Lisbon School of Economics & Management
Universidade de Lisboa

MASTERS IN MANAGEMENT (MIM)

MASTERS FINAL WORK

DISSERTATION

Motorways, Sprawl, and the (Un)Sustainable Economy

HUGO BAPTISTA FERREIRA

OCTOBER 2022

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Abstract

Urban sprawl is usually addressed with a negative connotation due to its negative impacts on land uptake and contribution to a greater dependence on the automobile, which subsequently affects the environment as more fuel is consumed and more greenhouse gas emissions are emitted. There is also international evidence that investments in motorways have promoted urban expansion models akin to urban sprawl, particularly low density and dispersed suburbanization patterns. Portugal has one of the densest motorway networks in the EU and experienced a relatively late process of urbanization compared to other European countries. We study the relationship between motorways, urban sprawl and its impacts on travel mobility patterns and fuel consumption for Portugal over the period from 1991 to 2011. The results show that both motorways and urban sprawl have played a role in the shift in travel mobility towards greater automobile dependency and greater fuel consumption, which limit the country's ability to meet the climate change targets set out in the national strategy for carbon neutrality by 2050.

Keywords: Urban Sprawl, Sprawl, Urban Growth, Sustainable Growth, Consequences of Urban Sprawl, Causes of Urban Sprawl, Motorways, Travel Mobility, Fuel Consumption

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1. Introduction

This MFW was elaborated in the context of ISEG's Masters in Management (MiM), a program which has a high focus on sustainability and is framed within the United Nation's 17 Sustainable Development Goals (SDGs). Therefore, as a student of the MiM course, one of my objectives for this MFW was to promote relevant research with valuable insights on possible answers towards a more sustainable future. More specifically, relating to the Sustainable Development Goal 11- Sustainable Cities and Communities.

Urban sprawl is usually considered to be a process of urban growth characterized by low-density, scattered, urban land development. It is caused by several factors, as explained in studies such as Ewing (2008), of which the combination of urban planning favoring monofunctional land uses combined with a transport system based on motorways and expressways are two key drivers.

There are several negative impacts from urban sprawl. It is thought to increase the dependency on car use, causing environmental problems such as congestion and air pollution, and reducing the viability of public transport and other publicly funded services, which can aggravate local authorities' public deficits. Consequently, urban sprawl has been heavily criticized for being socially, environmentally, and economically unsustainable (Bhatta, 2010; Neuman, 2005; Newman et al., 1995). It is therefore fundamental to consider how public policies can influence alternative urban land use developments to prevent the negative effects of urban sprawl.

Existing literature for Portugal argues that urban sprawl has influenced its urban structure, creating leapfrogging development patterns and a fragmented urban territory both within and outside metropolitan areas (Correia & de Abreu e Silva, 2018).

Additionally, as pointed out by OECD (2018), despite Portuguese cities being relatively centralized around a main central business district, presenting urban areas with monocentric patterns, there are large variations in population densities across the urban fabric. In relation to the possible drivers of urban sprawl, the impact of transport investments that favor the use of the automobile seem to be a focal point. During the last two decades of the 20th century, Portugal saw rapid urban growth along with economic and social developments during this period, especially since joining the European Economic Community in 1986. With its adhesion, Portugal benefited from the advantages of belonging to a larger community, experiencing high levels of European regional development funds, which were largely used for construction of transport infrastructures, notably roads and motorways.

As studied by Rocha et al., (2022a, 2022b) , from 1981 to 2011, the Portuguese motorway network was massively expanded and contributed to the increasing suburbanization of people and decentralization of jobs. Rocha et al., (2022a) conclude from their analyses that a 13.2 km increase in motorways led to a 10.2% increase in population growth. However, the effects in suburban municipalities were higher regarding population growth (ranging between 17-20%), which can be seen as evidence of increased suburbanization.

Suburbanization and motorways have been hypothesized to promote car use and thus greater car dependency of travel patterns. Since urban sprawl can be thought of as a type of suburbanization characterized by low densities and dispersed urban settlements, it is also likely that it favours car use. Studying the impact of the expansion of motorways, alongside with urban sprawl, on travel patterns is, therefore, important. Indeed, several studies have looked at the effects of motorways not only on population and employment growth (Duranton & Turner, 2012; Garcia-López et al., 2015; Möller & Zierer, 2018) , but also on increasing suburbanization (Baum-Snow, 2007; Rocha et al., 2022a). However, studies relating motorway expansion and urban sprawl for Portugal are still scarce.

Therefore, the main objective of this work is to study the relation between motorways, urban sprawl, and the (un)sustainability of travel mobility across Portugal's municipalities over the period from 1991 to 2011. Portugal invested substantially in the development of a dense motorway network which increased urban growth and suburbanization levels and may have contributed both directly and indirectly to making travel patterns less sustainable. We study the possible direct effects of motorways on car travel, and, additionally, the indirect effects arising through urban expansion patterns more conducive to car use over public transportation.

The remainder of the paper is organized as follows. Section 2 discusses the literature on urban sprawl, outlining its main dimensions, main determinants, and major consequences. Section 3 describes the data and gives some descriptive analysis for our main variables. Section 4 gives the conceptual model and empirical methods implemented to study the relationship between motorways, urban sprawl, and travel patterns at the municipality level for the years 1991, 2001, and 2011. Section 5 reports and discusses the main results. Section 6 provides the main conclusions.

2. Literature Review

2.1 Definition of urban sprawl and its dimensionsUrban sprawl is a complex process; thus, a clear definition and measurement is difficult to achieve. According to (Ewing, 2008), the most common term used to characterize urban sprawl is the scattered nature of urban land development. Additionally, several authors, including Glaeser & Kahn (2004), Duranton & Puga (2015), and Carruthers & Ulfarsson (2003), state that low population density is one of the main features of sprawl. Low-density tends to be associated with a more dispersed (in opposition to compact) pattern of land use and the “stretching” of population and supporting services outside of the urban cores into peripheral suburban areas.

However, as Glaeser & Kahn (2004) and other authors explain, density alone is not enough to characterize non-compact urban development, as it is possible to have decentralized polycentric-type urban agglomerations where each center can be quite dense. In addition, Carruthers & Ulfarsson (2003) add that suburbanization can also occur in high-density urban agglomerations, while still being considered sprawl. Urban sprawl can thus be seen as one form of suburbanization, but not all suburbanization must be urban sprawl like. Asian countries such as Korea and Japan are a prime example of high-density and compact forms of suburbanization (OECD, 2018). On the other hand, there are examples where urban sprawl presents patterns of suburbanization composed by high fragmentation and low-density levels, such as Graz in Austria and Darwin in Australia that present high levels of fragmentation and overall decentralization of its population (OECD, 2018). Despite being an important characteristic, low-density alone cannot characterize urban sprawl, and other variables should be considered as well.

Works addressing the multidimensionality of urban sprawl include studies such as Garcia-López (2019), in which the authors propose that sprawl has three main dimensions: size of the urban area, which is usually related with density indicators; isolation, which relates to the degree to which land developments are surrounded by undeveloped land; and fragmentation, which relates to the degree of discontinuity and dispersion of developed land. Together, these dimensions allow for a better identification and measurement of urban sprawl development, notably whether "… the expansion of cities with new land developments [occurs] in a scattered (compact) pattern and with an increase (decrease) in their undeveloped surroundings." (Garcia-López, 2019, p. 2)

Other studies have also proposed a multidimensional definition of urban sprawl. Duranton & Puga (2015) consider that the most common characteristic of urban sprawl is low-density spread-out development, along with the presence of scattered development. Carruthers & Ulfarsson (2003) argue that "sprawl can often be characterized by being the combination of low-density, scattered, strip and leapfrog development patterns" (Carruthers & Ulfarsson, 2003, p. 504). Johnson (2001) considers factors such as: land with separate land uses, automobile as the main form of transportation, a push for growth at the boundary of the metropolitan area, lower residential and employment densities at the suburbs when compared with the central city, homogeneity in terms of race, ethnicity, class and housing status, and the lack of coordination between municipality laws, in terms of building restrictions, that enable some areas to be more prone to sprawl. In addition, Ewing (2008) highlights two characteristics that are present throughout all sprawl archetypes: poor accessibility among related land uses and the lack of functional open space (spaces designed in urban areas specifically for greenspaces). Glaeser & Kahn (2004) discuss the association between density and decentralization in relation to the classical urban economics monocentric city model. Decentralization reflects the spreading of population and employment outside the urban core into other smaller, less dense, urban centers.

OECD (2018) also proposes a definition that considers various dimensions of urban sprawl: "… an urban development pattern characterized by low population density that can be manifested in multiple ways. That is, an urban area may be sprawled because the population density is, on average, low. Furthermore, urban areas characterized by high average density can be considered sprawled if density varies widely across their footprint, leaving a substantial portion of urban land exposed to very low-density levels. Urban sprawl can also be manifested in development that is discontinuous, strongly scattered and decentralized, where many unconnected fragments are separated by large parts of non-artificial surfaces." (OECD, 2018, p. 11)

In sum, despite urban sprawl being characterized in a variety of ways, some features seem to be prevalent in most studies, notably: low-density, dispersed, and fragmented land development, typically separated by single land uses (e.g., residential areas do not mix with commercial areas nor other types of land uses), with poor accessibility by public transport or active travel, and abundant road and parking infrastructure for the automobile.

