UNIVERSIDAD POLITÉCNICA DE MADRID
ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE CAMINOS, CANALES Y PUERTOS

ASSESSING SUSTAINABILITY IN CITIES.
ROLE OF INTEGRATED TRANSPORT
STRATEGIES

DOCTORAL THESIS

ANDREA ALONSO RAMOS

Ingeniero de Caminos, Canales y Puertos
Máster Universitario en Sistemas de Ingeniería Civil

Madrid, 2017

**DEPARTAMENTO DE INGENIERÍA CIVIL: TRANSPORTE Y
TERRITORIO**

**ESCUELA TÉCNICA SUPERIOR
DE INGENIEROS DE CAMINOS, CANALES Y PUERTOS**

DOCTORAL THESIS

**ASSESSING SUSTAINABILITY IN CITIES.
ROLE OF INTEGRATED TRANSPORT
STRATEGIES**

ANDREA ALONSO RAMOS

*Ingeniero de Caminos, Canales y Puertos
Máster Universitario en Sistemas de Ingeniería Civil*

Director:

ANDRÉS MONZÓN DE CÁCERES

Doctor Ingeniero de Caminos, Canales y Puertos

Madrid, 2017

Parte de esta tesis se ha realizado en el marco de la Cátedra de Investigación sobre Movilidad Sostenible, y gracias al apoyo del Consorcio Regional de Transportes de Madrid.

Tribunal nombrado por el Mgfc. y Excmo. Sr. Rector de la Universidad Politécnica de Madrid, el día ____ de _____ de 2017.

Presidente: _____

Vocal: _____

Vocal: _____

Vocal: _____

Secretario: _____

Suplente: _____

Suplente: _____

Realizado el acto de defensa y lectura de la Tesis el día ____ de _____ de 2017 en la E.T.S. de Ingenieros de Canales, Caminos y Puertos de la U.P.M.

Acuerda otorgarle la calificación de:

_____

Madrid, ____ de _____ de 2017.

EL PRESIENTE

LOS VOCALES

EL SECRETARIO

“Caminante no hay camino,

Se hace camino al andar”

Antonio Machado (1875-1939)

AGRADECIMIENTOS

El desarrollo de esta tesis y de todo el trabajo de investigación que ha implicado no hubiese sido posible sin muchas personas a las que quiero expresar mi agradecimiento:

En primer lugar a mi director de tesis, Andrés, por todo lo que me ha enseñado y por haber confiado en mí, muchas veces incluso más que yo misma. También le agradezco su guía durante el desarrollo de la tesis, especialmente todo lo que me ha exigido al principio y todos los ánimos que me ha dado al final.

A Rocío, Yang y Henar, que junto con Andrés forman parte de esta tesis.

A Paul, por acogerme tres meses en la universidad de Viena durante mi estancia, que ha sido importante para la investigación llevada a cabo.

A Juan Carlos, Julio y Luigi, que con sus comentarios constructivos han contribuido a mejorar este documento.

A María Eugenia, que despertó mi interés por la investigación al principio y que siempre me ha animado a seguir hasta el final.

A todos mis compañeros de TRANSyT, también a los que ya no están, que han hecho que sea más fácil ir a trabajar cada día. En especial a mi compañero de despacho Andrew, por su ayuda y su paciencia; a Guille, por lo que me ha hecho reír en épocas de estrés; a Juan, por sus consejos; a Carmen, Cristina, Vicky, Paola, Belén, y un largo etcétera. Quería nombrar de forma especial a Fiamma, Natalia y Sara, a las que considero ya más amigas que compañeras.

Por último, deseo expresar el más sincero agradecimiento a mi familia, que son mi motivación en la vida y en el trabajo. A mis padres, Rosa y Carlos, y a mi hermano, Carli, por su apoyo incondicional. Y por supuesto a mi marido, Quique, porque con él las alegrías día a día han sido dobles y las penas la mitad.

ABSTRACT

Urban mobility is a key element for achieving sustainable development in cities, as car dependence and inefficient transport systems are among the most important barriers to achieve this objective. This thesis is focused on European cities, which are considered among the most sustainable cities in the world, but which are currently exposed to some generalized problems and threats: demographic decline, social exclusion, environmental degradation, economic decline and urban sprawl. However, cities are also places where opportunities for agglomeration economies and social mix emerge. Both urban threats and opportunities define the city challenges: that is to become more liveable environments and efficient urban systems. Going back to the relevance of mobility and urban form for sustainability, these challenges could be partially addressed through transport management and land use strategies. All this background makes up the *city cycle*.

The general objective of this thesis was *to understand the key drivers of a sustainable urban mobility, and then to define long term strategies for achieving sustainable and efficient cities through land use and transport policies*. For this objective, three types of analyses were developed in five research studies, following the logic of the *city cycle*.

Firstly, a cross-site analysis was applied to compare the performance of different cities in the context of sustainability targets. This analysis was carried out in the first study, where the sustainability of urban transport systems was measured through composite indicators. The methodology was applied to 23 European cities and served to identify the factors that explain a sustainable mobility.

Secondly, a trend analysis was applied in three studies. In the second and third studies of the thesis, the main threats for sustainability in four European cities were identified through indicators to measure the evolution of their current and potential problems. The fourth study dealt with the problems in six Spanish cities caused by the economic crisis. This economic decline, in a context of urban sprawl, had a negative impact on the efficiency of their public transport systems.

Finally, in the fifth study ends the city cycle with an analysis measuring the contribution of three land use and transport policies –cordon toll, teleworking and re-densification– to meet the city challenges in the case of Madrid. The LUTI model MARS was used in this last analysis to consider the future impacts of the three policies in the long term.

The results highlight that in the context of European cities, there are four key factors that explain sustainable mobility patterns: bigger, wealthier and denser cities, with a higher public transport patronage resulted more sustainable cities.

The analyses also showed that there is a wide diversity of situations among European cities regarding the existing threats. This is somehow not properly reflected in the literature, which refers mainly to the common problems. These differences grew during the economic crisis, which especially affected Spanish cities. Apart from economic decline, they were also affected by urban sprawl, and both threats caused inefficiencies in their public transport systems. The study carried out for measuring these inefficiencies, demonstrated that transport

management policies are not enough to meet the city challenges. Land use strategies are also needed to face the urban threats, especially in adverse economic scenarios. The last analysis bears out these needs in the case of Madrid Region: the results showed that the only policy that really contributes at saving energy and reducing emissions in the long term is re-densification. Lastly, apart from these findings, the thesis constitutes a relevant contribution in the development of a number of tools based in indicators and LUTI models which can be applied as valid management tools to analyse other cities.

RESUMEN

La movilidad urbana es un elemento clave para lograr un desarrollo sostenible en las ciudades, ya que el uso excesivo del coche y las ineficiencias generadas por el transporte son importantes barreras para lograr este objetivo. Esta tesis está centrada en las ciudades europeas, que aunque están consideradas entre las más sostenibles del mundo, están expuestas a ciertos problemas y amenazas: declive demográfico, exclusión social, contaminación, recesión económica y dispersión urbana. Sin embargo, las ciudades son también lugares donde surgen oportunidades ligadas a las economías de escala y la diversidad social. Las amenazas, junto a las oportunidades dan lugar a los retos urbanos: hacer de las ciudades lugares vivibles y eficientes. Volviendo a la relevancia de los sistemas de transporte urbanos, estos retos se podrían abarcar parcialmente a través de estrategias de planificación urbana y gestión del transporte. Toda esta teoría conforma el *ciclo urbano*.

El objetivo general de esta tesis *es comprender los factores clave de una movilidad urbana sostenible, y definir estrategias a largo plazo para lograr ciudades eficientes y sostenibles a través de medidas de gestión de usos del suelo y el transporte*. Para lograr este objetivo, se han realizado tres tipos de análisis en cinco estudios de investigación, siguiendo la lógica del *ciclo urbano*.

El primer tipo de análisis es transversal, y se ha llevado a cabo para comparar la sostenibilidad de distintas ciudades. Este tipo de análisis se ha aplicado en el primer estudio, donde la sostenibilidad de los sistemas de transporte se ha medido a través de indicadores compuestos. La metodología se ha aplicado a 23 ciudades europeas y ha permitido identificar los factores explicativos de una movilidad sostenible.

En segundo lugar, un análisis de tendencias se ha usado en tres estudios de investigación. En el segundo y tercer estudio, las principales amenazas urbanas a la sostenibilidad en cuatro ciudades europeas se identifican a través de indicadores, que miden la evolución de los problemas existentes y potenciales. En el cuarto estudio se han analizado los problemas que la crisis económica ha causado en seis ciudades españolas. Este factor, en un contexto de dispersión urbana, ha tenido impactos negativos sobre la eficiencia de sus sistemas de transporte público.

Por último, en el quinto estudio, se cierra el *ciclo urbano* a través de un análisis para medir la contribución de tres políticas de usos del suelo y transporte—peaje urbano, teletrabajo y re-densificación urbana— a los retos urbanos en el caso de Madrid. El modelo MARS, un modelo LUTI, se ha utilizado en este último análisis para medir los impactos futuros de las tres políticas a largo plazo.

Los resultados muestran que en el contexto de las ciudades europeas, existen cuatro factores que explican una movilidad sostenible: aquellas ciudades compactas, de mayor tamaño y riqueza y donde se usa más el transporte público, resultan las más sostenibles.

Los análisis revelan también que existe una gran diversidad de situaciones entre las ciudades europeas en lo que se refiere a sus amenazas. Esto es algo que no se refleja adecuadamente en la literatura, centrada básicamente en los problemas comunes. Estas diferencias han

crecido con la crisis económica, que ha afectado particularmente a las ciudades españolas. Además del declive económico, las ciudades españolas se han visto afectadas por procesos de dispersión urbana, y ambos procesos han causado ineficiencias en sus sistemas de transporte público. El estudio llevado a cabo para medir estas ineficiencias, demuestra que las medidas de gestión del transporte no son suficientes para abarcar los retos urbanos: se necesitan además estrategias de gestión y usos del suelo. Esto es especialmente importante en escenarios económicos adversos. El último análisis confirma esta necesidad en el caso de la Comunidad de Madrid: los resultados muestran que la única medida política que realmente contribuye al ahorro energético y la reducción de emisiones es la re-densificación. Por último, además de estas conclusiones, la tesis supone una contribución importante en el desarrollo de herramientas de gestión basadas en indicadores y modelos LUTI que pueden ser aplicadas en el análisis de otras ciudades.

Assessing Sustainability in Cities. Role of Integrated Transport Strategies

Content

PART I- INTRODUCTION		
1.	Introduction.....	1
1.1.	General research objective and tools	3
1.2.	Thesis structure	5
2.	Literature review: sustainability in cities, threats and challenges.....	9
2.1.	Sustainable cities and sustainable mobility	9
2.2.	Threats over sustainability in cities: a European approach	11
2.3.	Main Opportunities and Challenges in European cities	23
2.4.	Integrated land use and transport strategies to face threats and challenges in cities	26
2.5.	Specific research objectives for sustainability challenges in cities	28
3.	Research Methodology.....	31
3.1.	Management indicators for measuring sustainability, threats and challenges in the context of European cities	31
3.2.	LUTI Models for modelling land use and transport policies	37
3.3.	Interaction between land use models and indicators	42
3.4.	Summary of methodologies and tools to achieve the research objectives	44
4.	Urban data for policy assessment.....	46
4.1.	Main databases for analysing cities	46
4.2.	Role of stakeholders- data validation	48
PART II- ANALYSIS		
5.	Moving towards sustainability in cities (<i>scientific papers</i>).....	51
5.1.	Comparative analysis of passenger transport sustainability in European cities	53
5.2.	Policy priority objectives: Comparative assessment in four European cities	71
5.3.	Assessing the progress towards sustainability and the role of urban transport- city of Madrid	87
5.4.	Measuring negative synergies of urban sprawl and economic crisis over public transport efficiency: the case of Spain	97
5.5.	Modelling land use and transport policies to measure their contribution to urban challenges the case of Madrid	137
PART III- CONCLUSIONS		
6.	Conclusions, main findings and future research.....	167
6.1.	Specific conclusions and findings	167
6.2.	General remarks and future research	177
7.	References.....	181
8.	Abbreviations.....	207

ANNEXES		
A.	Annex A) Characterization of cities of Section 5.1.....	209
B.	Annex B) Improvement of MARS model for its application in Section 5.5 (<i>scientific paper</i>).....	213
	Assessing accessibility with local coefficients for the LUTI model MARS	
	<i>Journal Computers, Environment and Urban Systems, 2017</i>	199
C.	Annex C) Characterization of the zones in MARS model for Madrid (Section 5.5).....	225

1. Introduction

Since the declaration of the earliest principles of sustainability (UN, 1972), achieving a sustainable development in cities, which are the major urban settlements, has become the primary and overarching objective of stakeholders from international, national and local institutions (UN, 1992; Newman and Kenworthy, 1999; OECD, 2013; Khan, 2014; UN-HABITAT, 2016, Güell, 2006). Urban mobility is a key issue for meeting this objective, since the most important barriers to achieve sustainable development include car dependence and inefficient transport systems (Newman and Kenworthy, 1999; European Commission, 2007).

