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Summary

Scholars have been widely divergent in defining which urban form is more sustainable. Furthermore, the debate about monocentrality and polycentrality in terms of energy demand behaviour is still much mitigated in the literature.

According to Anderson et al., (1996, p.10), “The archetypal forms prove useful in thinking about energy and environmental issues in cities, but their usefulness is limited by their fundamentally static nature.” Hence, in the present research, the sustainability of urban form is envisaged from the lens of travel behaviour by using CO2 emissions as a proxy. In that regard, the research compares two regions in Europe of opposite urban forms namely: The Randstad and Le Grand Paris. It is based on the empirical work of Shwanen et al., (2004; 2001) and Aguilera et al., (2014; 2009). Critical to previous inconsistencies, it attempts to find alternative methodologies (combination of The GHG Protocol, statistical data on travel behavior and The Global Moran I (GIS)) to solve two conflicts in assessing the sustainability of urban form.

The first one regards the definition of “urban form” itself. As the concept represents a complex ‘latent variable’, that is not directly observed but rather extrapolated from an imbrication of different variables. In this research the chosen definition of urban form is from its job-housing perspective, considering factors such as job and residential density, land use as well as work-journey CO2 emissions.

The second conflict regarding the sustainability assessment of urban form is the scaling consistency between the multitude of variables (urban form, travel behavior and CO2 emissions). In that regard, the research builds on previous conclusions from on-road gridded emission models in the research paper “Cities, traffic, and CO2: A multidecadal assessment of trends, drivers, and scaling relationships” (Gately et al., 2015).

The GHG Protocol is used as an alternative methodology to understand patterns of travel behavior and consequent CO2 emissions at the city scale based on quantitative/qualitative data of travel behavior. Complementarily with statistical correlations, spatial autocorrelations are also used by means of the Global Moran I in GIS. This gives insight into how variables of urban form such as land use and density are sensitive to spatial distributions (Monocentrality and Polycentrality). The final assessment of sustainability of urban form is extrapolated as a synthesis of the mixed methodologies.

Findings of the research indicate that in terms of the work-journey CO2 emissions, the monocentric urban form (Le Grand Paris) proves to be significantly more sustainable than the polycentric urban form (The Randstad). Furthermore, the analysis indicates that both density and compactness highly correlate with travel behavior in terms of modal choice, distances travelled and subsequent work-journey CO2 emissions. Supporting findings in the literature review indicate that the failure of the Dutch ABC policy in locating firms closer to accessible public transportation and quantitative, possibly qualitative mismatch between job and residential density (Shwanen et al., 2001; 2004) are all responsible factors for the low sustainability performance of The Randstad

Keywords

Urban form

Monocentrality

Polycentrality

Travel behavior

Work-journey CO_2 emissions

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The research would not have been possible without the previous empirical work on The Randstad by Shwanen et al., (2001) in “Travel behavior in Dutch monocentric and polycentric urban systems” and the work of Aguilera et al., (2014) in “Urban form, commuting patterns and CO2 emissions”. Both scholars provided significant insight to pursue my thesis project.

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Foreword

The basis for this research stems from my passion for architecture and planning as well as propensity towards social sciences. I regard the current thesis project as a combination of my architectural/planning background with the sustainability/socially driven goals of IHS.

The aim of conducting a research on urban form, travel behaviour and CO2 emissions is to understand the interaction of human behaviour with spatial components and sustainability. It is notable of mention that the guiding principles behind the thesis are from the cross-disciplinary nature of the Urban Environmental sustainability and Climate Change specialization at IHS.

Abbreviations

IHS	Institute for Housing and Urban Development Studies
ADEME	French Environment and Energy Management Agency
APUR	Atelier Parisien D'Urbanisme
CBD	Central Business District
CBS	Centraal Bureau Voor de Statistiek
CO2 e	Carbone Dioxide Equivalent
DARTE	Database of Road Transportation Emissions
EDGAR	Electronic Data Gathering, Analysis and Retrieval
GHG Protocol	Greenhouse Gas Protocol
GIS	Geographic Information Systems
IHS	Institute for Housing and Urban Development Studies
INSEE	National Institute of statistics and Economic Studies
IPCC	Intergovernmental Panel on Climate Change
JRC	The Joint Research Center
Moran's I	The Spatial Autocorrelation (Global Moran's I)
RCI	Rotterdam Climate Initiative
UN	The United Nations
WBCSD	World Business Council for Sustainable development
WRI	World Resources Institute

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Chapter 1: Introduction

1.1 Background information and problem statement

It is often assumed by scholars and planners that different urban forms, in terms of *size*, *monocentrality* and *polycentrality*, can influence both energy consumption patterns and pollution differently (Anderson et al., 1996; Aguilera and Voisin 2014; Glaeser and Kahn 2010; Louf and Barthelemy 2014). This is because, first, our urban mobility trends are significantly reliant on the shape of our cities. Second, the way infrastructure is planned is often a direct result of our built environments. In that regard, assessing how sustainable an urban form is starts by looking at its transportation system and the mobility trends it encourages.

Indeed, most of our contemporary cities largely reflect the implementation of their transport networks and technologies (Scott and Storper 2015). Furthermore, according to the WRI (World Resources Institute, 2016), 24 % of the world's global CO2 emissions were the result of car-dependant mobility. This suggests that the share of road transportation in terms of pollution is quite significant. Would it then be possible to draw a link between urban form itself and CO2 emissions?

At the present moment, greenhouse emissions provide substantial data for planners to take action because it gives a general idea on how *sustainable* or *green* a city is from its CO2 inventories (Brondfield et al., 2012; Gately et al., 2015; Gleaser and Kahn 2010). Although subject to many mismatches and non-linearity when downscaled to spatial accuracy (Gately et al., 2015; Gately et al., 2013), these emissions are still a reliable proxy to assess less measurable components in cities such as the *land use* activity (Anderson et al., 1996; Giuliano et al., 1993; Scott and Storper 2015) and travel behavior.

In recent years, there has been much research about the effectiveness of transit-oriented developments in reducing CO2 emissions. In his essay on sustainable forms, Jabareen (2006, p.40) suggests along with other sustainable design recommendations, that: "Compact, transit-oriented development shortens trips, thus encouraging non-motorized travel and conversion of low-occupancy auto trips to mass transit cuts down per capita fuel consumption." In fact, this proves the sustainable rationale behind the rapid transit development system. However, it does not give much information about which urban form per se encourages this rapid transit development. And more specifically how can different urban forms affect travel behaviors in different ways.

It is still quite unclear whether the most sustainable urban form is polycentric or monocentric. According to Engefriet and Koomen (2018, p.1274), "In general, there is a consensus in literature that dispersion leads to longer commuting distances and more use of cars." However, in the functional polycentric city model (Meijers 2005), inhabitants have more possibility to work closer to their homes which consequently reduces commuting distances and time resulting in less CO2 emission. In theory, this means polycentric urban regions are more sustainable because they are more connected by rapid transit systems. However, in practice, results may be surprising.

If we take the example of the Netherlands, and more specifically The Randstad region, the actual data provides alternative information on travel behavior. The Randstad region comprises four major cities namely: Amsterdam, Rotterdam, Utrecht and The Hague, which are administratively independent and efficiently connected by a strong infrastructure. The Randstad represents the best example of a polycentric urban region both morphologically and functionally (Meijers 2005). In theory, this would indicate that the highest number of commuters would choose public transport over individual modes of transportation. However, the National census of Transport and Mobility in 2016 (Statistics Netherlands (CBS), 2016) estimates the distances covered daily by car to 73 % against only 12 % for public transport. Other parameters, such as user preference, might hence come into play when assessing the encouraging factors of transportation.

Considering all these observations, it becomes important to investigate the most significant factors behind sustainable mobility and their consequences in terms of CO_2 emissions. Currently, sustainability issues and mitigation strategies are at the heart of the debate in the planning practice. Hence, it is important to ask whether urban form is the main indicator to transport induced CO_2 emissions or is it secondary to other indicators?

1.2 Relevance of the research topic

According to the UN, “68 % of the world population is projected to live in urban areas by 2050.” This percentage corresponds to a number of up to 2.5 billion people who are estimated to be joining cities by 2050.

As cities grow and expand, they inevitably impose challenging transportation strategies for climate change mitigation (Wright 2012). In terms of both design and policymaking, it becomes important to provide efficient and sustainable mobility that reduces the impact of CO_2 emissions on the environment. Urban form differentiation might play a substantial role in that regard, but it is still unclear how it affects travel behavior. Indeed, scholars have suggested that other factors, by nature socio-economic, might represent the major indicator when assessing travel behavior (Gately et al., 2015; Louf and Barthelemy 2014; Tsai 2005). The question of how urban form and transportation systems relate to sustainability is hence unclear because of the many other indicators that can impose limitations to direct conclusions. Travel behavior, contrary to what planners suggest might be conditioned less by the built environment and land use regulations and more by the choice of residence and the workplace. This usually represents a trade-off between how much an individual is paid and how much they are willing to spend on transportation in terms of monetary value but also time (Gately et al., 2015; Giuliano et al., 1993; Louf and Barthelemy 2014; Schwanen et al., 2004). This challenges the idea itself of a ‘sustainable urban form’ and would mean that congestion and CO_2 emission could be as much linked to user preference (Banister 2008).

For this reason, the research topic has a dual academic and policy making relevance. Academically, its aim is to acquire a new understanding on the interrelation of urban form, travel behavior and CO_2 emissions. As mentioned earlier, there is no clear evidence in the literature which urban form is more sustainable. Scholars have been largely divergent in that subject (Anderson et al., 1996; Engefriet and Koomen 2018; Giuliano et al., 1993; Jabareen 2006; Louf and Barthelemy 2014). For this reason, investigating new empirical case studies is essential, as it might bring complementary comprehension on how urban form performs in energy demand behavior and its environmental consequences. In that sense, the current thesis is a continuity of the academic work conducted by both Shwanen et al., (2004; 2001) for The Randstad and Aguilera et al., (2014; 2009) for Le Grand Paris. Critical to previous inconsistencies, the current research investigates alternative methodologies using a combination of the GHG Protocol, qualitative/quantitative data on travel behavior and The Global Moran I (GIS) in assessing the sustainability of urban form. It uses a set of different indicators that are representative of the most reasonable scale for policy intervention at regional levels. Ultimately, this could inform planners about the extent of the problem and provide more adapted design and policy-making solutions in the reduction of negative environmental effects.

1.3 Research objectives

The research has a dual objective of evaluation and explanation. First, the aim is to evaluate how urban form in terms of *polycentrality* and *monocentrality* performs in work journey CO2 emissions. The evaluation part compares two regions in Europe, that are comparable socio-economically but opposing in urban form (Bontje and Burdack 2005; Heitz et al., 2017). Le Grand Paris represents a monocentric urban form, a metropolis of 12 million inhabitants, with an active population of 6 Million people. On the other hand, The Randstad, is a polycentric urban region (Meijers 2005), of 8 Million inhabitants and an active population of 4 million people (Manshanden et al., 2017).

Using the distance-based inventory of the GHG Protocol (PROTOCOL, P.S., 2008), work journey CO2 emissions are respectively calculated for both Le Grand Paris and The Randstad. As opposed to other methodologies such as EDGAR, that uses "Road density as a sole spatial proxy to downscale national-level emissions." (Gately et al., 2015, p.5002), the GHG Protocol uses statistical data on *travel behavior* as a proxy for human activity in relation to urban form.

In light of the preliminary CO2 inventories, the second objective of this research is to explain the given results under other variables that are by nature socio spatial and economic. According to Gately et al., (2015, p.5002), "Correlation between population density, employment density, income, and lagged population growth suggests that these factors may be sufficient to explain the majority of variance in on-road emissions at *the country scale*, but further research into the influence of *urban typology and mobility patterns* will be vital to understanding emissions trends *at city and municipal scales.*"

Although there are many variables by nature socio-economic that influence on road emissions (Gately et al., 2015; Louf and Barthelemy 2014; Tsai 2005), in the research, the course of action deliberately includes spatial variables at regional scales namely: density, land use and travel behavior. This is particularly important, as in the current research the assessment of urban form is inherent to *mapping* human activity in relation to spatial distribution. Hence, land use and density will represent the moderating variables, under which new explanations may emerge.

1.4 Main research question and sub-questions

To reiterate, the problem statement aims at investigating the interrelations of urban form, travel behavior and sustainability by comparing two case studies: Le Grand Paris and The Randstad. The research uses three different variables: travel behavior, land use and density as well as a proxy (CO2 emissions) to assess sustainability. The main goal of the research is to answer the following question: How does urban form, under the influence of travel behavior affect work journey CO2 emissions?

From this, a series of concomitant interrogations emerge, exploring the possible relations between the different variables and their relation to sustainable development. How does urban form regarding polycentrality and monocentrality relate to work journey CO2 emissions and overall sustainability? How does urban form in terms of land use and density interact with travel behavior? What are some other possible external explanations to the work journey mobility trends? In terms of climate change mitigation, what should planners and policy makers be really looking at?`

Chapter 2: Literature review

2.1 State of art of the theories

2.1.1 An understanding of urban form

Before proceeding to the assessment of urban form in terms of sustainability, it is important to provide a scholarly outline of its multiple definitions that are present in the literature.

When addressing the concept of urban form, two indicators emerge: compactness and monocentrality; as opposed to polycentrality and sprawl (Tsai 2005). In that regard, a proper definition of urban form starts with identifying the variables that can measure either one of these indicators: compactness and sprawl.

For this purpose, the quantifying variables of urban form are of two distinct natures:

- Physical and geographical, indicating the spatial structure and city size; stemming from the formalist theories (Hillier 2009; Huang et al., 2007; Jabareen 2006)
- Socio-economic, indicating the population density and activity in terms of land use; stemming from the networking theories (Bettencourt 2007; Cottineau et al., 2017; Kühnert 2006)

A third definition of urban form, which specifically concerns the research, is a combination of both the geographical and socio-spatial variables. Because the research is assessing *travel behavior* in relation to *urban form*, a definition that combines human driven patterns that can possibly be *mapped* on spatial structures is chosen. This is even more possible in the 21st century, with the available technology of visual simulation modeling tools (Batty 2007). Such research could bring new fine scale insights on urban form. In that regard, the definition of urban form that suits the purpose of this research is: “The physical structure and size of the urban fabric as well as the distribution of population within the area.” (Schwarz 2010, p.30)

2.1.2 Urban form between monocentrality and polycentrality

In assessing urban form as monocentric or polycentric, the literature provides a wide range of quantitative indexes of compactness versus sprawl using the variables discussed in the previous chapter: city size, spatial structure, population density and activity. However, the variety of indexes provided by scholars scale differently when compared to each other (Anas and Kim 1996; Engefriet and Koomen 2018; Huang et al., 2007; Schwarz 2010, Tsai 2005). This means that there is no commonly agreed upon universal scale defining either type as being monocentric or polycentric. However, there is a consensual definition of urban form, in terms of compactness and sprawl, that is rather inherent to the *job-housing* distribution (Anderson et al., 1996; Aguilera et al., 2014; Engefriet and Koomen 2018; Giuliano et al., 1993; Scott and Storper 2015; Tsai 2005)

Urban form definitions

According to Scott and Storper (2015, p.8), the urban land nexus is “The extensive expression of agglomeration and in modern society is molded to a significant degree by the behavior of firms seeking locations for production and households seeking living spaces.” In other words, defining an urban form as monocentric or polycentric would entail describing “The spatial distribution and concentration of jobs and residences.”(Engefriet and Koomen 2018, p.1272)

In the literature, Anderson et al., (1996) and Tsai (2005), provide relevant conceptualizations of the *job-residence* relation that defines urban form as either monocentric or polycentric. An example of that, is the empirical research on US metropolitan areas conducted by Tsai (2005), using the global Moran coefficient as an indicator of spatial distribution and the Gini Index as an indicator for income distribution among the population. The conclusions of the research confirm that the *job-residence* relation (Giuliano et al., 1993) is the main indicator to urban form in terms of polycentrality and monocentrality. The empirical data of Tsai's (2005) research shows that employment and income are concentrated in areas that are monocentric with a high density of population. And the opposite was observed in more sparse metropolitan areas.

Urban form comparison between Le Grand Paris and The Randstad

According to Anderson et al., (1996), it is possible to distinguish between two urban forms: the concentric city and the multinucleated city. The first one is associated with a high economic concentration and transportation density around a central business district (CBD). This causes a mono-functional land use differentiation in terms of jobs and workplaces, as well as an imbalance with the rest of the areas outside the CBD. A typical example of that is La Défense district in Le Grand Paris, France. La Défense represents the heart of the agglomeration economies. This encourages trends of segregation such as gentrification and uneven access to mobility at the expense of adjacent areas (Aguilera et al., 2014; 2009; Glaeser 2011; Enright 2016; 2013).