2.2 Main drivers of urban sprawl

We now turn our attention to the main causes of urban sprawl, for which there is extensive literature. To provide a more structured overview of the literature, we have grouped the causes of urban sprawl into different categories, namely: economic, geographic, political, and socioeconomic.

2.2.1 Economic drivers

According to the monocentric city model, a common cause for urban sprawl can be related with the sectoral specialization of an urban area, or, in other terms, the degree to which employment is centralized in metropolitan areas. Addressing this cause, (Burchfield et al., 2006) argue that the degree to which metropolitan areas are specialized in employment sectors that tend to be more centralized in central areas, such as business services (where proximity and communication are particularly important), can directly lead to a more compact land development, thus, decreasing urban sprawl. Furthermore, Duranton & Puga (2015) also note the importance of agglomeration economies, explaining that localization and urbanization spillovers tend to produce urban structures where employment tends to be more concentrated in the central business district, as in the monocentric city model.

As noted in the initial section, the type of transportation systems most prevalent in a given area can also favor sprawl. Past literature highlights that urban agglomerations with better public transportation systems tend to be less sprawled. Burchfield et al., (2006) show that cities built around the automobile rather than public transportation systems tend to present more sprawl. Glaeser & Kohlhase (2004) also consider the role of transportation, particularly the decline in transportation costs, as a facilitator or urban sprawl. Lower commuting costs enable people to travel longer distances for the same price and time (assuming no congestion), which can facilitate more distant and dispersed residential land developments. The expansion of motorways seems to relate to this driver, as it enables a faster way of travelling that can ultimately allow people to reduce travel costs. A major point relates to the differing effects of transportation technology on spatial urban structures: whilst motorways tend to promote low(er)-density and scattered suburbanization by relocating population from central cities into more suburban areas, railways and metro services tend to favor high(er)-density urban development and the clustering of people and jobs around stations. This is in line with Glaeser & Kahn (2004) conclusion that transportation technology has always been a critical factor in shaping cities, and while public transportation enabled people to live far from their work, it still favored high density areas. In contrast, private motorized transportation, along with infrastructures that support this type of travelling, allows people to reside in low-density areas.

Factors related to expected urban growth can also be related with sprawl. Burchfield et al., (2006) argue that while people value open spaces, in areas where population is growing fast, people may not be willing to move farther out into housing that have larger access to open spaces if they expect those nearby vacant lands can soon be occupied. Furthermore, the author also relates higher levels of uncertainty about the future urban growth as a factor increasing urban sprawl, arguing that uncertainty levels about future urban growth can lead to greater rent uncertainty the farther away the parcel is from the city. This factor allied with possible construction lags and different expectations between developers can induce some landowners to choose earlier development while others choose to wait, creating a discontinuous leapfrogging development pattern (Ewing, 2008; OECD, 2018).

2.2.2 Physical geography drivers

Drivers related with physical constraints can also affect urban sprawl. Burchfield et al., (2006) explore these factors in detail. The presence of aquifers on the urban fringe can increase sprawl by providing a cheaper way for developers to make water connection by digging a well, without incurring on the large fees of extending the existing water supply infrastructure to more scattered areas. Other geographical factors considered are related to terrain elevation. High mountains surrounding urban areas can be a physical barrier for new land developments, constraining the total area available for development and leading to more compact land development. On the other hand, when terrain is rugged with small irregularities, we have the opposite effect, as flat portions of land are cheaper to develop when compared to more costly developments on steep hills, creating scattered development patterns that increase sprawl. In addition, OECD (2018) highlights other factors like the proximity to volcanoes and exposure to earthquakes may have the same impact, as they can be deterring factors for compact land developments and may limit population density levels. Burchfield et al., (2006) also consider the impact of natural amenities, e.g., cities with more pleasant climate tend to present more sprawl, as this characteristic makes open spaces more attractive.

2.2.3 Political drivers

Several political factors can explain urban sprawl. Burchfield et al., (2006) suggest that unincorporated areas around the urban fringe, where developers can escape municipal planning regulations, can increase urban sprawl. Additionally, it is also stated that when residents are accountable for infrastructure costs of new developments, they prefer more compact patterns of development that require less infrastructure spending, thus, decreasing urban sprawl.

Other popular causes of sprawl can be related to public policies that favor the automobile. For example, the presence of government subsidies to build roads and motorways, in addition to low fuel taxes and little subsidization of public transportation, have made the automobile the main form of transportation in the United States (Glaeser & Kahn, 2004). According to this view, urban areas that spend less on roads, promote public transportations, and have higher fuel taxes, experience less sprawl.

Furthermore, OECD (2018), Glaeser & Kahn (2004), Duranton & Puga (2015), and Gordon & Richardson (2011) all highlight zoning policies like single-use zoning or building height restrictions as having influenced urban sprawl. If municipalities closer to city centers have zoning policies limiting high-density construction or limit the type of land uses that can be constructed, this can encourage urban developments to move farther out into low-density municipalities around the edge of the city. Unintentionally, these zoning public policies may support urban sprawl by restricting new constructions in areas closer to city centers, which is the opposite effect of the implementation of zoning policies in the first place.

2.2.4 Socioeconomic drivers

Relating to socioeconomical drivers, rising household income has also contributed to suburbanization and urban sprawl (DeSalvo & Su, 2019; Duranton & Puga, 2015; Ewing, 2008; M. À. Garcia-López, 2019; Glaeser & Kahn, 2004; OECD, 2018). Rising incomes have allowed people to spend more on housing and transportation, which can translate into increased demand for larger houses and cars. The combination of rising income and reduction in transportation costs increased car ownership levels, which in turn enabled travelling longer distances, encouraging stronger household preferences for detached housing with greater access to open spaces and natural amenities, lower noise levels and better air quality. Margo (1992) supports this theory and argues that rising incomes can explain, in a large part, the increase in demand for land and suburbanization.

Likewise, Glaeser & Kahn (2004) emphasize that along with the importance of the automobile in the explanation of sprawl, the importance of rising household income throughout the 20th century as also a factor, coupled with the change in residential preferences for larger suburban plots of land. Quoting from their study: “Our view is that both the rising incomes and automobile ownership were necessary. After all, without rising incomes, Americans would not have had the money to pay for all those automobiles." (Glaeser & Kahn, 2004, p. 27)

2.3 Consequences of urban sprawl

Perhaps surprisingly, the literature on the impacts of sprawl is not as developed as the literature on its causes. The existing literature points to multiple effects of urban sprawl, covering economic, environmental, and social impacts. Some consequences of urban sprawl, such as the increased car dependency and increased costs of providing public services, cuts across the three main categories of impacts and provides important insights on what can be done in the future to prevent further urban sprawl. We discuss the main categories of consequences of urban sprawl addressed in past literature, focusing more on the impacts related with fuel consumption, mobility patterns and pollutant emissions, which we study empirically in the following sections.

2.3.1 Car dependency and travel mobility

As pointed by OECD (2018) and Litman (2015), in fragmented low-density areas it is easy to understand why people tend to travel more by car. Central cities or smart growth communities present more compact land developments that occupy a smaller geographical area with higher density levels and a more balanced land use mix between housing, jobs, services, and other amenities. With a smaller land uptake and balanced proportion of jobs and housing, compact land developments have everything needed in relatively close vicinities, thus, distances travelled between destinations can be minimized which translates into fewer kilometers travelled. Meanwhile, in sprawled areas, activities are dispersed and segregated, with single use development patterns. Houses are distant from workplaces and schools, and even local amenities such as supermarkets. Consequently, larger distances need to be covered. Litman (2015) states that smart growth community residents typically drive 20-60% fewer annual kilometers than in sprawled areas.

Besides increasing distances travelled, urban sprawl also has an impact on transportation mode choice. Bento et al., (2003; 2005) conclude that the likelihood to walk, cycle and use public transportation falls with decreased population density and urban sprawl. To this point, Litman (2015) argues that public transport use can be reduced by as much as 40-80% in sprawled areas, compared with more compact urban developments. In addition, Kahn (2000) shows that households located in city centers drive 17-43% less than seemingly identical households (in terms of lot size and income) located outside central areas. Likewise, Cervero (2002) argues that the probability of using public transport increases with residential density and mixed land use at the origin of the commuting trip. Overall, urban sprawl leads to dispersed development patterns that increase travel distances, which lead to an increased importance of the automobile and reduces travel options available, notably by public transport and active travel. Motorways also contribute to these impacts, given its direct effect on car use and the indirect effect on the urban spatial structure.

