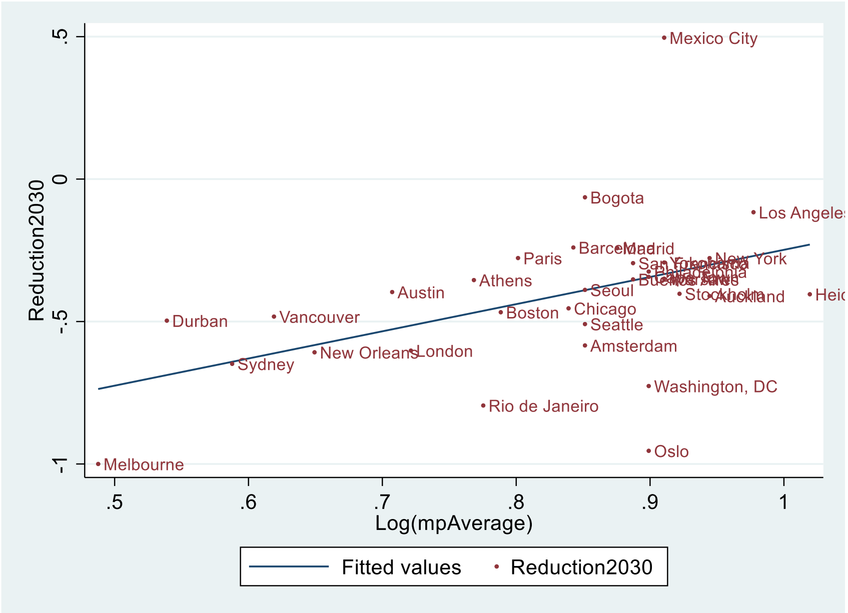

Figure 5: *Correlation between average mayoral powers and emission targets for 2030*

3. Regression analysis

We aim to determine the impact of city attributes and mayoral powers on emission targets by accounting for multiple factors simultaneously. To this end, we use a quantile regression, using bootstrap repetition of 100 to correct for the small sample size[6]. The advantage of using a quantile regression is that its coefficients are fitted to the median and not the mean of the distribution, allowing for inclusion of outliers without distorting the results. Furthermore, this approach also allows us to analyze how different parts of the distribution behave, by dividing the distribution into quantiles. This enables us to estimate coefficients of the independent variable for distinct parts of the distribution. This approach considers that distinct parts of the distribution may behave differently. We test for each type of mayoral powers (own and operate, set or enforce policy/regulations, control budget, set vision) separately and we also run one regression including an overall average of mayoral powers. The

[6] For future publication purposes, a bootstrap of 5000 or 10000 will be applied, but due to the extensive computational time required for such estimates, we resorted to using bootstrap of 100, which is sufficiently high to improve confidence intervals.

regression specification used to arrive at estimates is based on the minimization problem as formulated in equation (I):

$$\min_{\beta \in R^k} \left[\sum_{i \in \{i: y_i \geq x_i' \beta\}} \theta |y_i - x_i' \beta| + \sum_{i \in \{i: y_i < x_i' \beta\}} (1-\theta) |y_i - x_i' \beta| \right] \quad \text{(I)}$$

Here θ represents the quantile estimated $(0 < \theta < 1)$, y_i the dependent variable, x_i the vector of explanatory variables (with $k\,x1$ vector) for city i.

The small sample size refrained us from using many additional independent explanatory variables. This forced us also to focus our research question to a more specific one. Hence, we determine which cities are more ambitious: i) those with lower population size (alternately population density) as suggested by the correlations shown in the previous section, ii) cities with greater mayoral power, or iii) those with greater GDP per capita. We expect to find that mayoral powers encourage cities to be more ambitious in their targets and that cities' size may be a constraint to lowering emission targets.

4. Results

We demonstrate some of our regression results for emission targets in this section. We only display those which found at least one explanatory variable significant at 10%, 5% or 1% levels. The rest of the regressions found none of the explanatory variables to be statistically significant. Full regression results for years 2020, 2030, 2040 and 2050 are depicted in the Appendix A in Tables A2, A3, A4 and A5. For our quantile regression we used quantiles equal to 10%, 25%, 50%, 75% and 90%.

Table 2 depicts results for quantile regressions for emission targets in 2020. In the short run, the impact of population size on emission targets is positive and significant at 5% (eq.1) and 10% (eq.2). The impact of a city being from Latin America is found to be significant at 5% (eq.11, 16) for the bottom 10% of the distribution of emission targets in the presence of mayoral powers with budgetary policies or policies of setting a vision. Mayoral policies for budgetary measures were found to be significant at 5% for the 90^{th} quantile (eq.15) with impact of 0.429. Moreover, with 1% increase of average mayoral powers, the emission targets increase by 0.576% at significance level of 5% (eq. 25), implying lower ambition levels for the 90^{th} quantile of our distribution. Therefore, the impact of mayoral powers is relevant only for the top 10% of the sample distribution of cities' emission targets and the direction of the impact is positive, implying lower ambition levels in cities.

Table 2: Quantile regression for dependent variable: Reduction 2020, representing emission targets for 2030

Regression (eq.)	(1)	(3)	(11)	(15)	(16)	(21)	(25)
Quantile	0.1	0.5	0.1	0.9	0.1	0.1	0.9
Mayoral Power	Own/ Operate	Own/ Operate	Budget	Budget	Set Vision	Average	Average
Variables							
Log(Population)	0.201**	0.080*	0.02	-0.003	0.06	0.057	-0.01
	(-0.079)	(-0.044)	(-0.09)	(-0.051)	(-0.089)	(-0.085)	(-0.045)
Log(GdpCap)	0.063	0.005	-0.326*	-0.022	-0.22	-0.224	0.011
	(-0.164)	(-0.082)	(-0.177)	(-0.047)	(-0.188)	(-0.2)	(-0.059)
Africa	0.243	-0.103	-0.75	-0.086	-0.642	-0.664	-0.017
	(-0.436)	(-0.21)	(-0.503)	(-0.172)	(-0.469)	(-0.609)	(-0.175)
LatinAmerica	-0.274	-0.259	-0.958**	0.2	-0.912**	-0.925*	0.282
	(-0.413)	(-0.299)	(-0.382)	(-0.254)	(-0.436)	(-0.531)	(-0.28)
AsiaOceania	0.016	-0.137	-0.204	-0.073	-0.293	-0.307	-0.031
	(-0.26)	(-0.159)	(-0.263)	(-0.16)	(-0.276)	(-0.276)	(-0.17)
Europe	0.028	-0.055	-0.171	-0.002	-0.304	-0.317	0.04
	(-0.211)	(-0.106)	(-0.207)	(-0.059)	(-0.23)	(-0.25)	(-0.102)
Log(mpOwn)	0.516	0.3					
	(-0.598)	(-0.284)					
Log(mpSetEnforce)							
Log(mpBudget)			-0.491	0.429**			
			(-0.736)	(-0.201)			
Log(mpSetVision)					-0.096		
					(-0.662)		
Log(mpAverage)						-0.114	0.576**
						(-0.868)	(-0.281)
Observations	32	32	32	32	32	32	32
Bootstrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reps	100	100	100	100	100	100	100

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table 3 summarizes significance levels and sign of impact with number of occurrences among the remaining regressions. Based on our results we concluded that population tends to have a positive impact on emission targets. Distinct types of mayoral powers were found to have a positive impact on emission targets, pointing to lower ambition levels of these cities. On the contrary, GDP per capita has a negative impact on emission targets, implying higher levels of ambition in cities. Being part of a European, Asian, African or Latin American continent has proven to have a weakly significant (10%) and negative impact on emission targets, but the results were not as consistent as in the case of population size.

Table 3: Summarized number of regressions from quantile regression for dependent variable: Reduction for years 2020, 2030, 2040 and 2050, with assigned sign and significance levels

Sign		Positive Impact (+)			Negative Impact (-)		
Significance level		10%	5%	1%	10%	5%	1%
2020	Log(Population)	1/25	1/25				
	Log(GdpCap)				1/25		
	LatinAmerica				1/25	2/25	
	Log(mpBudget)	1/25					
	Log(mpAverage)	1/25					
2030	Log(Population)	4/25					
	Africa					1/25	
	LatinAmerica	2/25					
	AsiaOceania				2/25		1/25
	Europe				2/25		
	Log(mpSetEnforce)	1/25					
	Log(mpBudget)	1/25	1/25				
	Log(mpSetVision)		2/25				
2040	Log(Population)	7/25	2/25				
	Log(GdpCap)				1/25		
	LatinAmerica	3/25	2/25				
2050	Log(Population)	4/25	8/25	1/25			
	Log(GdpCap)				2/25		
	LatinAmerica	3/25	2/25				

5. Conclusions

This chapter analyzed the relationship between emission targets, mayoral powers and city attributes. We assessed whether mayoral powers reflect ambition regarding future emission targets. We first had to calculate future emission targets for years 2020, 2030, 2040 and 2050 using a common baseline for consistency. Statistical correlation and regression analysis suggest that mayoral powers have no impact on the emission targets in the long run (2040 and 2050). However, some of them affect emission targets in the years 2020 and 2030 positively, implying lower levels of ambition in cities. Nonetheless, most of the impacts on cities' emission targets do not depend on mayoral powers but rather on city attributes. We find that higher GDP per capita makes cities more ambitious in the long run, but not in the short run. Population size is relevant for both long and short run, impacting emission targets positively, implying lower levels of ambition. Further work is needed to expand the database to reinforce these results as well as higher number of bootstrap repetitions (e.g. 10000). Our goal is to create a dynamic panel database in order to track the impact of the environmental policies of mayors on emission targets over time. This would contribute to improving the quality of our estimates and allow exploring additional research questions. Finally, one could also decompose the emission targets by production sectors and test for a relation with the associated sectorial mayoral powers.

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Appendix A

Table A1: Target emission levels for years 2020, 2030, 2040 and 2050 based on emission targets (grey) with baseline 2015.

City	2015	2017	2020	2022	2025	2030	2032	2035	2040	2050
Amsterdam	4471000		3100500		2480400	1860300			1033500	206700
Athens	4711576		4147141.33			3041424			1935706.67	829989.333
Auckland	11309000		8002800			6669000			5335200	4446000
Austin	15200000		13057859.5			9173578.63			5289297.71	1405016.8
Barcelona	3433000		3323460			2608859			1894258	1179657
Bogotá	13217521		15465314.1			12372251.3			9279188.46	6186125.64
Boston	6900000		5512701			3675134			1837567	0
Buenos Aires	19667128		13230000			12,742,478			12,254,956	11,767,434
Cape Town	22683041		18,798,711	17,930,902		14893569			13282888.1	11672207.2
Chicago	33500000		24225000			18303333.3			12381666.7	6460000
Durban	22587081		16167499			11364696.7			7988640.15	5615492.69
Heidelberg	806000		697392.857			480178.571			262964.286	45750
London	40750490		29510000		18020000	16218000			12614000	9010000
Los Angeles	29024807		29350000		29700000	25650000		21600000	18000000	10800000
Madrid	10257048		8885900			7771800			6797384.08	5945138.89
Melbourne	5805437		0			0			0	0
Mexico City	24084942		29409567			36038443			44161458.5	54115390.5
New Orleans	4600000		3201549.75			1803099.5			1015498.14	571924.326
New York	50692754		46212000			36636000			24424000	12212000
Oslo	1298000		600000			60000			30000	0
Paris	5195663		4694571.75			3755657.4			2660257.33	1564857.25
Philadelphia	19212870		17084200.6		15168401.3	12977410			8595427.39	4213444.8
Rio de Janeiro	20268045		9121744			4160310.68			1897464.45	865409.248
San Francisco	4574578	4651461.75	4418888.5		3721169.4	3225013.6			2232702	1240389.8
Seattle	3171000		2652453.33			1557360			778680	0
Seoul	48550952		42555666.7			29667000			20681872.9	14418035.7
Stockholm	2511000		2000000			1500000			0	0
Sydney	5052256		3992000			1776000			790124.248	351518.203
Vancouver	2625609		1879350			1358444.78			981920.459	709758.544
Warsaw	12706696		10362387.2			8259928.34			6584044.29	5248185.87
Washington DC	8204579		3367298.33			2244865.56	2020379		1122432.78	0
Yokohama	21000000		16413600			14850400			9379200	3908000

Note: The reference baseline emission level is set at 2015. The highlighted (grey) values are the targets set by individual cities and the non-highlighted numbers are the estimates for years 2020, 2030, 2040 and 2050 based on these targets and baseline levels.

Table A2: Quantile regression for dependent variable: Reduction 2020

Regression	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)
Quantile	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9
Mayoral Power	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Budget	Budget	Budget	Budget	Budget	Set Vision	Set Vision	Set Vision	Set Vision	Set Vision	Avg	Avg	Avg	Avg	Avg
Variables																									
Log(Population)	0.201**	0.034	0.080*	0.017	0.006	0.086	0.034	0.028	0.017	0.019	0.02	0.034	0.044	0.024	-0.003	0.06	0.014	0.072	0.029	0.006	0.057	0.021	0.05	0.023	-0.01
	(-0.079)	(-0.042)	(-0.044)	(-0.041)	(-0.046)	(-0.085)	(-0.065)	(-0.049)	(-0.06)	(-0.061)	(-0.09)	(-0.076)	(-0.05)	(-0.049)	(-0.051)	(-0.089)	(-0.061)	(-0.048)	(-0.041)	(-0.05)	(-0.085)	(-0.076)	(-0.052)	(-0.043)	(-0.045)
Log(GdpCap)	0.063	-0.151	0.005	0.021	0.024	-0.091	-0.165	-0.007	0.004	0.029	-0.326*	-0.165	-0.018	0.016	-0.022	-0.22	-0.134	-0.003	0.022	-0.015	-0.224	-0.138	-0.012	0.031	0.011
	(-0.164)	(-0.123)	(-0.082)	(-0.067)	(-0.058)	(-0.157)	(-0.13)	(-0.066)	(-0.056)	(-0.054)	(-0.177)	(-0.133)	(-0.077)	(-0.037)	(-0.047)	(-0.188)	(-0.13)	(-0.083)	(-0.05)	(-0.049)	(-0.2)	(-0.168)	(-0.08)	(-0.057)	(-0.059)
Africa	0.243	-0.474	-0.103	-0.011	-0.058	-0.181	-0.437	-0.016	-0.052	-0.065	-0.75	-0.507	-0.086	-0.088	-0.086	-0.642	-0.462	-0.164	-0.091	-0.225	-0.664	-0.427	-0.069	-0.037	-0.017
	(-0.436)	(-0.322)	(-0.21)	(-0.213)	(-0.212)	(-0.513)	(-0.404)	(-0.215)	(-0.217)	(-0.225)	(-0.503)	(-0.374)	(-0.227)	(-0.158)	(-0.172)	(-0.469)	(-0.341)	(-0.215)	(-0.165)	(-0.166)	(-0.609)	(-0.538)	(-0.263)	(-0.2)	(-0.175)
LatinAmerica	-0.274	-0.41	-0.259	0.283	0.278	-0.452	-0.34	-0.154	0.282	0.273	-0.958**	-0.411	-0.278	0.25	0.2	-0.912**	-0.377	-0.272	0.256	0.194	-0.925*	-0.368	-0.272	0.292	0.282
	(-0.413)	(-0.365)	(-0.299)	(-0.274)	(-0.258)	(-0.451)	(-0.375)	(-0.264)	(-0.312)	(-0.254)	(-0.382)	(-0.317)	(-0.261)	(-0.27)	(-0.254)	(-0.436)	(-0.399)	(-0.329)	(-0.252)	(-0.249)	(-0.531)	(-0.469)	(-0.321)	(-0.276)	(-0.28)
AsiaOceania	0.016	-0.255	-0.137	-0.002	-0.037	-0.129	-0.236	-0.048	-0.036	-0.11	-0.204	-0.268	-0.202	-0.065	-0.073	-0.293	-0.333	-0.2	-0.064	-0.107	-0.307	-0.269	-0.18	-0.048	-0.031
	(-0.26)	(-0.171)	(-0.159)	(-0.171)	(-0.163)	(-0.281)	(-0.212)	(-0.16)	(-0.147)	(-0.169)	(-0.263)	(-0.217)	(-0.178)	(-0.162)	(-0.16)	(-0.276)	(-0.208)	(-0.172)	(-0.159)	(-0.177)	(-0.276)	(-0.264)	(-0.186)	(-0.161)	(-0.17)
Europe	0.028	-0.17	-0.055	0.003	0.091	-0.102	-0.154	-0.01	0.02	0.011	-0.171	-0.208	-0.065	-0.037	-0.002	-0.304	-0.187	-0.067	-0.043	-0.039	-0.317	-0.143	-0.071	-0.039	0.04
	(-0.211)	(-0.163)	(-0.106)	(-0.101)	(-0.11)	(-0.238)	(-0.175)	(-0.091)	(-0.096)	(-0.08)	(-0.207)	(-0.16)	(-0.101)	(-0.052)	(-0.059)	(-0.23)	(-0.154)	(-0.113)	(-0.092)	(-0.085)	(-0.25)	(-0.247)	(-0.118)	(-0.099)	(-0.102)
Log(mpOwn)	0.516	0.245	0.3	0.286	0.393																				
	(-0.598)	(-0.462)	(-0.284)	(-0.245)	(-0.349)																				
Log(mpSetEnforce)						0.461	0.398	0.428	0.057	0.159															
						(-0.829)	(-0.654)	(-0.369)	(-0.284)	(-0.298)															
Log(mpBudget)											-0.491	0.095	0.333	0.27	0.429**										
											(-0.736)	(-0.552)	(-0.285)	(-0.18)	(-0.201)										
Log(mpSetVision)																-0.096	0.429	0.272	0.241	0.261					
																(-0.662)	(-0.48)	(-0.246)	(-0.243)	(-0.335)					
Log(mpAverage)																					-0.114	0.489	0.484	0.335	0.576**
																					(-0.868)	(-0.679)	(-0.439)	(-0.292)	(-0.281)
Observations	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Bootstrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reps	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, regressions highlighted (grey) have at least 1 result which is statistically significant.