This thesis is focused on European cities. European cities are considered among the most sustainable cities in the world (Newman and Kenworthy, 1999; Haghshenas and Vaziri 2012), but they are exposed to some generalised problems and trends that threaten their sustainable development (European Union, 2011). Through a review of several documents published by European institutions¹ it was possible to determine the main urban threats for European cities:

- Demographic decline
- Social polarisation and segregation
- Depletion of natural resources and environmental impact
- Economic development and competitiveness under pressure
- Urban sprawl

However, “cities contribute both to problems and solutions” (European Union, 2011, p.5). The threats, together with the opportunities brought by urbanisation–agglomeration economies, efficient services, social integration– create the city challenges: to become liveable environments and efficient urban systems. Given the relevance of mobility and urban form for sustainability (Newman and Kenworthy, 1999; Golubchikov, 2011), many problems existing in cities could be partially addressed through transport management and land use strategies (Banister, 2008). For this reason, long term effects of strategies need to be evaluated, and the evaluation should include the potential contribution of strategies in meeting city challenges (Wegener, 2013).

The increasing complexity of urban problems, coupled with the political desire to base new policies on firm foundations requires adequate policy assessment tools (Nilsson et al., 2008). Research on urban planning and transport management should respond to these needs, through the development of tools for policy monitoring and implementation (May, Jopson, and Matthews, 2003). The research developed in this thesis addresses the policy issues and needs raised in the previous paragraphs. The urban threats and challenges, together with the role played by urban transport are represented in the **city cycle** (Figure 1.1), a scheme built through the literature review and the different research analysis carried out.

---

¹ (Uhel, 2006; European Commission, 2007; European Union, 2011; Campbell, Partridge and Soto, 2013; Colini et al., 2013; Enemark and Kneeshaw, 2013; Lewis, Hógáin and Borghi, 2013; Adams and Arnkil, 2013; Schlappa and Neil, 2013; Guerreiro, de Leeuw and Foltescu, 2013).

As a starting point, the **sustainability of urban transport systems** is analysed, by identifying the explanatory factors of sustainable mobility. Secondly, the general **threats over sustainability in European cities** are studied. In the thesis, a special attention is paid to two threats that particularly constrain the achievement of efficient urban systems and services:

- **Urban sprawl:** The suburbanisation of cities makes it more difficult to organise urban services and utilities and suburbanisation results in increased energy consumption and congestion (European Union, 2011). Sprawling cities are characterised by less efficient urban systems and services (Uhel, 2006). This particularly applies to the transport sector: “The lower densities in peripheral areas make it difficult to offer collective transport solutions of a sufficient quality to attract substantial amounts of users” (European Commission, 2007, p.15)
- **Economic decline:** The economic recession, accompanied by job losses and declining demand has severely affected the competitiveness, productivity and operational efficiency of services (European Commission, 2012a).

The **negative impacts** of both threats over the **efficiency of transport systems** and services are then analysed. Finally, at the end of the thesis, are considered the potential contribution of **land use and transport measures to face the city challenges of liveability and efficiency**, given the importance of a sustainable mobility to achieve sustainable cities.

Figure 1.1. City cycle for urban threats and challenges and the role of transport strategies

To analyse the different interactions represented in the city cycle, a series of research tools were developed and applied to different case studies: European cities for generic sustainability analyses, Spanish cities for more specific problems, and finally Madrid for particular solutions. These tools have brought the main outcomes of the thesis: a better understanding of the complexity of urban problems and a set of policy recommendations adapted to the different cases. Furthermore, the management tools developed are by themselves important contributions of the thesis, as they can be applied to other case studies for urban planning and policy making.

1.1. General research objective and tools

The **general objective** of this thesis was

to understand the key drivers of a sustainable urban mobility, and then to define long-term strategies for achieving sustainable and efficient cities through land use and transport policies.

For this objective, a series of tools based on indicators and Land Use and Transport Interaction (LUTI) models were developed to evaluate urban planning policies. The thesis is especially focused on the sustainability challenges brought about by urban sprawl and the economic crisis.

“Sustainable urban development is dependent upon the city being the centre of vitality, opportunity and wealth, and transport has a major role to play” (Banister, 2005, p.14). For this, urban planning needs to respond to current city challenges, this requires the development of new or enhanced management tools (Wegener, 2013). The main tools used in this thesis, the indicators and a LUTI model are widely considered as valuable tools for city management and policy making:

- Indicators

Cities authorities have recognized the need to pursue the sustainability agenda, and to do this they need to define indicators for sustainability (Newman and Kenworthy, 1999). Sustainability is a multidisciplinary concept, which involves several dimensions and opposing concerns (Brown et al., 1987). The key to finding a balance between these concerns is to identify appropriated environmental, economic and social indicators, and to integrate them into decision making and urban planning (TERM, 2000).

Indicators are also very valuable tools for benchmarking cities, to evaluate their performance on a comparative basis (Nardo et al., 2005). This is very useful for policy analysis, as it serves to establish real and achievable objectives and targets. Under this comparative approach, the cause-effect relations between different indicators can also be identified (Saisana, and Tarantola, 2002).

Finally, indicators can monitor the evolution over time of trends and problems, and the progress towards sustainability objectives (OECD, 2011). The success of integrated policies can be judged by identifying key indicators that can be tracked and compared with concrete policy objectives (TERM, 2000).

These characteristics have been exploited in different research analysis to achieve the general objective of the thesis (Figure 1.2). Indicators in this thesis have been applied to measure the sustainability of urban transport systems, to compare cities and identify the factors influencing sustainability, to monitor the evolution of problems and to assess different policies.

- LUTI models

LUTI models address one of the biggest complexities in modelling big urban areas for planning purposes, which is to properly represent the interaction between the transportation system and the spatial distribution of residents and activities (Bravo et al., 2010). Planning decisions in land use and transport have a wide range of effects. LUTI models can deal with an important range of long term impacts over sustainability that may arise from planning decisions (Geurs, Wee and Van, 2004b). However, if LUTI models are to be useful for urban challenges, they need to be adapted to current threats in cities (Wegener, 2013).

In the thesis, the LUTI model MARS (Metropolitan Activity Relocation Simulator) was applied to simulate the future impacts of land use and transport policies over different aspects of sustainability (Figure 1.2).

Figure 1.2. Tools for urban management: characteristics and application in the thesis

- Indicators and LUTI models

The two main tools used in the thesis are related. There is an interaction between LUTI models and indicators. On the one hand, data, in the form of indicators, serves to establish the baseline of models, and to measure the interactions between land use and transport (Coppola et al., 2013). On the other hand, the models produce the results in terms of output indicators (Geurs, Wee and Van, 2004b).

The output indicators of the MARS model for different policy scenarios are applied in the thesis to assess the contribution of land use and policy measures to long term city challenges.

1.2. Thesis structure

This thesis is structured in eight main chapters, and three annexes, which are divided into four parts:

PART I

The first part is an introduction to the main body of the thesis, which contains a general introduction (Chapter 1), a literature review (Chapter 2), a description of the main research tools (Chapter 3) and information on the data used, its validation and its application (Chapter 4).

PART II

The second part is the main body of the thesis: five research studies analysing different parts of the city cycle (Figure 1.1). These research studies are papers either published in scientific journals or presented at scientific transport conferences. The five papers constitute the different sections of Chapter 5, and the policy issues tackled in each of them are detailed in Figure 1.3 (page 6), following the logic of the policy cycle.

PART III

The third part includes the main conclusions and future research lines generated by the overall research work (Chapter 6), the compiled references (Chapter 7) and the abbreviations (Chapter 8).

ANNEXES

Finally, the fourth part includes three annexes containing supplementary information on the analyses of Chapter 5. One of these annexes (Annex B) is related to the performance and validation of the LUTI model used as a tool in the thesis, and is also a paper published in a scientific journal.

Figure 1.3. Structure of the main body of the thesis in relation to the city cycle: issues addressed, main tools used and research studies carried out (Chapter 5)

The following paragraphs describe more deeply the content of the main chapters for a better understanding of the thesis structure, particularly as regards to the research studies from Chapter 5:

- **Chapter 2** contains a literature review on urban planning and policy issues, following the logic presented in the city cycle. From the literature review, a series of research questions emerge in the different thematic sections. These research questions introduce the main research objectives related to sustainability city challenges addressed in the thesis (Section 2.5).
- To achieve these research objectives, new tools have been developed. These tools are based on indicators and a LUTI model. Both indicators and LUTI models have been widely applied in research. The main findings of these applications are highlighted in **Chapter 3**, and have served to develop new tools or improve existing ones, in order to make them suitable for the research objectives.
- **Chapter 4** contains information on the data used in the different research analysis: the main data sources (Section 4.1) and the role of stakeholders to validate and evaluate the data used (Section 4.2).
- **Chapter 5** contains five research studies carried. These studies respond to different research objectives, and analyse different interactions of the city cycle (Figure 1.3):
  - The research study from Section 5.1 was published in the scientific journal *Ecological Indicators* in 2015 (publisher Elsevier, Impact Factor 2015: 3.190). In this paper, the sustainability of urban transport systems is measured through composite indicators. The methodology was applied to 23 European cities and this served to identify the factors that explain sustainable mobility. Some complementary information on the 23 cities is provided in Annex A.
  - The research studies in Sections 5.2 and 5.3 were presented in two transport conferences: XII Congreso Internacional de Ingeniería del Transporte 2016 (Valencia, Spain) and 6th Transport Research Arena 2016 (Warsaw, Poland). In these research studies, the main threats for sustainability are identified through indicators to measure the evolution of the current and potential problems in four European cities.
  - Section 5.4 contains a research study which was published in the scientific journal *International Regional Science Review* in 2017 (Publisher SAGE, Impact Factor 2015: 0.917). In this paper, the inefficiencies caused by urban sprawl and economic decline over the Public Transport (PT) systems are measured through evolution indicators. The analysis is focused on six Spanish cities.
  - The research study presented in Section 5.5 was published in the scientific journal *Sustainability* in 2017 (Impact Factor 2015: 1.343), from MDPI. The paper is an analysis of the contribution of three land use and transport policies to address the

city challenges in the case of Madrid. The policies are simulated with a LUTI model, and the impacts measured through the output indicators. The LUTI model used in this paper, the MARS model, was previously improved and updated. These improvements were part of other research study which is not part of the main body of the thesis, but in which the author of this thesis collaborated. This research study is presented in the Annex B, and has been published in the scientific journal *Computers, Science and Environment* (Publisher Elsevier, Impact Factor 2015: 2.092). The paper is included as an annex to provide further explanations on the model and validate it as a useful tool for policy making and urban planning. In addition, some complementary information on the MARS model for the case of Madrid is provided in Annex C.

- The conclusions of the overall research are summarised in **Chapter 6**, which is divided into conclusions and findings for urban planning in relation to the research objectives (Section 6.1), and general remarks and future research lines (Section 6.2). **Chapter 7** contains all the references consulted in the thesis, and **Chapter 8** all the abbreviations used in the text.

2. Literature review: sustainability in cities, threats and challenges

2.1. Sustainable cities and sustainable mobility

2.1.1 Sustainable urban development: its origin and relevance

The evolution of human settlements and the unavoidable effects of social and economic development on the environment started to be raised at the global level at the Conference on the Human Environment in Stockholm (UN, 1972). The conference delegates proclaimed the need to safeguard and improve the human environment for present and future generations as a goal to be pursued together with worldwide economic and social development. This marked the earliest basis of sustainability, as a concept comprising three main dimensions: economy, society and environment. Later, along the same lines, the World Commission on Environment and Development (WCED) defined sustainable development as the development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (WECD, 1987). This definition of sustainable development has become the most widely accepted (Loos, 2014), and has been adopted by many authors for analysing sustainability in different fields (Butler, 1999; Loucks, 2000; Jeon and Amekudzi, 2005; Tanguay et al., 2010; Haghshenas and Vaziri, 2012; de Haan et al., 2014). Since the declaration of the earliest principles of sustainability, to achieve a sustainable development in the three dimensions, has become a major concern for decision makers and management stakeholders (Mebratu, 1998; Newman and Kenworthy, 1999; Backstrand, 2006; Epstein and Rejc, 2014; Waas et al., 2014).

The principles of sustainable development must be applied to cities, which are the major human settlements (UN, 1992). Currently, more than half of the world’s population resides in urban areas (UN-HABITAT, 2016). Cities are important sources of growth and innovation, and often serve as the engines of their national economies (European Union, 2011). As engines of development and generators of wealth, cities are also drivers of consumption and degradation of natural resources, being responsible for an important share of the global emissions, pollution and land occupation (Uhel, 2006; Golubchikov, 2011; Guerreiro, de Leeuw and Foltescu, 2013).

2.1.2 Sustainable mobility: definition

Analysis of the problems facing cities to achieve sustainable development, prioritize the issues related to mobility and urban form (Newman and Kenworthy, 1999; Golubchikov, 2011). Poor accessibility, few possibilities for affordable mobility choices and too much car traffic are always among the main complaints from citizens as problems in their cities (Enemark and

Kneeshaw 2013). Poor accessibility and few mobility choices are linked to social exclusion (Preston and Rajé, 2007). Too much traffic in cities, where the problems are more acute and concentrated, has many adverse consequences in terms of congestion, emissions, noise and accidents (European Commission, 2007). Achieving a sustainable transport system is a prerequisite for improving the urban environment and enhancing economic viability (European Commission, 1996).

Sustainability is a highly complex and multidisciplinary concept, and the meaning of the term is strongly dependent on the context in which it is applied (Brown et al., 1987). The most commonly accepted definition of a sustainable transport system was first established by the Council of the European Union (2001), which was supported by international institutions (OECD, 2002). Since then, it has been adopted by many authors to analyse the sustainability of transport systems (Miranda and Rodrigues da Silva, 2012; Haghshenas and Vaziri, 2012; Golinska and Hajdul, 2012). According to this definition, a sustainable transport system should be analysed from three different dimensions:

- Social: allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations.
- Environmental: limits emissions and waste within the planet's ability to absorb them, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise.
- Economy: affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development.