2.3.2 Fuel consumption and greenhouse gas emissions

Increased car use has environmental relevance as it can be directly related with higher fuel consumption, greenhouse gas emissions and overall air pollution. Studies like Neuman (2005), Bhatta (2010), and Ewing (2008) conclude that less compact cities present more vehicle kilometers, and subsequently, more emissions. According to Litman (2015), sprawled cities also produce more transport-related emissions than compact urban developments. As density levels per hectare double, per-capita transport energy consumption can decrease by orders of magnitude of 40-60%, thus, more compact developments can reduce transport emissions at a large scale, as energy efficiency tends to increase with densities. Energy consumption and pollution emissions also impose external costs such as fuel subsidy costs and economic costs of importing petroleum.

Nevertheless, Ewing (2008) argues the presence of polycentric urban development seems to be the best option in terms of energy efficiency. In addition, the author also concludes that vehicle emissions are more related with the total number of trips than with the distance travelled in total, since most of the pollution prevenient from automobiles is related with cold starts.

Glaeser & Kahn (2004) agree that driving is a major contributor to greenhouse gas emissions, as increased driving has played a role in increases in CO_2 carbon emission per capita. This is related with urban sprawl in the sense that in these areas, people drive more (Kahn, 2000; P. W. G. Newman & Kenworthy, 1989). Increased mileage leads to more fuel consumption and increases in greenhouse gas emissions. However, as Glaeser & Kahn (2004) also state, technological advancements on car manufacturing along with increases in the automobile´s fuel efficiency have had positive effects on mitigating the amount of greenhouse emissions.

2.3.3 Commuting times, congestion, and other external costs

Sprawl can also have impacts on traffic congestion, as more traffic can be directly correlated with higher congestion levels. With urban sprawl, people tend to rely more on the automobile as the main form of transportation, resulting in higher car use and increased congestion. Congestion issues are important to address as they can have major external economic, social, and environmental costs. As reviewed in OECD (2018), congestion alone caused 5.5 billion hours of delay in the US in 2011, which corresponds to a time cost equivalent to 0.9% of the GDP and 121 billion dollars of wasted fuel, which correspond to 0.78% of the GDP. Time wasted in traffic can also affect overall happiness of the population, as it is stressful to spend time stuck in transit. Thus, reducing congestion levels would not only increase the amount of time available for productive activities but also for leisure activities that can increase quality of life.

According to Ewing (2008), sprawl has an impact on travel demand and traffic congestion by favoring car use and reducing the opportunities to use public transport. Other externalities relate to road accidents, although they are partially internalized due to driving insurances. Litman (2015) concludes that traffic fatality rates are five times higher in sprawled areas when compared with smart growth areas.

2.3.4 Public finance and the high cost of providing public services

Since the provision of public transportation and other public services in sprawled low-density areas is generally economically inefficient and more expensive than in central cities, there is greater need for public subsidies. As elaborated in OECD (2018), even if public services like transportation were offered at the same frequency in sprawled areas as in downtown areas, car-dependency would not be eliminated because land use mixes and design are both car-oriented; furthermore, once people already own a car, they are more likely to use it. On the other hand, providing public transportation services at a higher rate may not be a solution because it leads to the need to incur large public subsidies due to the low-occupancy levels of public transport in sprawled areas.

OECD (2018) and Carruthers & Ulfarsson (2003) highlight that this problem is present not only in the transportation sector, but also in a large variety of different public services requiring economies of density to operate in an efficient and economically sustainable way, including: road cleaning and maintenance, waste collection and disposal, sewerage and water provision, police and fire protection, libraries and maintenance of parks and other recreational areas. This, in turn, leads to higher budget deficits and greater pressure on local public finances, which are hard to reverse on the short term. According to Litman (2015), urban sprawl can increase the costs of providing public services by 10-40%.

However, despite the wide support for the increased cost of providing public service caused by urban sprawl, it is important to note that some scholars also argue that infrastructure costs in compact land developments can be higher than in sprawled areas. Ladd & Yinger (1991) and Ladd (1994; 1992) suggest that greater densities are associated with higher, not lower, public service expenditures because the cost of services rises with density, exhibiting a U-shaped relationship: first declining as density increases but then increasing sharply, leading to average costs that exceed the minimum by as much as 43% in very dense areas. The implication is that services are subject to both urban economies and urban diseconomies, suggesting there may be an optimum size or scale beyond which the marginal costs exceed the marginal benefits of urban density (Ladd et al., 1998).

2.3.5 Loss of farmland and open spaces

The urban economics literature on sprawl argues that urbanization, and in particular sprawl, has contributed largely to the loss of farmland and open spaces (Ewing, 2008; Johnson, 2001; Litman, 2015; OECD, 2018). According to these studies, sprawled urban development displaces open spaces and reduces the productivity of nearby land, disrupting farming activities, disturbing wildlife, contaminating groundwater, and reducing the ecological services such as groundwater recharge, wildlife habitat. While sprawl residents may experience more private open spaces, this development pattern displaces more per capita open space, and sprawl residents can be considered to consume nature while more compact development residents preserve nature, resulting in more open space overall (Litman, 2015).

Loss of farmlands can subsequently decrease the levels of agricultural productivity as the first lands occupied by suburbanization are farmlands surrounding urban areas. This can have negative effects on food supply, and external impacts can be seen on communities dependent on the agricultural sector which can become extinct, increasing dependency on imported food related products and massive investments on undeveloped agricultural land in less developed parts of the world in order to provide these products (e.g., Africa´s agro-colonization made by the USA). Additionally, sprawl can also affect the positive outcomes of alternative land-uses such as forestry and open spaces. These spaces are essential for wildlife and generate positive effects related to air quality and carbon sequestration, along with other environmental benefits (OECD, 2018). Impact studies regarding this aspect of urban sprawl suggest there may have been an under estimation of the full benefits of these types of land uses, including people's value for open spaces such as greenspaces. The aggregate social value for the protection of open spaces may be higher than the willingness to pay by land developers, implying there may be positive welfare gains and high external social benefits.

Some other studies have offered a different perspective on the effects of urban sprawl on the loss of farmland and open spaces, arguing that despite sprawl consuming more land, the scale of cities and urbanization is still a fraction of the land available globally (Burchfield et al., 2006; Glaeser & Kahn, 2004), thus, the impact of urban sprawl is not a crucial consequence.

3. Data and Empirical Strategy

As stated in the first section, we consider that motorways can affect both directly and indirectly travel mobility and fuel consumption. The direct effect can arise from the fact that the investment in roads and motorways is an incentive for car traveling. Additionally, motorways may indirectly affect travel demand patterns, particularly mode choice, through the development of an urban spatial structure more prone to car use: motorways reduce the travel cost between homes and workplaces, which may incentive land developers and more suburban municipalities, particularly in metropolitan areas, to build new residential urbanizations (and consequently their supporting services such as supermarkets, etc.) close to the main motorways access nodes, reducing the density and increasing the fragmentation of urban development. The result is that both motorways and urban sprawl contribute to an increase in the proportion of trips by car and fuel consumption.

Although urban sprawl and motorways are addressed throughout the literature review in regions such as the USA and the European Union in general, studies focusing on the relationship between motorways, urban sprawl, and travel mobility are still relatively scarce, particularly in the Portuguese context. In this section, we describe the variables collected to implement empirical models that can test the effect of motorways and urban sprawl on the share of trips done by car and fuel consumption.

3.1 Variables and data sources

3.1.1 Urban Sprawl and Motorways[1]

To measure motorways, we considered the total extension of the motorway and expressway network in a given municipality and year. Regarding urban sprawl, we consider measures for two dimensions: size and fragmentation. Concerning size, we consider two density indicators that allow us to evaluate the size of a given urban area: 1) gross urban density, measuring the population living in urban land in relation to the urban land area, 2) net urban density, measuring the population living in urban land in relation to the residential urban land area.

To capture the degree of fragmentation, we use an indicator for the area of discontinuous urban land parcels in relation to total urban land area.

3.1.2 Travel mobility and Fuel consumption

As one of our objectives is to test how motorways and urban sprawl affected travel mobility and fuel consumption, we collected data for the percentage people who use the car as their main form of transportation during commuting trips and the consumption of fuel per capita across municipalities and for each time period. Data for commuting trips were obtained from the decennial population censuses tables, provides by INE (Instituto Nacional de Estatística). From this data, we constructed two sub-variables:

The percentage of commuting done by car as drivers, as this variable gives us a good base proxy for the proportion of private-own automobiles used in the total commuting trips done by students and active population.

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[1] The indicators for motorways and urban sprawl were obtained from the project "TiTuSS - Transportation Infrastructure and Urban Spatial Structure: Economic, Social and Environmental Effects" – see the Acknowledgements. For more details about urban sprawl indicators, please see the project's website.

The percentage of commuting done by car as car passengers, which refers to the trips made in car by non-drivers. This can be considered a form of car sharing, which is considerably better than solo driving.