Table A3: Quantile regression for dependent variable: Reduction 2030

Regression	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)	(40)	(41)	(42)	(43)	(44)	(45)	(46)	(47)	(48)	(49)	(50)
Quantile	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9
Mayoral Power	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Budget	Budget	Budget	Budget	Budget	Set Vision	Set Vision	Set Vision	Set Vision	Set Vision	Avg	Avg	Avg	Avg	Avg
Variables																									
Log(Population)	0.091	0.081	0.054	0.075*	0.104*	0.128	0.035	0.053	0.08	0.08	0.105	0.048	0.066	0.077*	0.068*	0.182*	0.063	0.068	0.089*	0.068	0.104	0.051	0.059	0.08	0.086
	(-0.094)	(-0.067)	(-0.05)	(-0.039)	(-0.055)	(-0.085)	(-0.078)	(-0.064)	(-0.053)	(-0.054)	(-0.086)	(-0.073)	(-0.059)	(-0.041)	(-0.037)	(-0.104)	(-0.089)	(-0.061)	(-0.051)	(-0.075)	(-0.086)	(-0.077)	(-0.053)	(-0.056)	(-0.057)
Log(GdpCap)	-0.088	-0.03	-0.041	-0.014	0.013	-0.046	0.027	-0.033	-0.026	-0.026	-0.08	-0.022	-0.029	0.004	-0.009	0.122	-0.05	-0.03	0.006	-0.009	-0.083	0.007	-0.038	-0.001	0.013
	(-0.177)	(-0.119)	(-0.062)	(-0.044)	(-0.063)	(-0.163)	(-0.11)	(-0.067)	(-0.043)	(-0.053)	(-0.162)	(-0.121)	(-0.088)	(-0.054)	(-0.048)	(-0.166)	(-0.123)	(-0.067)	(-0.032)	(-0.038)	(-0.181)	(-0.123)	(-0.08)	(-0.056)	(-0.047)
Africa	-0.318	-0.088	-0.138	-0.161	-0.157	-0.256	0.334	-0.072	-0.158	-0.225	-0.373	-0.056	-0.126	-0.087	-0.116	0.289	-0.178	-0.112	-0.192**	-0.21	-0.346	0.039	-0.14	-0.125	-0.147
	(-0.485)	(-0.32)	(-0.199)	(-0.154)	(-0.234)	(-0.593)	(-0.396)	(-0.23)	(-0.168)	(-0.209)	(-0.545)	(-0.37)	(-0.223)	(-0.162)	(-0.141)	(-0.465)	(-0.336)	(-0.199)	(-0.096)	(-0.14)	(-0.519)	(-0.373)	(-0.261)	(-0.19)	(-0.165)
LatinAmerica	-0.654	-0.057	0.099	0.043	0.57	-0.645	0.295	0.209	0.099	0.587	-0.661	-0.019	0.135	0.096	0.574	-0.145	-0.05	0.18	0.082	0.574*	-0.686	0.046	0.132	0.123	0.601*
	(-0.444)	(-0.364)	(-0.411)	(-0.391)	(-0.404)	(-0.596)	(-0.424)	(-0.434)	(-0.432)	(-0.443)	(-0.458)	(-0.397)	(-0.261)	(-0.339)	(-0.355)	(-0.469)	(-0.43)	(-0.383)	(-0.371)	(-0.334)	(-0.522)	(-0.436)	(-0.374)	(-0.383)	(-0.343)
AsiaOceania	-0.211	-0.131	-0.07	-0.062	-0.105	-0.191	0.044	-0.049	-0.054	-0.121	-0.224	-0.032	-0.07	-0.156*	-0.171***	0.046	-0.126	-0.077	-0.145	-0.171*	-0.225	-0.04	-0.085	-0.072	-0.118
	(-0.231)	(-0.152)	(-0.122)	(-0.095)	(-0.127)	(-0.304)	(-0.176)	(-0.113)	(-0.101)	(-0.113)	(-0.248)	(-0.179)	(-0.135)	(-0.083)	(-0.06)	(-0.206)	(-0.143)	(-0.117)	(-0.093)	(-0.093)	(-0.214)	(-0.156)	(-0.123)	(-0.102)	(-0.096)
Europe	-0.407*	-0.148	0.046	0.022	0.061	-0.397	0.124	0.07	0.067	0	-0.370*	-0.126	0.027	-0.017	-0.014	-0.196	-0.116	0.073	-0.026	-0.014	-0.404*	-0.089	0.047	0.027	0.03
	(-0.232)	(-0.156)	(-0.097)	(-0.074)	(-0.107)	(-0.293)	(-0.199)	(-0.11)	(-0.086)	(-0.091)	(-0.212)	(-0.203)	(-0.144)	(-0.106)	(-0.083)	(-0.213)	(-0.167)	(-0.141)	(-0.08)	(-0.084)	(-0.229)	(-0.179)	(-0.14)	(-0.129)	(-0.118)
Log(mpOwn)	-0.17	0.533	0.273	0.352	0.289																				
	(-0.773)	(-0.591)	(-0.375)	(-0.264)	(-0.354)																				
Log(mpSetEnforce)						-0.188	1.062*	0.239	0.19	0.189															
						(-0.944)	(-0.644)	(-0.446)	(-0.298)	(-0.339)															
Log(mpBudget)											-0.299	0.764	0.228	0.447*	0.456**										
											(-0.664)	(-0.55)	(-0.375)	(-0.25)	(-0.202)										
Log(mpSetVision)																0.475	0.515	0.3	0.382**	0.456**					
																(-0.709)	(-0.532)	(-0.355)	(-0.193)	(-0.214)					
Log(mpAverage)																					-0.26	1.041	0.277	0.39	0.434
																					(-0.953)	(-0.657)	(-0.55)	(-0.359)	(-0.319)
Observations	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Bootstrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reps	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, regressions highlighted (grey) have at least 1 result which is statistically significant.

Table A4: Quantile regression for dependent variable: Reduction 2040

Regression	(51)	(52)	(53)	(54)	(55)	(56)	(57)	(58)	(59)	(60)	(61)	(62)	(63)	(64)	(65)	(66)	(67)	(68)	(69)	(70)	(71)	(72)	(73)	(74)	(75)
Quantile	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9
Mayoral Power	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Budget	Budget	Budget	Budget	Budget	Set Vision	Set Vision	Set Vision	Set Vision	Set Vision	Avg	Avg	Avg	Avg	Avg
Variables																									
Log(Population)	0.08	0.017	0.067	0.1	0.088	0.107*	0.014	0.06	0.105*	0.110**	0.09	0.015	0.046	0.105**	0.088*	0.09	0.015	0.051	0.103*	0.088*	0.091	0.016	0.034	0.099*	0.094
	(-0.06)	(-0.068)	(-0.062)	(-0.067)	(-0.058)	(-0.061)	(-0.045)	(-0.052)	(-0.058)	(-0.054)	(-0.059)	(-0.055)	(-0.045)	(-0.05)	(-0.051)	(-0.063)	(-0.059)	(-0.064)	(-0.059)	(-0.052)	(-0.066)	(-0.068)	(-0.06)	(-0.059)	(-0.061)
Log(GdpCap)	-0.037	-0.135	-0.06	-0.028	-0.017	-0.018	-0.137	-0.071	-0.03	-0.033	-0.036	-0.137*	-0.052	-0.014	-0.049	-0.036	-0.136	-0.045	-0.029	-0.049	-0.033	-0.136	-0.061	-0.013	-0.044
	(-0.093)	(-0.094)	(-0.078)	(-0.054)	(-0.051)	(-0.097)	(-0.09)	(-0.083)	(-0.073)	(-0.064)	(-0.08)	(-0.07)	(-0.076)	(-0.06)	(-0.05)	(-0.093)	(-0.083)	(-0.072)	(-0.065)	(-0.054)	(-0.099)	(-0.094)	(-0.079)	(-0.067)	(-0.071)
Africa	-0.122	-0.227	-0.04	-0.117	-0.073	-0.15	-0.225	-0.16	-0.086	-0.14	-0.192	-0.221	-0.023	-0.037	-0.189	-0.138	-0.224	-0.021	-0.138	-0.207	-0.156	-0.226	-0.042	-0.064	-0.177
	(-0.27)	(-0.234)	(-0.258)	(-0.218)	(-0.211)	(-0.343)	(-0.257)	(-0.221)	(-0.257)	(-0.254)	(-0.217)	(-0.203)	(-0.244)	(-0.215)	(-0.177)	(-0.205)	(-0.204)	(-0.186)	(-0.206)	(-0.164)	(-0.326)	(-0.287)	(-0.282)	(-0.241)	(-0.249)
LatinAmerica	-0.401	0.001	0.096	-0.023	1.115**	-0.474	0.007	0.073	0.024	1.064*	-0.426	-0.001	0.104	0.049	1.045*	-0.426	0.008	0.123	-0.017	1.045**	-0.439	0.001	0.1	0.023	1.052*
	(-0.492)	(-0.495)	(-0.55)	(-0.55)	(-0.542)	(-0.497)	(-0.442)	(-0.415)	(-0.631)	(-0.578)	(-0.373)	(-0.354)	(-0.354)	(-0.568)	(-0.56)	(-0.444)	(-0.437)	(-0.46)	(-0.549)	(-0.521)	(-0.329)	(-0.352)	(-0.328)	(-0.61)	(-0.616)
AsiaOceania	-0.076	-0.06	-0.06	-0.077	-0.066	-0.103	-0.058	-0.054	-0.061	-0.035	-0.101	-0.068	-0.067	-0.022	-0.115	-0.101	-0.059	-0.075	-0.105	-0.115	-0.101	-0.063	-0.048	-0.068	-0.065
	(-0.127)	(-0.143)	(-0.124)	(-0.079)	(-0.089)	(-0.169)	(-0.118)	(-0.113)	(-0.134)	(-0.125)	(-0.135)	(-0.118)	(-0.12)	(-0.103)	(-0.102)	(-0.128)	(-0.113)	(-0.137)	(-0.135)	(-0.12)	(-0.153)	(-0.134)	(-0.122)	(-0.102)	(-0.101)
Europe	-0.196	-0.136	0.043	-0.009	0.055	-0.239	-0.134	0.037	0.028	-0.006	-0.179	-0.14	-0.041	0.041	0.003	-0.179	-0.133	-0.045	-0.012	0.003	-0.207	-0.137	-0.098	-0.005	0.004
	(-0.121)	(-0.125)	(-0.138)	(-0.113)	(-0.106)	(-0.186)	(-0.147)	(-0.153)	(-0.124)	(-0.109)	(-0.12)	(-0.149)	(-0.158)	(-0.113)	(-0.102)	(-0.122)	(-0.123)	(-0.135)	(-0.106)	(-0.099)	(-0.142)	(-0.157)	(-0.177)	(-0.103)	(-0.099)
Log(mpOwn)	-0.136	0.017	0.154	0.243	0.297																				
	(-0.561)	(-0.417)	(-0.442)	(-0.426)	(-0.365)																				
Log(mpSetEnforce)						-0.214	0.027	0.107	0.196	0.218															
						(-0.677)	(-0.438)	(-0.317)	(-0.411)	(-0.444)															
Log(mpBudget)											-0.259	0.036	0.341	0.378	0.203										
											(-0.489)	(-0.414)	(-0.36)	(-0.311)	(-0.264)										
Log(mpSetVision)																-0.259	0.022	0.287	0.134	0.203					
																(-0.358)	(-0.342)	(-0.313)	(-0.272)	(-0.202)					
Log(mpAverage)																					-0.207	0.028	0.429	0.263	0.267
																					(-0.575)	(-0.507)	(-0.507)	(-0.426)	(-0.494)
Observations	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Bootstrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reps	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, regressions highlighted (grey) have at least 1 result which is statistically significant.

Table A5: Quantile regression for dependent variable: Reduction 2040

Regression	(76)	(77)	(78)	(79)	(80)	(81)	(82)	(83)	(84)	(85)	(86)	(87)	(88)	(89)	(90)	(91)	(92)	(93)	(94)	(95)	(96)	(97)	(98)	(99)	(100)
Quantile	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9	0.1	0.25	0.5	0.75	0.9
Mayoral Power	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Own/ Operate	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Set/ enforce policies	Budget	Budget	Budget	Budget	Budget	Set Vision	Set Vision	Set Vision	Set Vision	Set Vision	Avg	Avg	Avg	Avg	Avg
Variables																									
Log(Population)	0.074**	0.081**	0.079*	0.076	0.109*	0.083**	0.07	0.001	0.086	0.11	0.071*	0.074**	0.061	0.117**	0.143**	0.071***	0.075**	0.061	0.117	0.136*	0.074	0.071	0.026	0.116*	0.138**
	(-0.029)	(-0.033)	(-0.045)	(-0.058)	(-0.066)	(-0.041)	(-0.047)	(-0.067)	(-0.07)	(-0.074)	(-0.038)	(-0.032)	(-0.045)	(-0.055)	(-0.068)	(-0.024)	(-0.034)	(-0.066)	(-0.077)	(-0.073)	(-0.047)	(-0.045)	(-0.052)	(-0.064)	(-0.07)
Log(GdpCap)	-0.019	-0.032	0.016	-0.052	-0.071	-0.015	-0.023	-0.034	-0.024	-0.109*	-0.017	-0.007	0.014	-0.06	-0.101*	-0.017	-0.003	0.014	-0.072	-0.074	-0.016	-0.015	0.01	-0.052	-0.108
	(-0.056)	(-0.063)	(-0.075)	(-0.078)	(-0.084)	(-0.075)	(-0.071)	(-0.089)	(-0.077)	(-0.065)	(-0.046)	(-0.061)	(-0.058)	(-0.058)	(-0.058)	(-0.044)	(-0.048)	(-0.068)	(-0.067)	(-0.07)	(-0.065)	(-0.083)	(-0.065)	(-0.061)	(-0.066)
Africa	0.083	0.051	0.352	-0.015	-0.138	0.07	0.034	0.253	0.07	-0.288	0.031	0.026	0.327	-0.1	-0.256	0.048	0.067	0.308	-0.12	-0.143	0.062	0.036	0.239	-0.056	-0.275
	(-0.201)	(-0.199)	(-0.254)	(-0.265)	(-0.272)	(-0.274)	(-0.22)	(-0.243)	(-0.266)	(-0.258)	(-0.217)	(-0.226)	(-0.241)	(-0.246)	(-0.245)	(-0.156)	(-0.173)	(-0.261)	(-0.27)	(-0.282)	(-0.246)	(-0.25)	(-0.224)	(-0.25)	(-0.27)
LatinAmerica	-0.162	0.156	0.436	0.158	1.612*	-0.192	0.2	0.388	0.213	1.503*	-0.154	0.258	0.407	0.104	1.506**	-0.177	0.261	0.407	0.087	1.569**	-0.167	0.243	0.39	0.134	1.494*
	(-0.475)	(-0.462)	(-0.62)	(-0.908)	(-0.832)	(-0.392)	(-0.391)	(-0.551)	(-0.873)	(-0.888)	(-0.365)	(-0.384)	(-0.717)	(-0.879)	(-0.735)	(-0.366)	(-0.367)	(-0.498)	(-0.866)	(-0.783)	(-0.317)	(-0.325)	(-0.284)	(-0.792)	(-0.842)
AsiaOceania	0.04	0.01	0.029	0.043	-0.009	0.021	0.066	0.034	0.053	-0.037	0.083	0.063	0.048	0.014	0.118	0.06	0.062	0.048	0.031	0.039	0.051	0.068	0.075	0.043	0.084
	(-0.085)	(-0.098)	(-0.142)	(-0.175)	(-0.173)	(-0.15)	(-0.114)	(-0.124)	(-0.148)	(-0.153)	(-0.095)	(-0.094)	(-0.126)	(-0.104)	(-0.105)	(-0.063)	(-0.101)	(-0.146)	(-0.156)	(-0.14)	(-0.144)	(-0.147)	(-0.15)	(-0.157)	(-0.148)
Europe	0.01	-0.013	0.119	0.032	-0.017	-0.008	-0.012	0.072	0.013	-0.02	0.031	0.007	0.015	-0.023	0.006	0.008	0.003	0.07	-0.012	0.046	0.009	-0.007	0.073	-0.006	0.001
	(-0.088)	(-0.109)	(-0.147)	(-0.141)	(-0.127)	(-0.115)	(-0.103)	(-0.116)	(-0.121)	(-0.128)	(-0.094)	(-0.1)	(-0.125)	(-0.115)	(-0.116)	(-0.055)	(-0.066)	(-0.12)	(-0.117)	(-0.126)	(-0.068)	(-0.107)	(-0.129)	(-0.13)	(-0.135)
Log(mpOwn)	-0.044	0.059	-0.046	0.177	-0.197																				
	(-0.296)	(-0.292)	(-0.463)	(-0.466)	(-0.503)																				
Log(mpSetEnforce)						-0.045	-0.122	0.389	0.239	-0.37															
						(-0.394)	(-0.364)	(-0.419)	(-0.456)	(-0.556)															
Log(mpBudget)											-0.191	-0.177	0.209	-0.152	-0.203										
											(-0.345)	(-0.351)	(-0.424)	(-0.41)	(-0.399)										
Log(mpSetVision)																-0.191	-0.163	0.209	-0.158	-0.255					
																(-0.258)	(-0.28)	(-0.414)	(-0.409)	(-0.387)					
Log(mpAverage)																					-0.127	-0.173	0.571	-0.084	-0.271
																					(-0.467)	(-0.459)	(-0.404)	(-0.463)	(-0.515)
Observations	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Bootstrap	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reps	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1, regressions highlighted (grey) have at least 1 result which is statistically significant.