All these issues, sometimes opposing each other and sometimes complementary, when not overlapping, should be considered for developing a sustainable transport system. The identification and monitoring of different indicators and the establishment of goals are the only ways to incorporate the many areas of sustainability in policy making and city management (Newman and Kenworthy, 1999). However, the goals or the adequate value of the indicators can only be established by comparing different cities or different years for the same city. "The success of current and future integrated policies can only be judged by identifying key indicators that can be tracked and compared with concrete policy objectives (benchmarking)" (TERM, 2000, p.4). Furthermore, monitoring and comparing different cities serves to understand which urban characteristics can help achieve sustainable transport systems (Newman and Kenworthy, 1999). In other words, the explanatory factors for a sustainable urban mobility.

The literature reviewed in the topic of sustainable mobility raises the following research questions:

- ✓ How do we measure sustainability in urban transport systems as a complex, multidisciplinary and multidimensional concept?
- ✓ How do we obtain indicative and real figures about sustainability measures to establish goals?
- ✓ What factors explain a sustainable urban mobility?

2.2. Threats over sustainability in cities: a European approach

2.2.1 History of urban trends and problems to achieve sustainable development

Today, cities are home to 54 percent of the world's population, this figure rises to 70 percent for European countries (UN- HABITAT, 2016). Cities play a key role in the social and economic development of all European territories and are the main centres of education, health care and transportation (European Union, 2010). Therefore, it is essential for cities to be sustainable and efficient (European Commission, 1996). While cities are powerhouses of economic growth and catalyst of inclusion and innovation, they also face major problems and trends that threaten their sustainable development (UN- HABITAT, 2016). Over the past four decades, some institutions launched initiatives to identify the problems and trends that threaten sustainable urban development:

- United Nations- First Conferences on the Human Environment

The first initiatives to analyse the problems in cities from all over the world to achieve a sustainable development, were launched by the United Nations and date back to the earliest definitions of the concept of sustainability (UN, 1972; 1992). The main concerns expressed in these initiatives were the rapid socio-economic growth in industrialised cities for their effect on the environment, and the lack of basic needs in cities from developing countries. The conclusions reached from these first initiatives were summarised in *Agenda 21*, a document resulting from the United Nations Conference on Environment and Development held in Rio de Janeiro (UN, 1992).

- UN-HABITAT- United Nations Human Settlements Programme

UN-HABITAT is an agency of the United Nations aiming to promote socially and environmentally sustainable towns and cities, which was fully consolidated in 2002 (UN-HABITAT, n.d). Under this initiative, several documents are published each year. These publications analyse the problems and solutions related to urban development. Some of these documents provide a general overview on the threats over sustainability in cities all over the

world (UN-HABITAT, 2009; 2016). The approach adopted in these documents is a comprehensive one, embracing urban problems existing in both developed and developing countries: increased residency in slums, lack of basic services, migration, climate change, exclusion, insecurity, and so on.

- URBACT- European Territorial Cooperation Programme

URBACT is a program supported by the European Union aiming to foster sustainable integrated urban development in cities across Europe (URBACT, 2016). Since 2003, the programme has financed a series of projects, reports and publications to help European cities address urban problems. One of the notable publications launched by this initiative is the report *Cities of Tomorrow* (European Union, 2011), which summarises the existing trends threatening sustainable development in European cities. This report opened different work streams for the different threats, which were analysed in more deep in other URBACT publications, such as: rising unemployment and lack of jobs (Campbell, Partridge and Soto, 2013), socio-spatial segregation and polarisation in cities (Colini et al., 2013), pollution and degradation of the environment due to unsustainable mobility and land use development (Enemark and Kneeshaw, 2013), contribution to climate change and energy consumption (Lewis, Hógáin and Borghi, 2013), and demographic decline (Adams and Arnkil, 2013; Schlappa and Neil, 2013).

The different urban trends and problems threatening sustainability and identified in each of these three initiatives are shown in Tables 2.1, 2.2, 2.3 and 2.4 (pages 13, 14 and 15). The majority of these trends can be divided into trends mainly affecting society (Table 2.1), trends mainly affecting the environment (Table 2.2) and trends mainly affecting the economy (Table 2.3). Finally, Table 2.4 shows the trends related to the spatial growth of urban settlements, which have significant negative effects over the three sustainability dimensions.

Table 2.1. Urban trends and problems threatening SOCIAL sustainability identified in different initiatives

United Nations- First Conferences on Human environment (UN, 1992)	UN- HABITAT- United Nations Human Settlements Programme (UN-HABITAT, 2009; 2016)	URBACT- European Territorial Cooperation Programme (European Union, 2011)
Demographic Dynamics •Rapidly growing cities (unless well-managed, face environmental problems) •Inability to assess implications of demographic trends and other factors	Housing problems • Lack of affordable houses in city centres for a growing urban population • Growth of slums • Lack of access to basic infrastructure and services such as water and sanitation systems • Exclusion and rising inequality	•Socio-economic polarisation •Socio-spatial segregation •Lack of affordable housing, especially in the city centres All these trends have been enhanced by the spatially dispersed growth of urban areas (sprawl)
Unhealthy urban environments, especially in industrialised countries •Pollution in water, air , earth and living beings	Lack of public spaces, infrastructures, parks and green areas for human well being Car-centred mobility that leads to pollution, noise stress and accidents	Pollution and degradation of space as human environment, largely due to unsustainable mobility patterns and land use development
Inadequate supplies of good quality water and scarcity of water	Lack of access to water from a clean, safe source, especially in the developing world	
Lack of integration of women and youth in all development activities	Exclusion of young people from decision making, and increasing difficulties for them to break into the labour market Gender inequalities : women more affected by violence, difficulties accessing jobs, worse paid	•Lack of jobs, especially during the economic crisis and for young people •Migration of active population and skilled workers
Deprivation of food and clothing, shelter and education, health and sanitation in developing countries	Unemployment and poverty-related to social exclusion and crime	
-	Increasing levels of crime, particularly in the developing world	-
-	Ageing population in developed countries	Ageing population

Source: Adapted from Romanillos, Alonso and Wang (2014)

Table 2.2. Urban trends and problems threatening ENVIRONMENTAL sustainability - different initiatives

United Nations- First Conferences on Human environment (UN, 1972; 1992)	UN- HABITAT- United Nations Human Settlements Programme (UN-HABITAT, 2009; 2016)	URBACT- European Territorial Cooperation Programme (European Union, 2011)
Damage to the atmosphere, due to •Excessive use of some energy sources •Inefficient transportation systems •Industry management		•Poor air quality •Fuel dependence
Depletion of the Earth's stratospheric ozone layer	Contribution to Green House Gas Emissions, mainly through energy generation, vehicles, industry and biomass use	Contribution to Green House Gas Emissions and Fuel dependence
Increasing pressures on land resources (expansion of human requirements and economic activities)	Land degradation	Land occupation and degradation , enhanced by urban sprawl
Difficulties in maintaining the quality and supply of water resources •Floods and droughts •Impacts of pollution in water resources •Growing effects of urbanisation on water demands and usage	–	–

Source: Adapted from Romanillos, Alonso and Wang (2014)

Table 2.3. Urban trends and problems threatening ECONOMIC sustainability - different initiatives

United Nations- First Conferences on Human environment (UN, 1972; 1992)	UN- HABITAT- United Nations Human Settlements Programme (UN-HABITAT, 2009; 2016)	URBACT- European Territorial Cooperation Programme (European Union, 2011)
Inefficient consumption patterns	Unsustainable consumption habits by end users (residents, businesses, industries). •Inefficient and unsustainable sources •Lack of incentives to encourage local produce	•Low productivity and competitiveness •Inefficient urban systems and services
Need to strengthen the role of business and industry •For a major prosperity and development •With more efficient production processes and cleaner productions	Financing needs for basic services and infrastructure •Need to create economic strategies •Need for a better comprehension of regional and global dynamics to foresee and address threats Need to provide attractive environments conducive for economic activities, investments and job creation	Negative economic trends have emerged during the recent economic crisis •Declining revenues and demand •Rising unemployment
–	Unemployment and poverty, especially in the developing world	
–	Development of informal economy	

Source: Adapted from Romanillos, Alonso and Wang (2014)

Table 2.4. Urban trends and problems related to the spatial growth of urban settlements, with effects over the SOCIAL, ENVIRONMENTAL and ECONOMIC sustainability of cities

United Nations- First Conferences on Human environment (UN, 1972; 1992)	UN- HABITAT- United Nations Human Settlements Programme (UN-HABITAT, 2009; 2016)	URBACT- European Territorial Cooperation Programme (European Union, 2011)
Human settlement development •Difficulties in managing metropolitan areas extended over different administrative areas •Suburbs creation and socio-spatial segregation	Rapid growth of land occupation, and cities loosing compactness •Less and more inefficient land use patterns, car-centred urban models, congestion problems •Social disaggregation, loss of accessibility to basic needs	Urban Sprawl •Socio-spatial segregation and social polarisation •Land occupation •Inefficiencies in services delivery
–	Vulnerability to severe impacts from earthquakes, surges, tsunamis and new impacts from climate change	–

Source: Adapted from Romanillos, Alonso and Wang (2014)

2.2.2 Main threats over sustainability in European cities

European cities are considered among the most sustainable cities in the world (Newman and Kenworthy, 1999; Haghshenas and Vaziri 2012). However, they are affected by specific trends that are threatening their sustainable development (European Union, 2011). Some of these threats constitute relatively old concerns for most cities over the world, such as the degradation of environmental resources (UN, 1972; 1992). Other trends, such as the ageing population, are more recent concerns in cities for developed countries (UN-HABITAT, 2016). Finally, a series of trends have emerged with the recent economic crisis, which has been particularly severe in Europe, leading to a reduction in revenues and employment (Campbell, Partridge and Soto, 2013).

In this section, the main threats affecting European cities, which are summarised and represented in Table 2.5 and Figure 2.1 (page 16), are described in detail. In this context, urban threats can be defined as existing or potential problems with negative effects on the sustainability of a city, following similar approaches to Jackson and Dutton (1988).

Table 2.5. Main trends and treats over sustainable development in European cities

Urban trends and problems	Threats
•Ageing population •Migration of active population and high skilled workers during the period of economic crisis •Degradation of the living environment, especially in the core cities	Demographic decline
•Socio-economic polarisation •Socio-spatial segregation, especially enhanced by urban sprawl •Housing problems, such as lack of affordable houses, gentrification and formation of ghettos	Social polarisation and segregation
•Contribution to Greenhouse effect •Fuel dependence •Poor air quality •Noise pollution	Depletion of natural resources and environmental impact
•Low productivity and competitiveness •Inefficient urban systems •Rising unemployment •Declining revenues and demand	Development and competitiveness under pressure
•Changes in core cities, degradation of some inner areas and gentrification of others •Individual housing preferences •Increased mobility •Investment decisions: to allocate commercial areas and activities outside the core cities •Land use policies	Urban sprawl

Source: Adapted from Romanillos, Alonso and Wang (2014)

Figure 2.1. Main threats over sustainable development in European cities

Source: Romanillos, Alonso and Wang (2014)

2.2.2.1 Social changes: Demographic decline

European cities are going through clear demographic changes such as ageing populations, shrinking cities or intense problems of suburbanisation (European Union, 2011). The increase of life expectancy and the continuous drop in the birth rate are causing an increase in the average age of the European population, and a decrease in the percentage of working age population (UN-HABITAT, 2016). Furthermore, the recent economic crisis has caused another trend that contributes to this effect: the migration of active population due to the lack of job offer (Schlappa and Neil, 2013). Most European countries are affected by these two trends, and so are in general the cities in these countries. Finally, traffic growth and other factors are causing the deterioration in living conditions of many core cities. This leads many people to move to the suburbs, and is considered to be a very important driver of urban sprawl.

Ageing population

An ageing population presents a major challenge to society in all Member States. The old age dependency ratio (population over 65 to population between 15 and 64) is expected to grow from 26 percent in 2010 to 50 percent in 2050 (European Commission, 2012b). These demographic changes are mainly due to a combination of continuing increases of life expectancy, as a result of considerable progress made in health care; and continuing low birth rates due to factors such as late access to employment, job instability, cost of housing and lack of incentives (European Commission, 2005). The ageing population is therefore linked to constraints in household budget and difficulties to find a job, both exacerbated by the economic crisis during the past few years (Schlappa and Neil, 2013).

Migration of active population and skilled workers

The financial crisis that hit the European economy in 2007 caused a large drop in economic activity in the EU, with millions of jobs lost and a high human cost (Directorate-General for Economic and Financial Affairs of the European Commission, 2009). In this framework, some European cities faced an out-migration of workers and especially skilled workers, which constituted another trend contributing to demographic decline. Some cities proved to be especially vulnerable to this threat, such as cities dependent on single sectors, traditional manufacturing, raw-material-based industries; or cities that strongly rely on foreign direct investment (European Union, 2011).

Socio-economic polarisation

Even if the situation differs widely between the different countries of Europe, traditionally European cities had shown a relative high level of social integration and equality, compared to cities in other Asian or American countries (Uhel, 2006). However, polarisation and segregation seem to be increasing. "Although average living standards have increased over time, there are signs not only of growing income disparities but also of the poor getting poorer. In some places, local populations suffer from a concentration of inequalities: poor housing, low-quality education, unemployment, and difficulties or inabilities to access some services (health,

transport, ICT)” (European Union, 2011, p. 22). The economic crisis seems to have worsened these inequalities (Colini et al., 2013).