Regarding fuel consumption, we collected information only for types of fuel usually connected with road transportation and vehicle transportation. Thus, for fuel consumption we considered the total amount of gasoline and diesel consumed. Additionally, it is important to note that fuel consumption corresponds to the total gasoline and diesel consumption by all types of road transportation vehicles. Ideally, we would have collected fuel consumption only for light passenger vehicles, but, due to the lack of data available on a municipality level for Portugal, especially in early years of our time period, we were only able to gather data related with total amount of gasoline and diesel consumption made by road transportation related vehicles, which also include heavy vehicles such as trucks used to transport goods. This variable is expressed in tonnes and was collected from the Directorate-General of Energy and Geology DGEG (Direção-Geral de Energia e Geologia) for the years 1991, 2001, 2011, and 2019.

3.1.3 Socioeconomics and Geography

For socioeconomics we will use both population density and average income indicators, obtained from INE (Instituto Nacional de Estatística) for the years 1991, 2001, 2011, and 2019. Our geography variable is the standard variation of altitude in meters, in a given municipality, and it was obtained from the TiTuSS project

Table 1 and table 2 relate to our dependent variables and main explanatory variables respectively, with the indicators used in empirical equations, along with its definitions and data source.

Table 1 – Model Dependent Variables definitions and original source

Variable	Definition	Source
% of car use	% People commuting by car	INE (Instituto Nacional de Estatistica)
DRIVER	% People commuting using the car as drivers	Author computations
PASS	% People commuting using the car as Passengers	Author computations
Log (Car_use)	DRIVER + PASS	Author computations
Fuel Consumption		DGEG (Direção-Geral de Energia e Geologia)
Log (FUELPC)	Log of Total fuel consumption per capita. (Tonnes of gasoline and diesel)	Author computations

Table 2 - Main explanatory variable definitions and original sources

Variable	Definition	Source
Motorways		TiTuSS project
Log (MTW)	Log of Total extent of motorways and expressways in kms.	Author computations
Urban Sprawl		TiTuSS project
log (NETDEN)	Log of the ratio between people in urban area and residential area	Author computations
log (GROSSDEN)	Log of the ratio between people in urban area and total urban area	Author computations
DULA	% of discontinuous urban land in relation with total urban land area	Author computations
Socioeconomics		
Log (INC)	Log of Average Income	PORDATA
Log (POPDEN)	Log of population density in total area of the municipality	TiTuSS project
Geography		TiTuSS project
ALTI_SD	Standard deviation of the average altitude for each municipality	TiTuSS project

3.2 Descriptive analysis of the main variables

We now turn our focus to describing the evolution of the main variables in the empirical models.

3.2.1 Percentage of people using the car as their main form of transportation in commuting trips.

The first main dependent variable is the Percentage people using the car as their main form of transportation in commuting trips. As stated in the previous point, this variable is sub-divided in two categories:

the percentage of commuting done by car as drivers

the percentage of commuting done by car as car passengers

Figure 1 shows the evolution of the percentage of people using the car as their main form of transportation in commuting trips during the period studied. We can see that, in general, the share of trips by car as a driver increased across Portugal's municipalities. On average, in 1991, only 15% of commuting trips was done by people driving a car. This increased drastically throughout the period and in 2011, the value reached an average of 45%. In an interval of 20 years, this variable has tripled its value. Regarding people using the car as their main form of transportation as passengers, the values also increase drastically. In 1991, only 5% of people used the automobile as passengers. At the end of the period of analysis, this indicator was around 17%. At last, by analyzing the variable where we add our two sub-variables, we reach a total of 19% of commuting trips made by car either as a driver or a passenger in 1991, while in 2011 this value was around 62%.

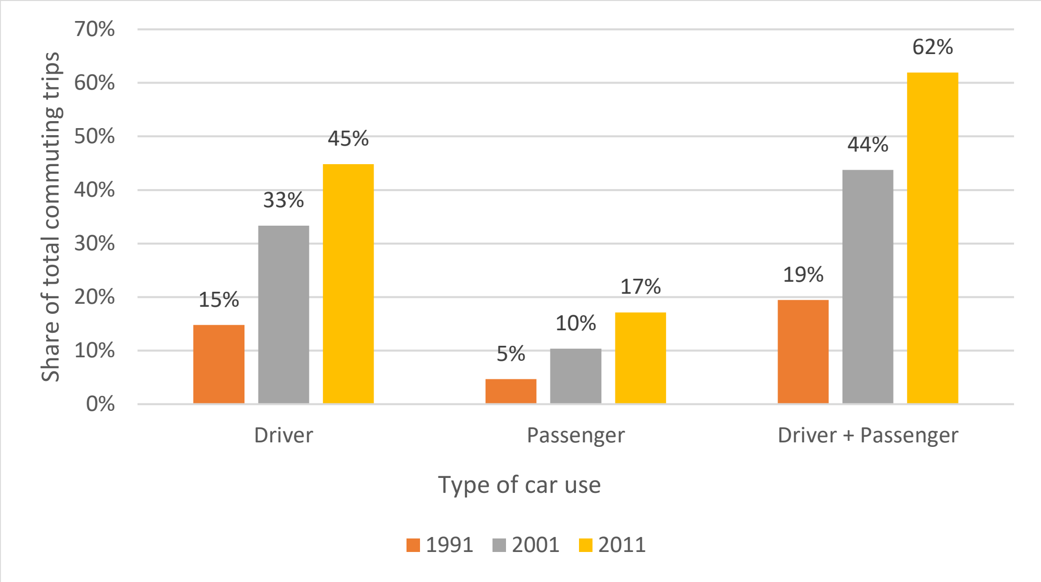

Figure 1- Share of total commuting trips (%) for active population and students, where the main form of transportation was the automobile, by people using the car as Drivers and as Passengers for the years of 1991,2001, and 2011. Data sourced from INE- Instituto Nacional de Estatística.

3.2.2 Fuel consumption

The second main dependent variable is fuel consumption. Despite fuel consumption being related to a large variety of activities, we calculated fuel consumption as the amount of gasoline and diesel used, as these are the types of fuel that are usually used in road transportation. We also consider 2019 as our last year of analysis because of the covid-19 pandemic that began in March of 2020 and would most likely affect this variable. As noted earlier, this indicator contains values for not only light passenger vehicles, but also includes values for types of vehicles such as trucks and heavy transportation vehicles used with a business objective.

Figure 2 shows the evolution of fuel consumption in Portugal for the last 30 years, mainly, the consumption of types of fuel usually related with road transportation, such as gasoline and diesel. Fuel consumption increased steadily during the 1990s and early 2000s, reaching its peak in 2004 with 6,857,945 tonnes of gasoline and diesel consumed. Afterwards, there was a slight decline, with special emphasis on the period between 2010 and 2013 where fuel consumption dropped from 6,283,111 tonnes to 5,181,196 tonnes respectively. This decline is associated with the economic recession in that period. After 2013, fuel consumption in Portugal slowly resumed its ascending trend until 2019 (just before the covid-19 pandemic), reaching around 5,676,249 tonnes of fuel consumed.

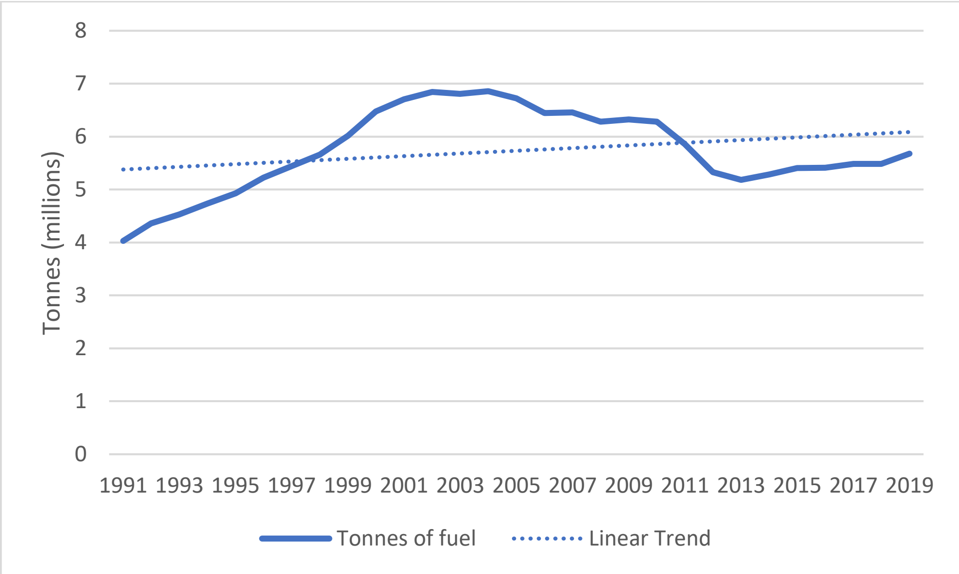

Figure 2 – Total tonnes (million) of fuel consumption (in gasoline and diesel) for the period of 1991-2019. Data sourced from DGEG (Direção-Geral de Energia e Geologia).