Table A6: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Reduction2020	32	-0.2185	0.22455	-1	0.22108
Reduction2030	32	-0.4176	0.26942	-1	0.49631
Reduction2040	32	-0.5864	0.32246	-1	0.83357
Reduction2050	32	-0.7192	0.40023	-1	1.24686
Log(Population)	32	14.2678	1.20703	11.6651	16.1562
Log(GdpCap)	32	11.1867	1.15284	8.66389	13.2725
Log(mpOwn)	32	0.84513	0.14813	0.55962	1.0116
Log(mpSetEnforce)	32	0.86954	0.15409	0.53063	1.06471
Log(mpBudget)	32	0.76871	0.14987	0.36772	0.98083
Log(mpSetVision)	32	0.79512	0.15057	0.44183	1.06087
Log(mpAverage)	32	0.82243	0.12869	0.4877	1.01936
Africa	32	0.0625	0.24593	0	1
LatinAmerica	32	0.125	0.33601	0	1
AsiaOceania	32	0.15625	0.3689	0	1
Europe	32	0.3125	0.47093	0	1

CHAPTER VI:

Eliciting preferences for hybrid vehicles in the Metropolitan Area of Barcelona

1. Introduction

According to the IPCC (2014), immediate action is needed to mitigate the climate change crisis and reduce the current emission levels. In the report's estimates, the transport sector is stated to be responsible for 14% of total greenhouse gases emissions worldwide. IPCC also identified a shift in transportation modes to more sustainable ones as key to achieving the desired reduction in emissions, besides technological change. The introduction of electromobility is on the forefront of this change and drives governments to promote adoption of electric (EV) and hybrid vehicles. They do so by providing incentives to potential buyers, such as price subsidies, rebates, tax credits, sales tax exemptions, and subsidized financing. In Europe, many cities have been promoting such policies and managed to improve their car fleet compositions to more environmentally-friendly ones. However, unlike the rest of Europe, the Spanish car fleet market is among the least penetrated by EVs, amounting only to 0-0.3% of the total car fleet (EEA, 2016). In order to analyze this market, we study the stated preferences of potential buyers in the Metropolitan Area of Barcelona concerning car attributes for distinct governmental incentives targeting hybrid and electric vehicle adoption.

Numerous studies have conducted research in this field. Bjerkan et al. (2016), study the importance of different incentives for owners of EVs in Norway. They find that incentives for reducing purchase costs, such as exemptions from purchase tax and VAT, are critical for over 80% of the respondents. Hence, an up-front price reduction is the most powerful incentive in promoting EV adoption. Income is a less prominent predictor, which probably results from the competitive price of EVs in the Norwegian market. DeShazo et al. (2017) compare various types of incentives in order to identify superior policy instruments which are to take into consideration consumers' heterogeneity. All this while ''increas[ing] total of PEVs purchased, [...] decreas[ing] total government costs, and [...] increas[ing] allocative equity''. They propose an updated design on the rebate policy which is currently in place with a progressive rebate schedule. They estimate a cost reduction of government spending of $77 million compared to the current expenses. Similar studies on government incentives were conducted by Langbroek et al. (2016), Mersky et al. (2016), Lévay et al. (2017), Sierzchula et al. (2014), Skerlos and Winebrake (2010), Tanaka et al. (2014), Wang et al. (2017), Zhang et al. (2016), Zhou et al. (2014). Moreover, studies such as Plötz et al, (2014), Vassileva and Campillo (2016), and Musti and Kockelman (2011) intent to identify potential EV buyers based on the current gasoline and EV car owners' profiles. Another study by Jenn et al. (2013) assess the impact of the Energy Policy Act of 2005 on the adoption of hybrid electric vehicles in the US. Their database runs from 2000 and 2010 and accounts for network externalities by including additional macroeconomics variables. They find The Act increased sales of hybrids from 3% to 20%, depending on the vehicle model. However, the incentives were found effective only when amount provided was large enough. Diamond (2009) analyzes a registration data of hybrid vehicles in the US, finding a strong relationship between gasoline prices and hybrid adoption, but a much weaker link between incentives and hybrid adoption. He concludes that payments up front seem be the most effective type of incentive, which is consistent with the literature. Javid and Nejat (2017) study the market penetration and adoption of plug-in electric vehicles (PEVs) in California. The authors draw data on PEV and conventional car buyers' information from 2012 California Household Travel Survey. The model of their choice was multiple logistic regression analysis, including demographic and travel-related characteristics, socioeconomic variables, and infrastructural and regional specifications. They concluded that household income, maximum level of education in the household, the buyer's car sharing status, density of charging stations, and gas price in the region were all found significant when it came to PEV adoption. On the contrary, personal characteristics, such as age, gender, and employment were found to be insignificant and the same held for trip duration.

Another line of literature research is about adaptation of EVs and hybrids studies consumer's range preferences. For instance, Franke and Krems (2013) estimate range preferences of EV users which have been using EVs for three months and how experience with EVs shaped their preferences toward them. The results show that range preferences are substantially higher than average daily range needs. Yet range preferences are not much higher than weekly maximum range needs. Authors attribute this discrepancy to lack of experience with EVs. Also, the higher the initial range preferences, the higher the EV range anxiety experienced by the consumer. In another study by Dianzano (2013), author studies the EV market in California by assessing consumers' concern about their limited driving range as it represents a serious barrier to adoption of EVs. Their case study is from consumers in California. They found a nonlinear valuation of driving range with an estimated willingness to pay (WTP) between 141$ at 75 miles and 107$ at 100 miles, which is much higher than in other studies. Hidrue et al. (2011) analyze stated preference for EVs based on a survey of 3029 respondents, where participants had to choose among a gasoline vehicle and two electric vehicle alternatives of that vehicle. Using latent class random utility model, they estimate the WTP for various vehicle attributes, including driving range, charging time, fuel cost saving, pollution reduction, and performance. Individuals were WTP from $35-$75/mile of added driving range, $425-$3250 per hour reduction in charging time. They suggest that battery cost must decrease significantly for EVs to enjoy mass market saturation without the help of a governmental subsidy. A study by Hoen and Koetse (2014) analyzes the stated choice experiment on preferences of Dutch private car owners for alternative fuel vehicles (AFVs, e.g. electric, plug-in, hybrid and flexi fuel) and their attributes using mixed logit model. Compared to previous studies, they made a wider range of vehicle attributes, including car type, purchase price, monthly costs, recharge/refuel time, number of available models, and policy measure. A distinction between second-hand and new car owner was included. Hoen and Koetse (2014) focused only on models currently available on the market. They found preferences for AFVs to be substantially lower than those for the conventional technology due to limited driving range, long refueling times and limited availability of refueling opportunities. According to their results, second-hand car buyers displayed double the price sensitivity of new car buyers. Furthermore, due to high heterogeneity found in this study, Hoen and Koetse (2014) suggest target-specific policies to boost the AFV adoption in the Netherlands. Jensen et al. (2013) study how the range preferences of EV change after 3 months of use. They contrast the data from prior to the EV use and after the fact. Authors find that individual preferences change significantly after the experience. They find that the preferences for attributes such as driving range, top speed, fuel cost do not change after the use. Hence, consumers worry about driving range prior to having had an experience with EVs, which fades. Their concern is caused by the mismatch between the range consumers think they need and their actual daily needs.

Another line of research explores if and which social aspects affect vehicle preferences. Kim et al, (2014) include attitudes about environmental concerns, technology acceptance and public perception of the EVs as a part of the potential buyer's utility function. Although they agree that the utility function remains impacted mostly by the associated costs, they find that the intention to purchase an EV is to some extent influenced by social aspects. In another study Krause et al, (2013) also emphasize the impact of the discrepancy between available incentives in place to promote PEVs and the public knowledge of their existence and their impact on purchasing PEVs. They found that 2/3 of all correspondents failed to answer correctly some of the basic facts about PEVs and their advantages.

2. Stylized facts about the database

2.1 Background

The database is constructed from a survey implemented in the Metropolitan Area of Barcelona. The questionnaire was created by the Turkish team of researchers which form part of the BREATHE project – Emine Zeren and Eren Inici from Sabanci University, Istanbul – with the purpose to be applied in other cities that were part of the project. It was later translated and adapted to the specificities of Barcelona. This included making some simplifications in the questionnaire. The contribution of this study is the construction of an original database from the raw survey data as well as its analysis and interpretation. Also, this analysis is original for the region selected. Moreover, the Turkish team has yet to complete their analysis and paper based on their questionnaire. Hence, all the analysis and empirical strategy done in this paper was ours. Furthermore, the conjoint section is in our study a choice-based conjoint (CBC) rather than adaptive choice-based conjoint (ACBC) as was done in Turkey. This was done with the intention to avoid a massive loss of observations and due to financial constraints. The difference between the two is that ACBC can estimate utilities regardless of price. However, as the literature identified price to be the key determinant of purchase, we found CBC more suitable in this case. Moreover, a loss of observations occurs when using ACBC because the model reduces the options in the future choice sets, based on selection options which are of no interest to the customer. The objective of the questionnaire was to assess consumer or household behaviour regarding purchase of a new transport vehicle. More specifically, we want to estimate the probability that a prospective buyer purchases an electric, hybrid or a conventional engine car (gasoline or diesel) and which car attributes and governmental incentives drive this selection. We include this under the hypothesis that different types of incentives and their effectiveness in persuading buyers to choose one type of vehicle over another. In this paper we will focus on the conjoint section of the questionnaire.

The questionnaire's implementation covered a geographical area determined by the project's needs and specificities. This included municipalities from the Metropolitan Area of Barcelona, as already discussed in Chapter 3. The questionnaire was presented to the participant in an online interactive format, implemented by a private company (Netquest a.s), which posseses a database of potential participants. The sample size is 500, which includes participants who passed the screening process and answered the survey in its entirety. The survey took the participants approximately 20-24 minutes to complete. The questionnaire included both multiple choice questions and rating scale type of answers. A couple of screening questions were included in the beginning, such as ¨Do you own a driver's licence?¨, ¨Are you the primary decision maker of your household?¨ and ¨Have you bought a car in the past two years or do you have an intention of purchasing one in the near future?¨. After participants passed these screening questions, data concerning their occupation, residence and driving habits and patterns were collected.

Table 1 represents the target distribution of population composition and number of residents in each of the municipalities in the selected region. This distribution was constructed prior to the field implementation in order to obtain a representative sample. Hence, quotas were set on the number of participants allowed from each target group. The full questionnaire, finalized on 17/09/2019, is found in its original version (Spanish) in Appendix A.

Table 1: *Target distribution of participants in the survey*

Target	18-64 years from the indicated municipalities	
Total	500	
Age	***Target***	***%***
18-24	68	14%
25-34	87	17%
35-44	129	26%
45-54	118	24%
55-64	98	20%
Gender	***Target***	***%***
Male	244	49%
Female	256	51%
Municipality	***Target***	***%***
Badalona	31	6%
Barcelona	338	68%
Castelldefels	9	2%
Cornellà de Llobregat	12	2%
Esplugues de Llobregat	6	1%
Gavà	6	1%
Hospitalet de Llobregat	35	7%
Montcada i Reixac	5	1%
Montgat	2	0%
El Prat de Llobregat	8	2%
Sant Adrià de Besós	5	1%
Sant Boi de Llobregat	11	2%
Sant Feliu de Llobregat	6	1%
Sant Joan de Despí	5	1%
Sant Just Desvern	2	0%
Santa Coloma de Gramenet	11	2%
Tiana	1	0%
Viladecans	7	2%

In Figure 1 we show the gender participation and age distribution of the survey. We observe balanced gender participation, with 51% being females and 49% males. We find the highest age group of participants lies in the 35-44 age range (28%) followed by groups of 45-54 (25.8%) and 25-34-year-olds (20%). The smallest groups represented were the youngest (18-24) and eldest (55-64).

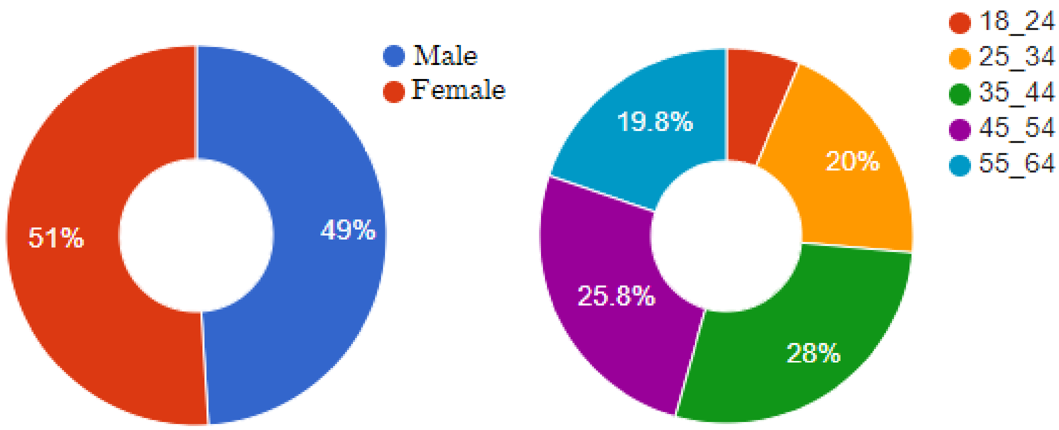

Figure 1: *Gender of participants (left) and age of the survey participants (right)*

Table 2 show that our sample is representative. To test this, we contrasted the Census 2011 data with our survey. It is important to keep in mind that our survey included only individuals above 18 years old, causing skewness in distribution and consequential comparison of the population distribution found in Census 2011 data. However, since we examine car purchase it makes sense to include only adults.