Socio-spatial segregation and lack of affordable housing

The spatial segregation is the spatial separation of the population according to their social or socio-economic position (Musterd, 2005). Almost all European cities face growing problems of spatial segregation, although Europe still has relatively less segregated urban structures compared to cities in other parts of the world (Colini et al., 2013). Spatial segregation is both cause and effect of the formation of ghettos and the gentrification of certain parts of the cities, which become unaffordable for low and even middle classes (European Union, 2011). This process usually leads to the fragmentation of the core cities, and induces middle class population to settle in the suburbs (Colini et al., 2013). Therefore the spatial segregation is also both cause and effect of urban sprawl processes (Uhel, 2006).

2.2.2.2 Depletion of natural resources and environmental impact

In many ways, cities offer solutions for a more sustainable way of life, but despite improvements in air and water quality, as well as efforts to mitigate climate change, European cities still face a number of environmental threats (European Union, 2011). As the living environment for most European population, the engines of growth and generators of wealth, cities are also drivers of consumption and use of material resources. Energy consumption in urban areas- especially in transport and housing sectors- is responsible for the largest share of CO₂ emissions (Lewis, Hógáin and Borghi, 2013). In addition, most of the energy sources are not renewable, and are responsible for air pollution; especially in the transport sector where the strong dependence on cars and therefore on fuel cause also air pollution and noise (European Commission, 2007).

Energy consumption, fuel dependence and contribution to greenhouse effect

Cities over the world are major contributors to climate change. “With more than 50 percent of the world’s population, cities account for between 60 and 80 percent of energy consumption and generate as much as 70 percent of the human-induced greenhouse gas emissions primarily through the consumption of fossil fuels for energy supply and transportation” (UN-HABITAT, 2016, p.16). In developed cities, most energy is used to heat and light residential and commercial buildings; transport and industry follow as the second and third greatest consumers of energy (UN-HABITAT, 2009).

European cities are also major contributors to energy consumption and emissions. About 69 percent of the total primary energy demand in Europe is consumed in urban areas, yet the energy consumption and CO₂ emissions per capita are lower in European towns than outside them (Birol, 2008). The density of urban areas allows for more energy-efficient forms of housing, transport and service provision, and measures to address climate change may be more effective. Therefore, cities are both the problem and the solution, especially in regard to

housing and transport sectors (Lewis, Hógáin and Borghi, 2013). The problem with the transport sector is the low rate of renewable energy it uses. “The main environmental issues in towns and cities are related to the predominance of oil as a transport fuel, which generates CO₂, air pollutant emissions and noise” (European Commission, 2007, p.8). European cities are responsible for 40% of CO₂ emissions due to transport (OECD, 2008).

Poor air quality and noise pollution

Pollution is a problem highly concentrated in cities (Guerreiro, de Leeuw and Foltescu, 2013). Air and noise pollution in cities not only contribute to the degradation of space as human environment, but have many adverse consequences over crops and are responsible of biodiversity losses (CE Delft, INFRAS and Fraunhofer ISI, 2011). Air pollution contributes to acid rain, water pollution, or soil pollution. Although in many European cities air quality has improved over the past decades due to national and European initiatives, it is still a main concern and a common problem to almost all major cities (Guerreiro et al., 2016).

Degradation of space as human environment

The degradation of cities as the living environment of the majority of the population is a relatively old and globally widespread concern. Meeting the urban health challenge was already one of the objectives set by United Nations in Agenda 21, where the poor living conditions in urban areas around the world were reported (United Nations, 1992). The main causes of the degradation of European cities are pollution, noise and the lack of safety and security, but also factors such as lack of green spaces, poverty and minorities with integration problems threaten the liveability of European cities (Uhel, 2006). City centres are particularly affected by these problems, which are thought to be important drivers of the urban sprawl process: “Out migration from the city centre to the peri-urban areas may result from a demand for a greener, more attractive and family- friendly environment” (European Commission, 2011, p.26).

Most of these problems are linked to transportation. Throughout Europe, increased traffic in town and city centres has resulted in congestion, with the many adverse consequences that this entails in terms of noise and air pollution – urban transport is responsible of 70% of emissions of some pollutants from road transport (European Commission, 2007) “Up to 30% of Europe’s urban citizens are potentially exposed to levels of air pollution that exceed some of the European Union air quality standards set to protect human health” (European Environment Agency, 2013). Also noise is primarily an urban problem. It is estimated that 149 million Europeans could actually be exposed to unhealthy noise levels, and in 60 percent of the cases it is due to road transport in urban areas (Nugent et al., 2014). Regarding urban safety, one in three fatal accidents happen in urban areas, and is the most vulnerable people, namely pedestrians and cyclists, who are the main victims (European Commission, 2007).

2.2.2.3 Economic decline. Development and Competitiveness under pressure

European cities play a key role in economic growth (European Commission, 2011). However, many of these cities are now exhibiting a dual personality of economic strength co-existing with weak demand and unemployment, the latter is related to factors such as an ageing and declining workforce and a lack of competitiveness (Campbell, Partridge and Soto, 2013).

Low productivity and competitiveness

Cities can contribute to economic growth and job creation by creating a competitive framework and enhancing productivity and efficiency (European Union, 2011). Inefficient energy consumption patterns are important barriers for economic growth and job creation (Lewis, Hógáin and Borghi, 2013). In Europe, energy consumption patterns are more sustainable in urban than in rural areas (Birol, 2008). However, European cities still have to improve the consumption patterns in the housing and transport sectors (European Union, 2011). The problem with the transport sector, is the predominance of non-renewable energy sources, mainly oil, beyond the high energy consumption (Enemark and Kneeshaw, 2013). Despite the progress in car technology, excessive car dependence generates inefficiencies and environmental problems (European Commission, 2007). The achievement of more efficient energy patterns is becoming more difficult due to the spatial dispersion of the population (Theodoridou, Papadopoulos and Hegger, 2012).

Another consequence of excessive car traffic in urban areas is congestion. Road congestion affects productivity of a city and constitutes a barrier for competitiveness. "Congestion is resource inefficient; it consumes energy and creates unnecessary pollution, it is time consuming and it consumes space" (European Union, 2011, p.45). It is estimated that more than 100 billion euros per year are lost in Europe due to congestion (CE Delft, INFRAS and Fraunhofer ISI, 2011).

Unemployment and declining revenues and demand

The economic recession caused a large drop in demand and the loss of millions of jobs in the European Union (Directorate-General for Economic and Financial Affairs of the European Commission, 2009). Cities, where the majority of the population in Europe live and where most of the GDP is created, are key actors for addressing this threat. Urban areas can foster job creation by providing a business friendly environment and competitive local conditions to encourage business attraction and inward investment (Campbell, Partridge and Soto, 2013). In some cases, the problem is not the lack of jobs, but the accessibility to existing jobs (Preston and Rajé, 2007). This problem could be partially addressed through land use and transport policies.

2.2.2.4 Urban Sprawl

Trends since mid-1950's, show that European cities have expanded on average by 78 percent whereas the population has grown by only 33 percent (Uhel, 2006). Historical concerns about demographic dynamics and sustainability were focused on the growth of cities linked to increasing population (United Nations, 1992). In contrast, urban sprawl is a more recent phenomenon, resulting from the spread of low-density settlements, and is one of the main threats over cities (European Union, 2011). Urban sprawl is tied to a variety of factors such as the development of the modern city, individual housing preferences, increased mobility, commercial investment decisions and the coherence and effectiveness of land use policies at all levels (Uhel, 2006).

Socio spatial segregation- social polarisation

From a social point of view, there are two main drivers of urban sprawl, and the sprawl itself reinforces those drivers. These drivers are described by several documents at the European level (Uhel, 2006; European Union, 2011; Colini et al., 2013). On the one hand, the degradation of some parts of the cities regarding human living conditions, due to pollution, noise and social problems, are making many families settle in peri-urban areas where they can find better quality housing. This particularly affects young families. Some of these new urbanisations attract wealthy social classes, forming wealthy ghettos and leaving poor and run-down city centres. On the other hand, the increased gentrification of other parts of the core-cities drives less affluent social classes to look for more affordable housing further from the city. Therefore, from a social perspective urban sprawl is due to the segregation of residential development according to income and exacerbates urban social and economic divisions, enhancing differences between the different zones inside and outside the cities (Colini et al., 2013). Furthermore, urban sprawl makes it more difficult to provide services and this leads to a reduction in accessibility to basic needs such as health care, education or transport and ultimately contributes to social exclusion (Uhel, 2006).

Land occupation and environment degradation

Urban development involves the substantial consumption of numerous natural resources. The use and degradation of land and soil itself are of particular concern as they are mostly non-renewable resources. Infrastructure development and urban sprawl result in a continued expansion of artificial surfaces across Europe, at the expense of agro-ecosystems, grasslands and wetlands (European Union, 2011).

Another consequence of urban sprawl is the growing consumption of energy. Generally, compact urban developments with a higher population density have more efficient consumption patterns (Uhel, 2006). For instance, individual households tend to be less efficient, regarding energy and water consumption, per person than larger households (Theodoridou, Papadopoulos and Hegger, 2012). Regarding transport energy, there is a significant increase in travel related energy consumption in cities as densities fall. "Essentially, the sprawling city is dominated by relatively energy inefficient car use, as the car is frequently

the only practical alternative to more energy efficient, but typically inadequate, relatively and increasingly expensive public transportation systems” (Uhel, 2006).

Economic losses and inefficiencies in services delivery

City centres have been always characterised by functional mix, but urban sprawl contributes to fragmentation of living and working spaces and pushes companies outside city centres, this may have negative effects over the economic dynamics in urban areas (European Union, 2011). Finally, sprawl is a more costly form of urban development. It leads to additional expenses due to the extension of urban infrastructures and services such as transport, energy or electricity, across the urban region (Uhel, 2006).

2.2.3 Setting policy priorities

Urban planning and policy making should provide solutions for the increasing problems that threaten the sustainability of cities (Nijkamp and Perrels, 2014). Solutions to urban problems are more likely to be found by understanding the nature of urban phenomena and monitoring the problems (Bracken, 2014). Given that urban threats involve not only existing but also potential problems (Jackson and Dutton, 1988), it is extremely important to monitor the evolution of urban trends. Therefore, an adequate urban planning requires identifying, measuring and monitoring the problems and trends that constitute the different threats over cities. This should help to determine the most important threats in each city and to establish its policy priority objectives accordingly (Jones and Baumgartner, 2005). European cities share some common trends compared to cities in other continents. However, policy priorities will vary among cities, since there is a diversity of situations between them, e.g. the economic crisis was especially severe in Spanish cities (Campbell, Partridge and Soto, 2013), small and medium sized cities in northern Italy are experienced strong processes of urban sprawl (Uhel, 2006), an air pollution is especially high in cities from Poland and Slovakia (Guerreiro, de Leeuw and Foltescu, 2013).

- ✓ How do we measure the potential and existing problems that constitute the different urban threats to achieve a sustainable development in European cities?
- ✓ How do we establish policy priorities according to the main threats in the different cities?

2.3. Main Opportunities and Challenges in European cities

European cities present not only threats and weaknesses, but also strengths and opportunities (European Union, 2011). Opportunities are characteristics that could bring positive and potential gain (Jackson, and Dutton, 1988). The opportunities in urban areas arise from the proximity between people, jobs and services:

- Economies of scale and agglomeration

European cities are home to the majority of the population, drive economic development, and attract investment and jobs. More than 70 percent of the Europeans live in cities (UN-HABITAT, 2016) and almost 85 percent of the EU's GDP is created in urban areas (European Commission, 2007). "More than two-thirds of the workforce in the European Union live in cities and one in four people lives in just 40 agglomerations of more than one million people" (Campbell, Partridge and Soto, 2013, p. 5). The concentration of consumers, workers and businesses in an area has the potential to produce increasing returns of scale (European Union, 2011). Cities benefit from agglomeration economies (Newman and Kenworthy, 1999). "Urbanisation has become widespread around the world, so at a macro level, apparently, the economies of scale in urban areas are by large superseding the diseconomies and external cost of modern city life" (Nijkamp and Perrels, 2014, p.3).

- Agglomeration allows for more efficient services and systems

Urban economist point out that there are significant economic benefits arising from increased size and density, e.g. systems such as transport, energy, electricity, waste treatment and recycling become more efficient as cities grow (Newman and Kenworthy, 1999). In the European Union, energy use and emissions per capita of city residents is lower than the national average (Birol, 2008). The density of urban areas compared to rural areas allows for more energy efficient forms of housing, transport and service provision (Lewis, Hógáin and Borghi, 2013). This is especially the case of European cities: "Cities in the European Union tend to use less energy per capita than the United States and Australasian cities, because of higher population densities, more extensive urban public transport systems and more district heating" (Birol, 2008, p. 182)

- Places for social progress, proximity and integration

"The European city often has a strong social mix, compared to other much more segregated models of urbanisation in other countries" (Colini et al., 2013). This characteristic makes it easier to achieve social cohesion, balance and integration (European Union, 2011)

Both threats and opportunities emerge in cities creating urban challenges (UN-HABITAT, 2016). Table 2.6 (page 24) shows the scheme of threats, opportunities and challenges for European cities.