The rise of alternative electric vehicles can also influence fuel consumption, especially in more recent years; although it would be interesting to include this dimension in a wider study of drivers of fuel consumption, for the purpose of this study we have decided not to include a measure for the use of electric vehicles. As we can see by the Figure 3, the total number of electric vehicles is still a fringe part of the total amount of vehicles in circulation, accounting for around 2.2% of the total light passenger vehicles in circulation. Thus, we chose not to include them in our analysis and stick to gasoline and diesel emissions.

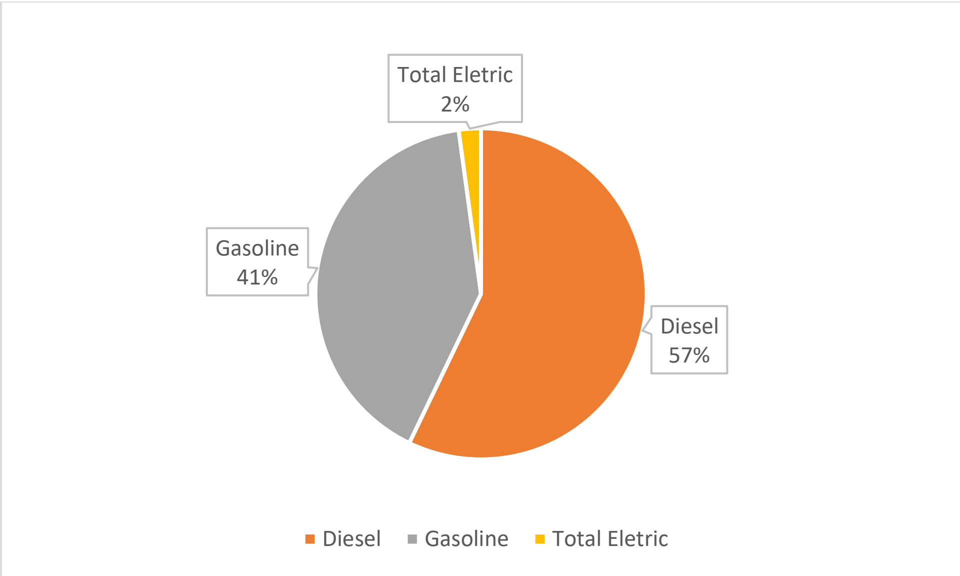

Figure 3 – Share of light passenger vehicles, in circulation in Portugal (2020), by type of energy consumed (Gasoline, Diesel and Electric Vehicles). Data sourced from INE (Instituto Nacional de Estatística).

3.2.3 Motorways

As previously stated, motorways saw a great expansion since Portugal joined the EU in 1986. We analyse the extension of motorways and expressways for the years of 1991, 2001, and 2011. Figure 4 shows the evolution of motorways and expressways in Portugal between 1991 and 2011. We can clearly see a great expansion of the motorway network. While in 1991, motorways were scarce and mainly serving the two main metropolitan areas, in 2011 motorways extended also to other parts of the country, serving connections to more interior regions of Portugal. There were also additional motorways built in the main metropolitan areas and between then, connecting the most populated areas along the coast of the country. During the analysis period of 1991-2011, the Portuguese motorway and expressways network grew from around 550 hundred kms to approximately 2,9 thousand Kms in 2011.

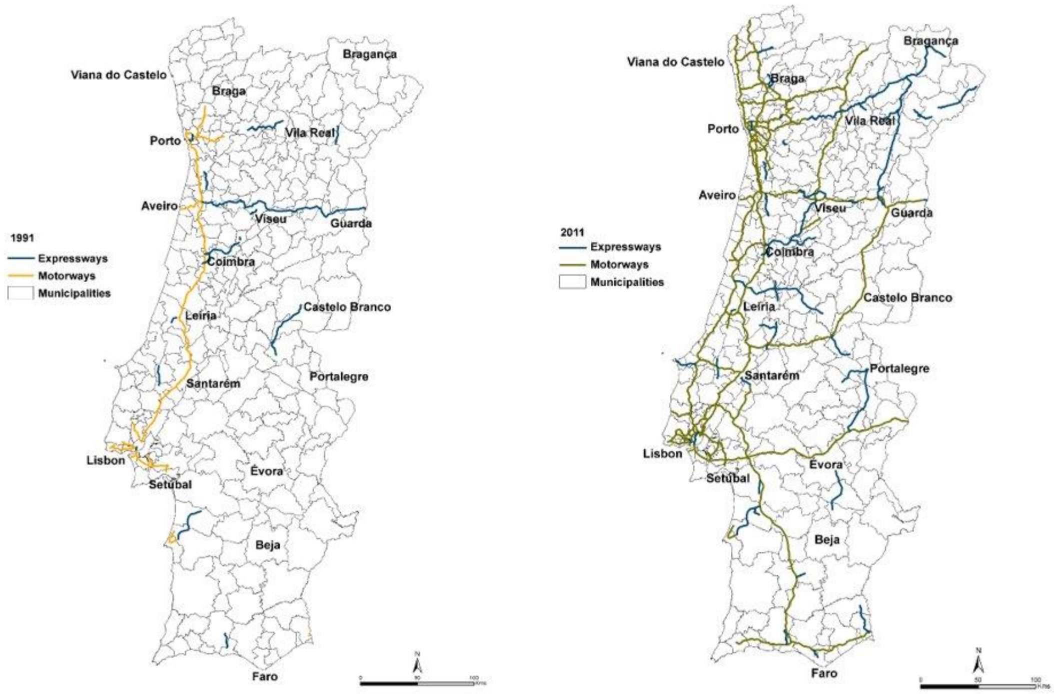

Figure 4 - Motorway network and expressways (Kms) in Portugal in 1991 and 2011. Data sourced from TiTuSS project.

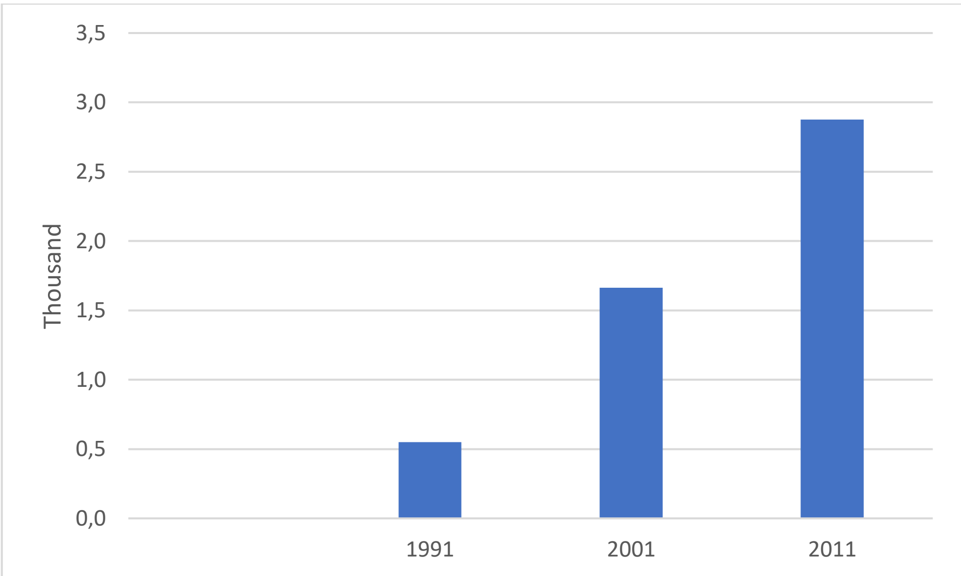

Figure 5 - Portuguese Motorway and expressways Extension (Thousand Kms), during the period of 1991-2001. Data sourced from TiTuSS project.

3.2.4 Urban sprawl

Figure 6 shows the evolution of the urban land development for 1991-2011 (the picture states 1990-2012 but data were sourced from census information relative to the years of 1991-2011, while the land cover uses refer to 1990 and 2012).