Table 2: *Census data comparison by municipality population*

Population distribution by municipality	***Census (INE, 2011)***	***Survey***
Badalona	7.73%	6.40%
Barcelona	56.78%	67.20%
Castelldefels	2.18%	1.80%
Cornellà de Llobregat	3.05%	2.40%
Esplugues de Llobregat	1.63%	1.20%
Gavà	1.63%	1.20%
Hospitalet de Llobregat (L')	9.04%	7%
Montcada i Reixac	1.22%	1%
Montgat	0.38%	0.40%
Prat de Llobregat (El)	2.22%	1.60%
Sant Adrià de Besós	1.21%	1%
Sant Boi de Llobregat	2.91%	2.20%
Sant Feliu de Llobregat	1.53%	1.20%
Sant Joan Despí	1.15%	1%
Sant Just Desvern	0.55%	0.40%
Santa Coloma de Gramenet	4.21%	2.40%
Tiana	0.29%	0.20%
Viladecans	2.29%	1.40%

2.2 Conjoint section

The database used in this chapter is based on the conjoint section of the survey. It consists of 18 choice sets, each containing 3 alternatives each. We have categorized these choice sets based on variation of vehicle model (conventional, hybrid and EV) into three categories: heterogeneous, dichotomous and homogeneous. In this study we will focus on the homogeneous and heterogeneous choice sets. Homogeneous choice set consisting of 4 choice sets whereas heterogeneous of 3. We motivate this study of homogeneous choice set by analyzing the probability of choosing a hybrid car from a heterogeneous choice set. An illustration of this is represented in Figure 2.

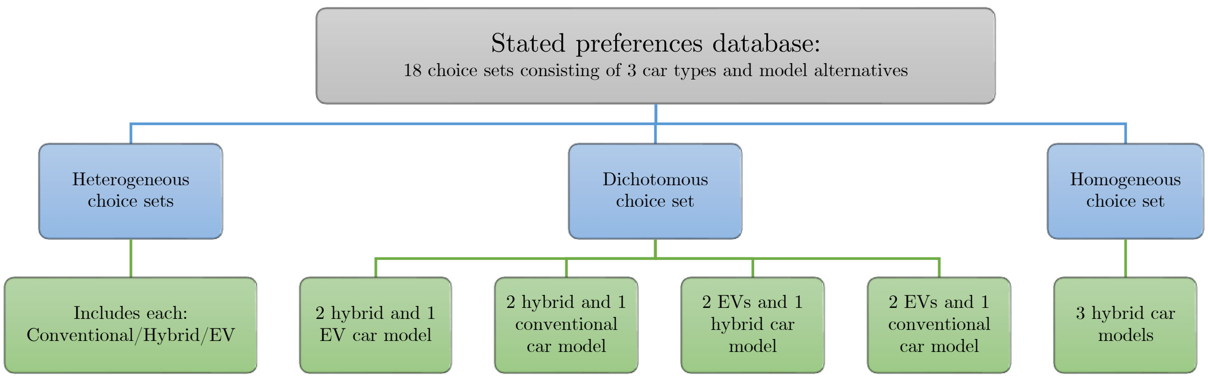

Figure 2: *Stated preferences database decomposition*

In Table 3 we have further categorized the various groups of alternatives in all 18 choice sets in order as presented to the candidates. Further, we have broken down into similar groups of the dichotomous-type of choice set. As we may observe, blue color symbolizes the heterogenious choice sets, the red the homogeneous and white characterizes the dichomous choice set. Table 7 describes the distinct car attributes considered, divided by car type.

Table 3: *Complete list of choice sets organized by types of vehicles described*

Alternatives	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***
Conventional	500	500	0	500	0	0	0	0	0	0	500	500	500	500	0	500	500	0
Electric	500	500	500	1,000	500	1,000	500	1,000	0	0	1,000	0	0	1,000	0	1,000	1,000	0
Hybrid	500	500	1,000	0	1,000	500	1,000	500	1,500	1,500	0	1,000	1,000	0	1,500	0	0	1,500

After analyzing the homogeneous choice sets we study which car attributes matters most forpotential hybrid-vehicle buyers in the Catalonian vehicle market. Furthermore, control for participants' attributes such as age, highest educational level achieved, family status, commuting distances and times. In Figure 3 depicts an example of a homogeneous choice set as displayed to the correspondents.

Alternative	1	2	3
Car type	Hybrid	Hybrid	Hybrid
Range	1600 km	1000 km	1300 km
Price	16 670 €	16 670 €	43 330 €
Emission reduction	60% less	80% less	80% less
Fuel cost reduction	60% less	30% less	30% less
Refuel time	5 minutes	5 minutes	3 minutes
Incentives	Use the paid tunnels free of	Use the paid tunnels free of	Use the paid tunnels free of

I am interested	O	O	O
I am not interested	O	O	O

Figure 3: *A sample of one of the choice sets used in our survey*

Furthermore, as part of the questionnaire, rating type of questions were included. This allows us to assess personal attitudes toward electric vehicles, environment, and emissions produced by cars as perceived by consumers. This is depicted in Figure 4.

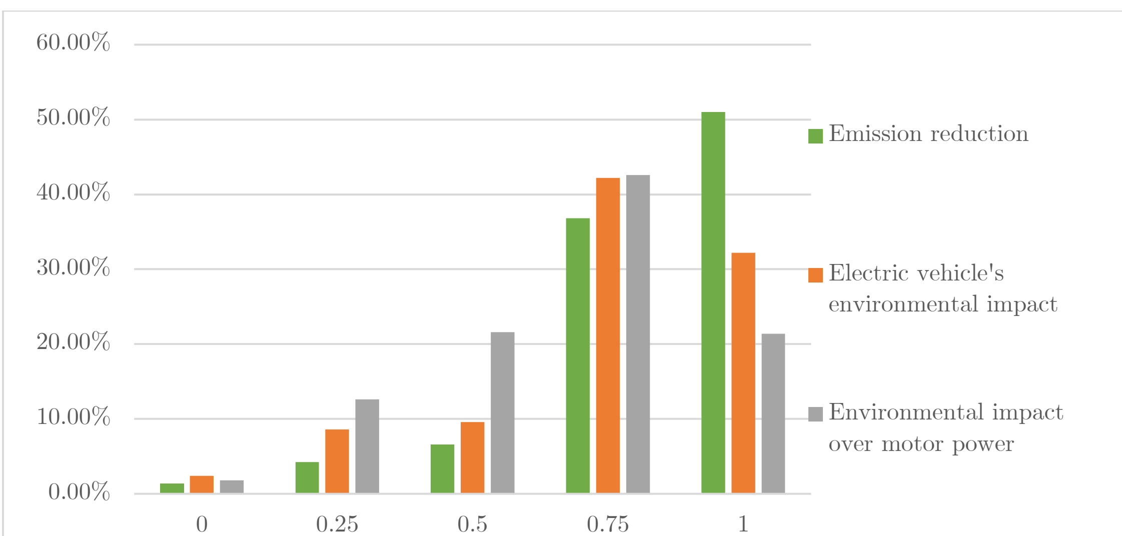

Figure 4: *Discrepancies among attitudes to environmental impacts*

In Figure 5 we display overall car preferences of the participants based on the information provided to them, without accounting for frequency of occurrence (this is found in Appendix A, under variable P24)[7]. Participants have chosen hybrid vehicle as the most attractive type of car, follows by conventional and electric cars.

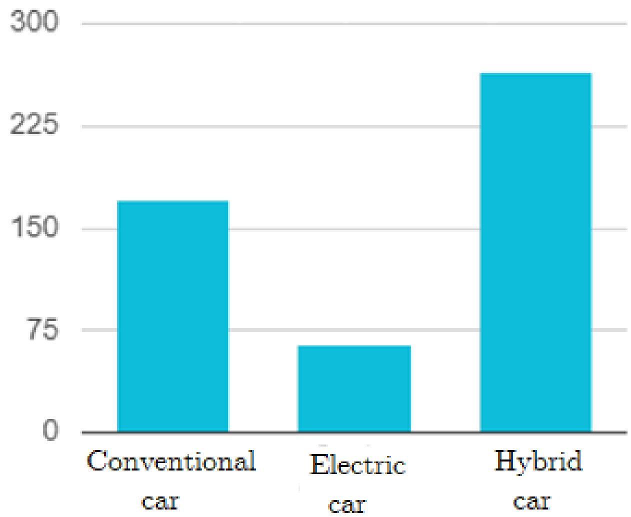

Figure 5: *Average car preferences*

3. Motivation

In this section we analyze the heterogeneous choice sets of the conjoint section. We use this as a basis of further analysis of the homogeneous dataset of hybrid car attributes found in the second part of this chapter. Here we analyze the impact of price and range on consumer preferences in the Metropolitan Area of Barcelona. This section of the questionnaire was characterized by the respective choice sets consisting of three car types- conventional. (gasoline), hybrid and electric vehicle models, from which correspondents had to choose one as their preferred choice. Table 4 contains the price and range characteristics of the cars presented in the heterogeneous choice sets.

Table 4: *Descriptive statistics of car attributes in the respective choice set*

	Hybrid		Electric		Conventional	
Attribute	Mean		Std.Dev		Mean	
Range	1390.00	316.61	331.33	130.60	1011.11	266.67
Price	27989.00	10674.33	32000.67	10803.82	23537.78	10415.38

Furthermore, Table 5 depicts the personal characteristics used as control variables in our regressions, including age, family size and salary.

[7] The complete list of the variables analyzed is displayed in Appendix B.

Table 5: *Personal characteristics of participants*		
Variable		Frequency
Age		
	18-24	6.4%
	25-44	48.0%
	44-64	45.6%
Family size		
	1	4.8%
	2	28.6%
	3	37.4%
	4	23.8%
	5	4.8%
	6	0.4%
	7	0.2%
Salary		
	250	0.0%
	750	0.4%
	1250	3.3%
	1750	8.6%
	2500	28.6%
	4000	43.1%
	5000	16.0%

In our regression we estimate the likelihood of making a choice made among the three alternatives – conventional, electric and hybrid cars, while controlling for correspondents' personal characteristics. These characteristics include salary, family size and age of the correspondent. We include two alternative-specific variables – price and range. In our regressions we use the mixed logit choice model. It is most frequently used and it serves to model the probability of an individual choosing one of several unordered alternatives (McFadden and Train 2000). We explore the choice of vehicles by implementing equation (1).

$$\pi_{ij}^{p} = \frac{\exp[\eta_{ij}^{\mathrm{p}}]}{\sum_{k=1}^{J} \exp[\eta_{ik}^{\mathrm{p}}]} \text{ where } j = 1, \dots J \tag{1}$$

where π_{ij}^{p} is the probability that a participant p choses a vehicle i from the choice set j with utility η_{ij}^{p}.

Table 6 depicts the regression results using mixed logit model for panel data. The conventional car is used as the baseline alternative.

Table 6: Likelihood of choosing between conventional, hybrid and electric vehicles.
Baseline: Conventional car

	Likelihood of the choice	Electric car alternative	Hybrid alternative
Case-specific variables			
Salary		0.00003219	0.00009183
		-0.0001044	-0.00009534
Family size		-0.15400909	-0.18039017*
		-0.1164844	-0.10630681
Age		-0.02847802***	-0.01580025*
		-0.01025687	-0.00937966
Alternative-specific variables			
Price	-0.00005231***		
	-0.00000897		
Range	-0.00063635		
	-0.00049904		
Observations	2,448	2,448	2,448

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

In our estimates from Table 6, we find that the price of a car has a negative impact which impacts the dependent variable by 0.00005231 and is significant at 1% significance level, when choosing an alternative. We also find that the range of a vehicle, although bearing a negative sign, is not significant at any level. Age is significant at 1% and 10% significance levels for electric vehicle and hybrid car respectively, while bearing a negative sign. Hence, as the age of the correspondent increases, he is less likely to purchase a conventional car. This may be due to a variety of reasons, such as the elderly prefer the conventional car because of higher levels of aversion to new technology. The same applies to family size in the case of a hybrid car: with an increase in family size, the likelihood of purchasing a conventional vehicle in comparison to a hybrid vehicle decreases by 0.18039017 at 10% significance level.

We estimated the marginal effects of a case-specific variables for choosing the alternative over the baseline. In Table 7 we present the marginal effects of salary set at 500 (minimum asked in our questionnaire) and 8000€. Figure 6 is the graphical representation of these results. One may observe that electric and conventional vehicles show the same trend for income increases. A conventional vehicle is estimated to have the likelihood of 15% of being chosen at income of 500€, whereas electric vehicle has a 28% probability of being chosen. We find that a hybrid car has the probability of 56% of being chosen for the same income level, which is double the level of an electric and triple the levels of a conventional vehicle. At income level of 8000€, correspondents have the likelihood of 67% of choosing a hybrid vehicle over the other two options. We may interpret this as a result of low risk fuel infrastructure associated with the hybrid car, combining elements of both electric and conventional vehicles.

Table 7: Marginal effects for income levels set at 500 and 8000 €

	Margin	Delta-method SE	95% Conf. Interval	
Conventional#1	0.1563047***	0.0320416	0.0935044	0.219105
Conventional#2	0.0983641***	0.041132	0.0177468	0.1789814
Electric#1	0.2829829***	0.0367544	0.2109456	0.3550202
Electric#2	0.2290644***	0.061835	0.1078699	0.3502588
Hybrid#1	0.5607124***	0.0399241	0.4824626	0.6389622
Hybrid#2	0.6725715***	0.0686497	0.5380205	0.8071225

Note: Number #1 and #2 denote scenarios at income of 500€ and 8000 € respectively

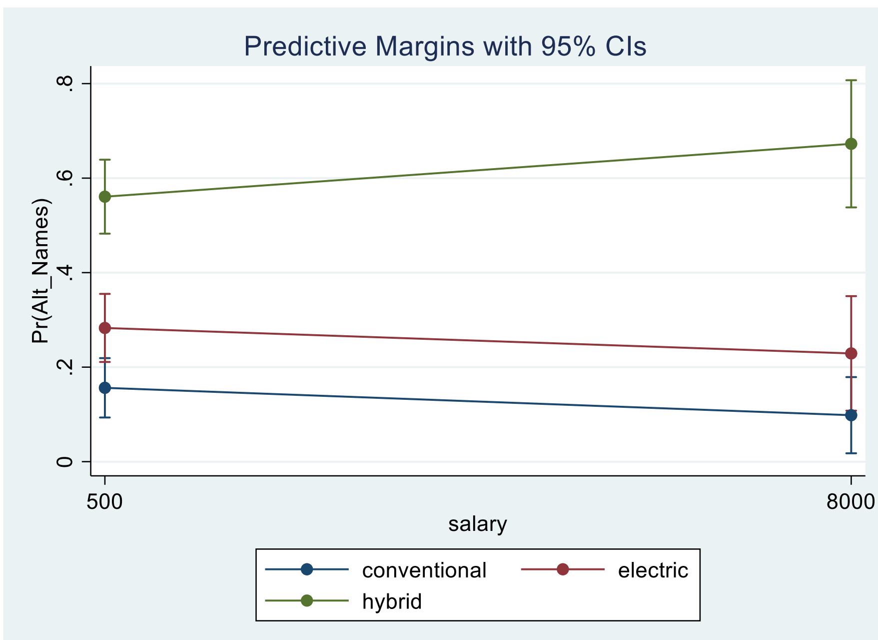

Figure 6: Marginal effects of income (set at 500€ and 800€) on probabilities of choosing conventional, electric or hybrid vehicle

We have also estimated the impact of age on the chosen alternative by setting the age of all correspondents to 20 and 80. In Table 8 we only include these two extreme values, although, Figure 7 we provide a more detailed plot with age increasing by 10 year increments and we highlight the 67 year mark, as this entails an equivalence cross of the probabilities of choosing an electric and conventional car. In Table 8 we may observe that people are only 8% likely to purchase an electric car at the age of 20 in comparison to 23% at the age of 80. Moreover, people have a decreasing tendency of purchasing an electric vehicle with increasing age of a total difference of 17% from the age of 20 to 80. We may also observe that the likelihood of purchasing a hybrid car, while being way above the other two alternatives, remains stable over time, with a minor increase of 2% from the initial 57%.