Home to 12 million inhabitants and an active population of 6 million, the metropolitan area of Le Grand Paris is currently challenged by its transportation system that is exclusively central and does not give access to all parts of the city. For that purpose, a new ring metro system under the name of The Grand Paris Express was launched in 2007 by Nicolas Sarkozy. The purpose of the ring line is to improve the mobility between developing neighborhoods by providing an access to "all". The ring as opposed to the existent central transportation system is particularly important because it is "The primary means of managing the diffusion of centrality from the wealthy and powerful historic core to a more amorphous networked or 'rhizomatic' metropolis." (Enright 2013, p.798)

As Paris has an ambition to shift towards a less centralized model, it might be interesting to compare it with a case of a typical polycentric urban model in Europe. The Randstad in the Netherlands represents a reasonable archetype. The region is comprised of four provinces namely: Zuid and Noord Holland, Flevoland and Utrecht. It is mainly characterized by an alternative multinuclear form that is not structured around a concentration of employments in a single CBD (Anderson et al., 1996). The relation between jobs and residences is equally diffused within the urban fabric to ensure at the scale of the region, not only a morphological polycentrality but also a functional one (Burger and Meijers 2012). Each city is closely monitored so it performs evenly in terms of socio-economic status with other cities. In that regard, there is a strong equalizing policy in terms of the number of jobs each province can provide, by economic sector (Burger and Meijers 2012; Meijers 2005; Kloosterman et al., 2001; Van Raan et al., 2016).

However, the question whether the socio-economic performance of The Randstad is in line with its sustainability performance, is a relevant issue in an era of climate change. Indeed, as The Randstad becomes highly connected, inhabitants might be trying to have access to more lucrative jobs in adjacent cities, and this, by using private modes of transportation instead of the available rapid public transit. To illustrate the point, while the region provides a local concentration of jobs and is efficiently connected through a rapid transit system; the National census of Transport and Mobility in 2016 (Statistics Netherlands (CBS), 2016) estimates the distances covered daily by car to a staggering 73 %. Since The Randstad accounts for more than half of the total population in the Netherlands, the number of car users remains quite significant for the region. In Le Grand Paris, this number is a mere 36 % according to the INSEE, 2016 (Institut National de La Statistique Et Des Etudes Economiques). This raises an important issue regarding the sustainability of either the monocentric or polycentric urban form. As “The archetypal forms prove useful in thinking about energy and environmental issues in cities, but their usefulness is limited by their fundamentally static nature.” (Anderson et al., 1996, p.10). In other words, the sustainability of urban form should always be regarded under its non-static variables, namely *travel behavior* that remains an important factor of influence.

2.1.3 Assessing the sustainability of urban form

In the literature, the debate over the sustainability of urban form in terms of monocentrality or polycentrality is much mitigated due to the multitude of socio-economic and spatial variables that come into play. Furthermore, the difficulty to bridge between the two variables becomes an important issue. The socio-economic factors of cities do not scale linearly with the spatial components (Bettencourt 2007; Cottineau et al., 2017; Hillier 2009; Huang et al., 2007). For this reason, the literature shows that attempts of regression analysis are a very common. They help assess variations in the analysis that combine both the socio-economic and spatial variables at the country scale (Tsai 2005; Van Raan et al., 2016), but do not explain the link between urban typology and mobility patterns at the city scale (Gately et al., 2015, p.5002).

As quoted by Cottineau et al., (2017, p.80) in their article “Diverse cities or the systematic paradox of Urban Scaling Laws”: because of “The heterogeneous morphologies and social landscapes in the cities' internal space, scaling estimations are subject to large variations, distorting many of the conclusions on which generative models are based.” For accuracy purposes in the sustainability assessment, the current research therefore considers only spatial variables that can be scaled with the same distance-based components. This point will be further explained in the next chapters on how to quantify the sustainability of urban form using CO2 distance-based emission inventories, as a proxy for travel behavior.

To reiterate, in objectively evaluating the sustainability of either polycentrality or monocentrality, the extensive literature might contain some limitations (Cottineau et al., 2017; Engefriet and Koomen 2018; Shwanen et al., 2004; 2001; Tsai 2005). In fact, there is no universal answer to which one of these archetypal forms is more sustainable if all existent variables are to be taken into account. It is important to emphasize that there might be no systematic answer to the question under all its aspects. However, in assessing the sustainability of urban form, the current research narrows down the issue to a few variables that can reasonably be measured within the same scope.

2.1.4 Urban form, travel behavior and climate mitigation

Although the literature remains divergent on which urban form is more sustainable in terms of monocentrality and polycentrality, a myriad of recommendations have been discussed to lessen the environmental implications of energy dependent cities (Banister 2008, Doherty et al., 2009; Jabareen 2006; Jenks 2019; Klinge et al., 2003; Mazzi and Dowlatabadi 2007; Papagiannaki and Diakoulaki 2009; Pucher and Buehler 2008; Stone et al., 2010). In this research, exploring the link between urban form, travel behavior and climate mitigation is necessary for the selection of indicators. To reiterate, the main external objective of the current work is to inform both designers and policy makers about the extent of the problem. Hence, it is important to select concomitant variables for both purposes. In the literature, the climate mitigation strategies aiming at the reduction of greenhouse gas emissions are of two natures. They operate either at the *urban morphology* level or at the *user* level by encouraging sustainable modes of transportation.

First, the strategies focusing on the spatial configurations address the planning practice from a design perspective (Doherty et al., 2009; Jabareen 2006; Jenks 2019; Stone et al., 2010). In regard to the growing concentration of CO2 emissions, Jabareen (2006, p.38) states that: “Prospects for the future are dire indeed, unless we act collectively in our *behavior* but also in the *design* of the built environment.” Jabareen (2006) proposes a synthetic framework of sustainable urban form based on seven design concepts namely: sustainable transport, density, mixed land uses, diversity, compactness, passive solar design and greening. Indeed, these concepts are consistent with most of the literature exploring the link between climate mitigation and urban form. To answer the research question “How does *urban form*, under the influence of *travel behavior* affect *work journey* induced CO2 emissions?” a focus will be first given to two of the design-related variables: density and land use as these show strong correlation with the previous definition of urban form from the *job-housing* perspective (Anderson et al., 1996; Aguilera et al., 2014; Engefriet and Koomen 2018; Giuliano et al., 1993; Scott and Storper 2015; Tsai 2005). To reiterate urban form is: “The physical structure and size of the urban fabric as well as the distribution of population within the area” (Schwarz 2010, p.30). The distribution of population refers to both the *job* and *residential density*. On the other hand, the structure of the urban fabric refers to the location of firms and households in terms of *land use* (Scott and Storper 2015). Hence, a combination of both *density* and *land use* is essential in assessing the sustainability of urban form.

Second, to extract indicators of travel behavior, policies for climate mitigation will be explored in the next paragraph. In terms of policy making, the literature shows that mitigation strategies operate mainly at the *user* level with regard to *modal choice*. In their paper “Making Cycling Irresistible: Lessons from The Netherlands, Denmark and Germany”, Pucher and Buehler (2008, p.496) states that: “Instead of catering to ever more motor vehicles by expanding roadways and parking facilities, Dutch, German and Danish cities have focused on serving people, making their cities people-friendly rather than car-friendly.”

This reveals that user behavior is crucial in achieving sustainable transition, as implementation strategies of sustainable transportation might find barriers due to a lack of derived demand (Banister 2008). According to the same source, the new “Sustainable mobility paradigm” should encourage *modal shift* as well as *time and distance* minimization in a combination with land-use policy measures. In regard to travel behavior, other drastic strategies have included taxing vehicles on CO2 emission rates as seen in the UK (Mazzi and Dowlatabadi 2007) or imposing high registration tax on car ownership of up to 180 percent in the case of Denmark (Klinge et al., 2003; Papagiannaki and Diakoulaki 2009). By and large, it is clear from the literature that climate mitigation strategies are concerned with overcoming challenges in both *urban form* and *travel behavior*. This ultimately helps define the key variables for the current research with regard to their potential environmental implications, which are summarized as follows:

- *Density* and *land-use* from a *design* perspective (Doherty et al., 2009; Jabareen 2006; Jenks 2019; Stone et al., 2010)

- *Travel behavior* from a *user* perspective (Banister 2008; Klinge et al., 2003; Mazzi and Dowlatabadi 2007; Papagiannaki and Diakoulaki 2009; Pucher and Buehler 2008).

To illustrate how these three variables might interact within the research question, it is important to do a projection on each of the cases selected for the study: The Randstad and Le Grand Paris. In the next chapters, the literature is conscientiously discussed for both cases.

2.1.5 Urban form and travel behavior: Cases of The Randstad and Le Grand Paris

In this chapter, the aim is to explore how *travel behavior* interrelates with urban form and how other moderating variables such as *Land use* and *density* influence travel behavior.

Background information

As mentioned earlier, the static nature of urban form, as either monocentric or polycentric, entails that the assessment of its sustainability cannot be evaluated unless seen from the angle of travel behavior (Anderson et al., 1996). Indeed, the discussion over how monocentrality and polycentrality affect travel behavior in terms of distance, time and CO2 emission is at the heart of the debate about sustainability (Engefriet and Koomen 2018).

In assessing the relationship between travel behavior and urban form in terms of monocentrality and polycentrality, the literature remains contradictory. In general, there is an agreement that sprawl causes longer commuting distances and an increase of private modes of transportation (Camagni et al., 2002; Engefriet and Koomen 2018; Jabareen 2006; Jenks 2019 Stone et al., 2010). However, according to other scholars, the polycentric urban model can also encourage to the principle of 'co-location'. This principle states that "Firms and households periodically readjust spatially to achieve balanced average commuting distances and duration." (Shwanen et al., 2001, p.174). In other words, polycentric urban models such as The Randstad also offer the possibility of working closer to residences. This might reduce the commuting distances and time and consequently the CO2 emissions. But it does not necessarily influence the modal choice. As seen in the case of The Randstad, having a functional polycentric urban region (Burger and Meijers 2012; Kloosterman et al., 2001) does not guarantee people choosing more sustainable mode of transportation with an average 73 % of car use (CBS, 2016). In the case of Le Grand Paris, this number drops to 36 % according to the INSEE (2016).

To reiterate, the contradiction between the sustainability of monocentrality and polycentrality amongst different scholars and case studies is mainly due to two inextricable variables: *land use* and *density*. While *land-use mix* acts on the daily commuting distances by distributing the locations of jobs and residences, *density* plays an important role in modal choice.

The case of The Randstad

In the research of Shwanen et al., (2001, p.185) on "Travel behavior in Dutch monocentric and polycentric urban systems"; results showed that the "De-concentration of urban land use and the development of polycentric urban structures seem to lead to more use of the private car." In areas of low density, inhabitants favor private modes of transportation over public ones. As high *density* is also one of the main drivers for the use of public transportation to avoid congestion (Jabareen 2006). In parallel with that, the same research of Shwanen et al., (2001), suggests that the "co-location" principle and *land-use mix* showed a tendency to reduce the distances travelled thanks to cross-commuting urban systems in Dutch cities. This suggests that *land use* acts on the distances travelled and the *density* on the modal choice.

In line with these conclusions, another research investigating the impact of Dutch urban planning policies on travel behavior in The Netherlands shows similar observations (Shwanen et al., 2004). Using quantitative/qualitative data on travel behavior from The National Travel surveys in 1998; the research suggests that policies that aimed for concentrated decentralization have simulated more use of *public transport* because of increased *density* in growth centers as opposed to suburban areas. However, this only reduced slightly the share of private cars. This is mainly because of the 'location choice' or the trade-off between time spent travelling and willingness to pay. On the long term, many inhabitants fled the center toward suburbs, commuting longer distances by private car. This is because the time spent in congestion by car in the growth center was equal to the time spent from the suburban areas to the center. Indeed, while *land use* and *density* remain significant factors of travel behavior; in the case of The Netherlands, planning policies failed to tackle the problem of commuting time (Shwanen et al., 2004). According to the analysis, the issue was inherent to user preference in terms of locational choices and modal choice. While planning in terms of improving *land use* and *density* helped to reduce distances and encouraged the use of sustainable modes of transportation, it operated only to a limited extend.

Since the late 90’s (Table 1), the policy recommendations for the reduction of CO2 induced transport emissions were to first implement an efficient public-transport network like the intercity-trains and metro systems at the level of the country, second to promote incentives for inhabitants to choose efficient job locations close to their residences, as “Much employment was situated on car-accessible locations that were poorly served by public transport.” (Shwanen et al., 2004, p.595). Indeed, twenty years later, the polycentric urban region policy shows that The Netherlands succeeded in both these challenges. As mentioned earlier, the country provides a strong equalizing system between municipalities to tackle the *job-residence* proximity, especially in The Randstad region (Burger and Meijers 2012; Kloosterman et al., 2001; Van Raan et al., 2016). Furthermore, the Sprinter Light train that entered in service since 2009 is considerably efficient into networking commuters at the conurbation level. However, the data on travel behavior is still contradictory with the high number of car commuters at the regional scale (CBS, 2016). It is therefore important to specifically investigate The Randstad region that is rather famous for its ‘bicycle highways’ (Fietsenroutenetwerk).

Table 1 Performance of national spatial planning policies in the Netherlands in terms of travel efficiency

	Modal choice				
	Reduction of driving	Stimulation of public transport	Stimulation of cycling and walking	Shorter travel distance (private car)	Shorter travel time (private car)
Policy of concentrated decentralisation (1970s and 1980s)	=	+	−	−	−
Strict compact-city policy (1980s and 1990s)	+	+	+	+	−
A-B-C location Policy	=	+	=	=	=
Retail planning	+/+ +	=	+ +	+	−

‘+’ policy made positive contribution; ‘=’ policy had little (neutral) effect; ‘-’ policy made negative contribution.

URBAN FORM AND TRAVEL

Source: Table from Schwanen, T., Dijst, M. and Dieleman, F.M., 2004. “Policies for urban form and their impact on travel: the Netherlands experience”. *Urban Studies*, 41 (3), pp. 579-603.

According to Shwanen et al., (2004), results showed that modal choice deviates in the less urbanized areas towards the private car for longer distances compared to The Randstad. Hence, assessing travel behavior in the most connected area of The Netherlands could bring more understanding on what role Dutch planning policies played in influencing travel behavior and how this relates to sustainability. In terms of climate mitigation, the Rotterdam Climate Initiative (RCI) set a target of “50 % reduction of CO2 emissions by 2025”. Furthermore, the national policy program on Climate Adaptation and Spatial Planning established in 2007 emphasized that: “Adaptation to climate change is largely a spatial issue and climate-proofing in The Netherlands represents one of the most important spatial challenges of the current century.” (Stead, 2014, p.22).

In that sense, this research is complementary with Shwanen et al., (2004) previous work. The purpose of a new empirical study is to provide explanation under new *spatial* developments in *land use* and *density*, as well as changes in *travel behavior* in terms of citizen’s engagement in sustainable modes of transportation. An assessment of the environmental implications of such recent developments could provide in terms of policy action, more informed solutions in climate mitigation, by looking at both the planning practice and actual travel trends.

The case of Le Grand Paris

After reviewing the case of The Randstad as a polycentric urban model, it is now important to look at the opposite urban form. As seen earlier, Le Grand Paris metropolitan area represents the typical monocentric urban form with its large central CBD known as La Défense (Aguilera et al., 2014; 2009; Glaeser 2011; Enright 2016; 2013). In his article "The Paris Agreement and the new logic of international climate politics", Falkner (2016) underlines the importance the Paris agreement played in soliciting the redesign of existent transportation systems. Indeed, much climate mitigation strategies find barriers as CO2 emissions are dependent on existent hard infrastructure. In that regard, a new ring system "The Grand Paris Express" was launched by Nicolas Sarkozy in 2007; and is planned to decentralize mobility and consequent CO2 emissions. In the next paragraph, a history of both planning and travel behavior in The Paris metropolitan area will be presented. This helps to contextualize the current environmental challenges regarding previous developments in both urban form and travel behavior.