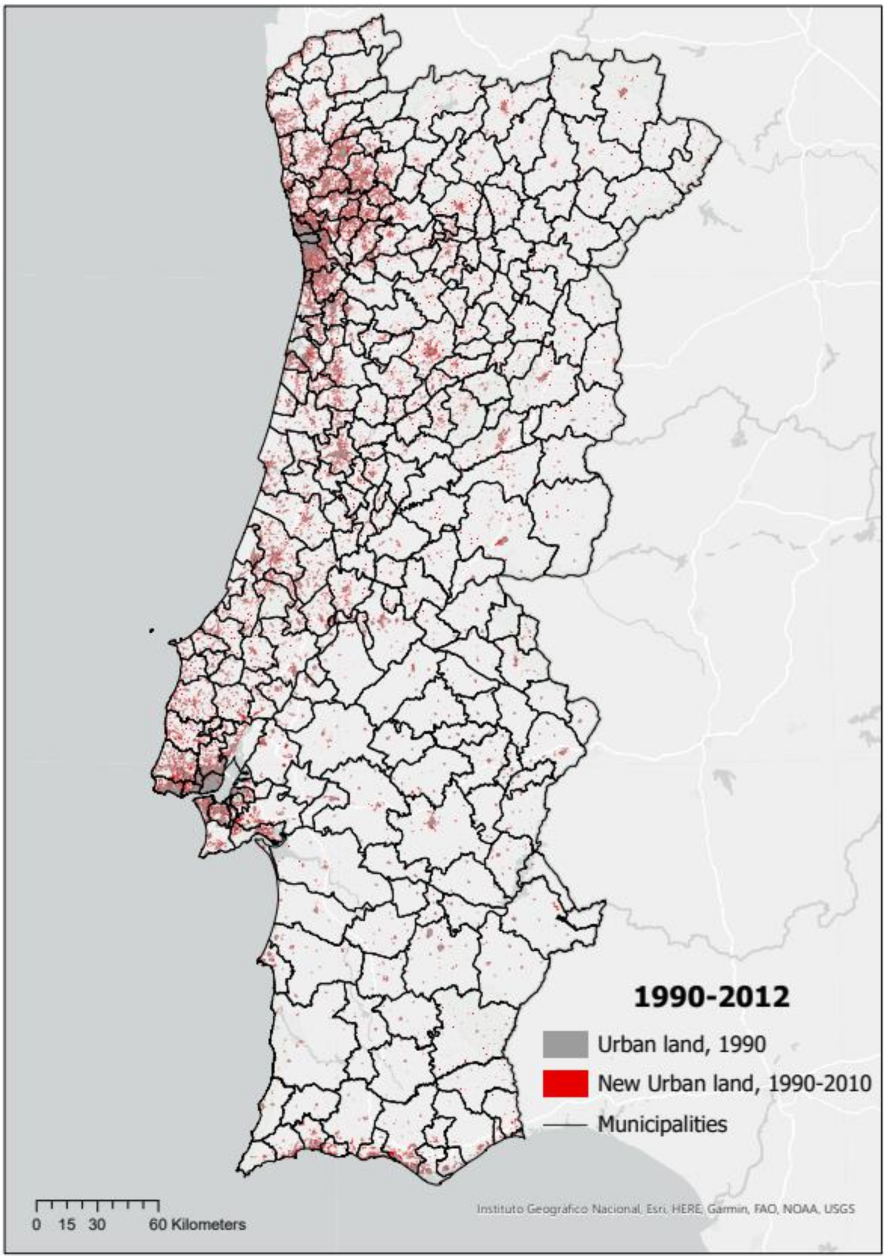

Figure 6 – Evolution of urban land development in Portugal. Data sourced from TiTuSS project.

The indicators relating to the dimension size – net and gross densities -, have been decreasing over the period 1991-2011. Figure 7 shows that the net density indicator reduce from around 1,972 people per square km of residential urban area in 1991 to about 1,707 people per squared km in 2011. Regarding the gross density indicator, the value reduced from around 1,799 people per square km of urban land area to 1,465 in 2011. On average, municipalities saw the net density levels decrease by 13.4 %, and by 18.6% in the case of gross density.

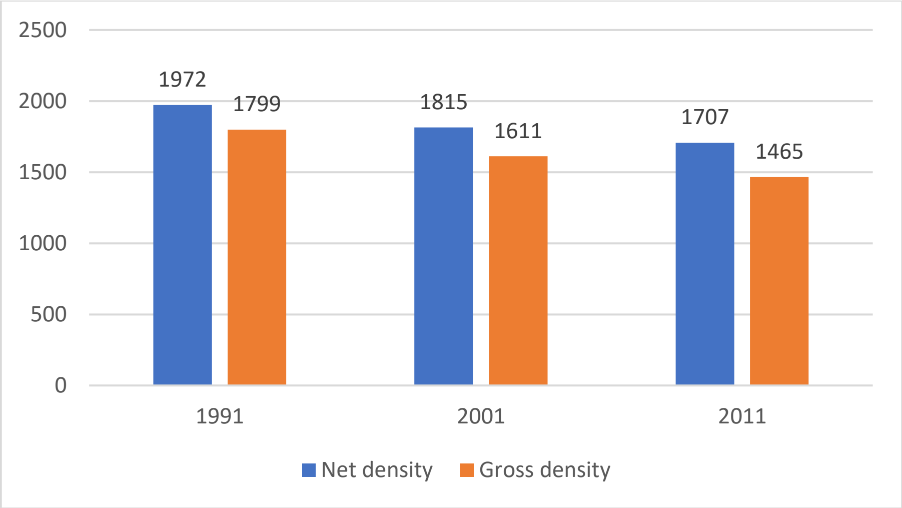

Figure 7- Size dimension indicators (net density and gross density) of Urban Sprawl for the years of 1991,2001, and 2011. Data sourced from TiTuSS project.

Regarding fragmentation, the ratio of discontinuous urban land units in relation to urban land area remained roughly the same, around 59%. Despite fragmentation levels remaining roughly the same, they are relatively high. On average more than 50% of urban land is discontinuous, and additionally, our size dimension indicators reveal that overall densities have been decreasing since 1991.

4. Conceptual model and empirical strategy

4.1 The conceptual model and model hypotheses

Figure 8 describes the conceptual model used for the empirical analysis and subsequent models and equations. The objective is to explain, in a visual and simple manner, the relationships we are interested in, and which form the basis of the empirical regression models. As stated previously, motorways may affect transport mode choice in a direct and indirect manner. The direct effect arises from the incentive on car travelling provided by the expansion of the motorway network and the indirect effect arises from the fact that motorways favour urban sprawl and low-density suburbanization, which also promote greater car use. Thus, as our first model hypothesis we have that Motorways may be directly leading to changes in travel mobilities (Hypothesis 1). Additionally, an increased expansion of the motorway network may also have an effect on fuel consumption through the effect of increased road supply on induced traffic demand and vehicle kms travelled (Hypothesis 2).

Urban sprawl also presents itself as a major explanatory variable, as sprawled areas may be increasing levels of dependency on the automobile (Hypothesis 3) and subsequently on Fuel consumption (Hypothesis 4). Relating Motorways and Urban Sprawl is also important to note that, throughout the literature, motorways may be seen both as a cause and a consequence of urban sprawl, revealing a feedback loop of mutually reinforcing effects. It would be interesting to study this bi-directional relationship, but it is out of the scope of this study, and thus it is not incorporated in our empirical analysis. Socioeconomic and geographic variables, particularly income levels but also physical geography constraints, can influence urban development patterns either by facilitating more dispersed or compacted urban patterns and levels of car use. Therefore, socioeconomic factors may be leading both to higher car use (Hypothesis 5) and higher fuel consumption (Hypothesis 6), in addition, possible geographic effects may be leading to increases in car travelling (Hypothesis 7) and increases in fuel consumption (Hypothesis 8).

In the case of the fuel consumption per capita model, and in addition to the factors already mentioned, we also consider the direct effect of the share of trips made by car given the direct link between car use and fuel consumption (Hypothesis 9)