Table 2.6. Main Challenges for European cities

Threats	Opportunities	Challenges
Demographic decline	- More than 70 percent of the European population lives in urban areas, and this percentage is expected to continue growing (UN-HABITAT, 2016). - As the living environment of the majority of the population, the quality of life in cities should be improved, addressing problems such as noise, pollution, safety and security (European Commission, 2007). - The European cities have a strong social mix, compared to other more segregated models of urbanisation (Colini et al., 2013). - Urban environments are the main centres of many public services such as education, healthcare and transportation, and people expect cities to cater for their needs (European Union, 2011).	Challenges of cities as living environments Enable social development, in an equitable, healthy and safe manner; and minimize the impact on the environment.
Social polarisation and segregation		
Depletion of natural resources and environmental impact		
Development and competitiveness under pressure	- European cities are responsible for 40% of CO₂ emissions from transport and 30% of CO₂ emissions arising from Industry (OECD, 2008). - Pollution is a problem highly concentrated in cities, with major effects over European ecosystems (Guerreiro, de Leeuw and Foltescu, 2013). - Urban living is both part of the problem and the solution (Lewis, Hógáin and Borghi, 2013). Due to agglomeration economies, emissions per capita of city residents is lower than the national average in the European Union (Biol, 2008).	Challenges related to the efficiency of urban systems Constitute appropriate frameworks for economic growth and efficiency; and minimize the consumption of resources.
Urban sprawl	- Cities are the main engines of the economy, innovation and jobs (European Union, 2011). Almost 85% of the EU's GDP is generated in urban areas (European Commission, 2007). - Cities can contribute to economic growth by providing a business friendly environment and competitive local conditions to encourage job creation (Campbell, Partridge and Soto, 2013). - Competitiveness requires more efficient consumption patterns, in this regard European cities have a lot of room for improvement (Lewis, Hógáin and Borghi, 2013; European Union, 2011).	
	- In Europe, cities have traditionally been compact, minimizing the use of resources and land consumption (Newman and Kenworthy, 1999). Compared to cities in other continents, European cities still remain in many cases compact (Uhel, 2006).	

Challenges come from reformulating threats into a more inspiring way, and each challenge can address several problems (European Union, 2011). Following this approach, the urban threats can be reformulated into two types of general challenges:

Challenges of cities as living environments

“Urban areas now constitute the living environment of the vast majority of the population and it is imperative that the quality of life in these areas should be as high as possible” (European Commission, 2007, p.3). Citizens expect urban environments to cater for their needs in an equitable manner, as cities are the main centres of public services such as education, health and transportation (European Union, 2011). There are several factors that shape citizen satisfaction with city life. These factors, which should not only attract individuals to become new citizens but also to encourage existing residents to stay, were identified by Węziak-Białowolska (2016):

- Physical features such as streets, pedestrian ways and green areas
- Accessibility for all, understood as access to main needs, services and facilities
- A healthy, safe and secure environment, free of pollution and noise
- Affordability

The challenges aimed at the achievement of more liveable cities are also aimed at minimizing the impact on the environment. These challenges would therefore be affected by the threats related to the demographic decline, the social polarisation and segregation and the depletion of natural resources and environmental impact.

Challenges related to the efficiency of urban systems

Urban regions are essentially large production systems and services encompassing the core economic activities of a country and acting as the focal point of an inter-urban, regional or national network (Nijkamp and Perrels, 2014). Like all systems, the cities consume inputs of land, energy and other resources, and produce outputs such as employment, income and urban design (Newman, 1999). In this regard, Newman (1999) points out the need for the cities to be efficient. However, agglomeration economies have limits, and negative externalities can result from agglomeration (Barca, 2009). Some of these negative externalities have negative effects over the efficient functioning of cities, e.g. congestion, urban sprawl and imbalances in the housing market (European Union, 2011).

Therefore, cities need to be efficient systems, and this means maximising the outputs in terms of development and minimizing the use of resources and negative impacts. Cities can contribute to economic growth and job creation by constituting efficient, attractive and competitive frameworks. All these efficiency challenges are constrained by trends such as the economic decline and the urban sprawl.

✓ How urban threats constrain the achievement of city challenges?

2.4. Integrated land use and transport strategies to face threats and challenges in cities

Mobility issues touch on, and connect to, many of the problems that cities face, e.g. segregation, lack of social cohesion, poor health due to pollution and land occupation (Enemark and Kneeshaw, 2013). Transport planners should consider the key challenges facing cities (Banister, 2005). “Sustainable mobility provides an alternative paradigm within which to investigate the complexity of cities, and to strengthen the links between the land use and transport” (Banister, 2008, p. 73). In his work, Banister (2008), proposes four basic types of actions to achieve sustainable mobility:

- **Reducing the need to travel**, mainly by substituting it through technology. This means that a trip is no longer made, since it was substituted by technology, e.g. internet shopping and teleworking.
- **Transport policy measures to change modal shift**. These type of measures can **reduce levels of car use**, through slowing down urban traffic and reallocating space to public transport, through parking controls and road pricing and by making it easier to use public transport.
- **Land use policy measures to reduce travel distances**. These measures address the spatial separation of activities, by developing mixed land uses or encouraging a compact urban growth. The intention is to build a sustainable mobility into the patterns of urban form and layouts, which in turn may lead to a switch to green modes of transport.
- **Technological innovation**. Technological improvements can increase efficiency in terms of engine design, alternative fuels and the use of renewable energy sources.

All these policy actions, which are related to land use and transport management, can **help to improve the liveability and efficiency of cities**, minimizing the impact over the environment and help to address different urban threats:

- Improving quality of life in cities to face the demographic decline

Assuming that the demographic decline exceeds the urban scale, the depletion of cities regarding their living conditions may exacerbate it (Schlappa and Neil, 2013). Pollution and other factors turn cities into unhealthy and unattractive environments (European Union, 2011), and drive many families out of the city (Uhel, 2006). Therefore, all those actions aiming to improve the quality of life in cities will improve their attractiveness for residents, contributing to address the demographic decline threat, e.g. creating public spaces such as parks and gardens, improving public transport efficiency and availability, reducing pollution and noise, increasing safety (Węziak-Białowska, 2016).

- Delivering accessibility and promoting social mix in urban spaces to avoid social polarisation and segregation.

This threat is linked to land use development, since it is partly due to the spatial segregation of residential zones according to income (Uhel, 2006). Spatial segregation usually leads to a growing degradation of the poorest areas, whose residents may be socially excluded due to the lack of accessibility to basic needs, jobs or activities (Preston and Raje, 2007). Some urban planning strategies can partly address this problem. Examples of these strategies are the improvement of degraded areas, the promotion of tenure mix in housing and the improvement of the accessibility to main needs (Colini et al., 2013).

- Reducing the use of cars and ensuring a compact urban development to reduce pollution and the impact on the environment

The transport sector is characterised by a strong dependence on cars and fuel, and it is a very important source of emissions and pollution in cities (Enemark and Kneeshaw, 2013). All strategies facilitating the use of cleaner energy sources in transport, restricting or reducing the use of cars in cities or promoting alternative modes, will help to reduce the environmental impact of urban areas on the environment (European Commission, 2007).

On the other hand, the degradation of land and other resources per person becomes greater as the urban areas sprawl (European Union, 2011). Urban dispersion especially increases the transport needs (Uhel, 2006). Therefore, those actions aiming to encourage compact urban growth, discourage sprawl, reduce travel distances or develop mixed land uses, should help to reduce the depletion and consumption of natural resources.

- Creating business friendly environments and efficient transport networks free of congestion to enhance economic competitiveness and development

Economic growth and job creation depend on demand. Cities can stimulate demand and attract investment by creating competitive frameworks able to enhance productivity and efficiency. In this regard, urban planning can help to create a business- friendly environment, by efficient infrastructures, good accessibility, competent transport networks or good quality public spaces (Campbell, Partridge and Soto, 2013).

Congestion in cities is one of the main problems for economic efficiency (European Commission, 2007). Policies aiming to reduce the need to travel or the levels of car use will help to improve the traffic flow and therefore the efficiency of the transport system.

- Compact developments, improvement of degraded zones and promotion of social mix to avoid urban sprawl

Urban sprawl is clearly an urban planning issue. This threat can be addressed through higher density developments with high quality public transport connections (de Oña et al, 2013), but also by preventing migration to peri-urban areas, either by improving inner city spaces in order to create more liveable and attractive environments or by promoting housing mix to avoid gentrification (Uhel, 2006).

New policies and policy packages in urban transport and land-use planning are required to face urban challenges in cities (Wegener, 2013). However, it is important to evaluate the impacts of all actions, a difficult task due to the long term impacts of the actions: “These policies take time to be implemented and until their impacts are felt and are likely to generate significant financial and distributive problems and still unknown social conflicts” (Wegener, 2013, p.278).

- ✓ How different land use and transport policies can address urban threats and contribute to meet urban challenges in the long term?

2.5. Specific research objectives for sustainability challenges in cities

The general objective of the thesis was set in Section 1.1. Furthermore, the literature review carried out in Chapter 2 has raised some research questions that define four specific research objectives for sustainability challenges in cities.

The first research questions emerged in Section 2.1:

- ✓ How do we measure sustainability in urban transport systems as a complex, multidisciplinary and multidimensional concept?
- ✓ How do we obtain indicative and real figures about sustainability measures to establish goals?
- ✓ What factors explain a sustainable urban mobility?

These questions introduce the first specific research objective:

To measure sustainability of urban transport systems on a comparative and real basis and to identify the explanatory factors of sustainable mobility in cities

Sustainable urban transport systems are essential to reach a sustainable development in cities. Cities need measurement tools to set goals and targets towards a sustainable mobility and to identify their main barriers to achieve it.

However, this is not an easy task. On the one hand, sustainability is a complex and multidisciplinary concept, which includes multiple dimensions. On the other hand, sustainability is not an absolute concept: there is not an absolutely sustainable urban transport system. Therefore, these measurement tools should incorporate multiple concepts and should be based on comparisons between different cities, to allow defining achievable objectives. Finally, these measurement tools should serve to identify the characteristics that explain sustainable mobility patterns in cities.

Section 2.2 introduces the following research questions:

- ✓ How do we measure the potential and existing problems that constitute the different urban threats to achieve a sustainable development in European cities?
- ✓ How do we establish policy priorities accordingly to the main threats in the different cities?

These questions lead to the second specific research objective:

To identify the main urban threats over sustainability in different European cities in order to establish their policy priorities

Literature on urban problems at the European level enabled the identification of a number of common trends in cities which are threatening their sustainable development: demographic decline, social segregation, environmental depletion, urban sprawl and economic decline. These threats include existing and potential problems. However, European cities face a wide diversity of situations and each city should identify its main threats to establish its policy priorities.

This requires an ad hoc evaluation framework, in which each threat is conceptualized. This framework should be complemented by tools for measuring the evolution of each current and potential problem. These tools should apply to various cities, allowing a consistent comparison among them to identify their main threats and priorities.

In Section 2.3 emerges one research question:

- ✓ How urban threats constrain the achievement of city challenges?

This question is formulated into the third research objective:

To analyse how certain urban threats can constrain the achievement of city challenges

Two main urban challenges have been established through the literature review: cities should become liveable environments and cities should facilitate the deployment of efficient urban systems. The common threats to European cities pose problems to meet these challenges. On the one hand, demographic decline, social polarisation and environmental depletion are barriers to achieve liveable urban environments. On the other hand, economic decline and urban sprawl cause inefficiencies in urban systems. A better understanding of the synergies and the impacts of these trends should help cities to deliver strategies able to face the urban threats and to meet the city challenges.

To analyse these types of trends, monitoring tools are required. These tools should be able to capture the changes over time for the different concepts, and to establish synergies between them.

Finally, in Section 2.4 is included the last research question related to urban planning and sustainability challenges in cities:

- ✓ How different land use and transport policies can address urban threats and contribute to meet urban challenges in the long term?

This last research question defines the last research objective:

To measure the potential contribution of land use and transport policies to meet long term city challenges

Urban transport is a key element for achieving sustainable and efficient cities. However, transport is linked to land use, and both systems interact dynamically over time, at different paces. Therefore, transport and land use policies are necessary to meet city challenges. In any case, before implementing policy measures, city managers should evaluate their impacts and their contribution to the long term city challenges

This task requires firstly, defining future scenarios for the implementation of policies. Secondly, tools are needed to simulate the future changes in the transport and land use systems caused by the policy measures, as well as the impacts of these changes. These impacts should be measurable and related to the city challenges.

These four research objectives for sustainability challenges in cities require the development of management tools. In this thesis, a number of tools based on indicators and LUTI models have been developed to answer the research questions and to achieve the specific research objectives.

The outcome of this thesis is twofold:

1. The conclusions from the research studies (Chapter 5), which respond to the specific research objectives through different analyses applied to different cities.
2. The findings related to the tools developed, which can be applied to analyse other cities in other contexts for similar objectives.

3. Research Methodology

3.1. Management indicators for measuring sustainability, threats and challenges in the context of European cities

Once the necessity of achieving a sustainable urban development in cities has been stated, it is convenient to measure its accomplishment in an objective way by creating tools for global control, assessment and comparison. In this thesis, indicators are considered appropriated tools for this purpose:

- Indicators are suitable for measuring complex and multidisciplinary concepts, with overlapping dimensions (Newman and Kenworthy, 1999; Haghshenas and Vaziri, 2012).
- Indicators are useful to compare the performance of different cases and benchmark them (Nardo et al., 2005).
- Indicators can identify interactions between problems, trends over time and actions. Therefore, they are valuable tools to establish policy objectives and priorities. “City administrations must have the capacity to share and analyse information, to establish causal links between indicators and action, and, not least, to formulate and measure long-term objectives” (European Union, 2011, p.74).
- Indicators are considered suitable tools to track and assess policies: “The success of current and future integrated policies can only be judged by identifying key indicators that can be tracked and compared with concrete policy objectives” (TERM, 2000, p. 4).

In this thesis, the indicators were applied to measure the sustainability of urban transport systems, to compare cities and benchmark them, to analyse the main problems and trends in cities and finally to assess the impacts of policy measures. In all the application cases, the first step has been the definition and conceptualization of the concepts to be measured, then the selection of appropriated indicators and finally the processing (if necessary).