In 2009, a research paper on "Reverse commuting and travel behavior in the Paris metropolitan area" provides explanation on how the region gentrified in the span of twenty years (1983 and 2001). It specifically investigates the impacts of gentrification on the employee's daily commuting behaviors (Aguilera et al., 2009). The research was based on travel behavior surveys conducted from the French national statistical and economic studies database (INSEE) between 1983 and 2001. The data analysis underlines that in the case of Le Grand Paris metropolitan area, commuting patterns where not the result of 'co-location' trends as seen in the case of The Randstad (Shwanen et al., 2001), but rather due to the 'suburbanisation' of jobs (Aguilera et al., 2009; Aguilera et al., 2014). To further explicit, the implementation of La Défense district, provided a concentration of highly skilled employment in contrast with suburban areas. Thus, the economic 'growth pole' brought more attractiveness in the center; however it also caused a higher number of reverse commuters as non-highly skilled employees were seeking either jobs or residences outside of the heart of Paris. As a result, from 1983 to 2001, car use decreased for residents living in the center of Paris by over 20 %. This was mainly due to increased density and availability of public transport in centralized areas. However, due to less served areas in the suburbs, reverse commuters were travelling longer distances by private means of transportation. This research concludes that in the case of Le Grand Paris, similarly with the case of The Randstad, *modal choice* and travel *distances* are "Very dependent on the workplace and, more precisely, on the way that residences and workplaces are connected." (Aguilera et al., 2009, p.690)

To further investigate on how *land-use* and *density* condition travel behavior in other contexts than the current case studies, the research of Engefriet and Koomen (2018) on "The impact of urban form on commuting in large Chinese cities." brings similar conclusions. The results demonstrate that spatial clustering in terms of *land-use* mix is a key criterion in lowering the average commuting distance and time and that these clustering should be reinforced to a level of *high-density*. This emphasizes the constancy of specific variables related to travel behavior in different contexts (density, modal choice and distance travelled). According to Gately et al., (2015, p.5000): "Population density is a proxy for less easily measured characteristics of the urban environment. A classic example is the exponential decline in per capita transport in energy use with increasing population density that was observed in a *large cross-section of cities worldwide.*"

Considering all these conclusions, sustainability of urban form as either monocentric or polycentric should be assessed from the lens of travel behavior. And travel behavior in terms of *distance* and *modal choice* is respectively linked to *land-use* and *density* as indicators of *urban form*. This conclusion is one of the main reasons to why fine scale distance-based inventories that include statistical data on both *distance* and *modal choice* could be the most accurate methodology in assessing the sustainability of urban form.

However, *land use* and *density* as indicators of urban form pose many limitations according to the literature (Aguilera et al., 2009; Aguilera et al., 2014; Engefriet and Koomen 2018; Shwanen et al., 2001; Shwanen et al., 2004), as they "Leave some aspects of commuting behavior unexplained." (Aguilera et al., 2014, p.249). For instance, the "time" component is one of them. According to Louf and Barthelemy (2014, p.767), "Commuting distance and time scale differently with population size, and the time spent commuting and CO2 emissions scale with the same exponent."

In line with these conclusions, the assessment will use *quantitative/qualitative* data on *travel behavior* in two archetypal urban forms: Le Grand Paris and The Randstad. The main variables used for the assessment and explanation will be density, land use (job/housing ratio) and travel behavior (modal choice/distance). Other variables by nature socio-economic or that are out of the scope of the research such as time will not be included. In the following section, a synthetic conceptual framework is provided to showcase the interrelation of different variables analyzed in the literature review.

2.2 Conceptual framework

2.2.1 Description

The academic relevance of the current thesis resides in its complementarity with previous empirical research for The Randstad (Shwanen et al., 2010; 2004; 2001) and Le Grand Paris (Aguilera et al., 2009; 2014). The proposed conceptual framework is a synthesis of variables from the literature review namely: Land use, density and travel behavior arranged from the lens of two new layers. The first one concerns the *sustainability assessment* of urban form (quantified by the Global Moran I in GIS) as *monocentric* and *polycentric* by making use of *CO2 emissions* as a proxy. The second layer demarcates this assessment as a single *work-journey* indicator of travel behavior. A combination of pre-existent variables with the research layers is arranged in a conceptual framework fitting the purpose of the research question: *How does urban form (monocentric/polycentric), under the influence of travel behavior affect work journey CO2 emissions?*

Concerning travel behavior, indicators such as modal choice and distance travelled remained consistent in all readings. However, the indicators of urban form largely differed. In the case of The Netherlands, Shwanen et al., (2004) represented urban form through a classification of *city size* elaborated by the Dutch planning policies on a country scale. No quantifiable data has been processed in terms of land use occupation despite being representative of the different trips (occupational and shopping). Indeed, correlations of travel behavior and policies might indicate which of these policies failed or succeeded but it does not provide a clear understanding on how travel patterns operate on a *regional scale* rather than *country scale*. Furthermore, the work of Shwanen et al., (2004) does not help in understanding the right policy implementation for reducing transport induced CO2 emissions. This represents one of the main objectives of the research. For climate mitigation, it is important to understand how travel behavior and urban form relate to energy demand behavior. In that regard, shrinking down the research to the work-journey trip provides the most accurate correlation to land use and travel behavior regarding residential and activity areas.

A similar 'activity' based analysis and its consequent CO2 emission was conducted by Aguilera et al., (2014) for the Marne-la-Vallée region in Le Grand Paris. The research used indicators of urban form such as density, compactness, job to resident ratio as well accessibility to public transport. However, a distinction was established between residents and nonresidents in CO2 inventories. According to the author: "Focusing on travel behaviorF of residents can lead to significant errors in CO2 emissions generated by a municipality and its environmental sustainability." (Aguilera et al., 2014, p.243). The question of the sustainability of a municipality *independently* is not relevant at the conurbation level. In Le Grand Paris, it is a well-known fact that commuting patterns are extra-municipal (Aguilera et al., 2014; 2009; Enright 2016; 2013). Furthermore, transit-oriented development operates strategically at the regional level and not the municipality level. While the work of Shwanen et al., (2004) was over scaled at the country level, the proposal of Aguilera et al., (2014) is also significantly downscaled at the municipality level. For this reason, the current research is envisaged from an *in-between regional scale* for both The Randstad and Le Grand Paris.

In that regard, assessing the sustainability of urban form as either *monocentric* or *polycentric* poses the question of which *indicators* for which *scale* of policy intervention. In the current research, travel behavior, density, and land use (residential/activity) are all indispensible variables at the regional level. Furthermore, CO2 inventories are mainly based on the employee footprint rather than emissions of separate municipalities; with a distinction of employees that are residents and nonresidents. In the current research, CO2 emissions of The Randstad and Le Grand Paris will be regarded as one regional CO2 inventory resulting from extra-municipal commuting.

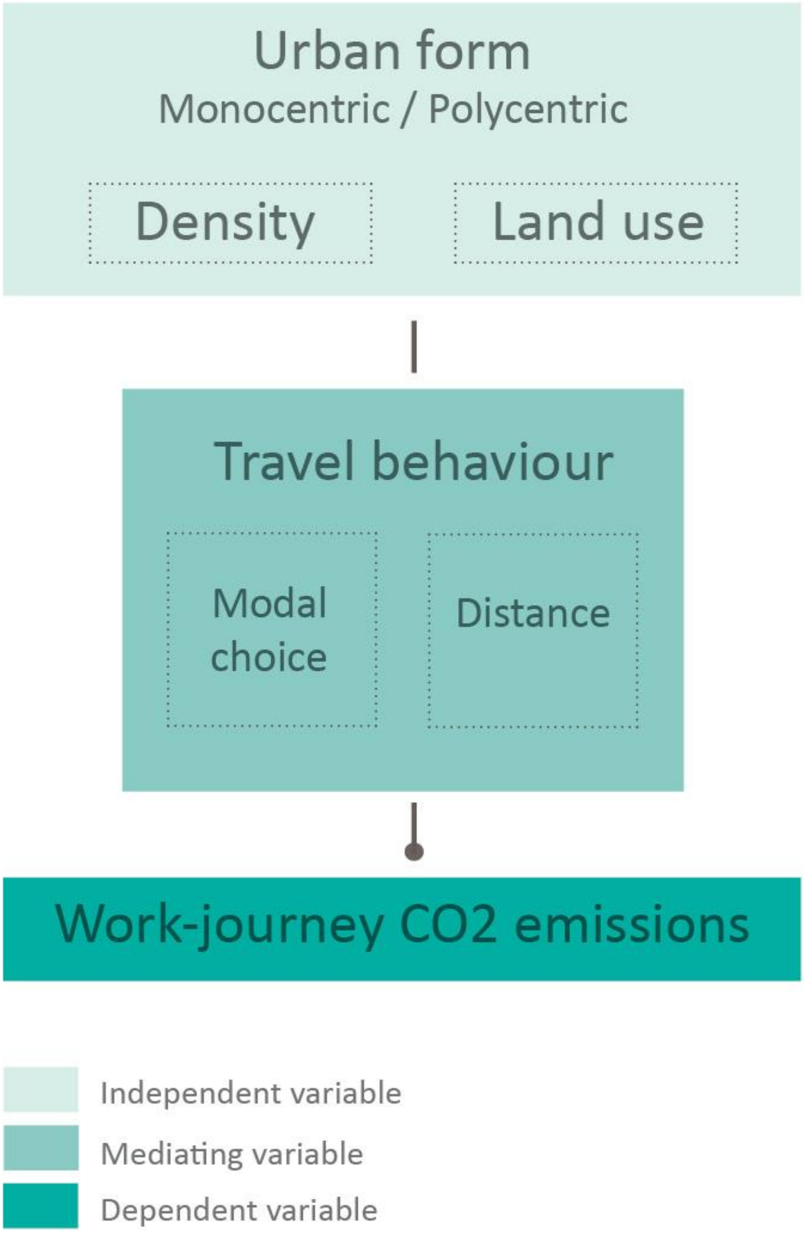


Figure 1 Conceptual framework by the author for analyzing the relation between different variables.

Chapter 3: Research design, methods and limitations

3.1 Description of the research design and methods

3.1.1 Research strategy

The current research is a desk research based on secondary data triangulation (ADEME, CBS, INSEE, APUR, ESRI Demographics, Geodienst Rijksuniversiteit Groningen) of quantitative (distance travelled) and qualitative (worded modal choice) data of travel behavior.

In the paper "Methodologies for exploring the link between urban form and travel behavior", Handy (1996) enumerates two distinct ways of assessing travel behavior in its relation to urban form. First, the aggregate studies that are solely based on averaged data of population size and socio-economic indicators. As mentioned earlier in the previous chapter, this type of research uses merely "Aggregate measures, and tests the strength of the relationship using simple comparisons, correlations or regression procedures." (Handy 1996, p.154)

On the other hand, the second methodology is defined by the same source as *the choice model* or the *activity-based* analysis. The latter focuses specifically on individuals' *travel behavior* (modal choice and distance travelled) in a circumscribed context. Indeed, the activity-based analysis would more accurately link to the daily CO2 emissions, as it uses fine scale *quantitative/qualitative* data at the *metropolitan scale*. This methodology is similar to the work of Aguilera et al., (2014) and Shwanen et al., (2004) respectively for Le Grand Paris and The Netherlands.

In the literature, most gridded emissions such as EDGAR or DARTE use population density as a proxy for CO2 emissions (Crippa et al., 2018; Gately et al., 2013). In a recent study conducted on road emissions in US metropolitan areas, results suggest that methods based on CO2 emissions per capita prove significant discrepancies as biases of "100 % or more in the spatial distribution of urban and rural emissions, are largely driven by mismatches between inventory downscaling proxies and the actual spatial *patterns of vehicle activity* at urban scale" (Gately et al., 2015, p.5004). Furthermore, emission databases such as EDGAR, uses "All human activities, except large scale biomass burning and *land use, land use change* and forestry" (Crippa et al., 2018, p.5). For this reason, the 'activity based' or ''modal choice' methodology will be used in the current research as it might provide more accurate results on the work journey CO2 emissions than aggregate measures based on CO2 emissions per capita.

3.1.2 Research scope

Prior to defining the research strategy, it is important to reiterate the internal objectives. The first objective has an evaluation nature. Its main purpose is to assess the sustainability of urban form (*monocentric/polycentric*) from its inhabitants' travel behavior, by using CO2 metric inventories as a proxy. For this, two regions in Europe that are comparable socio-economically and in opposite urban morphology are envisaged as two separate case studies: Le Grand Paris and The Randstad. The research strategy is divided into two phases. The first phase investigates the direct, quantifiable relation between urban form, travel behavior and CO2 emissions. The second phase has an explanatory nature; its aim is to explain the interrelation between urban form as an independent variable and travel behavior as a mediating variable with regard to CO2 emissions. Travel behavior (distance and *open worded* modal choice) is regarded as a combination of qualitative and quantitative study.

In the first phase, the aim is to assess the sustainability of urban form by using CO2 emissions from one journey that is fixed: the work-home journey. This is known as the *occupational trip* that estimates the contribution of *work only « trips »*, by subtracting CO2 emissions from other

« trips ». The work-journey trajectory is the most accurate assessment of urban form in relation to sustainability because it is a constant pattern that is very unlikely to change every day. Furthermore, it provides a good indication of the *job-housing* relationship of land use. The methodology used to calculate the CO2 emissions is the indirect inventory of the GHG Protocol (PROTOCOL, P.S., 2008). Second, for consistency matters data triangulation from two other national GHG emissions data sources will be used for inter-comparison and validity of the results. These sources are the ADEME (French Environment and Energy Management Agency) for Le Grand Paris and CBS (Statistics Netherlands) on transport related GHG emissions for The Randstad.

The GHG protocol that will constitute the base of our evaluation is a joint tool provided by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). It uses the IPCC Guidelines for national greenhouse gas emission in the following distance-based calculations:

1. “Total distance travelled by vehicle type (vehicle-km or passenger-km) = ∑ (daily one-way distance between home and work (km) × 2 × number of commuting days per year)”

2. “Then, sum across vehicle types to determine total emissions: kg CO2 e (Carbon dioxide equivalent) from employee commuting = ∑ (total distance travelled by vehicle type (vehicle-km or passenger-km) × vehicle specific emission factor (kg CO2 e/vehicle-km or kg CO2 e/passenger-km))”

Using this tool, all the selected variables can be measured. Travel behavior is extrapolated from travel surveys and urban form is indirectly quantified as the tool incorporates metric data in (km) on travel distance (PROTOCOL, P.S., 2008). After the completion of the first calculation phase, the second phase analyses the preliminary findings of phase 1 (CO2 inventories) with regard to mediating variables namely: modal choice and distance. To further elaborate, the second objective of the research is by nature explanatory; its aim is to provide correlations on how each urban model in our two case studies The Randstad (*monocentric*) and Le Grand Paris (*polycentric)* performs in sustainability with regard to other variables. These variables are by nature socio spatial namely: land use, density and travel behavior. As previously concluded in the literature review, a possible link between density and modal choice, as well as land use mix (activity/residential areas) and the daily distance travelled can be explored. Hence, it is important to include both density and land use as independent variables, as these significantly influence travel behavior and overall sustainability performance in terms of CO2 emissions.

It is crucial to emphasize that for the coherence of the conceptual framework; only variables that are distance based, possibly mapped, and spatially measured within the same metric unit (km) are investigated. Because the assessment of urban form is envisaged first from a morphological perspective and not a socio-economic one, land use mix (activity/residential areas) and job residential density were chosen out of other variables such as property value, GDP per capita, etc. Nevertheless, the research remains open to ulterior policy related interpretations which can be deducted as assumptions accordingly with the research findings.

3.1.3 Data source and collection methods

To use the GHG Protocol (PROTOCOL, P.S., 2008), the key data for processing the calculations is available in the National travel surveys for each of the two case studies. The GHG Protocol uses both distances travelled daily in (km) (quantitative) and modal choice (qualitative) with its correspondent emission factor. Data on distance travelled between home and work in (km) by vehicle type per year for occupational journeys is available for both regions: Le Grand Paris and The Randstad.

In the case of the Netherlands the information can be found in the Dutch governmental institution open data source (Statistics Netherlands CBS) and can be grouped by provinces. This is particularly important since the research is specifically analyzing The Randstad region that is comprised of four provinces: Zuid and Noord Holland, Flevoland and Utrecht. In the case of The Randstad, the methodology used is "An app-assisted travel surveys that uses location and motion sensors to measure location and to predict means of transportation." (CBS, 2017) The metadata represents the total passenger kilometers per year by modes of transport and regions from 2010 to 2017 over the country. It includes occupational trips that are done on a regular basis, in the context of work and excludes residents who are unemployed or working from home. It concerns all modes of transport used and if a journey to work was successively done by bicycle to the station, by train and on foot to the office, then all three modes of transport were counted separately. It also excludes travel on domestic holidays and cross-country borders. Occupational journeys and estimated passenger kilometers on domestic holidays are also not included (CBS, 2017).