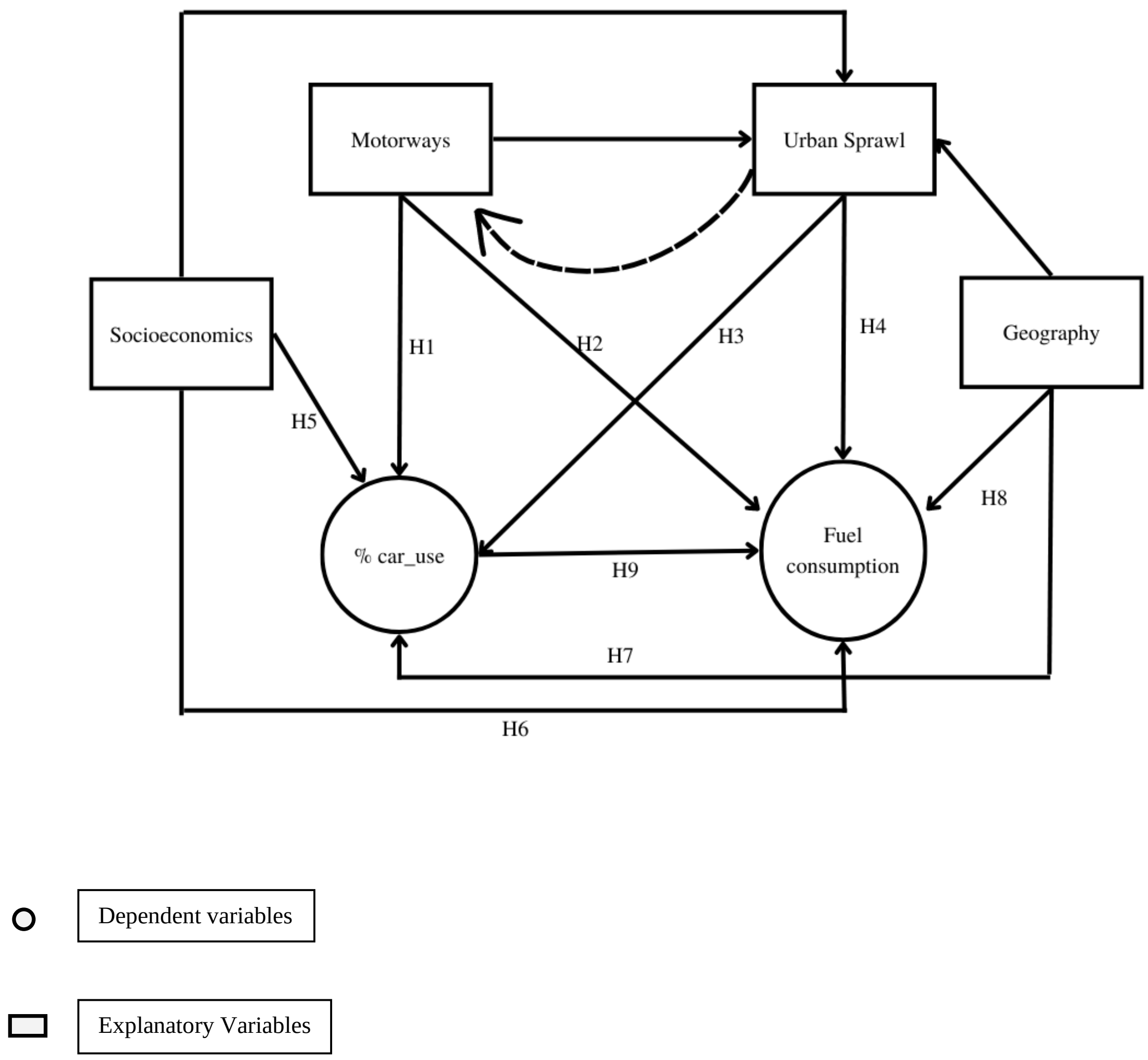

Figure 8 - Conceptual model for empirical analysis. Source: Design made by own author after taking inspiration from an initial sketch made by Professor Patricia Melo.

4.2 The empirical strategy

We consider the two econometric models below to estimate the effect of motorways and sprawl on car use levels and fuel consumption:

1) $\%car\_use_{it} = \beta_0 + \beta_1\, Motorways_{it} + \beta_2\, Sprawl_{it} + \beta_3\, Socioeconomics_{it} + \beta_4\, Geography_{it} + \varepsilon_{it}$

2) $FuelConsumption_{it} = \beta_0 + \beta_1\, Motorways_{it} + \beta_2\, Sprawl_{it} + \beta_3\, Socioeconomics_{it} + \beta_4\, \%car\_use_{it} + \beta_5\, Geography_{it} + \varepsilon_{it}$

Where the subscripts *i* and *t* refer to the 275 municipalities[2] of mainland Portugal and the years 1991, 2001, and 2011. The variables car use, measured in logarithm of the share of people who use the car as their main transportation form in their commuting trips, and fuel consumption, measured by the logarithm of the fuel consumption per capita for each municipality, are our dependent variables. The main explanatory variables of interests refer to: *motorways*, measured by the logarithm of the extension of motorways; *sprawl*, measured with indicators for the two dimensions size and fragmentation; referred in the previous section: size (i.e. either net density or gross density) and fragmentation. In addition to these variables, we have added control variables for *socioeconomics* (measured by the logarithm of average income and the logarithm of population density of the municipality) and *geography* (i.e. the indicator of topography and ruggedness based on the standard deviation of intra-municipality altitude). Although there are data available for some variables for more recent years, we considered the period limited to 1991-2001-2011due to the fact that the indicators for

[2] Mainland Portugal has 278 municipalities since 1998; five municipalities lost part of their territory to form the three new municipalities that were created in 1998. To ensure data consistency we use the pre-1998 administrative division of 275 municipalities.

urban sprawl and car use are not available after 2011 (we are waiting for definitive 2021 population census data). We estimated the models using panel data estimators in Stata, particularly the pooled OLS estimator, the random-effects estimator, and the fixed-effects estimator.

Before discussion the regression results in the following section, we present some descriptive statistics in Table 3, and checked for pairwise correlations between variables to help in the model specification (see Table 4). For example, we see that gross and net density are strongly correlated with each other: this is not surprising as they are both density indicators capturing the same effect. To avoid bias we consider a density indicator at a time in our models. In addition, we used income as the main socioeconomic variable, rather than municipality population density, to reduce possible bias from partial overlap with the two density variables referring only to urban land (although the pairwise correlations are not very strong). Additionally, as time effects may have significant impacts on our estimations, we added a time trend in order to take that into account and prevent possible unobserved influences on the results.

Table 3 - Summary Statistics of all variables

Variable	Obs	Mean	Std. Dev.	Min	Max
logCar use	825	-1.006	.551	-2.578	-.202
log FUELPC	825	-.888	.745	-6.241	2.72
log MTW	825	3.648	4.593	0	11.238
log NETDEN	825	7.35	.533	5.641	9.506
log GROSSDEN	825	7.239	.528	5.641	9.429
DULA	825	.583	.23	0	.982
log INC	825	6.353	.42	5.471	7.451
log POPDEN	825	4.361	1.414	1.629	8.967
ALTI SD	825	65.98	49.683	2.656	254.765

Table 4 - Correlation Matrix of all variables

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) logCar_use	1.000								
(2) log_FUELPC	0.143	1.000							
(3) log_MTW	0.337	0.221	1.000						
(4) log_NETDEN	-0.073	0.025	0.213	1.000					
(5) log_GROSSDEN	-0.126	-0.062	0.131	0.935	1.000				
(6) DULA	-0.023	0.054	0.030	-0.489	-0.524	1.000			
(7) log_INC	0.848	0.188	0.463	0.085	-0.017	-0.093	1.000		
(8) log_POPDEN	0.060	-0.007	0.494	0.422	0.398	-0.260	0.126	1.000	
(9) ALTI_SD	-0.032	-0.222	-0.274	-0.244	-0.174	0.002	-0.122	-0.122	1.000

5. Results and Discussion

5.1 The effect of motorways and sprawl on the share of people using the car as their main form of transportation.

The results obtained from the estimation of the equation referring to the share of people who use the car as their main form of commuting are presented in Table 5. There are six model specifications. Specification (1) and (2) are concerned to our Pooled OLS estimations. Specification (3) and (4) are related to the fixed effects model version, and (5) and (6) regard the random effects model estimation. In addition, equations (1), (3), and (5) are computed using only net density for our size dimension of sprawl, and equations (2), (4), and (6) are computed using only gross density.

In panel data model analysis, the big question usually concerns if our unobserved individual effects and our explanatory variables are correlated or not. If we assume they are not, we proceed with Random Effects or the Pooled OLS model estimations. In case we assume our individual effects and our explanatory variables may be correlated, we should proceed with the fixed effects model version.

The Pooled OLS model estimation gives us a simple overview of the effects of our variables, using the ordinary least squares regression method. More often than not, this model estimation is not considered for interpretating results, given that in panel data analysis, the Random effects estimator has higher capacity of exploring the panel nature of the data and is usually more efficient than the Pooled OLS. Thus, Random effects is usually preferred over the Pooled OLS. By using the Durbin–Wu–Hausman (DWH) test we can choose between fixed effects and random effects in a simple manner, and thus, decide which model estimator to use. According to the Hausman test, for the share of people who use the automobile as their main form of transportation either by driving or being a passenger, we should focus on the fixed effects estimator, as the null hypothesis for the model being random effects, was rejected.

For overall car use, we can see that motorways are statistically significant at the one percent level, revealing that motorways play a role in explaining shifts in car use and overall car dependencies and changes in travel mobilities. However, the effect of motorways is unexpected: the coefficient is negative, indicating that extensions on motorways lead to less car use. A 1% increase in the total extent of motorways and expressways lead to a -0.01% decrease in the share of people who use the car as their main form of transportation on their commuting trips. This contradicts usual theory seen on past studies on the effects of this variable. However, a possible explanation for this may be due to the fact of our motorway variable not including the "network" effect of these types of transportation infrastructures. Motorway effects may not be restricted only on the specific municipality in which they are inserted, and, most likely, have impacts on a regional level that our indicator is not able to capture.

Concerning our urban sprawl indicator, we can perceive that, by analyzing the results, only our size indicators seem to explain shifts in car use. With both net density and gross density being negative and significant at the one percent level, this indicates that higher densities in urban areas leads to less people using the car as their form of commuting, which is in line with expected results and past literature on density effects of urban sprawl. A 1% increase in net density led to a – 0.35% decrease in the share of people who use the car as their main form of transportation on their commuting trips. In addition, a 1% increase in gross density led to a -0.32% decrease in the share of people who use the car as their main form of transportation on their commuting trips.

Income is also a major explanatory variable, being positive and statistically significant at the one percent level, an indication that higher average wages encourage more car use. This effect goes along with previous studies, when stating that higher incomes have allowed people to own more automobiles and, subsequently, use them more. A 1% increase in average incomes lead to a 0.64% increase in the share of people who use the car as their main form of transportation on their commuting trips.

On a final note, we can also see that our time trend is also positive and significant, explaining that these values have a linear tendency to grow over time.