Requirements for management indicators

Not all indicators are appropriate for management purposes or able to support decision making towards sustainability objectives (Newman and Kenworthy, 1999). Several authors have analysed the requirements that indicators should fulfil to serve management purposes (May, Page and Hull, 2008; Jourard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012). The outputs from these studies can be summarised in seven desirable characteristics, which are described below.

- Sensitivity

Indicators for management should be sensitive enough to capture changes, in order to reveal the evolution and trends of the phenomenon being measured (Newman and Kenworthy, 1999; May, Page and Hull, 2008; Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012).

- Target relevance

Indicators for decision making purposes must measure performance with regard to articulated objectives (Newman and Kenworthy, 1999; Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012).

- Transparency

Indicators have to be transparent and easy to understand (May, Page and Hull, 2008; Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012).

- Validity

A valid indicator must measure the aspect it is supposed to measure (Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012). For this purpose, concepts have to be clearly defined, and the indicators have to be adapted to the definition.

- Unambiguous

Indicators should be unambiguous and not depend on interpretations when used to manage, compare and assess cities or policies (Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012).

- Data available, measurable and reliable

The data needed for the indicator should be available, measurable and come from a reliable source (Joumard and Gudmundsson, 2010; Haghshenas and Vaziri, 2012).

- Standardized

Ideally, cities should be able not only to assess their own situation, but also to compare themselves with other cities (European Union, 2011). Indicators for benchmarking and comparison purposes should allow standardisation per city size (Haghshenas and Vaziri, 2012).

Throughout the thesis, a number of indicators are proposed for multiple purposes related to urban planning and policy management in the context of European cities. To the extent possible, all these indicators fulfil the requirements defined above.

Processing indicators to achieve different objectives

There are various methodologies for computing indicators to compare the performance of different case studies, and they are being increasingly recognised as useful tools in policy analysis (Nardo et al., 2005). The six main computing methodologies for policy analysis have been collected by various authors in their studies (Saisana, and Tarantola, 2002; Nardo et al., 2005; Joumard and Gudmundsson, 2010). These studies highlight the main characteristics and the most common applications of each methodology, as well as the main advantages of applying these methodologies to obtain computed indicators:

- Allow aggregating multiple concepts in a single indicators,
- Provide big pictures: allow for identifying trends ,
- Facilitate the task of ranking case studies on complex issues in a benchmarking exercise,
- Can assess progress of case studies over time on complex issues,
- Reduce the size of a set of indicators,
- Place issues of case studies performance and progress at the centre of the policy arena,
- Facilitate communication with general public and promote accountability,

In this thesis, the results and conclusions are often based in the comparison of indicators among different cities or years. For this purpose, two computing methodologies out of the six proposed have been applied. Tables 3.1 and 3.2 (pages 34 and 35) compile these methodologies, the main applications and characteristics. The last column details how the methodologies were applied in this thesis to achieve the research objectives (in the research studies from Chapter 5). The computing method used in each case has been selected taking into account the data properties and the objectives of the analysis, as recommended by Nardo et al. (2005).

Table 3.1. Methodologies for computing indicators- Rankings and time series

Method	Equation	Main characteristics	Applications in the thesis
Rankings	$I_c^t = \sum_{i=1}^N Rank_{ic}^t$	-Based on ordinal levels -Simple	n.a.
Number of indicators above the mean minus the number below the mean	$I_c^t = \sum_{i=1}^N Sgn \left[\frac{x_{ic}^t}{\bar{x}_i^t} - (1 + p) \right]$	-Independent from outliers -They lose absolute level information - Widely used to rank companies	n.a.
Ratio of percentage differences form the mean	$I_c^t = \frac{\sum_{i=1}^N w_i * y_{ic}^t}{\sum_{i=1}^N w_i}, \text{ where } y_{ic}^t = \frac{x_{ic}^t}{\bar{x}_i^t}$	-Normally used to compare countries and analyse their relative position -The method is not robust for outliers	n.a.
Percentage of annual differences over consecutive years	$I_c^t = \frac{\sum_{i=1}^N w_i * y_{ic}^t}{\sum_{i=1}^N w_i}, \text{ where } y_{ic}^t = \frac{x_{ic}^t - x_{ic}^{t-1}}{x_{ic}^t}$	-Represent the percentage growth with respect to the previous year instead of the absolute level -less affected by spot values or errors -Adequate to measure evolution or progress -It can be used only when the indicators are available for a number of years	Applied in Sections 5.3 and 5.4 E_{ic}: Evolution indicators for measuring the threats urban sprawl and economic decline, as well as the evolution of PT demand, supply and efficiency API_{ic}: Indicators to measure the Annual Progress towards different sustainability objectives

Sources: (Saisana, and Tarantola, 2002; Nardo et al., 2005; Joumard and Gudmundsson, 2010)

Note: x_i^t is the value for indicator i for cases study c at time t, w_i is the weight given to the indicator I in the formulation (if any). In the second method, p is an arbitrarily chosen threshold above and below the mean

n.a.:not applied

Table 3.2. Complex methodologies for computing indicators- Re-scaling and standardization

Method	Equation	Main characteristics	Applications in the thesis
Standardized values	$I_c^t = \frac{\sum_{i=1}^N w_i * y_{ic}^t}{\sum_{i=1}^N w_i}, \text{ where}$ $y_{ic}^t = \frac{x_{ic}^t - \bar{x}_i^t}{\sigma_i^t}$	-The method standardises scores for each indicator, which equal the difference in the indicator for each case and the mean, divided by the standard error -Converts indicators to a common scale with a mean of zero and standard deviation of one -The range between the minimum and the maximum value will vary for each indicator (standard error vary for each indicator). This gives greater importance to indicators with extreme values, and therefore is not totally independent from outliers (may be a desirable characteristic) -Appropriated for comparing various case studies in several aspects and penalising or rewarding exceptional behaviour	Applied in Section 5.1 CI_{DC} : Composite Indicators for measuring the sustainability of the urban transport systems in a group of cities
Re-scaled values	$I_c^t = \frac{\sum_{i=1}^N w_i * y_{ic}^t}{\sum_{i=1}^N w_i}, \text{ where}$ $y_{ic}^t = \frac{x_{ic}^t - \min(x_i^t)}{\text{range}(x_i^t)}$	-This method is similar to the previous one , except that it uses re-scaled values of the constituent indicators - This method is more robust when there are outliers. However, it does not penalise exceptional behaviour	n.a.

Sources: (Saisana, and Tarantola, 2002; Nardo et al., 2005; Joumard and Gudmundsson, 2010)

Note: x_i^t is the value for indicator i for cases study c at time t, w_i is the weight given to the indicator I in the formulation (if any).

n.a: not applied

Management indicators to answer the research questions

Overall, the indicators are considered to be valuable tools for policy management. They allow measuring complex concepts, are useful to compare case studies, enable the identification of cause-effect relations and are appropriated to track objectives. However, to meet these management purposes, indicators have to fulfil some requirements, and sometimes it is advisable to compute them with an appropriated methodology.

In this thesis, management indicators and computing methodologies have been used to answer most of the research questions that have emerged in the literature review on urban planning and transport management. These management tools are applied in the research studies of Chapter 5 to analyse different cities. The following text boxes include a summary on how the research studies answer the different research questions and objectives, and which tools based on indicators were applied in the analyses.

To measure sustainability of urban transport systems on a comparative and real basis and to identify the explanatory factors of sustainable mobility in cities

- ✓ How do we measure sustainability in urban transport systems as a complex, multidisciplinary and multidimensional concept?

By developing indicators able to consider the different concerns behind the concept. In Section 5.1, composite indicators were developed for measuring the sustainability of urban transport systems in 23 European cities. These composite indicators were able to compile multiple indicators related to different issues in one single index, and therefore serve to measure sustainability.

- ✓ How do we obtain indicative and real figures about sustainability measures to establish goals?

By Comparing real cases. In Sections 5.1, 5.2 and 5.4 the values of indicators for different cities are compared. Therefore, the indicators shown in these sections are useful to establish achievable goals and targets.

- ✓ What factors explain a sustainable urban mobility?

This question can be answered by analysing sustainability indicators for various cities and comparing them with urban characteristics to identify relationships. Section 5.1 provides the correlation coefficients between the characteristics of cities and their sustainability scores; measured by the composite indicators. This serves to identify the explanatory factors of sustainable urban mobility. In addition, a cluster analysis of the 23 cities based on the composite indicators, was used to explore more deeply the role of these factors.

To identify the main urban threats over sustainability in different European cities in order to establish their policy priorities

- ✓ How do we measure the potential and existing problems that constitute the different urban threats to achieve a sustainable development in the context of European cities?

By identifying indicators related to the different problems and trends that conform each threat, and analysing the progress of these indicators. A set of indicators related to the common threats for European cities are applied in Sections 5.2 and 5.3 and used to analyse of four cities. Measuring the evolution of these indicators over time enables the identification of the current and potential problems existing in each city.

- ✓ How do we establish policy priorities accordingly to the main threats in the different cities?

By comparing between different cities the values of indicators related to each threat as well as their evolution. In Section 5.2, this type of comparison analysis enables the identification of the main threats and policy priorities in each of the four cities.

To analyse how certain urban threats can constrain the achievement of city challenges

- ✓ How urban threats constrain the achievement of city challenges?

This question can be answered through a trend-analysis of indicators related to the threats and indicators related to the challenges, in order to identify the synergies among them. In Section 5.4, evolution indicators were calculated for analysing the impacts of urban sprawl and economic decline over the efficiency of urban PT systems. The study, complemented with a cluster analysis, is focused on six Spanish cities and helps to understand the negative effects of both threats over PT efficiency.

3.2. LUTI Models for modelling land use and transport policies

Urban planning needs to respond to the city challenges, which is a complex task due to the uncertainty of future developments (Wegener, 2013). The long-term planning horizon, the wide spectrum of potential policy packages, the need for effective and efficient

implementation, the large geographic scope, and the necessity to consider economic, social, and environmental goals, make policy design and assessment complex and uncertain (Shiftan et al., 2003). According to some authors, LUTI models are “the only available method that deals with an important range of impacts that may arise from planning decisions in land use and transport” (Geurs, Wee and Van, 2004b, p. 334).

LUTI models combine theory, data, and algorithms to simulate the interactions between the two main components of urban areas: the transport and land use subsystems (Torrens, 2000). Both transport and land use variables interact in urban areas at different paces (Abreu e Silva, 2009). Lowry’s Model of Metropolis (Lowry, 1964), is thought to be the first attempt to quantify the land use transport feedback cycle in a single integrated model (Pfaffenbichler, Emberger and Shepherd, 2008). The core assumption of the Lowry model is that regional and urban growth is a function of the expansion of the basic sector. The basic sector is employment that meets non-local demand, producing goods and services which are exported outside the urban area. Employment in the basic sector influences the spatial distribution of the population and service employment. This level of influence is related to transport costs, or the friction of distance. The higher the friction of distance, the closer places of basic and service employment and residential areas are. After the Lowry Model, many spatial interaction location tools were developed to model the location of residents and economic activities as origins and destinations of trips, i.e. METPLAN (Echenique et al., 1990), which is based on INPUT/OUTPUT matrices, or PECAS (Hunt and Abraham, 2005), which is a generalized approach for simulating spatial economic systems.

Other generation of LUTI models do not predict actual spatial interactions but the opportunity for spatial interactions are expressed as accessibility. These LUTI models have diverse theoretical foundation and modelling techniques, but they share the use of an accessibility indicator as one of a critical link between land use and transport system (Wegener, 2004). Compared to the first urban models, which were static equilibrium models, accessibility-based location models tend to be more dynamic, and attempt to capture the dynamics of urban processes (Coppola et al., 2013). There are various examples of these type of models, i.e. INPUD (Wegener, 2011), MUSSA (Martínez, 1996a; 1996b), DELTA (Simmonds, 1999) or MARS (Pfaffenbichler, 2003). Sheperd (Shepherd, 2014) advocated dynamic approaches in LUTI models, since they are suited to the existing time lags and the complex interactions between the transport and the land use systems. This author highlighted the MARS model among others, due to its validation and transferability between cities.

3.2.1 MARS model for the case of Madrid

MARS (Metropolitan Activity Relocation Simulator) model was first developed by Pfaffenbichler (2003) for the city of Vienna. MARS is a LUTI model developed for urban planning which integrates forecasting, assessment and optimisation procedures (May et al., 2003). It has a flexible platform to tailor and modify the conditions of analysis as required by planners and model users (Pfaffenbichler, Emberger and Shepherd, 2008). It is also a Sketch

Planning Model, which is embedded in an assessment and optimisation framework. The core concept of MARS is that it adopts the principles of System Dynamic (Sterman, 2000) and Synergetic (Haken, 1983). In particular it is developed in a system dynamic programming environment, based on the concept of causal loop diagrams and represents the relation of cause and effect of the variables in the model. MARS model can simulate the interaction between land use and transport sub-systems. The model works with a significant level of aggregation and makes long-term assessments. It is important to clarify that MARS model does not include transport networks.

Figure 3.1. Basic structure for MARS model for the case of Madrid
Source: Adapted from (Pfaffenbichler, Emberger and Shepherd, 2008).

Figure 3.1 shows the basic structure of the MARS model, including the required input—the external variables and policy instruments—and output that are a series of performance indicators related to the objectives defined:

- The **external scenarios** are an input of MARS. They include a number of variables in relation to demographic indices, transport data and land use development that can be collected via the local statistic census or mobility survey.
- The **policy instruments** are the policy interventions to be simulated and tested. They serve to define the different policy scenarios and are considered another input of the model. They can be divided into two categories i.e., transport policy measures and land use policy measures. The policy instrument needs to be defined in terms of the year of implementation and duration, geographical scale and intensity.