In the case of Le Grand Paris, metadata on travel surveys (qualitative) can be found in the INSEE open database (Institut National de La Statistique Et Des Etudes Economiques). However, in the case of the monocentric urban form, the system is based on a "couronne" classification rather than provinces as seen in The Randstad. Le Grand Paris region is characterized by three crowns namely: Paris centre, the 'Petite couronne' and the 'Grande couronne'. Respectively each of these 'crowns' is further away from the center. The metadata from the INSEE (2015) is available specifically for each of these crowns, which helps draw more accurate correlations in relation to land use mix in terms of activity/residential areas and job/residential density.

According to the "Analysis of National Travel Statistics in Europe" (JRC et al., 2013), the frame of the INSEE survey is based on the population census with a land use update regarding residences built since the most recent census. For each occupational trip, two types of distances are entered: an air-line distance between home and the place of work and a declared distance by the interviewed. A combination of the two types of distances is used to enhance the accuracy of data collection. When the inhabitants work in their commune of residence, the distance kept is the declared one. Otherwise, the satellite distance is entered for inhabitants who work outside their commune of residence (Caenen et al., 2011).

Concerning the second phase of the research that aims at describing changes in travel behavior according to land use mix (Activity/residential areas) and job/residential density, data is also easily accessible for both regions. The most recent data for land occupation is from 2015 for both The Randstad and Le Grand Paris. In the case of The Randstad, CBS database provides insights into the use of the available space in The Netherlands by region and category of activity. In the case of Le Grand Paris, L'Apur (Atelier Parisien D'urbanisme) provides an extensive cross-scale digital map of land use by territories and 'arrondissements' in the Parisian region.

3.2 Operationalization: variables, indicators

The table below operationalizes the conceptual framework in chapter 2 to answer the research question: *How does urban form (monocentric/polycentric), under the influence of travel behavior affect work journey CO2 emissions?* It contains a description of the main concepts and indicators that will be assessed regarding the research question. These are: urban form, travel behavior and work journey CO2 emissions. Both CBS and INSEE constitute substantial data sources to measure all variables. In line with previous empirical academic work, the same databases have been used in the work of Shwanen et al., (2004; 2001) for The Randstad and Aguilera et al., (2014; 2009) for Le Grand Paris.

Table 2 List of variables and indicators

Concept/Variable	Definition	Indicators	Source of data
Urban form **(Independent)**	"The physical structure and size of the urban fabric as well as the distribution of population within the area." (Schwarz 2010, p.30)	**a-Land use mix:** - Activity area / Residential area in % - Accessibility to public transportation in % or (Km) **b-Density :** -Job density (Number of jobs / area (sqkm)) -Residential density (Habitants/ area (sqkm))	**The Randstad** **CBS** Statistics Netherlands (Centraal Bureau Voor de Statistiek) **Le Grand Paris** **INSEE** National Institute of statistics and Economic Studies
Travel behavior **(Mediating)**	Travel behaviour is a concept used in the context of travel related activity analysis (Handy 1996). It focuses on the behaviour of travellers. This includes a range of criteria such as modal choice, distance travelled as well as trip motive and frequency.	-Modal choice: Car, motorcycle, train, bus/tram/metro, bicycle, walking **(Qualitative)** -Distance travelled between home and work (Km) **(Quantitative)**	**The Randstad** **CBS** Statistics Netherlands (Centraal Bureau Voor de Statistiek) **Esri demographics** **Geodienst** **Rijksuniversiteit Groningen** **Le Grand Paris** **INSEE** National Institute of statistics and Economic Studies **APUR** Atelier Parisien D'Urbanisme
Work journey CO2 emissions **(Dependent)**	Work journey induced carbon dioxide (CO_2) emissions are due to fuel combustion in the context of work journey « trips ». Their sources include all means of transportation namely: road vehicles, rail, tram and metro.	-Distance travelled by vehicle type (Vehicle-Km) -Vehicle emission factor (Kg CO_2 e/Vehicle Km)	**GHG Protocol** The protocol is a joint tool provided by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD)

In the second phase, correlations of urban form, travel behavior and CO2 emissions will be based on seven observation: the four provinces of The Randstad (Flevoland, Utrecht, North Holland and South Holland) and the three crowns of Le Grand Paris (Paris centre, the first crown 'La petite couronne' and the second crown 'La grande couronne'). The purpose of identifying correlations is to understand to what extend the three variables: urban form, travel behavior and work-journey CO_2 emissions can be interlinked and to answer the research sub-question: *How does urban form in terms of land use and density interact with travel behavior?*

The comparison between the two case studies is *empirical* and *explanatory* at the city scale. It builds on previous empirical study of Shwanen et al., (2004; 2001) and Aguilera et al., (2014; 2009). The research is specifically interested into understanding how *urban typology* and *mobility patterns* operate from a *'geographical'* perspective. In that regard, after correlating statistical data on travel patterns and consequent CO_2 emissions (CBS and INSEE), the Global Moran I will be used as a tool to measure the spread of these statistical values over space. The tool will process geo data from L'APUR, INSEE, ESRI Demographics, Geodienst Rijksuniversiteit Groningen and CBS on *land use* and *density*. Similarly to Pearson's correlation, the strength of correlations is measured from -1 to +1. A positive spatial autocorrelation indicates that values are similarly clustered together in a map. A negative correlation indicates that the values are disseminated. A value of 0 indicates the absence of any spatial correlation.

The Global Moran I tool (using GIS) is important to assess the geographical dimension of our variables. As it could provide insight into how socio-economic indicators measured statistically such as land use and densities operate regarding the compactness level (monocentrality/polycentrality) in The Randstad and Le Grand Paris. In the last stage of the analysis, final considerations on sustainability will be made considering both statistical and spatial autocorrelations as well as CO_2 inventories as a proxy of sustainability with regard to travel behavior.

3.3 Expected challenges and limitations

In The Netherlands, data from the National travel survey is updated each year. The most recent metadata regarding the average commuting distance of employees by mode of transportation has been recently processed in 2017. In the case of Le Grand Paris, data on the modal choice is available for 2015. However, complementary data on the average distance travelled by employees dates from 2008. In the case of France, the National travel survey also known as the « Enquête sur la mobilité des personnes » is realized every ten years (JRC et al., 2013). According to the INSEE, the most recent national travel survey took place from April 2018 to April 2019. The new report of the 2018-2019 travel survey is scheduled for publication in the first semester of 2020. In case the publication of the new survey results is delayed due to the coronavirus crisis, data on the average distance travelled by employees will be used from 2008 national report.

Chapter 4: Presentation of data and analysis

4.1 Phase I: Evaluation of work-journey CO2 emissions for The Randstad and Le Grand Paris

The initial objective has an evaluation nature. The aim of phase I of the analysis is to evaluate the sustainability of both The Randstad and Le Grand Paris in terms of work-journey CO2 emissions using the GHG Protocol. The initial results of CO2 metric inventories will be later used in phase II to draw correlations with urban form (land use and density) as well as travel behavior (distance and modal choice).

4.1.1 Data presentation

The Randstad

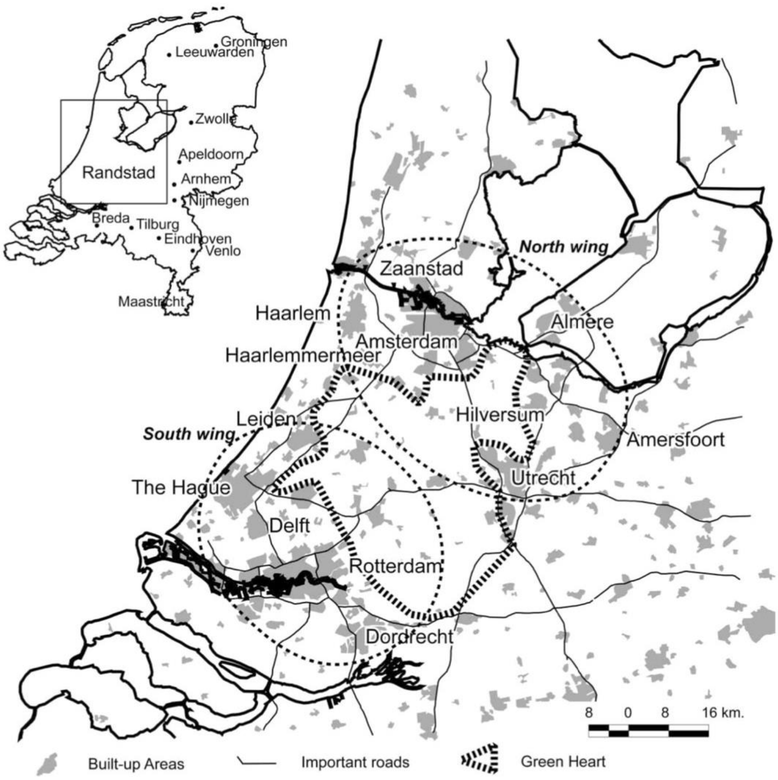


Figure 2 Illustrative map of The Randstad

Source: Map from Meijers, E., 2005. "Polycentric urban regions and the quest for synergy: is a network of cities more than the sum of the parts?" *Urban Studies,* 42 (4), pp. 765-781.

The map above shows that The Randstad region comprises four of the largest cities in The Netherlands (Amsterdam, Rotterdam, The Hague and Utrecht) as well as their adjacent municipalities. Since the daily commuting of employees is extra-municipal in the highly connected area, the CO2 inventories will not only include the four main cities but rather the four provinces that constitute The Randstad. These are Flevoland, Utrecht, North Holland and South Holland. Table 4 shows that data of travel behavior has been collected by specific regions from Statistics Netherlands (CBS).

The table below shows that the distances travelled by car are the most significant in all provinces of The Randstad (Flevoland, Utrecht, North Holland and South Holland), with the highest average Km being concentrated in North and South Holland. The second most covered distances in all provinces is done by the train. Other modes in terms of distance travelled are respectively classified as the bike, bus/tram/metro, walking then mopeds. The results also show that in both North and South Holland the km travelled by trains and bicycles as sustainable modes of transportation is the highest compared to other provinces. However, this does not compensate for the high level of distances travelled by car in the two regions (North and South Holland).

Table 3 Total passenger kilometres in The Randstad by provinces and modes of transportation (2015).

Transport mode	Province	Billion km
Car	Flevoland	3,0
	Utrecht	7,6
	South Holland	18,6
	North Holland	13,6
Train	Flevoland	0,6
	Utrecht	1,6
	South Holland	3,1
	North Holland	3,1
Bus / tram / metro	Flevoland	0,2
	Utrecht	0,3
	South Holland	1,8
	North Holland	1,3
Moped / light moped	Flevoland	0,0
	Utrecht	0,1
	South Holland	0,2
	North Holland	0,2
Bike	Flevoland	0,2
	Utrecht	1,2
	South Holland	2,9
	North Holland	2,7
walk	Flevoland	0,1
	Utrecht	0,4
	South Holland	1,2
	North Holland	0,9

Source: Statistics Netherlands (CBS 2015)

Le Grand Paris

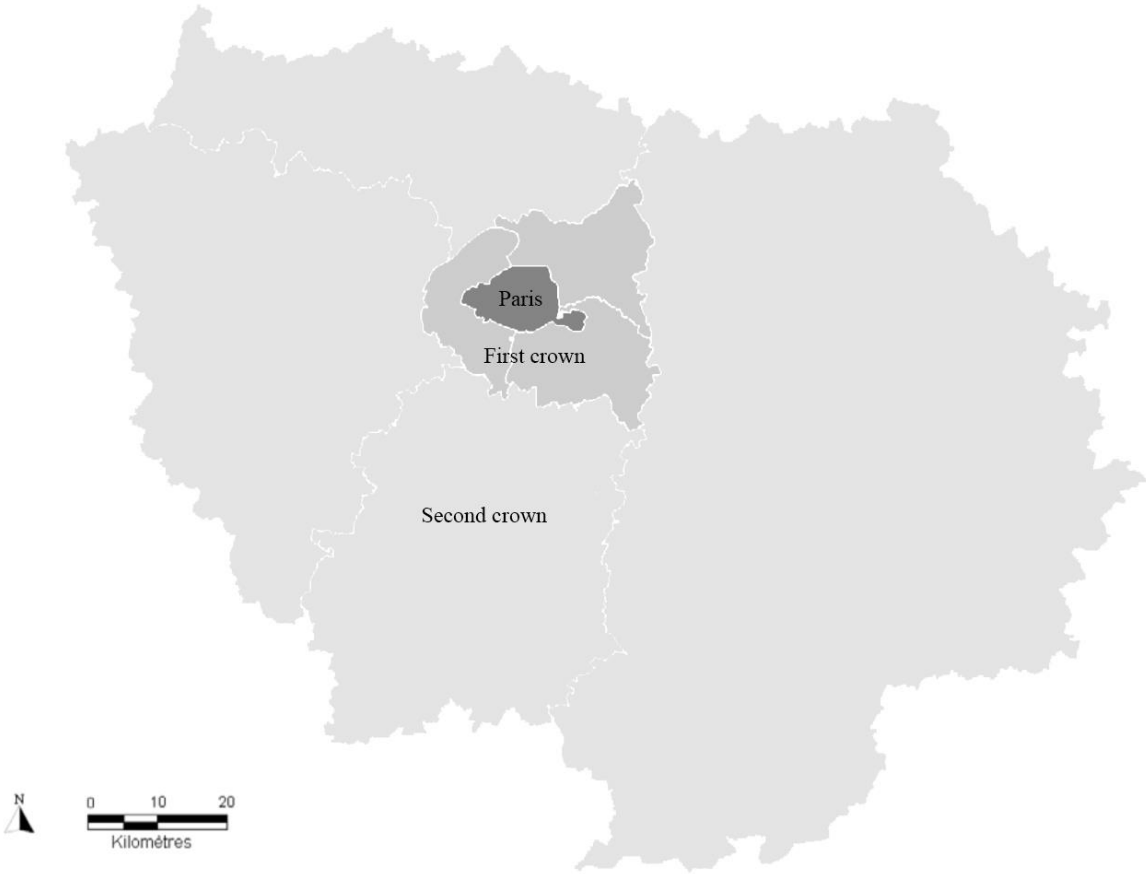


Figure 3 Illustrative map of Le Grand Paris metropolitan area (Region Ile de france)

Source: Illustrated by the author for the purpose of the thesis.

Le Grand Paris constitutes the archetype of the monocentric urban form. In the map above, it can be seen that the region is divided into three distinct crowns namely: Paris centre, the first crown 'La petite couronne' and the second crown 'La grande couronne'. Each of these crowns comprises multiple municipalities. The CO_2 inventories in the case of Le Grand Paris will be calculated in accordance with the 'crown' classification. As discussed in chapter 3 the sustainability assessment of urban form and travel behavior should be inscribed in the most appropriate scale for *regional* intervention. Therefore, the analysis will be conducted in an *in-between scale* that is best representative of *travel trends* in the *metropolitan* area. Table 4 shows that data of travel behavior has been collected by specific crowns from The National Institute of Statistics and Economic Studies (INSEE).

Table 4 shows that the most prevalent mode of transportation in Le Grand Paris is public transportation (tram, bus, metro) for both the 'Paris center' and the 'first crown'. However when travel distances are more significant, which is the case of reverse commuters within the second crown (Aguilera et al., 2009), the percentage of public transportation drops to 29, 9 % as the share of car use rises to 58, 9 %. Hence, in phase II of the research, the analysis will not only establish a comparison between The Randstad and Le Grand Paris but also provide an understanding to discrepancies between sub regions of each of the case studies. These are represented by the three crowns of Le Grand Paris (Figure 3, p.21) and the four provinces of The Randstad (Figure 2, p.19).

Table 4 The share of 'employee' modal choice in Le Grand Paris in % (2015).

Modal choice (%)	Paris center	First crown	Second crown
Walking	9,5	7,6	5
Bike	4,2	1,9	0,9
Motorcycle	4,5	3,6	1,9
Road transport (Car, truck)	12,3	36,6	58,9
Public transportation (Tram, bus, metro)	64,8	47,5	29,9

Source: The National Institute of Statistics and Economic Studies (INSEE), 2015.