Table 5 - Model estimations for the share of people using the car as their main form of transportation in commuting trips

	Pooled OLS (1)	Pooled OLS (2)	Fixed Effects (3)	Fixed Effects (4)	Random Effects (5)	Random Effects (6)
VARIABLES	logCar_use	logCar_use	logCar_use	logCar_use	logCar_use	logCar_use
log_MTW	0.00113	0.000887	-0.0113***	-0.0115***	0.000937	0.000639
	(0.00200)	(0.00202)	(0.00339)	(0.00337)	(0.00210)	(0.00211)
log_NETDEN	-0.0537***		-0.346***		-0.0533**	
	(0.0207)		(0.0782)		(0.0209)	
DULA	-0.0614	-0.0548	0.0669	0.0231	-0.0571	-0.0517
	(0.0454)	(0.0474)	(0.129)	(0.127)	(0.0464)	(0.0488)
log_INC	0.348***	0.324***	0.654***	0.639***	0.365***	0.341***
	(0.0648)	(0.0645)	(0.0762)	(0.0759)	(0.0738)	(0.0769)
ALTI_SD	-0.000113	-7.99e-05				
	(0.000199)	(0.000198)				
year	0.0433***	0.0443***	0.0296***	0.0294***	0.0425***	0.0436***
	(0.00306)	(0.00306)	(0.00356)	(0.00356)	(0.00338)	(0.00363)
log_GROSSDEN		-0.0418*		-0.315***		-0.0421*
		(0.0215)		(0.0689)		(0.0246)
Constant	-89.36***	-91.46***	-61.79***	-61.68***	-87.94***	-90.14***
	(5.797)	(5.800)	(6.805)	(6.784)	(6.360)	(6.895)
Observations	825	825	825	825	825	825
R-squared	0.803	0.802				
Whithin R-squared			0.871	0.8707	0.8624	0.8619
Between R-squared			0.0039	0.0010	0.0381	0.0375
Overall R-squared			0.7149	0.7277	0.8029	0.8023
Corr (u_i, Xb)			-0.2521	-0.2315	0	0
rho			.4938	.4699	0.0279	0.0272
Number of ID			275	275	275	275

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5.2 The effect of motorways and sprawl on fuel consumption per capitaThe results obtained from the estimation of the equation referring to the fuel consumption per capita are presented in Table 6. There are six model specifications. Specification (1) and (2) are concerned with our Pooled OLS estimations. Specification (3) and (4) are related to the fixed effects model version, and (5) and (6) regard the random effects model estimation. Is also of notice that equations (1), (3), and (5) are computed using only net density for our size dimension of sprawl, and equations (2), (4), and (6) are computed using only gross density. Using the same logic as in the case before, we used the Hausman test to choose between the Fixed Effects and Random Effects estimators. Since we cannot reject the null hypothesis of the model being random effects, we consider the random effects model estimator for interpreting results. According to the random effects estimator, our variable for car use has a positive and statistically significant effect, at the one percent level, which indicates that as more people use the automobile, more fuel is consumed. The coefficient parameter suggests that an increase of 1 percent in car share is associated with an increase of about + 0.3% in fuel consumption per capita.

Regarding motorway's effect on fuel consumption, we see that more kms of motorways increase fuel consumption per capita. This is intuitive and in agreement with past literature research on the effects of motorways. The average effect of an increase of 1% in motorways is about + 0.01% increase in fuel consumption per capita, which is much smaller than the effect of car use.

For our urban sprawl variables, only the size dimension indicators seem to explain effects on fuel consumption, as higher densities lead to less fuel consumed, which is intuitive given that in higher density areas, people use the car less and prefer public transportation methods. The average effect of an increase of 1% in net density is around - 0.19% decrease in fuel consumption per capita. The average effect of an increase of

1% in gross density is about - 0.23% decrease in fuel consumption per capita, which is much smaller than the effect of car use.

For our control variables, we see that income assumes a major explanatory role, presenting the highest coefficient of all indicators, suggesting that, at a significance level of one percent, increases in incomes have undoubtedly allowed people to not only own more cars, but also consume more fuel. The average effect of an increase of 1% in average income is about + 1.2% increase in fuel consumption per capita. Regarding this variable, it would be interesting to study if public policies relying on the rise of fuel prices and lowering the prices of public transportation may have had a large impact on both car use and overall fuel consumption.

Table 6 - Model estimations for fuel consumption per capita

VARIABLES	Pooled OLS (1) log_FUELPC	Pooled OLS (2) log_FUELPC	Fixed Effects (3) log_FUELPC	Fixed Effects (4) log_FUELPC	Random Effects (5) log_FUELPC	Random Effects (6) log_FUELPC
logCar_use	0.389***	0.386***	0.216**	0.226**	0.324***	0.323***
	(0.0804)	(0.0795)	(0.103)	(0.103)	(0.0906)	(0.0903)
log_MTW	0.0127**	0.0137**	0.00813	0.00796	0.0123*	0.0127*
	(0.00578)	(0.00575)	(0.00883)	(0.00885)	(0.00652)	(0.00648)
log_NETDEN	-0.148**		-0.502***		-0.182***	
	(0.0597)		(0.179)		(0.0668)	
DULA	0.233*	0.139	0.00602	-0.0494	0.173	0.0983
	(0.137)	(0.143)	(0.261)	(0.263)	(0.140)	(0.143)
log_INC	1.192***	1.145***	1.250***	1.220***	1.212***	1.170***
	(0.161)	(0.156)	(0.207)	(0.206)	(0.162)	(0.159)
ALTI_SD	-0.00203***	-0.00205***			-0.00213***	-0.00211***
	(0.000424)	(0.000419)			(0.000650)	(0.000639)
year	-0.0772***	-0.0761***	-0.0708***	-0.0707***	-0.0743***	-0.0735***
	(0.00850)	(0.00828)	(0.00997)	(0.0100)	(0.00830)	(0.00820)
log_GROSSDEN		-0.211***		-0.406**		-0.231***
		(0.0598)		(0.168)		(0.0660)
Constant	147.4***	146.0***	136.8***	136.0***	141.8***	140.8***
	(16.39)	(15.92)	(19.19)	(19.28)	(16.03)	(15.81)
Observations	825	825	825	825	825	825
R-squared	0.171	0.179				
Whithin R-squared			0.1151	0.112	0.1084	0.1086
Between R-squared			0.0743	0.1493	0.2176	0.2306
Overall R-squared			0.0873	0.1330	0.1703	0.1779
Corr (u_i, Xb)			-0.1343	-0.0270	0	0
rho			0.4848	0.4564	0.3099	0.3030
Number of ID			275	275	275	275

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6. Conclusions

6.1 Academic implications

Studies on urban sprawl and motorways for Portugal are scarce. Thus, this MFW is relevant as it is a first step in studying the impacts of motorways and urban sprawl in Portugal, and, hopefully, can be a starting point for future research on this topic.

6.2 Implications for practitioners and policy makers

By applying econometric techniques and computing panel data model estimations for 275 municipalities of Portuguese mainland for the year of 1991,2001, and 2011, we find that both urban sprawl and motorways seem to play a role in explaining shifts in travel mobilities, suggesting that lower density urban areas experience increases in the share of people who use the automobile as their main form of transportation in commuting trips. Additionally, according to computations, motorways have a negative effect on car use, which may indicate that our variable is not capturing the "network" effects of this type of transportation infrastructure. Socioeconomic indicators such as income also seem to play a role, revealing that increases in income lead to a larger share of people using the car as their form of commuting and subsequently also having impacts on the amount of fuel used, leading to more per capita fuel consumption. Motorways were also a contributing factor for higher per capita fuel consumption, with a positive effect on the total amount of fuel consumed. Urban sprawl density variables are also relevant, showing that as density increases, in both residential urban land area and total urban land area, per capita fuel consumption decreases, corroborating the theoretical effects for urban sprawl consequences in past literature.

In sum, as in this work it is possible to conclude, public policies based on promoting a balanced land use mix in addition to higher public transportation infrastructures along with incentives for using more sustainable forms of travelling, can be a solution in mitigating urban sprawl.

6.3 Limitations

One of the main limitations of this MFW is also related to it's nature. Despite being a first step in studying the impacts of the urban sprawl phenomenon in Portuguese soil, it is just that: a first step. Further research will be needed, such as tests on the robustness of our model computations, along with tests on possible multicollinearity and endogeneity problems. These tests, along with other model specifications adding more control variables to further prevent unbiased results, will certainly add more validity to our initial computations. It would also be of use to gather the most recent data from the 2021 National Census, to further investigate the evolution of urban Sprawl and address possible shifts in our model results.

6.4 Next steps

Moving forward on this topic, although in this MFW we only look at their correlational relationship (even if corrected by other factors), studying the causal relationship between urban sprawl and motorways for the Portuguese context, is of most importance in order to make valuable insights on possible solutions of urban sprawl.

Furthermore, future research may focus on analysing how some recent public decisions such as the increases in fuel prices and lower costs for public transportation may have affected travel mobilities and overall fuel consumption in Portugal.

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