- In MARS the **transport sub-model** is developed as an alternative to the traditional four stage model. It includes a trip generation sub-model, trip distribution and mode choice sub-model. It works with speed-intensity ratios between different zones (Origin-Destination pairs) instead of a transport network. The sub-model uses the highest possible level of simplification to represent the modes of car, public transport and soft modes, i.e. the network is aggregated to one link per origin-destination (OD) pair.
  - The generation, distribution and modal split influence the **accessibility**, which is an input for the land use sub-model location.
- The **land use sub-model** comprises a module for the location of residents and another for the location of workplaces. The land use modules use in general LOGIT or gravity type models. The ratio of the exponential function value of utilities and disutilities of an alternative to the sum of all alternatives is used to distribute a potential to different locations.
  - The **location of households and workplaces** is an output from the land use sub-model and an input for the transport sub-model, since it affects the attraction and generation of the trips and to the accessibility of each zone.
- The **output** of MARS model is used for the policy **assessment**. The results are provided in terms of indicators that should be related to the objectives.

The MARS model can simulate the cause-effect-relations:

- Between urban sprawl and the transport modal share, for example, urban sprawl leads to longer travel distance, thus increasing the use of the private car and decreasing the share of PT and non-motorized modes;
- Between economic development and travel demand: if the number of consumers increases, the travel demand increases, and vice versa, when travel demand increases, the potential profit increases.

MARS model for the case of Madrid was developed and calibrated first time by Guzmán (2011), who applied it to maximise the welfare of pricing policies (Guzmán, de la Hoz and Monzón, 2014). Later, (Wang, 2014) made some developments in the model, which improved the sensitivity of the model to capture the changes in the accessibility-to-jobs levels produced by transport policies, i.e. (Wang, Monzon and Di Ciommo, 2015).

The MARS model divides the whole region of Madrid into 90 zones (Figure 3.2, page 41). These zones, classified by Guzmán (2011), are homogeneous territories in terms of socioeconomic characteristics and mobility patterns.

- The 90 zones are characterised by features such as the average household size, the number of residents and employees, the motorisation levels and the average income.

- The most important factors for attractiveness of each zone are the green areas, the accessibility and the available number of workplaces.
- The transport modes considered are the car, the slow modes public transport rail modes and buses.
- Two time periods are considered for the trip generation: peak and off peak hours. Similarly, two journey purposes are considered: commuting and other.
- The model works on the basis of more or less inelastic commuting trips and constant time budget.
- The time travelling includes the in-vehicle time, the time searching for a park place, waiting time and transfer time
- Congestion is measured through origin-destination speed flow curves for commuting trips.

Figure 3.2. Zones of MARS model for the case of Madrid

Source: Guzmán (2011)

3.3. Interaction between land use models and indicators

LUTI models depend to a great extent on data, implemented, processed and extracted in the form of indicators (Efthymiou et al., 2014). This data serves to establish baselines, identify trends, predict problems, measure interactions, set performance targets, and evaluate the impacts of policy actions (Geurs, Wee and Van, 2004b). Therefore, indicators play different roles in LUTI models. According to these roles, modelling indicators can be classified into four groups: input indicators, policy strategy indicators, process indicators and output indicators (Romanillos, Alonso and Wang, 2014). The four types of indicators and their role in the MARS model are represented in Figure 3.3.

Figure 3.3. Role of indicators in LUTI models: Scheme for the case of MARS model in Madrid

Source: Adapted from Romanillos, Alonso and Wang (2014)

Input indicator

Input indicators are used to establish the baselines of LUTI models, so that the transport and land use sub-models can simulate trip generation and the spatial allocation of activities (Coppola et al., 2013). The input data in LUTI models determine their reliability and responsiveness (Zondag, 2011). This makes especially important for input indicators to be accessible, transparent and to come from reliable sources. The number of residents per zone, the car ownership or the car speed are examples of input indicators in MARS model (Pfaffenbichler, 2003). The data required for many of these indicators is available in official

statistical sources at different levels and mobility surveys. However, some indicators such as the average speed between different zones and in different zones are generally obtained through other complementary sources, such as disaggregated transport models. New data sources and big data open up new opportunities to obtain high quality input data for urban models (Wilson, 2016).

Policy Strategy indicator

Policy strategy indicators are related to planning decisions that change the conditions of urban development or transport management, e.g. increasing supply of transport services, modifying prices, land use investments or decisions (Hunt and Simmons, 1993). Policy Strategy indicators can be considered as Input indicators, since they are also used to establish the baselines of different scenarios of the model. The definition of policy scenarios is particularly useful to assess the effects policies in the long term (Soria-Lara and Banister, 2017). Increases in PT frequencies and road charges are typical policy measures that are easily measured by means of indicators.

Process indicator

Process indicators measure the changes in the functioning of the land-use or transport system, and they can be understood as intermediate impacts of the different policy scenarios (Geurs, Wee and Van, 2004b). Process indicators are variables computed during the simulation of policy measures and they result in the final impacts outside the land use and transport sub-systems. This type of indicators include the impedances, car speeds, the number of trips distributed per zone, the attracted number of residents and workplaces per zone, etc.

Output indicator

Model output indicators are the final results of a model (Geurs, Wee and Van, 2004b). In LUTI models, the output indicators reflect the impacts of land use development and transport activities of different policies, and they should be related to the objectives (Wang, Monzon and Di Ciommo, 2015). This type of indicators should be comparable, easy to understand, and obviously, they should be relevant to the objectives.

Output indicators from LUTI models are adequate for an integrated assessment of policies, since they measure economic, social and environmental impacts of urban development in different policy scenarios (Geurs, Wee and Van, 2004b). Therefore, output indicators are the best tools to measure the contribution of different policies to address sustainability challenges in cities. This application of output indicators has answered the latest research question raised in the literature review for city challenges, which has been addressed in Section 5.5 in order to arrive at the last research objective.

To measure the potential contribution of land use and transport policies to meet long term city challenges

- ✓ How different land use and transport policies can address urban threats and contribute to meet urban challenges in the long term?

By simulating different policy scenarios through LUTI models to compare the long term effects of policies in the future. In Section 5.5, the MARS model is used to analyse the impacts of three land use and transport policy measures. The policies are assessed through the output indicators of the model. The output indicators used are related to the urban threats, and therefore serve to measure the contribution of the policies to the long term city challenges

3.4. Summary of methodologies and tools to achieve the research objectives

Urban planning and management are complex tasks for policy makers due to a high degree of uncertainty. The long-term planning horizon, the wide spectrum of policy packages, the large geographical scope and the need to consider economic, social and environmental goals make the policy design and assessment tasks very complex (Shiftan, Kaplan and Hakkert, 2003). This immense complexity requires the use of impact analysis tools as well as tools for measuring the achievement of objectives and challenges. Following this approach, two main tools are used in this thesis: Indicators and models. Both tools are combined for meeting the research objectives that have been raised in Chapter 2. Moreover, the development and the different applications of these tools are also important outcomes of the thesis, as they add new value to the field of urban planning and transport management.

The relations between the research objectives, research questions, methodological tools and main applications in the research studies of Chapter 5 are summarised in Table 3.3 (page 45).

Table 3.3. Research objectives, methodological tools and outcomes

Specific research objectives for sustainability challenges in cities	Research questions	Methodological tools developed to answer the research questions	Main application (Research studies- Chapter 5)
To measure sustainability of urban transport systems on a comparative and real basis and to identify the explanatory factors of a sustainable mobility in cities	✓ How do we measure sustainability in urban transport systems as a complex, multidisciplinary and multidimensional concept?	o The Composite indicators are developed to measure sustainability; they compile different concepts into a single index and they are based on comparisons	23 European cities (Cross site analysis- Section 5.1)
	✓ How do we obtain indicative and real figures about sustainability measures to establish goals?	o The values of key indicators in different cities are Compared to obtain real figures which can serve to establish achievable objectives	
	✓ What factors explain a sustainable urban mobility?	- o The factors are identified through the correlations between sustainability scores in cities (Composite Indicators) and their urban characteristics - o The Cluster analysis serves to explore more deeply the role of these factors	
To identify the main urban threats over sustainability in different European cities in order to establish their policy priorities	✓ How do we measure the potential and existing problems that constitute the different urban threats to achieve a sustainable development in European cities?	- o Measuring the progress of indicators related to the common threats allows identifying the current and potential problems in cities - o The comparison of these indicators among cities helps to establish policy priorities in each city	4 European cities (Trend-analysis- Sections 5.2 and 5.3)
	✓ How do we establish policy priorities accordingly to the main threats in the different cities?		
To analyse how certain urban threats can constrain the achievement of city challenges	✓ How urban threats constrain the achievement of city challenges?	- o The Evolution indicators are calculated for each threat and challenge, in order to analyse the synergies between them - o The cluster analysis helps to understand the results	6 Spanish cities (Trend-analysis- Section 5.4)
To measure the potential contribution of land use and transport policies to meet long term city challenges	✓ How different land use and transport policies can address urban threats and contribute to meet urban challenges in the long term?	- o The LUTI model MARS is used to simulate the long term impacts of land use and policy measures in the future - o The contribution to the city challenges is assessed through the output indicators of the model. These output indicators are linked to the threats.	Madrid Region (Analysis of future trends- Section 5.5)

4. Urban data for policy assessment

Chapter 4 is a summary of the key issues regarding the data used in the analyses of Chapter 5: the main databases and the role of stakeholders to validate the data for policy assessment. This thesis has been developed in the frame of two main research initiatives on which the authors of the thesis have collaborated. Both initiatives are related to the data used in the policy assessments:

- The Metropolitan Mobility Observatory (MMO, 2017).

The MMO is an initiative of analysis and reflection, comprised by the Public Transport Authorities (PTA) of the main Spanish metropolitan areas and other Spanish government institutions. This initiative—currently active—was launched in 2002 to reflect the contribution of public transport to improve the quality of life and sustainable development in cities. The MMO publishes an annual report analysing the mobility of the participating urban areas through data provided by the PTA.

- The project INSIGHT- 7th FP EC (INSIGHT, 2017)

INSIGHT (*Innovative Policy Modelling and Governance Tools for Sustainable Post-Crisis Urban Development*) is a research project developed between 2013 and 2016 under the ICT Theme of the European Union Seventh Framework Programme. The main objective of the project was to investigate how urban data and models can help European cities formulate and evaluate policies to stimulate a balanced economic recovery and a sustainable urban development.

Both the MMO and INSIGHT project have been fundamental for the development of the thesis, which is the result of the main contributions of the authors to both initiatives. The MMO has been an important data source for carrying out the research analyses in Chapter 5, and especially the analyses in Sections 5.1 and 5.4. The INSIGHT project has been an adequate work environment, where stakeholders participated giving their feedback. During the project, the identified urban threats and challenges, the research tools developed (indicators and models), and even the land use and transport policies tested, were assessed by city managers and experts in urban planning. Therefore, the methodology and objectives of the thesis have been validated by stakeholders in the topic, particularly as regards to the research studies from Sections 5.2, 5.3 and 5.5.

4.1. Main databases for analysing cities

The five research studies presented in the main body of the thesis (Chapter 5) required data. Apart from the MMO, various common data sources have provided the necessary information for the different analyses. In this section, the most important ones are described.

4.1.1 Observatories on urban transport: EMTA and MMO

At the European level there are two associations of Public Transport Authorities (PTA) that provide and analyse information on urban transport and mobility in cities:

- European Mobility Transport Authorities (EMTA, 2013)

The EMTA was created in 1998, to exchange information and best practices between public authorities responsible for planning, integrating and financing public transport services in European cities. The EMTA annually publishes a Barometer, which contains indicators for analysing the main characteristics of the urban transport systems in the participant cities. The platform currently comprises 26 PTAs, and the last barometer included information on 25 cities (EMTA, 2017).

The annual EMTA barometers were important data sources for the analysis of European cities, especially in the case of cities outside Spain: Paris, London, Stockholm, Amsterdam, and Rotterdam, which are case studies of Sections 5.1, 5.2 and 5.3.

- The Metropolitan Mobility Observatory (MMO)

The MMO initiative, which has been described in the introductory part of this chapter, can be considered as a counterpart of the EMTA association at a smaller and national scale. The MMO actually comprises 23 Spanish PTAs, and the last report contained information on 19 cities (Monzón et al., 2016).

The MMO database was fundamental for the research studies carried out in the thesis, especially in Sections 5.1 and 5.4, as it has provided information on the Spanish analysed cities: Madrid, Barcelona, Valencia, Murcia, Seville, Asturias, Malaga, Majorca, Gran Canaria, Cadiz, Saragossa, Gipuzkoa, Tarragona, Granada, Alicante, Pamplona, Girona, Corunna and Leon.

4.1.2 Statistical databases on cities

At the international level, various institutions have made an effort to compile homogeneous statistical information that can be used to compare cities. In this thesis, two databases on cities were mainly consulted to collect general information about the urban areas for the analyses:

- Organization for Economic Cooperation and Development (OECD, 2012)

The OECD provides general information on demography, environment, labour market, economy and inequalities of the main cities from countries around the world.

- Urban Audit- EUROSTAT

Urban Audit (2017) is a EUROSTAT database containing information on most European cities. Urban audit provides detailed information on a wide variety of topics: population structure, living conditions, education, labour market, transport, environment, economy and finance.

The OECD and Urban audit databases have been important sources of information, especially for the research work carried out in Section 5.2, which includes an analysis of the common threats for European cities. Both data sources contain diverse and varied information on urban areas, and this was very useful for Section 5.2, which focused on urban problems from a general perspective, and not only from a transport and land use perspective.