In the case of Le Grand Paris, there is no direct available data on total passenger kilometers per year. Therefore, in order to proceed with the CO2 inventories, data triangulation on travel behavior was used from both the INSEE and L'APUR databases. To extract the total yearly passenger kilometers as seen in The Randstad (see table 3), a second treatment of data from table 4 and 5 was used for Le Grand Paris. First the number of employees per crown was extracted from L'APUR (see table 5), and then multiplied by the share of modal choice within each crown (see table 4). Second, the total daily passenger kilometers was calculated based on the average daily passenger kilometers of employees per modal choice per crown, as respectively seen table 6, 7 and 8. Third, the average daily passenger kilometers were multiplied by the official 251 working days in France to get the total passenger kilometers per year per mode of transportation by crown. Below is a complete summary of the second data treatment. Later in the next chapter, these results will be entered in the GHG Protocol calculation tool to calculate the CO2 emissions. Then they will be compared with the GHG inventory of ADEME (French Environment and Energy Management Agency) to assess the accuracy of the results.

Table 5 The share of daily passenger kilometers by crowns and N° of Employees in Le Grand Paris.

	Paris center	First crown	Second crown
Total active population (N° of Employees)	1574183	2 112 381	2 369 436
Average passenger kilometers per day (km)	6,6	8,3	14,6

Source: L'Atelier d'Urbanisme de Paris (L'APUR) 2015 and The National Institute of Statistics and Economic Studies (INSEE), 2008.

Table 6 Total passenger kilometres in 'Paris center' area in Le Grand Paris by modes of transportation.

Paris center	N° of Employees	Daily Passenger KM	Yearly Passenger Billion KM
Walking	149 547	987 013	0,25
Bike	66 116	436 364	0,11
Motorcycle	70 838	467 532	0,12
Road transport (Car, truck)	193 625	1 277 922	0,32
Public transportation (Tram, bus, metro)	1 020 071	6 732 466	1,69

Source: Data extrapolated by the author using INSEE data base for the purpose of the research.

Table 7 Total passenger kilometres in the 'First crown' in Le Grand Paris by mode of transportation.

First crown	N° of Employees	Daily Passenger KM	Yearly Passenger Billion KM
Walking	160 541	1 332 490	0,33
Bike	40 135	333 122	0,08
Motorcycle	76 046	631 179	0,16
Road transport (Car, truck)	773 131	6 416 991	1,61
Public transportation (Tram, bus, metro)	1 003 381	8 328 062	2,09

Source: Data extrapolated by the author using INSEE data base for the purpose of the research.

Table 8 Total passenger kilometres in the 'Second crown' in Le Grand Paris by mode of transportation.

Second crown	N° of Employees	Daily Passenger KM	Yearly Passenger Billion KM
Walking	118 472	1 729 688	0,43
Bike	21 325	311 344	0,08
Motorcycle	45 019	657 282	0,16
Road transport (Car, truck)	1 395 598	20 375 728	5,11
Public transportation (Tram, bus, metro)	708 461	10 343 536	2,60

Source: Data extrapolated by the author using INSEE data base for the purpose of the research.

4.1.2 Work-journey CO_2 emissions inventory results

Before proceeding with the CO_2 inventories for both The Randstad and Le Grand Paris, the accuracy of the GHG protocol is tested using the most recent data on travel behavior on a national level in The Netherlands (CBS 2017). Then results are compared with the most recent official data on CO_2 emissions based on the IPCC regulations (see table 10) (CBS 2017). The complete data set is summarized in table 9 and 10 below.

Table 9 The Netherlands work-journey CO_2 inventory using the GHG Protocol.

Total GHG Emissions (Million metric tons MtCO2e)	**29,89**

GREENHOUSE GAS PROTOCOL	**Travel activity data (CBS 2017)**		
Vehicle type	**Province**	**Distance Travelled** (Billion Km)	**GHG Emissions** (Million Metric tons MtCO2e)
Car	Flevoland	2,6	0,73
	Utrecht	7,3	2,04
	North Holland	13,5	3,78
	Zuid Holland	17,9	5,01
	Groningen	3,1	0,87
	Friesland	4	1,12
	Drenthe	3,6	1,01
	Overijssel	7	1,96
	Gelderland	12,6	3,53
	Zeeland	2,1	0,59
	North Brabant	15,7	4,39
	Limburg	6,7	1,87
Bus	Flevoland	0,2	0,01
	Utrecht	0,4	0,03
	North Holland	1,3	0,09
	Zuid Holland	1,7	0,11
	Groningen	0,2	0,02
	Friesland	0,2	0,01
	Drenthe	0,2	0,01
	Overijssel	0,1	0,01
	Gelderland	0,5	0,03
	Zeeland	0,1	0,01
	North Brabant	0,5	0,03
	Limburg	0,2	0,01

Motorbike	Flevoland	0	0,00
	Utrecht	0,1	0,01
	North Holland	0,2	0,03
	Zuid Holland	0,2	0,03
	Groningen	0	0,00
	Friesland	0	0,00
	Drenthe	0	0,00
	Overijssel	0	0,00
	Gelderland	0,1	0,01
	Zeeland	0	0,00
	North Brabant	0,1	0,01
	Limburg	0	0,00
Train- Subway	Flevoland	0,2	0,02
	Utrecht	0,4	0,04
	North Holland	1,3	0,13
	Zuid Holland	1,7	0,17
	Groningen	0,2	0,02
	Friesland	0,2	0,02
	Drenthe	0,2	0,02
	Overijssel	0,1	0,01
	Gelderland	0,5	0,05
	Zeeland	0,1	0,01
	North Brabant	0,5	0,05
	Limburg	0,2	0,02
Train - National Rail	Flevoland	0,7	0,08
	Utrecht	2,3	0,26
	North Holland	3,3	0,38
	Zuid Holland	3,4	0,39
	Groningen	0,6	0,07
	Friesland	0,4	0,05
	Drenthe	0,2	0,02
	Overijssel	1	0,12
	Gelderland	2	0,23
	Zeeland	0,1	0,01
	North Brabant	2	0,23
	Limburg	1,1	0,13

Source: Inventory extrapolated by the author using the GHG Protocol tool and data from CBS.

Table 10 shows that the share of CO_2 emissions from road traffic for occupational journey trips in the Netherlands is dramatically higher than other sources such as shipping, aviation, and rail traffic. This indicates that cars are the main source of transport related CO_2 emissions in the case of The Netherlands according to the IPCC. The latter provides an insight into the Dutch greenhouse gas emissions as reported by the United Nations and the European Union. This takes place in the context of the reporting obligations of the United Nations Framework Convention on Climate Change (UNFCCC) and the European Union's Greenhouse Gas Monitoring Mechanism. The IPCC estimations show according to table 10 a total of 29.87 Million tCO_2. This includes both rail and road traffic. In comparison, the results using the GHG protocol show a total of 29.89 tCO_2 (1 Million $kgCO_2$ equals 1000 tCO_2) (see table 10, p.26). This represents a similarity of more than 99 %. The tool is hence *reliable* to calculate the CO_2 emissions in The Randstad region using the same travel behavior data from CBS.

Table 10 The Netherlands transport related Greenhouse gas emissions calculated according to IPCC regulations

	Transport type			
GHG Emission	**Rail traffic**	**Road traffic**	**Shipping**	**Aviation**
CO2 (Million Kg)	84	29790	988	32
CH4 (Million Kg)	0,00	2,47	0,13	0,00
N2O (Million Kg)	0,00	0,83	0,03	0,00

Source: Statistics Netherlands (CBS 2017)

Table 11 shows that cars remain the most significant source of CO_2 emissions compared with other modes of road and rail transportation in The Randstad. Furthermore, the highest emissions are concentrated respectively in South Holland, North Holland, Utrecht then Flevoland. This strongly correlates with the high number of yearly passenger kilometers done by car which respectively are for the four provinces: 18.6, 13.6, 7.6, 3 Billon Km (see table 3, p.20). Beyond the comparison with Le Grand Paris, the aim of the inventory in phase II is to understand the differences in CO_2 emissions between the different provinces of The Randstad by finding correlations with variables of urban form, namely density and land use.

Table 11 The Randstad work-journey CO2 inventory using the GHG Protocol.

Total GHG Emissions (Million metric tons MtCO2e)	**13,6**

GREENHOUSE GAS PROTOCOL	**Travel activity Data (CBS 2015)**			
Province	**Vehicle Type**	**Distance Travelled** (Billion Km)	**GHG Emissions** (Million Metric tons MtCO2e)	**Total GHG Emissions** (Million Metric tons MtCO2e)
Flevoland	Car Bus Motorbike Train - Subway Train - National Rail	3 0,2 0 0,2 0,6	0,84 0,01 0,00 0,02 0,07	**0,94**
Utrecht	Car Bus Motorbike Train - Subway Train - National Rail	7,6 0,3 0,1 0,3 1,6	2,13 0,02 0,01 0,03 0,18	**2,37**
North Holland	Car Bus Motorbike Train - Subway Train - National Rail	13,6 1,3 0,2 1,3 3,1	3,81 0,09 0,03 0,13 0,36	**4,40**
Zuid Holland	Car Bus Motorbike Train - Subway Train - National Rail	18,6 1,8 0,2 1,8 3,1	5,20 0,12 0,03 0,18 0,36	**5,89**

Source: Inventory extrapolated by the author using the GHG Protocol tool and data from CBS.

Table 12 shows that the highest CO2 emissions are concentrated respectively in the second crown, first crown then Paris center. This strongly correlates with the share of car use in the three sub regions respectively: 12.3 %, 36.6 %, 58.9 % (see table 4, p.22). The GHG Protocol results have been compared with the official 2018 GHG report of the city of Paris 'Bilan des émissions de Gaz à effets de serre de Paris' published in January 2020 by ADEME (French Environment and Energy Management Agency, figure 4). This data source was used as the main CO2 inventory in the work of Aguilera et al., (2014) on commuting patterns and CO2 emissions in the Marne-La-Vallée region in the Paris metropolitan area (see chapter 2). The GHG inventory for trips that are done in the context of work including deliveries and taxi drivers amount to 4.2 Million t CO2e (ADEME 2018). This includes both the trips done within Paris center 'Transport intra-muros' and the trips in the first and second crown at the metropolitan level 'Transport hors Paris'. The GHG Protocol shows a result of 3.8 Million t CO2e. This signifies a correlation of 90 % (table 12). Although the inventories are from different years (2015 and 2018), the goal of the comparison is to evaluate the proportional exactitude of the GHG Protocol results before establishing a comparison with The Randstad.

Table 12 Le Grand Paris work-journey CO2 inventory using the GHG Protocol.

Total GHG Emissions (Million metric tons MtCO2e)	**3,83**

GREENHOUSE GAS PROTOCOL

	Travel activity Data (INSEE 2015)			
Region	**Vehicle Type**	**Distance Travelled** (Billion Km)	**GHG Emissions** (Million Metric tons MtCO2e)	**Total GHG Emissions** (Million Metric tons MtCO2e)
Paris center	Car	0,32	0,09	**0,58**
	Bus	1,69	0,11	
	Motorbike	0,12	0,01	
	Train - Subway	1,69	0,17	
	Train - National Rail	1,69	0,19	
First crown	Car	1,61	0,45	**1,06**
	Bus	2,09	0,14	
	Motorbike	0,16	0,02	
	Train - Subway	2,09	0,21	
	Train - National Rail	2,09	0,24	
Second crown	Car	5,11	1,43	**2,19**
	Bus	2,60	0,17	
	Motorbike	0,16	0,02	
	Train - Subway	2,60	0,26	
	Train - National Rail	2,60	0,30	

Source: Inventory extrapolated by the author using the GHG Protocol tool and data from INSEE.

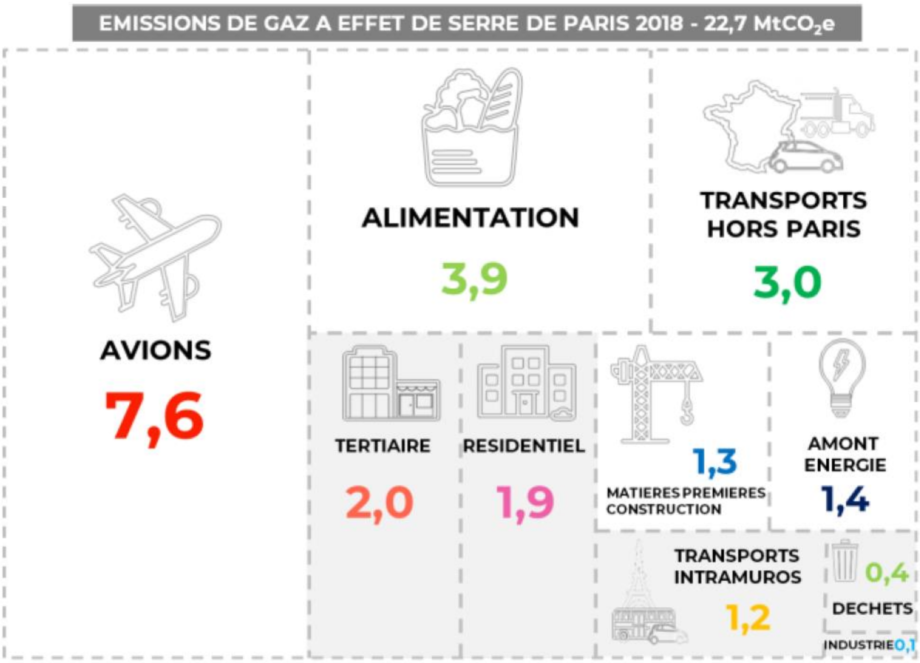


Figure 4 Le Grand Paris carbon footprint by sector.

Source : 'Bilan des émissions de Gaz à effets de serre de Paris' (ADEME 2018)

4.1.3 Work-journey CO2 inventory comparison between The Randstad and Le Grand Paris

To reiterate the objective of phase I of the analysis is to evaluate the sustainability of both The Randstad and Le Grand Paris (*monocentric versus polycentric*) using quantitative and qualitative secondary data triangulation on travel behavior. The results from the GHG protocol inventory on work journey CO2 emissions indicate that The Randstad region has a total yearly emissions of **13.6 Million tCO2e** (see table 11) in comparison with a mere **3.8 Million tCO2e** in the case of **Le Grand Paris** (see table 12). This means that **The Randstad** pollutes **3.5 times** more than **Le Grand Paris**. The difference is even more significant if the number of employees is considered. As there is roughly 2 million more employees in Le Grand Paris than in The Randstad region. This indicates that the discrepancies regarding the work journey CO2 emissions per capita are even higher between the two regions. It also challenges the idea that the monocentric urban form, because of its strong centrality and gentrification induces reverse commuters that use unsustainable modes of transportation for longer commuting distances (Aguilera et al., 2009). While this is the case for 2.3 million employees in the second crown of Le Grand Paris, if we look at the metropolitan scale, another 3.6 million employees rely more on public transportation (see table 4 and 5, p.22).

Furthermore, the conclusions of the work journey CO2 evaluation also challenges the *planning ideal* behind the polycentric urban form from the 'co-location' principle that is explained in chapter 2 (Shwanen et al., 2001; Burger and Meijers 2012; Kloosterman et al., 2001). As a reminder, the 'co-location' principle indicates that commuters in the case of functional polycentrality are encouraged to find work placement near their residences. According to the literature, the provinces of The Randstad are closely monitored so they perform evenly in terms of the number of jobs each can provide by economic sector (Burger and Meijers 2012; Meijers 2005; Kloosterman et al., 2001; Van Raan et al., 2016). In theory this would reduce the commuting distances in favor of more sustainable modes of transportation. However, even in Le Grand Paris with its central CBD known as 'La Défense', the highest share of car use (58,9

%) (see table 4, p.22) in the most remote area from the center 'second crown' remains lower than average share of car use in The Randstad of 73 % (CBS 2016). Phase I of the analysis also answers part of the interrogations in the literature review with regard to the previous work of Shwanen et al., (2004) on "Policies for urban form and their impact on travel: the Netherlands experience." The current evaluation indicates that despite the new spatial developments regarding the strong Dutch planning policies aiming at reducing car use (see table 1, p.9), *travel behavior* in terms of citizen's engagement remains questionable.