Table 8: Marginal effects with predictive values at ages of 20 and 80

	Margin	Delta-method SE	95% Confidence Interval	
Conventional#1	0.0881637***	0.0194868	0.0499702	0.12636
Conventional#2	0.2387077***	0.0593415	0.1224004	0.35501
Electric#1	0.3331907***	0.0354577	0.263695	0.40269
Electric#2	0.1653233***	0.037771	0.0912936	0.23935
Hybrid#1	0.5786456***	0.0359088	0.5082657	0.64903
Hybrid#2	0.595969***	0.0585326	0.4812473	0.71069

Note: Number #1 and #2 denote scenarios at age of 20 and 80 years respecively

Next, Table 6 shows that the impact of age on the choice of an EV is negative, hence it is no surprise that marginal predictions in Figure 7 depict just that. The older generations might not be as trusting in new technology cars, and this might explain that preferences lean toward conventional vehicle after the age of 67. Yet, a hybrid vehicle experiences a stable, long-term trend, which can be explained by the fact that it does provide the benefits of an electric car, but with a backup plan in terms of re-fuel.

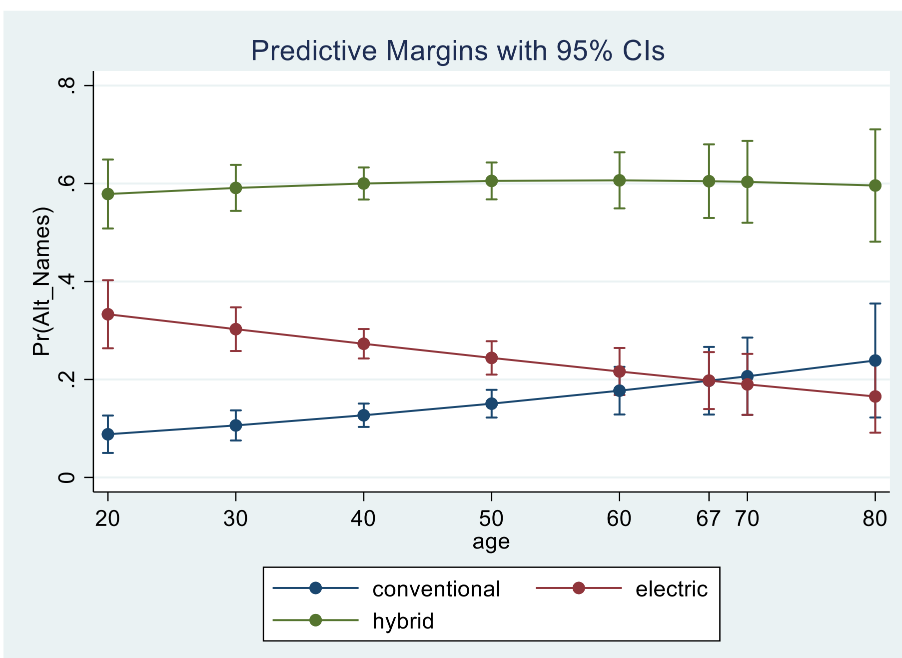

Figure 7: Marginal effects of choosing a conventional, electric or hybrid vehicle at ages 20, 30, 40, 50, 60, 67, 70 and 80.

4. Regression analysis

Descriptive statistics for homogeneous hybrid choice sets

In our analysis of hybrid vehicles we include variables than we did when analyzing the heterogeneous set. For this reason, we provide an overview of the additional variables in Table 9. It summarizes the options presented with associated frequency derived from option's occurrence in the database. We have organized the included both explanatory and control variables into four categories: car attributes, personal characteristics, opinions about climate change and correspondents' travel patterns. Variables in 'opinions about climate change' category include values on scale 0-1 for each of the 3 variables.

Table 9: *Frequency of options within included variables*

Variable		Frequency	Variable		Frequency
Car attributes			*Personal characteristics*		
Range			Gender		
	1000	32.10%		Male	49.00%
	1300	25.00%		Female	51.00%
	1600	30.80%	Age		
	1900	12.20%		18-24	6.40%
Price				25-44	48.00%
	16670	19.20%		44-64	45.60%
	23330	13.50%	Education		
	30000	17.30%		Primary	5.20%
	43330	50.00%		High	29.80%
Reduction Emissions				Bachelor	43.40%
	-50%	18.80%		Master	18.20%
	-60%	15.00%		PhD	3.40%
	-70%	26.30%	Salary		
	-80%	40.00%		250	0.00%
Reduction Fuel Cost				750	0.40%
	-30%	42.00%		1250	3.30%
	-50%	10.00%		1750	8.60%
	-60%	48.00%		2500	28.60%
Refuel Time (min)				4000	43.10%
	3	54.50%		5000	16.00%
	5	45.50%	Number of kids		
Incentives				1	38.20%
	Free tunnels	41.70%		2	30.20%
	Toll-free	8.30%		3	26%
	Free parking	33.30%		4	4.80%
	None	16.70%		5	0.40%
			Env. impact over motor power		
				0	1.80%
				0.25	12.60%
				0.5	21.60%
				0.75	42.60%
				1	21.40%

Empirical strategy for econometric estimation

Following the latest literature (Hoen and Koetse, 2014), we use a mixed logit model for panel data to estimate our results. With our estimates we wish to find out which car attribute is the most relevant when it comes to choosing a hybrid vehicle. Also, we account for incentives in order to find which is the most effective among them. Do preferences change with age, gender or education levels. In order to explore these questions, we implement equation (1) with i representing hybrid vehicle option 1, 2 and 3. Car attributes in our estimates are represented by range, price, emission reduction, reduction in cost of fuel, refill time[8]. Wefurther include three incentive scenarios, namely 1) free access to paid tunnels, 2) free toll, and 3) free parking and the no incentive scenario. The regression

$$\begin{aligned} log(choice)_{ij} = \beta_0 + \beta_1 Range_{ij} + \beta_2 Price_{ij} + \beta_3 EmissionReduction_{ij} \\ + \beta_4 FuelCostReduction_{ij} + \beta_5 RefuelTime_{ij} + \beta_6 Incentive_{ij} + \beta_6 X_{ij} \\ + \varepsilon_{ij} \end{aligned} \quad (2)$$

specification used to arrive at estimates is found in equation (2).
Here i represents the car choice, j the choice set, X the personal characteristics, and ε_{ij} the composite error term.

5. *Results*

5.1 Overall

We have summarized the results from four sets of regressions with the distinct incentives types, resulting in four regressions. These are depicted in Table 10. The structure of Table 10 entails two sets of variables: alternative and case-specific. Case-specific variables depict the participants' characteristics (e.g. income) and are invariant throughout alternatives. Alternative-specific variables (e.g. price) change from one alternative to another. The coefficients for the alternative-specific attributes demonstrate how each of the attributes impacts participants choice of an alternative, while personal characteristics' coefficients depict how personal characteristics steer participants toward choosing a non-baseline alternative. We find that price bears a negative sign is all regressions and is significant at 1% regressions (I), (II) and (IV) and 5% in (III). Range is found to positively affect a vehicle choice with a coefficient of approximately 0.00172 in all regressions and levels of significance of 1% (I, II, IV) and 10% (III). Emission reduction was also found significant with a positive sign at 1% (I, III) and 10% (IV). In our estimates, no significant results were found for refuel time or any of the listed incentives. Moreover, incentives with free tunnel access bears a negative sign. In terms of personal attributes and their impact on choosing an alternative, age was found to be affecting positively the choice of alternative 3 across all regressions at a 10% significance level. Moreover, we found having a PhD to

[8] Extra detour time was excluded as all vehicles in this section had no additional time assigned.

Table 10: Choice probability based on car attributes while controlling for corespondents' personal characteristics. Baseline is set to vehicle alternative number 1

	(I) Free access to tunnels			***(II) Toll-free highways***			***(III) Free parking***			***(IV) No Incentives***		
Hybrid	1	2	3	1	2	3	1	2	3	1	2	3
Salary		-0.000017	-0.000019		-0.000017	-0.000019		-0.000017	-0.000019		-0.000017	-0.000019
		(-0.000063)	(-0.000066)		(-0.000063)	(-0.000066)		(-0.000063)	(-0.000066)		(-0.000063)	(-0.000066)
Male		-0.087814	-0.077534		-0.087814	-0.077534		-0.087814	-0.077534		-0.087814	-0.077534
		(-0.146135)	(-0.154435)		(-0.146135)	(-0.154435)		(-0.146135)	(-0.154435)		(-0.146135)	(-0.154435)
Age		0.005762	0.013706*		0.005762	0.013706*		0.005762	0.013706*		0.005762	0.013706*
		(-0.007078)	(-0.007459)		(-0.007078)	(-0.007459)		(-0.007078)	(-0.007459)		(-0.007078)	(-0.007459)
Number of kids		-0.024893	0.008793		-0.024893	0.008793		-0.024893	0.008793		-0.024893	0.008793
		(-0.082581)	(-0.08625)		(-0.082581)	(-0.08625)		(-0.082581)	(-0.08625)		(-0.082581)	(-0.08625)
Env. evaluation		0.291114	0.320683		0.291114	0.320683		0.291114	0.320683		0.291114	0.320683
		(-0.272714)	(-0.287052)		(-0.272714)	(-0.287052)		(-0.272714)	(-0.287052)		(-0.272714)	(-0.287052)
High School		0.056168	-0.012374		0.056168	-0.012374		0.056168	-0.012374		0.056168	-0.012374
		(-0.340855)	(-0.349836)		(-0.340855)	(-0.349836)		(-0.340855)	(-0.349836)		(-0.340855)	(-0.349836)
Bachelor		0.277393	0.124126		0.277393	0.124126		0.277393	0.124126		0.277393	0.124126
		(-0.340218)	(-0.350139)		(-0.340218)	(-0.350139)		(-0.340218)	(-0.350139)		(-0.340218)	(-0.350139)
Master		0.415261	0.526347		0.415261	0.526347		0.415261	0.526347		0.415261	0.526347
		(-0.366968)	(-0.37769)		(-0.366968)	(-0.37769)		(-0.366968)	(-0.37769)		(-0.366968)	(-0.37769)
PhD		0.885970*	0.742568		0.885970*	0.742568		0.885970*	0.742568		0.885970*	0.742568
		(-0.525277)	(-0.558189)		(-0.525277)	(-0.558189)		(-0.525277)	(-0.558189)		(-0.525277)	(-0.558189)
Range	0.001722***			0.001718***			0.001742*			0.001720***		
	(-0.000308)			(-0.000302)			(-0.00104)			(-0.000294)		
Price	-0.000061***			-0.000061***			-0.000060**			-0.000061***		
	(-0.000012)			(-0.000013)			(-0.000024)			(-0.000017)		
Emission reduction	0.022017***			0.021755			0.022093***			0.022267*		
	(-0.007021)			(-0.013326)			(-0.007778)			(-0.01299)		
Fuel cost reduction	0.018460**			0.018366*			0.018096			0.018654*		
	(-0.008287)			(-0.010017)			(-0.019423)			(-0.010413)		
Refuel time	0.185223			0.185067			0.211932			0.178279		
	(-0.257174)			(-0.256238)			(-1.225308)			(-0.365672)		
Incentive: tunnels	-0.003795											
	(-0.164799)											
Incentive: toll				0.008450								
				(0.366955)								
Incentive: parking							0.032779					
							(1.423563)					
Incentives: none										0.008721		
										(-0.378729)		
Observations	4,896	4,896	4,896	4,896	4,896	4,896	4,896	4,896	4,896	4,896	4,896	4,896

Note: Standard errors reported in brackets. Significance levels represented in the following manner: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

be positively affecting the probability of choosing the second alternative. It is statistically significant at 10% with an average impact of 0.88 across all regressions and with no level of significance and impact of 0.7 for choosing the third alternative.

5.2 Marginal effects

To further analyze the impact of salary on the vehicle choice, we set salaries of all participants to be 500€, 2000€, 5000€ and 800€. We found that the choices converge with the increase of income, which is to be expected given the fact that consumer's utility and WTP is closely tied to his/her income. Once income constrained is removed, other factors become important to the consumer. Hence, we have estimated the marginal effects of income on the choice of the vehicle among the three hybrid car alternatives. These effects are depicted in Figure 8.

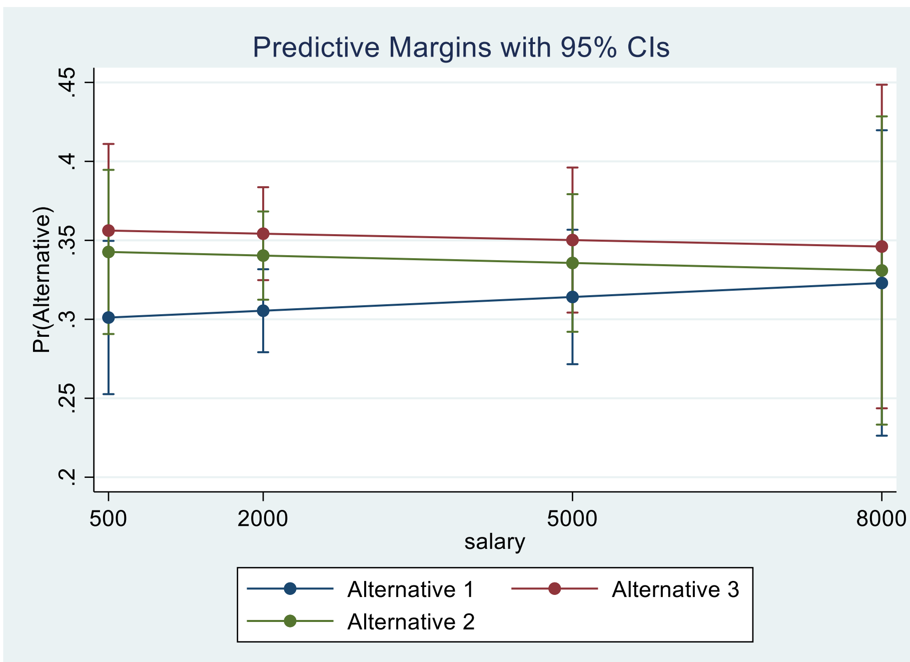

Figure 8: Marginal effects of salary on car choice

As we can see in Figure 8, the third alternative enjoys a positive slope when it comes to income with respect to the other two alternatives. Contrary, with the increase of personal evaluation of environmental impacts (in contrast to motor's potency), we find that the probability of choosing alternatives 1 and 2 increases and 3 decreases. This is displayed in Figure 9.

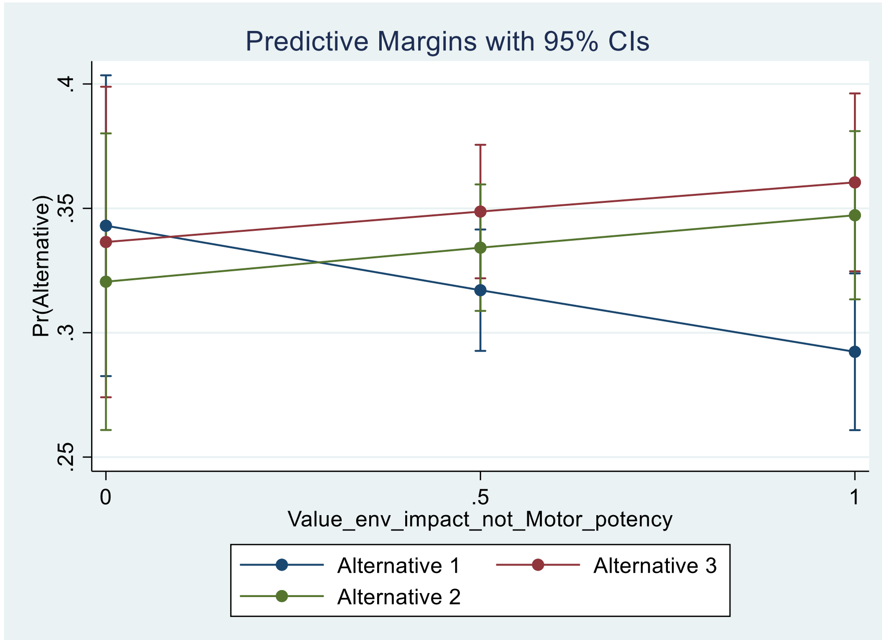

Figure 9: Marginal effects of environmental impact evaluation on car choice

5.3 Willingness to pay

From our regressions we can calculate the willingness-to-pay (WTP) of the potential consumers. The WTP was calculated for improvements of individual car attributes. WTP is the marginal rate of substitution between car attribute improvements and purchase price. We have estimated this for all the respective regressions (I) through (IV). The attributes estimated are car range, emission reduction, fuel cost reduction and fuel time. We have used the equations 3-6 to make our estimates.

$$WTP_{range} = \frac{d\ Range}{-d\ Price} = \frac{\beta_1}{-\beta_2} \tag{3}$$

$$WTP_{EmissionReduction} = \frac{d\ EmissionReduction}{-\ d\ Price} = \frac{\beta_3}{-\beta_2} \tag{4}$$

$$WTP_{FuelCostReduction} = \frac{d\ FuelCostReduction}{-\ d\ Price} = \frac{\beta_4}{-\beta_2} \tag{5}$$

$$WTP_{FuelTime} = \frac{d\ FuelTime}{-\ d\ Price} = \frac{\beta_5}{-\beta_2} \tag{6}$$

Based on the formulas depicted above, the results of our calculations of WTP for car attributes are displayed in Table 11. We find that due to regression results being consistent among each other, the estimated WTP are also coherent. We find that the average WTP for an additional kilometer of driving range is 22.49 €, whereas the WTP for an additional 1% emission reduction is about 363.87€. Furthermore, the fuel cost reduction is found to have consumers willing to pay 303.76€ per additional 1% reduction. The most valued feature in monetary terms, out of the four presented, was fuel time. The consumers' estimated WTP for a fuel time reduction of a minute was on average valued to be 3140,87€. Our findings were consistent with the findings in the related literature (e.g. DeShazo et al., 2017).