In the section "Urban form, travel behavior and climate mitigation" of chapter 2, policy action in terms of climate mitigation is interested in both the planning practice and actual travel trends. While in phase 1 of the evaluation, the dramatic differences between the two regions could be explained by travel behavior, this only answers the first research sub question related to our two cases studies: "*How does urban form in regard to polycentrality and monocentrality (in The Randstad and Le Grand Paris) relate to work journey CO2 emissions and overall sustainability?"* However, it does not yet fully answer the research question with regard to how urban form interacts with travel behavior: "*How does urban form (monocentric/polycentric), under the influence of travel behavior affect work journey CO2 emissions?"*

The conceptual framework as a synthesis of the literature review indicates that travel behavior itself is conditioned by other variables of urban form namely *land use* and *density*. While phase I highlights the discrepancies in travel behavior between the two urban forms and evaluates how they perform in sustainability via CO2 inventories, the purpose of phase II will be to provide correlations and analysis of urban form, travel behavior and CO2 emissions. This helps find answers to: *How far is travel behavior linked to urban form? And what are the possible interactions with regard sustainability?*

4.2 Phase II: Correlations between CO2 emissions, urban form and travel behavior

In phase I, the work-journey CO2 evaluation showed that The Randstad performs 3.5 times less than Le Grand Paris based on secondary data triangulation of travel behavior. In Phase II, it is important to understand in both case studies (The Randstad and Le Grand Paris) to what extend is travel behavior linked to urban form in terms of land use and density.

In phase II, the assessment of the link between *Urban form, Travel behavior and Work-journey CO2 emissions* will make use of cross-tabulation, Pearson's correlation coefficient (r) and the Global Moran I spatial autocorrelations to measure the relationship between variables based on seven observations. Phase II tries to answer the research sub-question: *How does urban form in terms of land use and density interact with travel behavior?*

4.2.1 Data presentation and comparison between The Randstad and Le Grand Paris

Correlations between work-journey CO2 emissions and density

From Table 13 below, there is a strong correlation between density (job/residential) and work journey induced CO2 emissions. However, this relationship operates differently in the two opposite urban forms (Monocentric/Polycentric). In Le Grand Paris, the correlation is highly negative, in a way that the amount of CO2 emissions is proportionally lowered when density gets higher. Earlier in chapter 2, it was discussed that "Population density is a proxy for less easily measured characteristics of the urban environment. A classic example is the *exponential decline* in per capita *transport in energy* use with *increasing population density* that was observed in a large cross-section of cities worldwide." (Gately et al., 2015, p.5000). This is particularly visible in the Paris Center which is regarded as one of the highest densities in the world (21 0657 Hab/sqkm). In table 13, the work journey CO2 emissions are dramatically low (583446 Metric tons CO2e).

On the opposite side, the polycentric urban model known as The Randstad shows a positive correlation between density and CO2 emissions. As densities get higher, work journey CO2 emissions also increase proportionally. The difference between the two regions might be due to the fact that The Randstad has a "*concentrated decentralization*" urban system that spreads density evenly and does not allow reaching a *critical density* such as in the case of Le Grand Paris (Shwanen et al., 2004; 2001). This critical density is important as in chapter 2; it was assumed that *high density* is also one of the main drivers for the use of public transportation to avoid congestion (Jabareen 2006).

Table 13 Correlation between work journey CO2 emissions and density

		Work journey CO2 emissions (Million Metric tons)	Residential density (Habitants/ area (sqkm))	Job density (Number of jobs / area (sqkm))
Le Grand Paris (monocentric)	Paris centre	0,58	21 067	14 992
	First crown	1,06	6901	3215
	Second Crown	2,19	469	210
The Randstad (polycenntric)	Flevoland	0,94	284	59
	Utrecht	2,37	914	460
	North Holland	4,40	1037	349
	Zuid Holland	5,89	1283	480

Source: CBS, INSEE, APUR, GHG Protocol 2015.

Le Grand Paris

Correlation between work journey CO2 emissions and residential density: r= -0,90

Correlation between work journey CO2 emissions and job density: r= -0,84

The Randstad

Correlation between work journey CO2 emissions and residential density: r= 0,92

Correlation between work journey CO2 emissions and job density: r= 0,72

Hence, to understand the discrepancies in work journey CO2 emissions between the two regions, the next step is to assess the link between density and travel behavior (share of modal choice and distance travelled). As deducted in phase I, the most significant CO2 emitter remains the car for both regions. For this reason, it is logical with regard to the current results to draw links between density, modal choice and distance travelled as seen below (table 14 and 15, p.33 p.34).

Correlations between density and travel behavior

First, table 14 p.33 shows a negative correlation between residential density and share of car use in both The Randstad and Le Grand Paris. However, the correlation is more significant in the case of Le Grand Paris than in The Randstad. As explained earlier, in Le Grand Paris, the highest share of car use (58, 9 %) (see table 4, p.22) in the most remote area from the center 'second crown' remains lower than average share of car use in The Randstad of 73 % (CBS 2016).

Second, table 14 p.33 shows a positive correlation between residential density and share of public transportation in both The Randstad and Le Grand Paris. However, this is again much significant in the case of Le Grand Paris. In chapter 2 of the literature review, the research of

Shwanen et al., (2004) based on National travel behavior (CBS 1998) suggested that "Policies that aimed for *concentrated decentralization* have simulated more use of *public transport* because of increased *density* in growth centers as opposed to suburban areas. However, this only *reduced slightly* the *share of private cars*."

Indeed, 17 years later the current results (CBS 2015) are still consistent with Shwanen et al., (2004) assumptions on the efficiency of the "*concentrated decentralization"* planning policy. Table 14 p.33 shows a slight negative correlation between residential density and car use in The Randstad region, but the correlation is not strong enough to encourage significant public transportation use with regard sustainability in terms of CO2 emissions (table 13, p.31). To reiterate, the hypothesis is that *the critical density* that significantly encourages sustainable modes of transportation and work journey CO2 emissions has not been reached the critical density in the "*concentrated decentralization"* planning policy of The Randstad. Conversely, regarding the "*monocentric urban model"* of Le Grand Paris, the relationship between work journey CO2 emission, density and share of car use/public transportation remains consistent.

Third, table 15 p.34 shows a strong negative correlation between job/residential density and the distance travelled with car/public transportation in the case of Le Grand Paris. In the same table, The Randstad shows again an opposite relationship. The difference is curious since both regions geographically cover an area of 12 012 sqkm and 11 372 sqkm respectively for Le Grand Paris and The Randstad (see table 16, p.34). In terms of the passenger distance covered (work to home), the difference between the two regions should clearly be investigated from a *compactness* or *centralization/decentralization* perspective.

In the monocentric model, (Le Grand Paris, see figure 3, p.21), table 15 p.34 and 16 p.34 show a significant match between the high residential density and high job density in the Paris center. And this within a relatively small ring of 105 sqkm. This indicates the high compactness of the monocentric urban typology. This also means that a significant share of work journey trips is done within an area in which the average commute trip is 6,6 km (see table 5, p.22). Furthermore, the mismatch between the residential density (6901 sqkm) (see table 15, p.34) and job density in the first crown (3215 sqkm) entails that the share of work journey commutes is likely to happen between the first crown towards the Paris center where the density of jobs is very high (14 992 sqkm). The total area that covers both the Paris center and the first crown is 762sqkm. And the average commute distance in this area is 8,3 km (see table 5, p.22). In comparison, the share of reverse commuters is expected to be very low from Paris center to the second crown and vice versa with a job and residential density of respectively 210sqkm and 469sqkm in the second crown. This indicates that in the case of Le Grand Paris both density and compactness are respectively correlated to modal choice and distance travelled by significantly reducing the CO2 emissions.

In the case of the polycentric urban model (The Randstad), the relatively low compactness reveals opposite results in comparison with the monocentric urban model (see table 15 p.34 figure 2, p.19, figure 3, p.21). Because of the "*concentrated decentralization"* policy, both job and residential densities remain relatively low in comparison to the compact Parisian metropolitan area. The density estimates in The Randstad are also closely distributed between the three different provinces: Utrecht, North and South Holland (Table 15, p.34) in comparison with Le Grand Paris. Furthermore, the same tables show a higher mismatch between residential density and job density in The Randstad than in Le Grand Paris. This indicates that work journey trips might even happen for longer distances outside The Randstad. This issue has already been evoked in the work of Shwanen et al., (2004) on the impact of Dutch urban planning policies on travel behavior in The Netherlands. The strong "*concentrated decentralization"* equalizing policy aiming at providing an equal number of jobs by economic sector in The Netherlands (Burger and Meijers 2012; Meijers 2005; Kloosterman et al., 2001; Van Raan et al., 2016) primary induces "Qualitative and quantitative mismatch between workers and employment in new towns." To escape the problem the same author suggests that through the co-location principle "Households periodically change jobs/residential location, so they travel shorter distances." (Shwanen et al., 2004, p.594).

In the case of The Randstad, the significant mismatch between job and residential density is potentially responsible for the longer commuting distances regardless of modal choice (both correlations for car and public transportation are positive). This might be due to the relatively low compactness. The commutes in The Randstad happen within a more extensive area in comparison with Le Grand Paris. Furthermore, in the monocentric urban model (Le Grand Paris), it is possible to make assumptions on the trajectories of work trips converging from the second crown to the center towards high job densities. It is not possible to draw similar conclusions in the polycentric urban model. As directions of work trips cannot be interpreted.

All previous interpretations provide a possible explanation to the relation between density and travel behavior in our two case studies, however it only answers part of our second research sub-question: *How does urban form in terms of land use and density interact with travel behavior?* In chapter 2 of the literature review, an assumption was made that *land-use mix* acts on the daily commuting distances by distributing the locations of jobs and residences and that *density* plays an important role in modal choice. Hence, in the next correlations the aim is to look at the second indicator of urban form '*land use*' and its possible interactions with travel behavior.

Table 14 Correlation between residential density and modal choice

		Residential density (Habitants/ area (sqkm))	Share of car use in %	Share of public transportation in %
Le Grand Paris (monocentric)	Paris centre	21 067	12,3	64,8
	First crown	6901	36,6	47,5
	Second Crown	469	58,9	29,9
The Randstad (polycenntric)	Flevoland	284	75,0	25,0
	Utrecht	914	77,6	22,2
	North Holland	1037	70,0	29,2
	Zuid Holland	1283	73,0	26,3

Source: CBS, INSEE, APUR 2015.

Le Grand Paris

Correlation between residential density and share of car use: r= -0,98

Correlation between residential density and share of public transportation use: r= 0,97

The Randstad

Correlation between residential density and share of car use: r= -0,36

Correlation between residential density and share of public transportation use: r= 0,29

Table 15 Correlation between density and distance travelled

		Residential density (Habitants/ area (sqkm))	Job density (Number of jobs / area (sqkm))	Total car passenger in Billion km	Total public transportation Passenger in Billion km
Le Grand Paris (monocentric)	Paris centre	21 067	14 992	0,32	5,07
	First crown	6901	3215	1,61	6,27
	Second Crown	469	210	5,11	7,79
The Randstad (polycenntric)	Flevoland	284	59	3,00	1,00
	Utrecht	914	460	7,60	2,20
	North Holland	1037	349	13,60	5,70
	Zuid Holland	1283	480	18,60	6,70

Source: CBS, INSEE, APUR 2015.

Le Grand Paris

Correlation between residential density and distance travelled by car: r= -0,88

Correlation between residential density and distance travelled by public transportation: r= -0,96

Correlation between job density and distance travelled by car: r=-0,83

Correlation between job density and distance travelled by public transportation: r=-0,92

The Randstad

Correlation between residential density and distance travelled by car: r= 0,93

Correlation between residential density and distance travelled by public transportation: r=0,88

Correlation between job density and distance travelled by car: r=0,73

Correlation between job density and distance travelled by public transportation: r=0,63

Table 16 Total area of The Randstad and Le Grand Paris

		Area per region (sqkm)	Total area (sqkm)
Le Grand Paris (monocentric)	Paris centre	105	12 012
	First crown	657	
	Second Crown	11250	
The Randstad (polycenntric)	Flevoland	2412	11 372
	Utrecht	1449	
	North Holland	4092	
	Zuid Holland	3419	

Source: CBS, INSEE, APUR 2015.

Correlations between land use mix and travel behavior

First, table 17 p.36 show a negative correlation between land use mix and share of car use and a positive correlation between land use mix and share of public transportation. Both regions The Randstad and Le Grand Paris correlate in the same direction. However, the correlation is more significant in the case of Le Grand Paris than in The Randstad. A similar pattern in the previous table 14 p.33 showed that density encouraged the use of public transportation and reduced the share of car use in both regions, but to a greater extend in Le Grand Paris.

It can be concluded from table 14 p.33 and table 17 p.36 that higher density and land use mix potentially encourages more sustainable modes of transportation and this regardless of the urban typology (monocentric/polycentric). However, travel behavior is a combination of *distance* and *modal choice*. When assessing travel behavior from its *'distance'* indicator by introducing variables of land use and density, the two regions show opposite relationships. In table 18 p.36, land use mix reduces the distances travelled in Le Grand Paris regardless of the modal choice, while it increases the distances travelled in the case of The Randstad. As previously seen with the density and distance correlations in table 15 p.34 the relationship is also opposite between the two regions.

In chapter 2 it has already been discussed how the literature is contradictory in terms of which urban form monocentric or polycentric is more sustainable (Camagni et al., 2002; Engefriet and Koomen 2018; Jabareen 2006; Jenks 2019 Stone et al., 2010). It was also mentioned that there is an agreement that sprawl causes longer commuting distances and an increase of private modes of transportation. The Randstad from the literature review indicates that jobs and residences are equally diffused within the urban fabric to ensure at the scale of the region, not only a morphological polycentrality but also a functional one in terms of the number of jobs each province can provide (Burger and Meijers 2012; Meijers 2005; Kloosterman et al., 2001; Van Raan et al., 2016). However, table 15 p.34 show a significant mismatch between residential density and job density. Furthermore, a potential qualitative mismatch in jobs induces more travelling distances within the region. The functional polycentrality based on the 'co-location' principle might be difficult to adapt to the polycentric morphology under the planning principle of *'concentrated decentralization'* inducing longer commuting distances. Despite promoting incentives for inhabitants to choose efficient job locations close to their residences, according to Shwanen et al., (2004, p.595) "Much employment was situated on car-accessible locations that were poorly served by public transport." In table 20 p.37, data on the average distance to important transfer stations (Train and metro) in The Randstad show that catchment distance varies between 6,8 km to 11,11 km (CBS 2015). It is also possible to see in the same table that areas with the lowest distance to transfer stations (North and Zuid Holland) correlate with a higher use of public transportation and less use of cars.

In terms of *'distance'* or *'compactness'* as an indicator of monocentrality and polycentrality, the two regions largely differ. In table 16 p.34 and table 19 p.37, the highly compact center of Paris (105 sqkm) shows a high percentage of public transportation accessibility (92, 5 %). Meaning that 92,5 % of the population in the area resides within 500m of a metro or tram, and within 1000m of a RER or train according to L'APUR 2015. Table 20 p.37 also shows that areas with high accessibility within le Grand Paris register the lowest share of car use and highest use of public transportation for respectively: Paris center, first crown, second crown. The assumption of this research is that the *'geographical'* and *'planning'* differences between the two regions in terms of compactness and urban typology (see figure 2, p.19, and figure 3, p.21) is an explanation to significant differences in CO2 emission. The Randstad pollutes 3.5 times more than Le Grand Paris, while in fact their respective geographical areas are 11 372 and 12 012 sqkm. The differences in work journey CO2 emissions are even higher if we consider that Le Grand Paris has 2 million more employees than The Randstad, which means 2 million more work journey trips daily. The difference is due to the *'distance'* component within each urban typology. The *'distance'* variable does not only refer to the work-journey trip itinerary but also to the accessibility to public transportation with regard to modal choice. In low compactness (polycentrality), employees are also not encouraged to use sustainable modes of transportation because they are not easily accessible (see table 20, p.37).

Table 17 Correlation between land use mix and modal choice

		Land use mix (Activity area / Residential area) (%)	Share of car use in %	Share of public transportation in %
Le Grand Paris (monocentric)	Paris centre	57	12,3	64,8
	First crown	56	36,6	47,5
	Second Crown	22	58,9	29,9
The Randstad (polycenntric)	Flevoland	39	75,0	25,0
	Utrecht	29	77,6	22,2
	North Holland	32	70,0	29,2
	Zuid Holland	46	73,0	26,3

Source: CBS, INSEE, APUR 2015.

Le Grand Paris

Correlation between land use mix and share of car use: r= -0,86

Correlation between land use mix and share of public transportation: r= 0,87

The Randstad

Correlation between land use mix and share of car use: r= -0,26

Correlation between land use mix and share of public transportation: r= 0,26

Table 18 Correlation between land use mix and distance travelled

		Land use mix (Activity area / Residential area) (%)	Total car passenger in Billion km	Total public transportation Passenger in Billion km
Le Grand Paris (monocentric)	Paris centre	57	0,32	5,07
	First crown	56	1,61	6,27
	Second Crown	22	5,11	7,79
The Randstad (polycenntric)	Flevoland	39	3,00	1,00
	Utrecht	29	7,60	2,20
	North Holland	32	13,60	5,70
	Zuid Holland	46	18,60	6,70

Source: CBS, INSEE, APUR 2015.

Le Grand Paris

Correlation between land use mix and distance travelled by car: r= -0,97

Correlation between land use mix and distance travelled by public transportation: r=-0,90

The Randstad

Correlation between land use mix and distance travelled by car: r= 0,43

Correlation between land use mix and distance travelled by public transportation: r=0,40

Table 19 Accessibility to public transportation in Le Grand Paris

		Accessibility to public transportation in (%)	Share of car use in %	Share of public transportation in %
Le Grand Paris (monocentric)	Paris centre	92,5	12,3	64,8
	First crown	44,5	36,6	47,5
	Second Crown	10	58,9	29,9

Source: INSEE, APUR 2015.

***Percentage of accessibility: percentage of population residing within 500m of a metro or tram, and within 1000m of a RER or train.**

Table 20 Accessibility to public transportation in The Randstad

		Average distance to important transfer stations in (km)	Share of car use in %	Share of public transportation in %
The Randstad (polycenntric)	Flevoland	11,1	75,0	25,0
	Utrecht	8,1	77,6	22,2
	North Holland	6,8	70,0	29,2
	Zuid Holland	9,6	73,0	26,3

Source: CBS, APUR 2015.

Correlations between work-journey CO2 emissions and land use

Table 21 Correlation between work journey CO2 emissions and land use mix

		Land use mix (Activity area / Residential area) (%)	Work journey CO2 emissions (Million Metric tons)
Le Grand Paris (monocentric)	Paris centre	57	0,58
	First crown	56	1,06
	Second Crown	22	2,19
The Randstad (polycenntric)	Flevoland	39	0,94
	Utrecht	29	2,37
	North Holland	32	4,40
	Zuid Holland	46	5,89

Source: CBS, INSEE, APUR, GHG Protocol 2015.

Le Grand Paris

Correlation between work journey CO2 emissions and land use mix r=-0,96

The Randstad

Correlation between work journey CO2 emissions and land use mix r=0,40

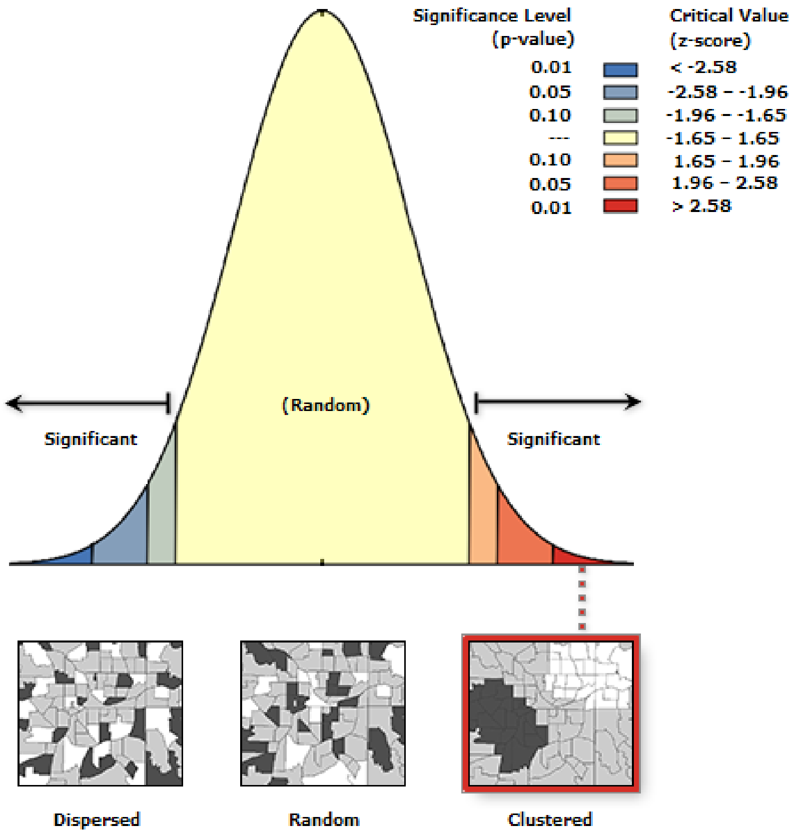
4.2.2 Preliminary findings

To summarize, both land use mix and density positively correlate with modal choice by encouraging sustainable modes of transportation in both regions (see table 14 p.33 and 17 p.36). However, land use mix and density operate differently when it comes to the *distances traveled* in the two regions (see table 15 p.34 and table 18 p.36) and this is suspected to be related to the differences in compactness (monocentrality/polycentrality). Because CO2 emissions scale linearly with *distance* and *share of modal choice*, these emissions might be significantly lower in Le Grand Paris because both the distances travelled and modal choice show strong negative correlation with land use mix and density (table 13 p.31, table 14 p.33, table 15 p.34, table 17,18 p.36, table 21 p.37) while it is not the case of The Randstad. Only modal choice shows negative correlation with land use mix and density but not *'distance'* travelled. It is suspected that the "*concentrated decentralization"* planning policy is indirectly responsible of travel behavior in The Randstad. This includes not only locational choices (job-residence) but also the average catchment distance to important train stations (see table 20, p.37).

4.3 The Global Moran I simulation

From a *'distance'* and *'geographical'* analysis, the next step is to assess spatial autocorrelation using the Global Moran I tool in GIS to measure both the *'distance'* indicator and feature values of land use, transportation and density. The Global Moran I is a tool that measures the spread of values over space. A positive spatial autocorrelation indicates that values are similarly clustered together in a map. Conversely, a negative correlation indicates that the values are disseminated. A value of 0 indicates the absence of any spatial correlation. This tool provides insight into how variables such as land use mix and density operate with regard to the compactness level (monocentrality/polycentrality) of both regions. In the current analysis, the Global Moran I of spatial autocorrelation is complementary with the Pearson's correlation. Hence, it has the potential to confirm the preliminary results from a 'spatial' lens. Statistical data on travel patterns and consequent CO2 emissions has already been processed based on a population sample for both regions (INSEE and CBS). Descriptive statistics via correlations showcase the link between urban form in terms of density and land use, travel behavior and CO2 emissions. However, to give more strength to the conclusions based on the 'urban morphology' differences, it is important to see how the same indicators of urban form: land use and density 'spatially' correlate in the two regions with regard to the 'distance' indicator. This reveals more conclusions in relation to the *urban typology* and *mobility patterns*. For this purpose, the Global Moran I will process geo data from L'APUR, INSEE, ESRI Demographics, Geodienst Rijksuniversiteit Groningen and CBS on *land use* and *density*.

The aim of the current research is to be consistent in the scaling relationship between socio economic variables, geographical attributes, and CO2 emissions. As stated previously by Gately et al., (2015, p.5002) in "Cities, traffic, and CO2: A multidecadal assessment of trends, drivers, and scaling relationships" : "Correlation between population density, employment density, income, and lagged population growth suggests that these factors may be sufficient to explain the majority of variance in on-road emissions at *the country scale*, but further research into the influence of *urban typology and mobility patterns* will be vital to understanding emissions trends *at city and municipal scales.*"



Graph 1 Example of the Global Moran report.

Source: Spatial autocorrelation report generated on ArcGis.

The Z score indicates “standard deviation and is associated with the normal distribution of statistical values.” (ArcGIS)

The P value indicates “the numerical approximations of the area under the curve for a known distribution, limited by the test statistic.” (ArcGIS)

Both the Z score and P Value confirm or reject the null hypothesis by indicating statistical significance.

4.3.1 The Global Moran I simulation for Le Grand Paris

Figure 5, p.40 below supports the main findings of phase II in terms of spread of residential and job density as well as accessibility of public transportation. The Paris center is the area that registers the highest residential/job density as well a high concentration of rapid transit stops. Regarding the CO_2 emissions (see table 13 p.31), this same area (Paris center) shows a significant decline in emissions. From phase II, higher densities, land use mix (job/residential areas) and accessibility to public transportation perform better in emissions in the case of Le Grand Paris. The next step is to evaluate how each of these variables relates to spatial autocorrelations regarding the ‘monocentrality/polycentrality’ or ‘compactness’ indicator.

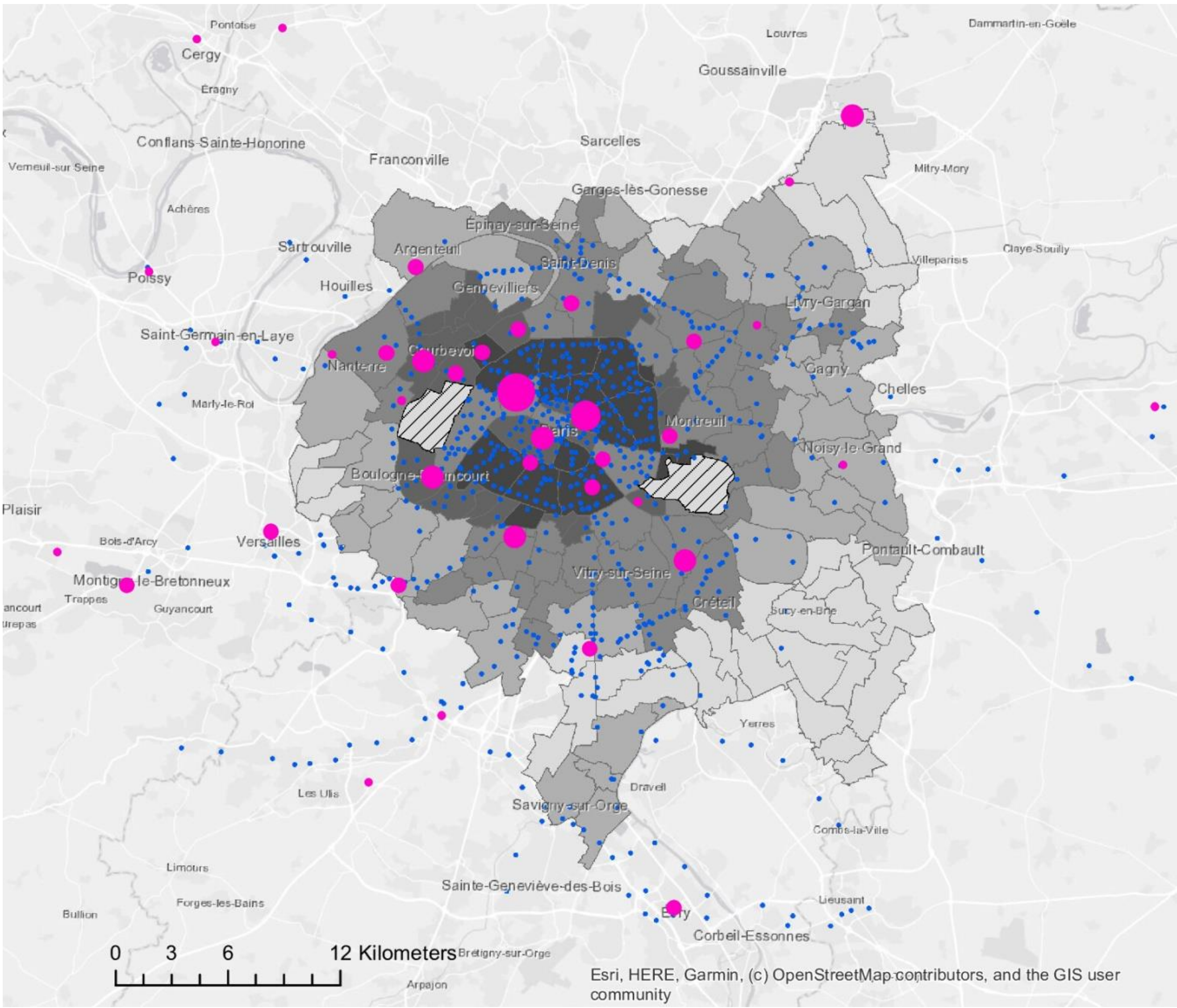
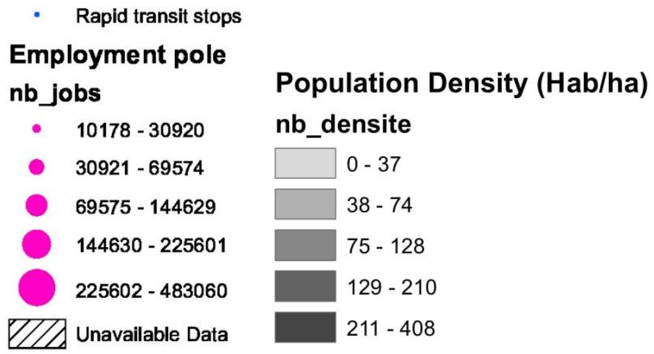


Figure 5 Illustrative map of projected density and rapid transit stops in Le Grand Paris

Source: Created by the author on ArcGis using data set from L'APUR geodatabase and INSEE

Legend



Global Moran report for residential density in Le Grand Paris

z-score = 16.27 p value = 0,00 Moran Index=0.76 (see graph 1, p.39)

Given the z-score of 16.27 and p value of 0,00, there is less than 1% likelihood that this clustered pattern could be the result of random chance. Results indicate a high clustering pattern of residential density with a Moran Index of 0.76. This means that residential density in the case of Le Grand Paris spatially correlates with a strong clustering/compactness pattern.

Global Moran report for job density in Le Grand Paris.

z-score = 12.73 p value = 0,00 Moran Index=0.58

Results indicate a high clustering pattern of job density with a Moran Index of 0.58. This means that job density in the case of Le Grand Paris is also highly correlated with a strong clustering/compactness pattern. If both job and residential density show high positive spatial autocorrelation, this could be an explanation to the dramatic decrease in CO2 emissions, resulting from shorter work trip distances in Le Grand Paris (see table 15 p.34).

Global Moran report for rapid transit stops in Le Grand Paris.

z-score = 172.47 p value = 0,00 Moran Index=0.82

Results indicate a significantly high clustering pattern of rapid transit stops with a Moran Index of 0.82. This means that rapid transit in the case of Le Grand Paris is strongly correlated with the spatial clustering/compactness pattern as well.

Similarly to job and residential density, the high clustering pattern of rapid transit could be significant in lowering CO2 emissions. As CO2 scales with both distance and modal choice, having a high spatial autocorrelation with sustainable modal choice justifies more sustainable work journey trip.

As a conclusion, in Le Grand Paris all of job/residential density and accessibility to public transportation show high positive spatial autocorrelation. This gives more insight into the reason behind lower CO2 emissions. The next step is to evaluate those findings in comparison with the spatial autocorrelations of the opposite urban form The Randstad.

4.3.2 The Global Moran I simulation for The Randstad

Figure 6, p.42 illustrates the main findings of phase II in terms of spread of residential and job density as well as accessibility of public transportation. Major cities in North and South Holland provinces are more connected than Flevoland and Utrecht in terms of Rapid transit. This is an explanation to the relatively high share of car use in both Utrecht and Flevoland (see table 3, p.20). Furthermore, density in The Randstad does not follow a strong clustering pattern as seen in the case of Le Grand Paris in figure 5, p.40. This shows a clear indication of the 'concentrated decentralization' planning policy. On the other hand, numbers of job density are close between the three regions (major cities of North/South Holland and Utrecht) with the lowest being registered in Flevoland.