Table 11: Willingness to pay (€) for an additional unit of car attributes, tested against incentives introduced

	Incentives				Overall
Attributes	Tunnels	Toll	Parking	None	Average
Range	28.39	28.38	28.96	28.25	28.49
Emission Reduction	363.09	359.50	367.24	365.68	363.87
Fuel Cost Reduction	304.43	303.49	300.795	306.34	303.76
Fuel Time	3054.60	3058.24	3522.84	2927.81	3140.87

6. Conclusions

In this chapter we have analysed the data obtained through a survey implemented in the Metropolitan Area of Barcelona about consumer car preferences. We have created a database based on its conjoint section. This was analysed using multinomial logit regression. The results indicate that the most important attributes for choosing among conventional, hybrid and electric vehicles are price and range. Furthermore, when it comes to choosing among hybrid vehicles, the aspects found to be significant were range, price, emission reduction and fuel cost. On the other hand, fuel time was not found to be significant for any of our regressions. We found that the willingness to pay for additional kilometre of driving is about 28€, 363€ for additional 1% emission reduction and 303€ for additional fuel cost reduction. Although statistically insignificant, the highest willingness to pay was for fuel time reduction, estimated at 3140€ per additional minute. These results are consistent with estimates provided by the literature. We also estimated that the presence of incentives such as free parking, toll-free highways or free tunnels access, does not affect consumer's choice of vehicle.

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Appendix A. Questionnaire about electric vehicles implemented in the Barcelona Metropolitan Area

Preferencias sobre coches eléctricos

1. ¿Eres…?

- Hombre
- Mujer

2. ¿Cuántos años tienes?

_____________ *Respuesta abierta*

P_Generacion ¿En qué año naciste? * *Respuesta simple*

- Antes de 2000 -> Si edad >19
- En 2000 o después -> Si edad <=19 *After the last question in this section, stop filling out this form.*

(SI P_Generacion = 2, MOSTRAR P3, P4, P5, P6 Y P7 DESPUÉS FILTER OUT)

3. ¿En qué municipio vives? * *Respuesta simple*

- Badalona
- Barcelona
- Castelldefels
- Cornellà de Llobregat
- Esplugues de Llobregat
- Gavà
- Hospitalet de Llobregat (L')
- Montcada i Reixac
- Montgat
- Prat de Llobregat (El)
- Sant Adrià de Besós
- Sant Boi de Llobregat
- Sant Feliu de Llobregat
- Sant Joan Despí
- Sant Just Desvern
- Santa Coloma de Gramenet
- Tiana
- Viladecans
- 96. Otro: **- FILTER OUT** ____________

49. ¿En qué municipio trabajas? * *Respuesta simple*

- Badalona
- Barcelona
- Castelldefels
- Cornellà de Llobregat
- Esplugues de Llobregat
- Gavà
- Hospitalet de Llobregat (L')
- Montcada i Reixac
- Montgat
- Prat de Llobregat (El)
- Sant Adrià de Besós
- Sant Boi de Llobregat
- Sant Feliu de Llobregat
- Sant Joan Despí
- Sant Just Desvern
- Santa Coloma de Gramenet
- Tiana
- Viladecans
- Otro: *Respuesta abierta*

2. ¿Tenéis actualmente algún coche en tu hogar? * *Respuesta simple*

- Sí
- No *After the last question in this section, stop filling out this form.*

(Si P4 = 2, MOSTRAR P5, P6, P7, DESPUÉS FILTER OUT)

3. ¿Has comprado un coche nuevo en los últimos 2 años o tienes la intención de comprarlo en el próximo año? * *Respuesta simple*

- He comprado un coche nuevo en los últimos 2 años, y no tengo intención de comprar otro en el próximo año
- He comprado un coche nuevo en los últimos 2 años y tengo la intención de comprar otro en el próximo año
- No he comprado un coche nuevo en los últimos 2 años, pero tengo la intención de comprar uno en el próximo año
- No he comprado un coche nuevo en los últimos 2 años y no tengo ninguna intención de comprar uno en el próximo año *After the last question in this section, stop filling out this form.*

(Si P5 = 4, MOSTRAR P6, P7 DESPUÉS FILTER OUT)

4. ¿Quién es la persona responsable de la toma de decisiones al comprar un coche en el hogar? * *Respuesta simple*

- Yo
- Decidimos toda la familia conjuntamente
- Otro miembro de la familia *After the last question in this section, stop filling out this form.*

(SI P6 = 3, MOSTRAR P7 DESPUÉS FILTER OUT)

2. Si estuvieras en condiciones de comprar un coche nuevo, ¿cuál sería el precio que estarías dispuesto/a a pagar? * *Respuesta simple*

- Menos de 11.500 €
- Entre 11.500 € – 16.999 €
- Entre 17.000 € – 24.999 €
- Entre 25.000 € – 32.999 €
- 33.000 € o más

SECCIÓN 1

3. ¿Cuántas personas de tu hogar tienen permiso de conducir? * *Respuesta simple*

- 1
- 2
- 3 o más

4. ¿Cuántos coches hay en tu hogar? * *Respuesta simple*

- 1
- 2
- 3
- 4 o más

14. ¿Cuál es el tamaño de tu coche principal? * *Respuesta simple*

- Un coche pequeño (segmentos A y B, por ejemplo: Volkswagen Polo)
- Un coche mediano (segmento C, por ejemplo: Volkswagen Jetta)
- Un coche grande (segmentos D y más, por ejemplo: Volkswagen Passat)

5. ¿Cuál es la marca del coche principal (el que usáis con mayor frecuencia) en tu hogar? * *Respuesta simple*

1) Audi
2) BMW
3) Citroën
4) Dacia
5) Fiat
6) Ford
7) Hyundai
8) Jaguar
9) Kia
10) Lexus
11) Mazda
12) Nissan
13) Opel
14) Peugeot
15) Renault
16) Seat
17) Škoda
18) Smart
19) Suzuki

1) Tesla
2) Toyota
3) Volvo
4) Volkswagen
5) Otra

2. ¿Cuál es el modelo del coche principal de tu hogar?

Mostrar el listado de modelos del fichero en Excel para la marca escogida en P10.
MOSTRAR LOS ÍTEMS EN ORDEN ALFABÉTICO

3. ¿Cuál es el año de fabricación del coche principal de tu hogar? * *Respuesta simple*

- 2019
- 2018
- 2017
- 2016
- 2015
- 2014
- 2013
- 2012
- 2011
- 2010
- 2009
- 2008
- 2007
- 2006
- 2005
- 2004
- 2003
- 2002
- 2001
- 2000
- 1999
- 1998
- 1997
- 1996
- 1995
- 1994
- 1993
- 1992
- 1991
- 1990
- Otro: *Respuesta abierta*

2. **¿Cuál es el precio del coche principal de tu hogar?** * *Respuesta simple*

- Menos de 11.500 €
- Entre 11.500€ – 16.999 €
- Entre 17.000 € – 24.999 €
- Entre 25.000 € – 32.999 €
- 33.000 € o más

4. **¿De qué tipo es tu coche principal?** * *Respuesta simple*

- Coche convencional (gasolina o gasoil)
- Coche eléctrico
- Coche hibrido
- Coche híbrido enchufable

(MOSTRAR P16 SI P15=1)

5. **¿Qué tipo de combustible utiliza tu coche principal?** * *Respuesta simple*

- Gasolina
- Diesel
- GLP

6. **Si estuvieras en condiciones de comprar un coche nuevo, ¿de qué tamaño sería?** * *Respuesta simple*

- Un coche pequeño (segmentos A y B, por ejemplo: Volkswagen Polo)
- Un coche mediano (segmento C, por ejemplo: Volkswagen Jetta)
- Un coche grande (segmentos D y más, por ejemplo: Volkswagen Passat)

SECCIÓN 2

7. **En promedio, ¿cuánto tiempo diario dedicas a tus desplazamientos cotidianos?** * *Respuesta simple*

- Menos de 15 minutos
- De 15 a 30 minutos
- De 31 a 45 minutos
- De 46 a 60 minutos (1 hora)
- De 61 a 75 minutos
- De 76 a 90 minutos (1 hora y media)
- De 91 a 105 minutos
- De 106 a 120 minutos (2 horas)
- Más de 120 minutos (Más de 2 horas)
- No sé

2. ¿Cuál es el motivo principal de tu viaje? * *Respuesta simple,* ***rotar***

- Ir al trabajo
- Ir al trabajo con parada en el medio (p.ej. parar dejar los niños en su centro de estudios, ir de compras)
- Ir a mi centro de estudios
- Ir de compras
- Ir de ocio / entretenimiento
- Recoger / Dejar a alguien
- Otro

3. ¿Cuál es el principal medio de transporte que utilizas (en el que más tiempo viajas)? *
Respuesta múltiple, ***rotar***

- Coche propio / de hogar
- Autobús
- Renfe / Ferrocarriles
- Taxi
- Coche compartido
- Servicio de transporte proporcionado por la empresa
- Metro / Tranvía
- Moto
- Bicicleta
- Caminando

4. ¿Con qué frecuencia utilizas tu coche durante la semana? * *Respuesta simple*

- Nunca
- Una vez por semana
- Entre 2 y 4 veces por semana
- 5 veces o más

5. En promedio, ¿cuánto tiempo utilizas tu coche al día? * *Respuesta simple*

- Menos de 15 minutos
- De 15 a 30 minutos
- De 31 a 45 minutos
- De 46 a 60 minutos (1 hora)
- De 61 a 75 minutos
- De 76 a 90 minutos (1 hora y media)
- De 91 a 105 minutos
- De 106 a 120 minutos (2 horas)
- Más de 120 minutos (Más de 2 horas)
- No sé

2. **En promedio, ¿cuántos kilómetros haces con tu coche al día?** * *Respuesta simple*

- Menos de 5 kilómetros
- De 5 a 10 kilómetros
- De 11 a 15 kilómetros
- De 16 a 20 kilómetros
- De 21 a 25 kilómetros
- De 26 a 30 kilómetros
- De 31 a 35 kilómetros
- De 36 a 40 kilómetros
- De 41 a 45 kilómetros
- De 46 a 50 kilómetros
- De 51 a 60 kilómetros
- Más de 60 kilómetros
- No sé

Sección 3

3. **Basándote en la siguiente información, ¿qué coche comprarías para tu hogar?**

Tipo	**Vehículo convencional**	**Vehículo eléctrico**	**Vehículo híbrido**
Descripción	Dispone de motor de combustión interna. Utiliza gasoline, GLP o diesel como combustible.	Dispone de un motor eléctrico solamente. Se debe enchufar para recargar, la carga completa requiere de 4-10 horas. La carga rápida es posible en la estación y requiere de 15-45 minutos. Su costo de combustible es menor en comparación con el automóvil convencional.	Dispone de un motor de gasolina pequeño con motor eléctrico de batería pequeña. Tanto el motor de gasolina como el frenado regenerativo cargan la batería. Por lo tanto, el consumo de gasolina se reduce y su costo de combustible es menor en comparación con el vehículo convencional.

Respuesta simple

- Coche convencional *Pasa a la descripción del coche convencional, p. 8*
- Coche eléctrico *Pasa a la descripción del coche convencional, p. 9*
- Coche híbrido *Pasa a la descripción del coche híbrido, p. 11*

Coche convencional

Definición de los términos usados:

Tipo	Descripción
Rango	Rango de conducción en el depósito lleno o batería completamente cargada.
Precio	Precio final en € (todos los impuestos y tasas incluidas).
Reducción de emisiones	La reducción de emisiones en porcentaje en comparación con los vehículos convencionales que producen la mayor cantidad de emisiones. Por ejemplo, un nivel de "10% menos" para un vehículo significa que produce un 10% menos de emisiones en comparación con el vehículo convencional que produce la mayor cantidad de emisiones.
Reducción de costo del combustible	Reducción del coste del combustible en porcentaje en comparación con el vehículo convencional. Por ejemplo, un nivel de "10% menos" en un vehículo implica que su coste de combustible es un 10% menor que el coste de combustible de un vehículo convencional.
Rellenar el depósito o recargar la batería en el punto de recarga	Tiempo requerido para rellenar el depósito del vehículo convencional o el híbrido o para recargar la batería del vehículo eléctrico en el punto de recarga.
Tiempo asignado al desvío	Es posible que cada gasolinera dispone de instalaciones de carga rápida para el vehículo eléctrico. En tal caso, el propietario del vehículo tiene que viajar más (desvío) para encontrar un punto de recarga. El tiempo total del desvío para llegar al punto de recarga más cercano se compara con el tiempo de viaje a las gasolineras usadas por los vehículos convencionales o híbridos.
Incentivos	Incentivos otorgados por el gobierno a los conductores que poseen un tipo particular de vehículos.

SCR Y QA: RANGO, PRECIO Y TAL NO SON PREGUNTAS, SON OPCIONES PARA MOSTRAR.

Rango

- ◯ 700 kilómetros
- ◯ 900 kilómetros
- ◯ 1100 kilómetros
- ◯ 1300 kilómetros

Precio

- ◯ 11 670 €
- ◯ 15 000 €
- ◯ 21 670 €
- ◯ 28 330 €
- ◯ 35 000 €

Reducción de emisiones

- ◯ Nada
- ◯ 10% menos

Reducción coste de combustible

- ◯ Nada
- ◯ 10% menos

Tiempo para rellenar el depósito

- ◯ 3 minutos
- 5 minutos

Coche eléctrico

Definición de los términos usados:

Tipo	Descripción
Rango	Rango de conducción en el depósito lleno o batería completamente cargada.
Precio	Precio final en € (todos los impuestos y tasas incluidas).
Reducción de emisiones	La reducción de emisiones en porcentaje en comparación con los vehículos convencionales que producen la mayor cantidad de emisiones. Por ejemplo, un nivel de "10% menos" para un vehículo significa que produce un 10% menos de emisiones en comparación con el vehículo convencional que produce la mayor cantidad de emisiones.
Reducción de costo del combustible	Reducción del coste del combustible en porcentaje en comparación con el vehículo convencional. Por ejemplo, un nivel de "10% menos" en un vehículo implica que su coste de combustible es un 10% menor que el coste de combustible de un vehículo convencional.
Rellenar el depósito o recargar la batería en el punto de recarga	Tiempo requerido para rellenar el depósito del vehículo convencional o el híbrido o para recargar la batería del vehículo eléctrico en el punto de recarga.
Tiempo asignado al desvío	Es posible que cada gasolinera dispone de instalaciones de carga rápida para el vehículo eléctrico. En tal caso, el propietario del vehículo tiene que viajar más (desvío) para encontrar un punto de recarga. El tiempo total del desvío para llegar al punto de recarga más cercano se compara con el tiempo de viaje a las gasolineras usadas por los vehículos convencionales o híbridos.
Incentivos	Incentivos otorgados por el gobierno a los conductores que poseen un tipo particular de vehículos.

SCR Y QA: RANGO, PRECIO Y TAL NO SON PREGUNTAS, SON OPCIONES PARA MOSTRAR.