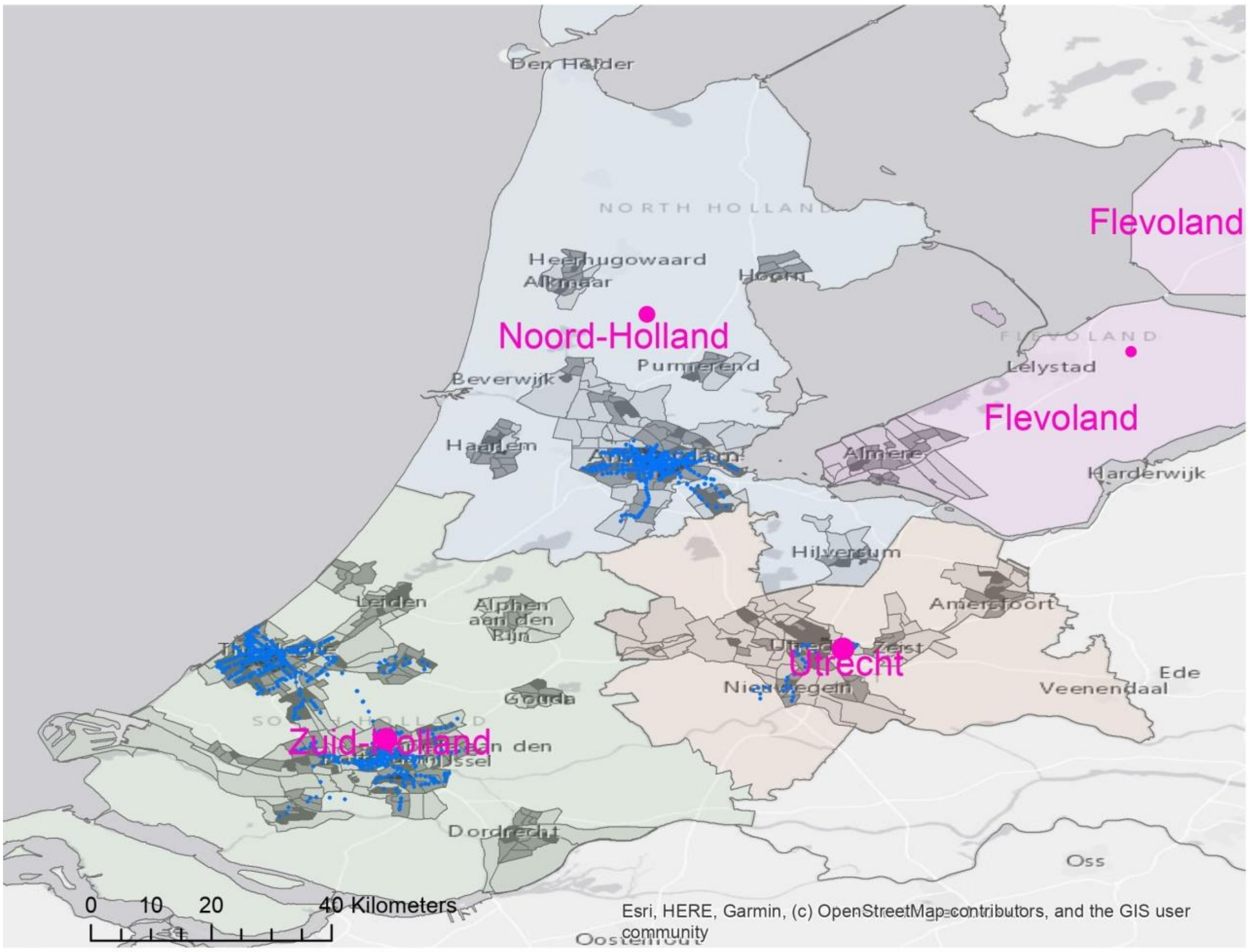
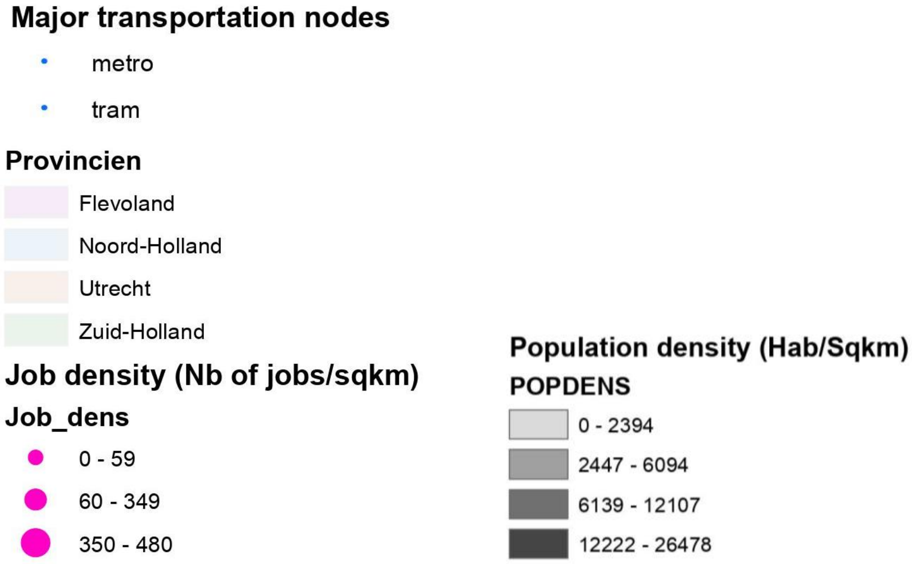


Figure 6 Illustrative map of projected density and major transportation nodes in The Randstad

Source: Created by the author on ArcGis using data set from ESRI Demographics, Geodienst Rijksuniversiteit Groningen and CBS

Legend



Global Moran report for residential density in The Randstad

z-score = 27.75 p value = 0,00 Moran Index=0.22

Given the z-score of 27.75 and p value of 0,00, there is less than 1% likelihood that this clustered pattern could be the result of random chance (see graph 1, p.39). Results indicate a low clustering pattern of residential density with a Global Moran Index of 0.22. This means that residential density in the case of The Ranstad is positively but not strongly correlated with compactness. As discussed in phase II, the 'concentrated decentralized' planning policy deliberately induced decentralization (also visible in figure 6, p.42). From the CO2 inventories of phase I, it is also important to stress how this decentralization correlates with the negative environmental implications because of longer distances travelled (see table 13, p.31).

Global Moran report for job density in The Randstad

z-score = 68.21 p value = 0,00 Moran Index=0.58

Unlike residential density that has a low index of 0.22; results of job density indicate a high clustering pattern with a Moran Index of 0.58. This means that in terms of compactness, activity areas are significantly located in contiguity to each other. However as seen in the preliminary discussions, the longer distances travelled between home and work in The Randstad are rather due to the quantitative/qualitative mismatch between job and residential density rather than the contiguity of activity areas.

Global Moran report for major transportation nodes in The Randstad

z-score = 323 p value = 0,00 Moran Index=0.90

This means that major transportation nodes in the case of The Randstad are strongly correlated with the spatial clustering/compactness pattern. However, unlike Le Grand Paris, the high clustering pattern of rapid transit in The Randstad does not relate to a higher use of public transportation (table 20 p.37). An explanation to that is due to both low densities (figure 5 p.40 in comparison with figure 6 p.42) and possibly failure of the ABC policy to locate firms closer to rapid transit nodes (Shwanen et al., 2004). According to Jabareen (2006, p.41), "*Density* is the single most important factor associated with *transit use* (Transportation Research Board of the National Academy 1996). As density increases, automobile ownership declines, and automobile travel as measured by gasoline consumption or per capita vehicle miles of travel (VMT)".

Chapter 5: Conclusions

Discussions

The Global Moran I is a significant tool that confirms the findings of Phase II regarding the interrelation of compactness/sprawl with densities and travel behavior. Results of Le Grand Paris show that a high clustering in both job and residential density is associated with the dramatic CO_2 emissions because of the shorter distances travelled and more sustainable modal choice. Furthermore, high clustering of public transportation stops is another confirmation of the findings of phase II in terms of accessibility to public transportation in Le Grand Paris. Indeed, the significantly low CO_2 emissions correlate with high compactness of both job and residential density as well as high accessibility of public transportation. As a reminder, CO_2 emission scales linearly with both distance and modal choice. In le Grand Paris, critical densities encourage more sustainable modal choice within compact commuting areas with high transit accessibility. Hence, CO_2 emissions are dramatically low.

This is not the case of The Randstad. As it presents opposite results because of the 'concentrated decentralized' planning policy that deliberately induced mid to low densities but also failed the co-location principle (relocation near homes). As previously stated by Shwanen et al., (2004, p.595) "Much employment was situated on car-accessible locations that were poorly served by public transport." Furthermore the 'concentrated decentralized' planning policy did not necessarily induce modal shift because the time spent in congestion by car in the growth centers was equal to the time spent driving from the suburban areas to the center. Thus, many households preferred to relocate further from the center, driving longer distances by car (Shwanen et al., 2001).

From figure 6 p.42, there is indeed a mid-level density in the four provinces of The Randstad, which coupled with polycentrality might induce longer travelling distances. Hence, a low level of compactness is responsible of the negative influence on the distances travelled in The Randstad. As seen in phase II, the distances travelled decrease proportionally with density in the case of Le Grand Paris and increase in The Randstad (see table 15 p.34). While both regions cover approximately the same geographical area, the current results (from statistical and spatial correlations) indicate that a high job/residential density with high clustering/compactness (monocentric model) indeed shortens distances, favours more sustainable transport modes and can dramatically lower CO_2 emissions. On the other hand, lower clustering (polycentric model) and mid to low densities increases distances travelled, favours car use and increases CO_2 emissions.

Further explanations from the literature review can be associated with the present results. In the paper of Shwanen et al., (2004) on the "Policies for urban form and their impact on Travel", the analysis suggests a possible failure of the Dutch A-B-C policy. The aim of this planning policy was to encourage public transportation by locating firms in well served areas. Hence, A and B locations were reasonably connected in sites closer to rail and metro stations. On the other hand, C locations have excellent car accessibility and typically include port, industry areas and car dependent companies. However, according to Shwanen et al., (2004, p.582), the large employment demand could not be placed only in A and B locations. As "The largest employment growth in the 1990s occurred at C locations". This is also an explanation supporting the higher share of car use for longer work trips in The Randstad.

Main findings

Following the discussion, to answer the first and second research questions: “How does urban form, under the influence of travel behavior affect work journey CO2 emissions?” and “How does urban form in terms of land use and density interact with travel behavior?” There is indeed a correlation between the three concepts of urban form, travel behavior and CO2 emissions (proxy for sustainability). Correlations between urban form and travel behavior at the city scale show that a higher land use mix and density correlate with a higher use of public transportation and lower the use of cars in both regions, but to a great extend in Le Grand Paris. On the other hand, correlations between land use, density and distance travelled show that the two regions perform in opposite ways. The distances travelled increase in The Randstad as density and land use mix get higher while they decrease in Le Grand Paris. It is notable of mention that in the ‘Paris center’ high job densities can reach up to 44 000 jobs per sqkm (case of the 8ème arrondissement, CBS 2015). These numbers are far greater than any region in The Randstad. Furthermore, Paris accounts for 6.5 Million employees versus 4.3 Million in The Randstad (Randstad Monitor 2017). The explanation to such low CO2 emissions in Le Grand Paris is supported by the ‘discussion’ chapter regarding high correlations between both residential and job densities with regard to compactness. It is not the case of The Randstad, where low densities and low compactness as well as mismatch between job and residential densities induced longer work journey trips. This conclusion is further supported by Shwanen et al., (2004) paper on the failure of the Dutch ABC policy to adjust firm locations and employment opportunities to well served public transportation (see discussion paragraph, p.44).

To answer the third research question: “How does urban form with regard to polycentrality and monocentrality relate to work journey CO2 emissions and overall sustainability?” In our two case studies, the monocentric model shows a better performance than the polycentric model with regard to the CO2 emissions. As CO2 emissions scale linearly with distance and share of modal choice, and since both density and land use mix have a similar positive effect on share of modal choice in both regions; the significant difference in emissions is most likely due to the ‘distance’ indicator or ‘compactness level’. It is notable of mention that the two regions cover similar geographical areas respectively (12 012 sqkm and 11 372 sqkm). The Randstad is emitting 3.5 more than Le Grand Paris. The spatial autocorrelation using the Global Moran I tool in GIS measured both the ‘distance’ indicator and feature values of job/residential density and public transportation nodes. Results indicated that both regions perform similarly in terms of clustering of job density and public transportation stops. However, when it comes to residential density, Le Grand Paris shows a high correlation in comparison with The Randstad. The current assumption is that a high density coupled with high compactness reduces CO2 emissions. However mid-densities in the case of The Randstad and quantitative or possibly qualitative mismatch between residential and job densities might have induced more distances travelled and CO2 emissions. This conclusion is supported by the work of Shwanen et al., (2004, 2001) in the discussion chapter.

Suggestions for future work

To answer the fourth question: “What are some other possible external explanations to the work journey mobility trends?” Other factors such as accessibility to public transportation play a major role in explaining the work journey mobility trends in our two case studies (see table 19, 20 p.37). A good example is the average distance to access major rapid transit nodes in The Randstad that is 6.8 km. This same distance is a mere 1km in the centre of Paris. Other explanations of socio-economic nature are not included in the analysis but regarded as equally significant. One is the trade-off between how much an individual is paid and how much they are willing to spend on transportation in terms of monetary value and time which might hinder the co-location principle (Gately et al., 2015). A more in-depth socio-economic study could hence look at encouraging and discouraging monetary factors, in terms of user preference and cost effectiveness of public transportation (Banister 2008). Another reason to mobility trends might be property value or reverse gentrification, as individuals who earn higher incomes are willing to settle for larger homes outside the city center (Aguilera et al., 2009).

In that regard, solutions to the ‘co-location’ problem and failure of the A-B-C policy in The Randstad (Shwanen et al., 2004, 2001) could be achieved by providing incentives for work from home as the experiment was conducted indirectly during the COVID-19 crisis and showed positive environmental effects from car induced CO_2 emissions. In that sense, the current research does not exclude the many other explanations of travel behavior. However, from the current analysis, there is a strong evidence that the planning plays a highly significant role in guiding travel behavior such as matching job density with residential density, locating firms in areas that are accessible to public transportation.

Concluding remarks and recommendations

To answer the last research question: “In terms of climate change mitigation, what should planners and policy makers be really looking at?” The complexity of cities entails that the “Sustainability of urban form” is a combination of design principles and efficient policy making decisions to encourage the sustainability paradigm among users (Banister 2008). Furthermore, the interplay between the design principles is particularly important. A good example in the current two case studies is how density interacts with compactness. The case of Le Grand Paris showed that critical (job/residential) density, land use mix and high compactness encouraged sustainable modal choice and reduced travel distances. This resulted in lower CO_2 emissions. However, in the case of The Randstad, density and land use mix still encouraged sustainable modal choice to a certain extent, but because of the “concentrated decentralized” principle, mid-densities never reached the critical point such in the case of Le Grand Paris to lower CO_2 emissions as “A classic example is the *exponential decline* in per capita *transport in energy* use with *increasing population density* that was observed in a large cross-section of cities worldwide.” (Gately et al., 2015, p.5000). In our case studies, the CO_2 decline is suspected to be due not only to population density but also job density and compactness with regard to firm locations. In The Randstad, the potential failure of the ABC locational policy in distributing jobs near homes is an important factor to mention (Shwanen et al., 2004, 2001).

In the current analysis, The Global Moran I was a crucial comparative indicator to evaluate the level of compactness between the two regions and how this relates to density. According to the article "Sustainable urban form" from Jabareen (2006, p.39), compactness uses “Urban land more efficiently by increasing the density of development and activity above a certain threshold”. As seen in the case of The Randstad, both mid densities and low compactness had an adverse effect in terms of length of work journey trips and consequent CO_2 emissions in comparison with a better sustainability performance in Le Grand Paris.

To conclude, the current research uses mixed methodologies (GHG Protocol, Statistical correlations based on qualitative/quantitative secondary data, The Global Moran I in GIS) as well as data triangulation from different sources to provide new evidence for the debate about the sustainability of urban form. It is conducted on two case studies in Europe representing the archetypes of the monocentric and polycentric urban form. Most of the findings in urban planning have been based on cross-sectional empirical studies of cities around the world. The current thesis is hence an addition to the debate and supports findings on the relationship between density, compactness, travel behaviour and sustainability. As previously seen in chapter 2, scholars have largely been divergent about monocentrality and polycentrality in terms of energy demand behaviour (Anderson et al., 1996; Aguilera et al., 2014; Engefriet and Koomen 2018; Giuliano et al., 1993; Tsai 2005). The current thesis also tries to investigate the conflict of the scaling relationships between the multitude of variables : urban form, travel behavior and CO2 emissions (Aguilera et al., 2014; Gately et al., 2015, p.5000; Louf and Barthelemy 2014), and calls for complementary empirical research to further support the findings.

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Annex 1: Research Instruments and Time schedule

The current thesis was conducted using data triangulation from the following Data bases:

INSEE, ADEME, L'APUR, CBS, ESRI Demographics, Geodienst Rijksuniversiteit Groningen.

The methodology includes CO_2 inventories using the GHG Protocol, statistical correlations using excel as well as spatial autocorrelations using ArcGIS.

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