Rango

- 170 kilómetros
- 280 kilómetros
- 390 kilómetros
- 500 kilómetros

Precio

- 21 670 €
- 28 330 €
- 35 000 €
- 41 670 €
- 48 330 €

Reducción de emisiones

- 70% menos
- 80% menos
- 90% menos
- 100% menos

Reducción coste de combustible

- 50% menos
- 60% menos
- 70% menos
- 80% menos

Tiempo para recargar la batería en el punto de recarga

- 5 minutos
- 15 minutos
- 25 minutos
- 35 minutos
- 45 minutos

Tiempo asignado al desvío

- 0 minutos
- 10 minutos
- 20 minutos

Incentivos para el uso de coches eléctricos

- Ninguno
- No pagar el acceso a los túneles/ puentes de pago
- No pagar el peaje de autopistas
- Aparcamiento gratuito

Skip to question 25.

Coche híbrido

Definición de los términos usados:

Tipo	Descripción
Rango	Rango de conducción en el depósito lleno o batería completamente cargada.
Precio	Precio final en € (todos los impuestos y tasas incluidas).
Reducción de emisiones	La reducción de emisiones en porcentaje en comparación con los vehículos convencionales que producen la mayor cantidad de emisiones. Por ejemplo, un nivel de "10% menos" para un vehículo significa que produce un 10% menos de emisiones en comparación con el vehículo convencional que produce la mayor cantidad de emisiones.
Reducción de costo del combustible	Reducción del coste del combustible en porcentaje en comparación con el vehículo convencional. Por ejemplo, un nivel de "10% menos" en un vehículo implica que su coste de combustible es un 10% menor que el coste de combustible de un vehículo convencional.
Rellenar el depósito o recargar la batería en el punto de recarga	Tiempo requerido para rellenar el depósito del vehículo convencional o el híbrido o para recargar la batería del vehículo eléctrico en el punto de recarga.
Tiempo asignado al desvío	Es posible que cada gasolinera dispone de instalaciones de carga rápida para el vehículo eléctrico. En tal caso, el propietario del vehículo tiene que viajar más (desvío) para encontrar un punto de recarga. El tiempo total del desvío para llegar al punto de recarga más cercano se compara con el tiempo de viaje a las gasolineras usadas por los vehículos convencionales o híbridos.
Incentivos	Incentivos otorgados por el gobierno a los conductores que poseen un tipo particular de vehículos.

Rango

- 1000 kilómetros
- 1200 kilómetros
- 1400 kilómetros
- 1600 kilómetros

Precio

- 16 670 €
- 23 330 €
- 30 000 €
- 36 670 €
- 43 330 €

Reducción de emisiones

- 50% menos
- 60% menos
- 70% menos
- 80% menos

Reducción coste de combustible

- 30% menos
- 40% menos
- 50% menos
- 60% menos

Tiempo para rellenar el depósito

- 3 minutos
- 5 minutos

Incentivos para el uso de coches híbridos

- Ninguno
- No pagar el acceso a los túneles/ puentes de pago
- No pagar el peaje de autopistas
- Aparcamiento gratuito

Skip to question 25.

Comparaciones A

2. Elige una de las siguientes opciones, basándote en la información que se muestra a continuación. Es posible que algunos de los coches no estén todavía en el mercado, pero toma una decisión como si ya lo estuvieran

Tipo	Vehículo eléctrico	Vehículo convencional	Vehículo híbrido
Rango	500 km	700 km	1300 km
Precio	11 670 €	21 670 €	23 000 €
Reducción de emisiones	90% menos	10% menos	50% menos
Reducción de costo del combustible	60% menos	Nada	40% menos
Rellenar el depósito o recargar la batería en el punto de recarga	35 minutos	5 minutos	5 minutos
Tiempo asignado para el desvío	10 minutos	Nada	Nada
Incentivos	No pagar el peaje	Nada	No pagar el acceso a los túneles/ puentes de pago

Mark only one oval per row.

	Coche eléctrico	Coche convencional	Coche híbrido
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

3. Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:

Tipo	Vehículo eléctrico	Vehículo convencional	Vehículo híbrido
Rango	170 km	1100 km	1600 km
Precio	41 670 €	35 000 €	16 670 €
Reducción de emisiones	80% menos	Nada	70% menos
Reducción de costo del combustible	80% menos	Nada	60% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	5 minutos	3 minutos
Tiempo asignado para el desvío	20 minutos	Nada	Nada
Incentivos	Nada	Nada	No pagar por el aparcamiento

Mark only one oval per row.

	Coche eléctrico	Coche convencional	Coche híbrido
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo eléctrico	Vehículo híbrido B
Rango	1600 km	390 km	1900 km
Precio	30 000 €	35 000 €	36 670 €
Reducción de emisiones	50% menos	70% menos	60% menos
Reducción de costo del combustible	50% menos	70% menos	50% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	45 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar el peaje	No pagar por el aparcamiento	Nada

Mark only one oval per row.

	Coche híbrido A	Coche eléctrico	Coche híbrido B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo eléctrico A	Vehículo convencional	Vehículo eléctrico B
Rango	280 km	1300 km	500 km
Precio	26 670 €	26 670 €	48 330 €
Reducción de emisiones	100% menos	Nada	90% menos
Reducción de costo del combustible	50% menos	Nada	80% menos
Rellenar el depósito o recargar la batería en el punto de recarga	15 minutos	5 minutos	25 minutos
Tiempo asignado para el desvío	20 minutos	Nada	Nada
Incentivos	No pagar el acceso a los túneles/ puentes de pago	Nada	No pagar por el aparcamiento

Mark only one oval per row.

	Coche eléctrico A	Coche convencional	Coche eléctrico B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo eléctrico	Vehículo híbrido B
Rango	1000 km	170 km	1300 km
Precio	43 330 €	48 330 €	36 670 €
Reducción de emisiones	80% menos	70% menos	80% menos
Reducción de costo del combustible	30% menos	60% menos	60% menos
Rellenar el depósito o recargar la batería en el punto de recarga	15 minutos	45 minutos	3 minutos
Tiempo asignado para el desvío	Nada	10 minutos	Nada
Incentivos	No pagar por el aparcamiento	No pagar el acceso a los túneles/ puentes de pago	No pagar el acceso a los túneles/ puentes de pago

Mark only one oval per row.

	Coche híbrido A	Coche eléctrico	Coche híbrido B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido	Vehículo eléctrico A	Vehículo eléctrico B
Rango	1000 km	280 km	390 km
Precio	16 670 €	28 330 €	35 000 €
Reducción de emisiones	60% menos	80% menos	100% menos
Reducción de costo del combustible	30% menos	70% menos	50% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	5 minutos	15 minutos
Tiempo asignado para el desvío	Nada	Nada	20 minutos
Incentivos	Nada	Nada	No pagar el peaje

Mark only one oval per row.

	Coche híbrido	Coche eléctrico A	Coche eléctrico B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

Comparaciones B

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo eléctrico	Vehículo híbrido B
Rango	1900 km	170 km	1300 km
Precio	23 330 €	41 670 €	43 330 €
Reducción de emisiones	60% menos	80% menos	70% menos
Reducción de costo del combustible	60% menos	60% menos	30% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	25 minutos	5 minutos
Tiempo asignado para el desvío	Nada	10 minutos	Nada
Incentivos	No pagar el peaje	No pagar el acceso a los túneles	Nada

Mark only one oval per row.

	Coche híbrido A	Coche eléctrico	Coche híbrido B
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo eléctrico A	Vehículo híbrido	Vehículo eléctrico B
Rango	500 km	1600 km	390 km
Precio	21 670 €	16 670 €	21 670 €
Reducción de emisiones	100% menos	80% menos	90% menos
Reducción de costo del combustible	70% menos	50% menos	80% menos
Rellenar el depósito o recargar la batería en el punto de recarga	35 minutos	5 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	10 minutos
Incentivos	No pagar el peaje	No pagar el acceso a los túneles	Nada

Mark only one oval per row.

	Coche eléctrico A	Coche híbrido	Coche eléctrico B
Sí, es una posibilidad	⬭	⬭	⬭
	⬭	⬭	⬭

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo híbrido B	Vehículo híbrido C
Rango	1000 km	1300 km	1000 km
Precio	23 330 €	43 330 €	16 670 €
Reducción de emisiones	50% menos	80% menos	70% menos
Reducción de costo del combustible	60% menos	30% menos	60% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	3 minutos	3 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar por el aparcamiento	No pagar el acceso a los túneles	No pagar el peaje

Mark only one oval per row.

	Coche híbrido A	Coche híbrido B	Coche híbrido C
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo híbrido B	Vehículo híbrido C
Rango	1600 km	1300 km	1900 km
Precio	43 330 €	30 000 €	30 000 €
Reducción de emisiones	70% menos	60% menos	50% menos
Reducción de costo del combustible	30% menos	50% menos	30% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	5 minutos	3 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar por el aparcamiento	Nada	Nada

Mark only one oval per row.

	Coche híbrido A	Coche híbrido B	Coche híbrido C
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo convencional	Vehículo eléctrico A	Vehículo eléctrico B
Rango	700 km	280 km	500 km
Precio	35 000 €	21 670 €	41 670 €
Reducción de emisiones	10% menos	70% menos	90% menos
Reducción de costo del combustible	10% menos	80% menos	70% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	15 minutos	5 minutos
Tiempo asignado para el desvío	Nada	10 minutos	20 minutos
Incentivos	Nada	No pagar por el aparcamiento	Nada

Mark only one oval per row.

	Coche convencional	Coche eléctrico A	Coche eléctrico B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo híbrido B	Vehículo convencional
Rango	1300 km	1300 km	900 km
Precio	30 000 €	23 330 €	11 670 €
Reducción de emisiones	50% menos	70% menos	Nada
Reducción de costo del combustible	40% menos	50% menos	10% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	3 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar el peaje	No pagar por el aparcamiento	Nada

Mark only one oval per row.

	Coche híbrido A	Coche híbrido B	Coche convencional
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

Comparaciones C

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo convencional	Vehículo híbrido B
Rango	1900 km	1100 km	1300 km
Precio	16 670 €	21 670 €	36 670 €
Reducción de emisiones	70% menos	Nada	70% menos
Reducción de costo del combustible	30% menos	Nada	50% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	3 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar por el aparcamiento	No pagar el acceso a túneles de pago	Nada

Mark only one oval per row.

	Coche híbrido A	Coche convencional	Coche híbrido B
Sí, es una posibilidad	◯	◯	◯
No, no me interesa	◯	◯	◯

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo eléctrico A	Vehículo eléctrico B	Vehículo convencional
Rango	170 km	280 km	1300 km
Precio	28 330 €	28 330 €	28 330 €
Reducción de emisiones	80% menos	80% menos	10% menos
Reducción de costo del combustible	50% menos	60% menos	Nada
Rellenar el depósito o recargar la batería en el punto de recarga	45 minutos	25 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar el peaje	No pagar el acceso a túneles de pago	Nada

Mark only one oval per row.

	Coche eléctrico A	Coche eléctrico B	Coche convencional
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo híbrido B	Vehículo híbrido C
Rango	1600 km	1000 km	1300 km
Precio	16 670 €	16 670 €	43 330 €
Reducción de emisiones	60% menos	80% menos	80% menos
Reducción de costo del combustible	60% menos	30% menos	30% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	5 minutos	3 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar el acceso a túneles de pago	No pagar el acceso a túneles de pago	No pagar el acceso a túneles de pago

Mark only one oval per row.

	Coche híbrido A	Coche híbrido B	Coche híbrido C
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo convencional	Vehículo híbrido B
Rango	1600 km	700 km	1300 km
Precio	43 330 €	35 000 €	23 330 €
Reducción de emisiones	70% menos	10% menos	70% menos
Reducción de costo del combustible	30% menos	10% menos	50% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	5 minutos	3 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar por el aparcamiento	Nada	No pagar el acceso a túneles de pago

Mark only one oval per row.

	Coche híbrido A	Coche convencional	Coche híbrido B
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

3. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo convencional	Vehículo híbrido A	Vehículo híbrido B
Rango	1300 km	1900 km	1000 km
Precio	28 330 €	16 670 €	16 670 €
Reducción de emisiones	10% menos	70% menos	80% menos
Reducción de costo del combustible	Nada	30% menos	30% menos
Rellenar el depósito o recargar la batería en el punto de recarga	5 minutos	5 minutos	5 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	Nada	No pagar por el aparcamiento	No pagar el acceso a túneles de pago

Mark only one oval per row.

	Coche convencional	Coche híbrido A	Coche híbrido B
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

2. **Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:**

Tipo	Vehículo híbrido A	Vehículo híbrido B	Vehículo híbrido C
Rango	1600 km	1000 km	1000 km
Precio	43 330 €	16 670 €	23 330 €
Reducción de emisiones	70% menos	80% menos	50% menos
Reducción de costo del combustible	30% menos	30% menos	60% menos
Rellenar el depósito o recargar la batería en el punto de recarga	3 minutos	5 minutos	3 minutos
Tiempo asignado para el desvío	Nada	Nada	Nada
Incentivos	No pagar por el aparcamiento	No pagar el acceso a túneles de pago	No pagar por el aparcamiento

Mark only one oval per row.

	Coche híbrido A	Coche híbrido B	Coche híbrido C
Sí, es una posibilidad	⬭	⬭	⬭
No, no me interesa	⬭	⬭	⬭

SECCIÓN 4

3. **¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?**

		Muy en desacuerdo	En desacuerdo	Indiferente	De acuerdo	Muy de acuerdo
1	Es urgente disminuir las emisiones de los coches para salvar el medio ambiente					
2	El cambio de coches convencionales por coches eléctricos tiene un gran impacto a la reducción de las emisiones de $CO2$					
3	Tener un coche con un menor impacto negativo medioambiental, es más importante que la potencia de su motor					
4	Las nuevas tecnologías facilitan nuestras vidas					
5	Estoy dispuesto/a a pagar más por coches con tecnologías menos contaminantes					
6	Actualmente es importante adaptarse a las mejoras tecnológicas					
7	El coche es un símbolo de clase social					
8	Mi coche define mi carácter					

Sección 5

2. **Nivel de estudios terminados: cargar la variable ES_education_level**

3. **¿Cuál es el nivel de ingresos netos mensuales de todo tu hogar?** * *Respuesta simple*
   - Menos de 500€
   - De 500 € a 999 €
   - De 1.000 € a 1.499 €
   - De 1.500 € a 1.999 €
   - De 2.000 € a 2.999 €
   - De 3.000 € a 5.000 €
   - Más de 5.000 €
   - Prefiero no contestar

4. **Número de personas en el hogar: cargar la variable hh_numberofpeople**

5. **Número de hijos/as: cargar la variable number_kids**

6. **Estado civil: cargar la variable marital_status**

50. **Sector: cargar la variable ES_position**

Appendix B: Variables analyzed and participation

In Table B1 are displayed the official count of participants from the field implementation. In this survey, a total of 1303 people took part in the survey, but only 500 completed it. Hence, the remaining 803 people have been filtered out by the screening questions, residence and age quotas or due to lack of validation.

Table B1: *Final distribution of the included and excluded participants*[9]

Type	***Count***
FilterOut_KIDS	22
FilterOut_P3	17
FilterOut_P4	148
FilterOut_P5	225
FilterOut_P6	20
FilterOut_POSITION	157
FilterOut_P_GENERACION	3
complete	500
completeISO	1
filteroutISO	10
filterout_nq_fraud_relevantID	14
filterout_reCaptcha	14
no_valido	12
quotafull_Edad	21
quotafull_Poblacion	22
quotafull_rot_edad	47
quotafull_sexo	12
securityQuestionKO	1
Incomplete	57
Total	1303

[9] Filter out in Table 4 represents the distinct screening and security questions, which result in being excluded from continuing the questionnaire (e.g. FilterOut_KIDS, FilterOut_P3, FilterOut_P4, etc). Similarly, after meeting the pre-established quota from Table 3, participants were screened out.

In Table B2 summarizes the progress of the survey's implementation based on the participants' residences. Table B3 represents the typology of all the reordered variables in the survey.

Table B2: *Targets and progress report on participants by municipality*

P3	***Objective***	***Completed***	***Pending***	***Progress***
Badalona (1)	31	32	0	103.23%
Barcelona (2)	338	336	2	99.41%
Castelldefels (3)	9	9	0	100%
Cornellà de Llobregat (4)	12	12	0	100%
Esplugues de Llobregat (5)	6	6	0	100%
Gavà (6)	6	6	0	100%
Hospitalet de Llobregat (L') (7)	35	35	0	100%
Montcada i Reixac (8)	5	5	0	100%
Montgat (9)	2	2	0	100%
Prat de Llobregat (El) (10)	8	8	0	100%
Sant Adrià de Besós (11)	5	5	0	100%
Sant Boi de Llobregat (12)	11	11	0	100%
Sant Feliu de Llobregat (13)	6	6	0	100%
Sant Joan Despí (14)	5	5	0	100%
Sant Just Desvern (15)	2	2	0	100%
Santa Coloma de Gramenet (16)	11	12	0	109.09%
Tiana (17)	1	1	0	100%
Viladecans (18)	7	7	0	100%
Total	500	500	0	100%

Table B3: *Variables analyzed with results*

NOMBRE	***ETIQUETA***	***TIPO***
DEVICE	DEVICE	Categórica
P1	¿Eres...?	Categórica
P2	¿Cuántos años tienes?	Numérica
P2R	recode de edad	Categórica
EDUCATION	EDUCATION	Categórica
PEOPLE	PEOPLE	Numérica
KIDS	KIDS	Categórica
MARITAL	MARITAL	Categórica
POSITION	POSITION	Categórica
P_GENERACION	P_GENERACION	Categórica
P3	¿En qué municipio vives?	Categórica
P49	¿En qué municipio trabajas?	Categórica
P4	¿Tenéis actualmente algún coche en tu hogar?	Categórica
P5	¿Has comprado un coche nuevo en los últimos 2 años o tienes la intención de comprarlo en el próximo año?	Categórica
P6	¿Quién es la persona responsable de la toma de decisiones al comprar un coche en el hogar?	Categórica
P7	Si estuvieras en condiciones de comprar un coche nuevo, ¿cuál sería el precio que estarías dispuesto/a a pagar?	Categórica
P8	¿Cuántas personas de tu hogar tienen permiso de conducir?	Categórica
P9	¿Cuántos coches hay en tu hogar?	Categórica
P14	¿Cuál es el tamaño de tu coche principal?	Categórica
P10	¿Cuál es la marca del coche principal. (el que usáis con mayor frecuencia) en tu hogar?	Categórica
CAMBIO20190906	Añadido el filtro para el sort porque si seleccionamos otra marca de choche petaba	Numérica
P11	¿Cuál es el modelo del coche principal de tu hogar?	Categórica
P12	¿Cuál es el año de fabricación del coche principal de tu hogar?	Categórica
P13	¿Cuál es el precio del coche principal de tu hogar?	Categórica
P15	¿De qué tipo es tu coche principal?	Categórica
P16	¿Qué tipo de combustible utiliza tu coche principal?	Categórica
P17	Si estuvieras en condiciones de comprar un coche nuevo, ¿de qué tamaño sería?	Categórica
P18	En promedio, ¿cuánto tiempo diario dedicas a tus desplazamientos cotidianos?	Categórica
P19	¿Cuál es el motivo principal de tu viaje?	Categórica
P20	¿Cuál es el principal medio de transporte que utilizas (en el que más tiempo viajas)?	Categórica
P21	¿Con qué frecuencia utilizas tu coche durante la semana?	Categórica

NOMBRE	*ETIQUETA*	*TIPO*
P22	En promedio, ¿cuánto tiempo utilizas tu coche al día?	Categórica
P23	En promedio, ¿cuántos kilómetros haces con tu coche al día?	Categórica
P24	Basándote en la siguiente información, ¿qué coche comprarías para tu hogar?	Categórica
ROTATION	ROTATION GRUPOS	Categórica
P25_1	P25_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:_Es posible que algunos de los coches no estén todavía en el mercado, pero toma una decisión como si ya lo estuvieran	Categórica
P25_2	P25_1_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:_Es posible que algunos de los coches no estén todavía en el mercado, pero toma una decisión como si ya lo estuvieran	Categórica
P26_1	P26_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P26_2	P26_2_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P27_1	P27_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P27_2	P27_2_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P28_1	P28_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P28_2	P28_2_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P29_1	P29_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P29_2	P29_2_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P30_1	P30_1_COMPARACION_A_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P30_2	P30_1_COMPARACION_A_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P31_1	P31_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P31_2	P31_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P32_1	P32_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P32_2	P32_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P33_1	P33_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica

NOMBRE	***ETIQUETA***	***TIPO***
P33_2	P33_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P34_1	P34_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P34_2	P34_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P35_1	P35_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P35_2	P35_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P36_1	P36_1COMPARACION_B_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P36_2	P36_2_COMPARACION_B_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P37_1	P37_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P37_2	P37_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P38_1	P38_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P38_2	P38_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P39_1	P39_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P39_2	P39_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P40_1	P40_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P40_2	P40_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P41_1	P41_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P41_2	P41_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P42_1	P42_1_COMPARACION_C_Sí, es una posibilidad_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P42_2	P42_2_COMPARACION_C_No, no me interesa_Elige una de las siguientes opciones, basándote en la información que se muestra a continuación:	Categórica
P43_1	Es urgente disminuir las emisiones de los coches para salvar el medio ambiente_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_2	El cambio de coches convencionales por coches eléctricos tiene un gran impacto a la	Categórica

NOMBRE	*ETIQUETA*	*TIPO*
	reducción de las emisiones de CO2_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	
P43_3	Tener un coche con un menor impacto negativo medioambiental, es más importante que la potencia de su motor_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_4	Las nuevas tecnologías facilitan nuestras vidas_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_5	Estoy dispuesto/a a pagar más por coches con tecnologías menos contaminantes_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_6	Actualmente es importante adaptarse a las mejoras tecnológicas_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_7	El coche es un símbolo de clase social_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P43_8	Mi coche define mi carácter_¿Cuál es tu nivel de acuerdo con cada una de las siguientes afirmaciones?	Categórica
P45	¿Cuál es el nivel de ingresos netos mensuales de todo tu hogar?	Categórica

In Figure B1, we show responses to the question how important it is to minimize car emissions in order to reduce the negative impact on environment and rate answers by participants from strongly agree to strongly disagree. The results show that 51% of participants strongly agree that this is a pressing issue and 36.8% agree. The remaining responses for this question were a minority. Other interesting responses concern the willingness to adapt to new technologies where 59% of the correspondents believed this to be true. Yet most contestants to the next question expressed that they were not willing for less-contaminating technologies (15.4%). This controversial attitude is not uncommon in the literature of environmental pollution – everyone wants to live in an area with less pollution, yet no one is willing to pay for this change.

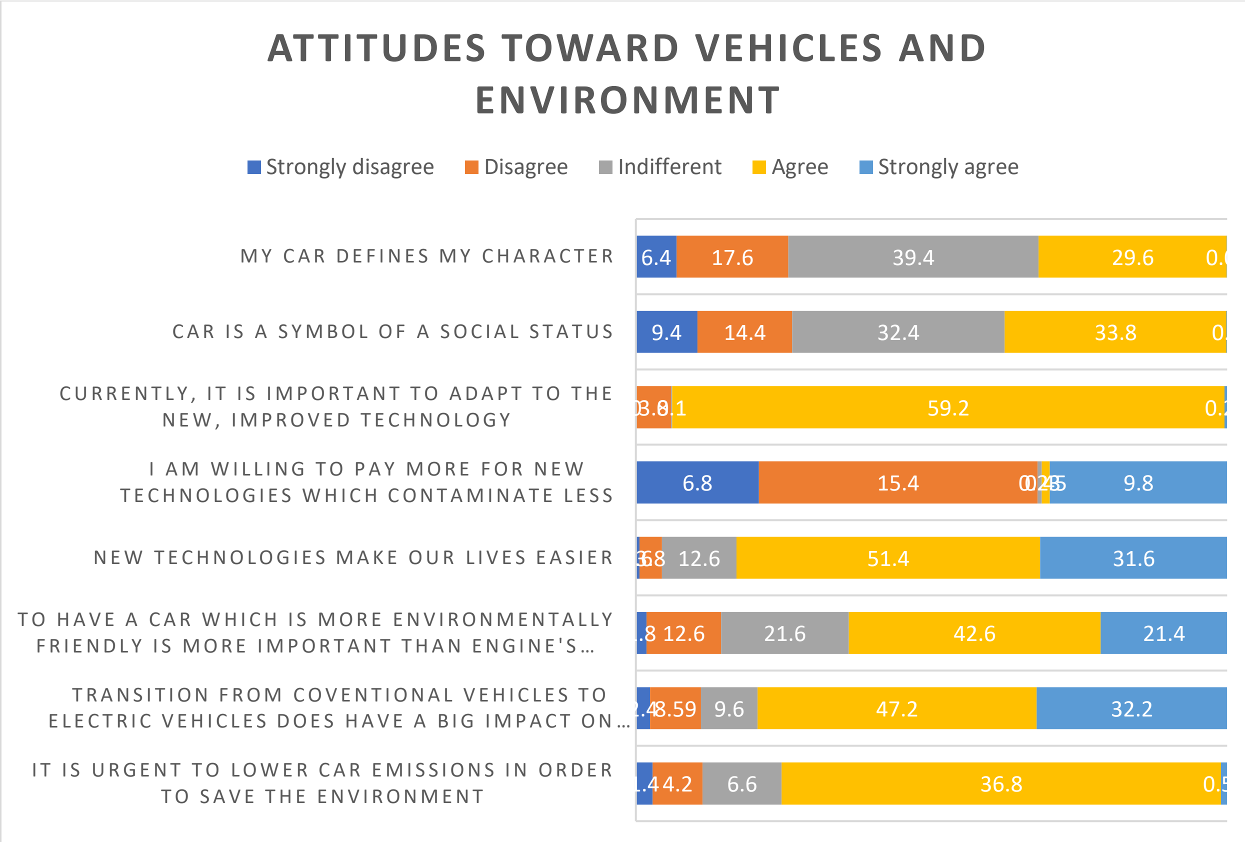

Figure B1: *Personal attitudes toward vehicles, vehicle-related emissions and their impact on the environment.*

CHAPTER VII:

Conclusion

This thesis reports a set of studies on the relationship between cities and climate change, and possible pathways to its effective mitigation. Each chapter addressed a distinct aspect of how cities, city policies, scenarios or targets can contribute to combating climate change, ranging from adapting or altering city's urban form, use of alternative sources of energy, incentives for the adoption of electric and hybrid vehicles or setting emission targets. The thesis contributes to existing research regarding cities and climate change mitigation by proposing possible transition pathways to urban forms which result in a lower level of GHG emissions. Furthermore, we analyzed a combination of car features and consumer characteristics on the basis of which one can design effective incentives to assure increased adoption of hybrid and electric vehicles. We have also assessed emission targets and associated policies for a subset of C40 cities which suggests the need for improvement and strengthening of current policy instruments as well as the for integration of governmental powers on multiple levels. In the following we discuss details for each chapter along with specific conclusions and policy insights.

Chapter 2 reviewed and compared the literature on urban form in economics and geography. We looked closely at studies of the interaction of urban form and environmental externalities. Missing gaps in the related literature which merit further research were identified. We concluded that the biggest discrepancies among geographic models and urban economic models were related to the definition of the center and sub-centers as well as the presence of (a)symmetry in urban form. Moreover, the movement of agents in urban economic models was defined to be radial and organized rather than chaotic. We assessed the solutions to environmental externalities proposed by the literature and contrasted these with current environmental policies in cities today. On that note we have concluded that there is a lack of studies addressing the impacts of these new policies which are being applied worldwide together with future research based on said gaps. Chapter 3 we explain the process behind the collection of data for both Chapter 4 of this thesis as well as a general equilibrium model used for the BREATHE project. This data was collected for the Metropolitan Area of Barcelona.

In Chapter 4 we determine which urban form generates minimal global and local emissions. To this end, we develop a spatial accounting model of a circular city consisting of six zones. Activities comprise low and high density housing, offices and industry. Spatial interactions among activities give rise to freight and passenger transport. We assess global emissions of greenhouse gases due to the direct and indirect use of coal, oil and gas by economic activities and transport. In addition, we calculate local emissions which are zone-specific. Distribution and health effects of such emissions are also taken into account. The model analyses each urban form for various scenarios of distinct shares of electric vehicles in transport and of renewable energy in electricity production. included a modelled relationship between emissions, economic activity and land uses for these activities. The various allocations of economic activities in a monocentric city created various land-use patterns. The objective of this study was to identify the best-performing urban form in terms of the evaluation criteria and the long-term transition to a more sustainable urban form. We have considered 4 catefories of urban forms: compact, spread-out, intermediate and green city. We have performed a numerical exercise and evaluated the results by distinct indicators, including total global emissions, share of transport in global emissions, total local emissions, local emissions in each zone, distribution of local emissions across zones (Gini index), average local emissions and two indexes for health. The urban forms which performed best had the most populated residential zones and zones with greater share of workers placed in close proximity, which in turn minimized the commuting distances. We have also explored different shares of car fleet composition and renewable energy. We conclude that the benefits of using electric vehicles diminishes if the electricity used for their production and running is not renewable. We also anticipate that the shift toward the use of electric vehicles will be done at a faster pace than the shift to renewable energy over the upcoming decades. We considered Barcelona to be closest in its current state to compact urban form we named UFC4. We have analyzed potential transitions to the three most desirable final urban forms. We found that a transition to an intermediate urban form (UFI2) involves the lowest effort, while a transition to spread-out urban form (UFS3) requires double the effort while achieving the most desirable outcome.

Chapter 5 analyzed the relationship between emission targets, mayoral powers and city attributes for 32 C40 cities. We calculated emission targets for the years 2020, 2030, 2040 and 2050 using a common baseline and stated objectives. Statistical correlation and quantile regression analysis suggested that mayoral powers had no impact on the emission targets in the years 2040 and 2050. However, some mayoral powers did impact emission targets in the years 2020 and 2030 positively. This implied that cities with higher mayoral powers tend to have lower levels of ambition in cities for setting emission targets. We also found that higher GDP per capita to have a negative and significant impact in the long run. Hence, cities set with higher per capita GDP are more likely to set their emission targets below current emissions, making them more ambitious. Population size is relevant for both long and short run, impacting emission targets positively, implying lower levels of ambition. However, most of the impacts on cities' emission targets do not depend on mayoral powers but rather on city attributes. Further work is needed to expand the database to reinforce these results as well as higher number of bootstrap repetitions (e.g. 10000). Our goal is to create a dynamic panel database in order to track the impact of the environmental policies of mayors on emission targets over time. This would contribute to improving the quality of our estimates and allow exploring additional research questions. Finally, one could also decompose the emission targets by production sectors and test for a relation with the associated sectorial mayoral powers.

Chapter 6 was dedicated to data analysis of a survey implemented in the Metropolitan Area of Barcelona, which studied consumer vehicle preferences. A multinomial logit regression was undertaken. The results indicate that the most important attributes for choosing among conventional, hybrid and electric vehicles are price and range. Furthermore, when it comes to choosing among hybrid vehicles, the aspects found to be significant were range, price, emission reduction and fuel cost. We have estimated the amount price an individual is willing to sacrificed in monetary terms to improve some of the car attributes, called the willingness to pay. The estimated willingness to pay for an additional kilometre of driving range is about 28€, while the estimated willingness to pay for 1% emission reduction to be 363€ and 303€ for additional 1% of fuel cost reduction. Although statistically insignificant, the willingness to pay was for fuel time reduction, estimated at 3140€ per additional minute. These results are consistent with estimates provided by the literature. We also estimated that the presence of incentives such as free parking, toll-free highways or free tunnels access affected the choice of vehicle by respondents. These estimates are meant for policy purposes for creating incentives for local consumers to transition into purchasing electric and hybrid vehicles.

In terms of theoretical-modelling work, notably expanding on the model from Chapter 3, further research could include more spatial detail, such as particular infrastructure connections between urban zones, or a distinction between a small, central shopping center and a large shopping mall in the city outskirts, as this characterizes many large cities nowadays. In addition, the model could be extended to other urban structures, such as polycentric and multi-nuclei cities. A third type of extension would be to describe distinct transportation modes and their differences, such as regarding emissions and congestion, including bicycles, public transport and cars. This could improve the analysis of different performances of compact and spread-out cities. Finally, land scarcity and associate prices may be introduced in order to assess social welfare impacts and determine optimal pricing policies, such as carbon and congestion pricing, as complements to urban form policies or even to slowly alter urban form.

In future research, we wish to study the missing links in the literature addressing urban form and emissions, such as time-dynamics and technology in relation to emission production. In term of further research, regarding city's climate policies and emission targets, a larger consistent database would be worth striving for. The main problem is however that so far cities do a lot of greenwashing but little implementation of clear policies, notably effective regulation of mobile and immobile activities. As time evolves, one could possibly construct a dynamic panel of urban climate policies. This would enable one to track how the environmental policies of mayors affect the commitments to GHG emissions over time.