4.1.3 Statistical sources

The statistical offices constitute the third type of data source fundamental for the development of the thesis:

- Instituto Nacional de Estadística (INE, 2017): The Spanish Statistical Office, which contains detailed information for the different Spanish regions
- ALMUDENA (2017) and DESVAN (2017): Statistical Databases for Madrid Region
- Ayuntamiento de Madrid (2017): Statistical Database of Madrid City Council

These statistical sources contain detailed and specific information on Madrid, which is the main case study of the thesis. This information was essential for the analyses carried out in Sections 5.3 and 5.5, which are focused on the case of Madrid and required data at a disaggregated level.

4.2. Role of stakeholders: data validation

Ten experts in urban planning and policy making in European cities played a role in the development of this thesis through their participation in the INSIGHT project, which was introduced at the beginning of this chapter. These stakeholders were selected by the project consortium for their expertise in the field, and took part in the project as external advisors, participating in two ways. Firstly, they participated in a survey carried out by García et al. (2014). The results of this survey served to identify the main areas of interest and to focus the research studies. Secondly, some of them attended to various meetings and workshops held during the project. In both activities, the theoretical framework (threats and problems) and the tools (indicators and models) developed by the authors of the thesis during the project, were assessed by the stakeholders, who gave their feedback to improve the outcomes. Therefore, the approach, objectives and outcomes of the thesis were developed with the support and the advice of experts in urban planning.

The main results of the stakeholders survey carried out by Garcia et al (2014) regarding the thesis are summarised in the paragraphs below.

The stakeholders participating in the survey were from nine different countries and ten different cities: Stockholm (Sweden), Aarhus (Denmark), Oslo (Norway), Madrid and Barcelona (Spain), Thessaloniki (Greece), Bergamo (Italy), Vienna (Austria), Brussels (Belgium), and Rotterdam (Netherlands). All of them worked in urban planning at different departments in their cities or regions.

The stakeholders were asked to select the most important sustainability objectives related to the main challenges and threats defined in the literature review in Chapter 2. Ten sustainability objectives or city challenges, together with a set of indicators related to each objective were defined by the authors of this thesis. Stakeholders had to select a maximum of 4 main objectives, and give their opinion on the relevance of the indicators. Only those indicators considered valid by at least 5 stakeholders were applied and used in the thesis. The results of this consultation process are presented in Tables 4.1 and 4.2.

Table 4.1. Stakeholders assessment of challenges for cities as efficient systems

Sustainability objectives- City Challenges	Importance for stakeholders	Indicators	Validation (no. of stakeholders validating the indicator out of 10)
Economic activity	Essential (selected by 6 out of 10 stakeholders)	Household budget	Valid for 9 stakeholders
		GDP	
		Unemployment rate	Valid for 9 stakeholders
		Job creation	Valid for all stakeholders
		Land prices	Valid for 7 stakeholders
Economic efficiency	Little importance (Selected by 2 out of 10 stakeholders)	Unoccupied flats or buildings	Valid for all stakeholders
		Congestion levels	Valid for 7 stakeholders
		Time spent travelling	
Energy efficiency	Very important (selected by 5 out of 10 stakeholders)	Energy consumption	Valid for all stakeholders
		Share of energy consumption by sector (transport, industry, residential, services...)	Valid for all stakeholders
		Share of energy consumption from renewable sources	Valid for all stakeholders
		Fuel dependence	
Urban sprawl	Important (selected by 4 out of 10 stakeholders)	Urban density	Valid for all stakeholders
		Land occupied by infrastructures	Valid for 7 stakeholders
		Share of the metropolitan area population living in the main city	Valid for 8 stakeholders

Table 4.2. Stakeholders assessment of challenges for cities as living environments

Sustainability objectives- City Challenges	Importance for stakeholders (no. of stakeholders selecting the challenge as a main one- maximum 4)	Indicators	Validation (no. of stakeholders validating the indicator out of 10)
Liveable streets and neighbours	Very important (selected by 5 out of 10 stakeholders)	Pedestrians & cyclists injured in traffic accidents	Valid for 6 stakeholders
		Space for pedestrian use	Valid for all stakeholders
		Length of bicycle lanes	Valid for all stakeholders
		Road land occupation	Valid for 7 stakeholders
		Green areas	Valid for all stakeholders
Equal, safe and secure society	Neutral (Selected by 3 out of 10 stakeholders)	Use and coverage of PT	Valid for all stakeholders
		Income inequality	Valid for 7 stakeholders
		Share of the household budget devoted to main needs	
		Essential services provision in each zone (health, educational and social services)	Valid for all stakeholders
		Traffic accidents with casualties	Valid for 5 stakeholders
		Fatalities occurred in traffic accidents	Valid for 5 stakeholders
		Crime	Valid for 5 stakeholders
Pollution	Very important (selected by 5 out of 10 stakeholders)	Rate of diseases potentially related to air pollution	Valid for 7 stakeholders
		Air concentration of NOx and particles	Valid for 7 stakeholders
		Emissions of NOx and particles	Valid for 9 stakeholders
	Unimportant (selected by 0 out of 10 stakeholders)	Noise intensity levels	Valid for 5 stakeholders
		Population declaring noise problems	Valid for all stakeholders
Climate Change	Important (selected by 4 out of 10 stakeholders)	Greenhouse gases emissions	Valid for 8 stakeholders
		Share of Greenhouse gases emissions per sector	Valid for 9 stakeholders
Demographic decline	Unimportant (selected by 0 out of 10 stakeholders)	Share of active population	Valid for 9 stakeholders
		Share of population over 60 years	Valid for 8 stakeholders
		Share of population under 25 years	Valid for 9 stakeholders
		Skilled workers and migration tendencies	Valid for 9 stakeholders
Education and culture	Little importance (selected by 0 out of 10 stakeholders)	Drop-out rates from secondary education	Valid for 9 stakeholders
		Cultural offer (museums, cinema, etc.)	Valid for all stakeholders

This set of indicators is used in Sections 5.2 and 5.3 to identify the main threats and policy priorities in four European cities. In addition, in Section 5.5, these indicators are also used to analyse the contribution of three land use and transport policies to the city challenges in the Region of Madrid. Regarding the challenges, the stakeholders assessment revealed important objectives: those related to economy, energy efficiency, urban sprawl, liveability, pollution and climate change. All these objectives are considered in Section 5.5 in the policy assessment. Finally, in Section 5.4 special attention was given to the issues of sprawl and economic decline.

5. Moving towards sustainability in cities

Chapter 5 is divided into five sections, which contain different research studies developed to answer the research objectives that emerged from the general literature review in Chapter 2. These sections present different analysis at different geographical scales, depending on the level of detail required in each analysis. Some analyses were made at the European level; others are focused in Spanish cities; and the last one is focused in Madrid Region.

All the research studies from Chapter 5 contain their own introduction, state of the art, description of the methodology, results and specific conclusions. Beyond this, Chapters 2 and 3 provide a general review of the literature on urban planning and the main research tools applied in the thesis, and Chapter 5 highlights the general conclusions.

Figure 5.1 presents the structure in relation to the city cycle and the main characteristics of each research study, which are briefly described below:

- The need to achieve a sustainable urban development shows the importance of a sustainable mobility in cities. In Section 5.1, the sustainability of urban transport systems was analysed in 23 European cities through indicators. The cities are classified according to their sustainability scores, and the main characteristics that influence sustainability are determined.
- The literature on urban development highlights some general threats over sustainability in European cities: demographic decline, social segregation, environmental depletion, urban sprawl and economic decline. However, each city faces specific problems and trends, and should establish policy priorities according to these problems and trends. In Sections 5.2 and 5.3 the main threats over sustainability are determined in four European cities. For this objective, indicators to measure the evolution of the current and potential problems are analysed.
- Among the general threats in European cities, there are two which have negative effects over the efficiency of urban systems and services: urban sprawl and economic decline. In Section 5.4, the impacts of suburbanisation and economic crisis over the PT systems in six Spanish cities are measured through evolution indicators
- Given that urban mobility and development are essential to achieve sustainable cities, transport and land use policies can help to face the sustainability city challenges in cities. In this regard, Section 5.5 presents an analysis of the contribution of three land use and transport policies—cordon toll, teleworking and re-densification—to address the city challenges in the Region of Madrid. The policies are simulated with a LUTI model, and the impacts measured through assessment indicators.

Figure 5.1. Structure of the research studies carried out in each section of Chapter 5

5.1. Comparative analysis of passenger transport sustainability in European cities

The need to achieve a sustainable urban development points out the importance of sustainable mobility in cities. In Section 5.1, the sustainability of urban transport systems was measured through composite indicators. The methodology was applied to 23 European cities and enabled the identification of the factors that explain sustainable mobility. Figure 5.2 shows the role of this analysis in the structure of the thesis and the policy cycle.

This research study was published in the scientific journal *Ecological Indicators* (Impact Factor 2015: 3.190), from Elsevier.

Figure 5.2. Policy issues analysed in Section 5.1 within the structure of the thesis

Comparative analysis of passenger transport sustainability in European cities

Andrea Alonso^{a,*}, Andrés Monzón^b, Rocío Cascajo^a

^a TRANSyT – Transport Research Centre, Universidad Politécnica de Madrid, Calle Profesor Aranguren s/n, 28040 Madrid, Spain

^b Transport – Civil Engineering Department, Universidad Politécnica de Madrid, Calle Profesor Aranguren s/n, 28040 Madrid, Spain

ARTICLE INFO

Article history:

Received 12 February 2014

Received in revised form 9 September 2014

Accepted 14 September 2014

Keywords:

Urban transport

Sustainable management

Composite indicators

ABSTRACT

Sustainable development in its three dimensions – economic, social and environmental – has become a major concern on an international scale. The problem is global, but must be solved locally. Most of the world's population lives in cities that act as centres of economic growth and productivity, but which – if they develop in the wrong direction – can cause social inequalities, or irreversibly harm the environment. Urban transport causes a number of negative impacts that can affect sustainability targets. The objective of this study is to propose an analysis of sustainability of urban passenger transport systems based on available indicators in most cities. This will serve to benchmark the practices of different cities and manage their transport systems. This work involves the creation of composite indicators (CI) to measure the sustainability of urban passenger transport systems. The methodology is applied to 23 European cities. The indicators are based on a benchmarking approach, and the evaluation of each aspect in each case therefore depends on the performance of the whole sample. The CI enabled us to identify which characteristics have the greatest influence on the sustainability of a city's transport system, and to establish transport policies that could potentially improve its shortcomings. Finally, the cities are clustered according to the values obtained from the CIs, and thus according to the weaknesses and strengths of their transport systems.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Concern about the evolution of human settlements and the unavoidable effects of social development on the environment were first viewed by the global community as comprising three main dimensions – economic, social and environmental – at the Conference on the Human Environment in Stockholm (United Nations, 1972), which marked the earliest definition of the basis of sustainability. The conclusions included the need to safeguard and improve the human environment for present and future generations as a goal to be pursued together with worldwide economic and social development. Since the declaration of these principles, sustainability has become a major concern for decision makers and management stakeholders (Newman and Kenworthy, 1999; Jeon and Amekudzi, 2005; Haghsheenas and Vaziri, 2012).

Abbreviations: CI, composite indicators; EMTA, European Metropolitan Transport Authorities; MMO, Metropolitan Mobility Observatory (Spain); PT, public transport; PTA, Public Transport Authorities.

* Corresponding author. Tel.: +34 91 336 52 34.

E-mail addresses: andrea.alonso@upm.es, alonsoramos.andrea@gmail.com (A. Alonso), andres.monzon@upm.es (A. Monzón), rocio.cascajo@upm.es (R. Cascajo).

This sustainable development must be applied to cities on a global basis, as they play a key role in our society. Cities are important generators of wealth, employment and productivity, and often serve as the engines of their national economies (OECD, 2013). According to the Green Paper, just under 85% of the EU's gross domestic product is created in urban areas, which are home to over 60% of the population (European Commission, 2007). Analyses of the challenges facing cities in their efforts to achieve a more sustainable development invariably give a high priority to the problems of mobility and access (Newman and Kenworthy, 1999; UNECE, 2011). At the urban level, where transport problems are more acute and concentrated, achieving a sustainable form of mobility is a prerequisite for improving the environment – including social aspects –, and enhancing economic viability (European Commission, 1996). Some problems in meeting this challenge were raised in the EU 2011 White Paper on transport, namely congestion and its consequences on delays – and thus on the economy –, noise, air pollution, GHG emissions, impacts on land or accidents (European Commission, 2011).

Urban transport therefore has several negative impacts that can hinder the achievement of sustainability targets. According to TERM (2000), these can be prevented by identifying key indicators that can be tracked and compared with concrete policy objectives,

based on the premise: “You can’t manage what you can’t measure”. Within this framework, the aim of this research is to identify practical indicators to analyse the economic, social and environmental sustainability of urban passenger transport systems. This would help to manage the different aspects of sustainability from a comprehensive point of view and would also make it easier to benchmark one city’s performance against another’s. The first section of the paper explains the process for selecting the indicators and the cities in the analysis. The next section contains the methodologies used to compile, compare and classify the chosen indicators, in order to analyse different sustainability aspects of urban passenger transport systems in the 23 European cities selected. The final sections include the results of the analysis and some conclusions.

2. Measuring sustainability using indicators

There is a common consensus as to the usefulness of indicators to highlight the many overlapping areas of sustainability, and the need to achieve sustainable urban transport systems has been largely discussed (TERM, 2000; Newman and Kenworthy, 1999). But before selecting the appropriate indicators for measuring sustainable transport, we should rely on an established definition. We have therefore, selected a definition supported by international institutions (Council of the European Union, 2001; OECD, 2001). According to this definition, a sustainable transport system should be analysed from three different dimensions:

- Economic: affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development,
- Social: allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations
- Environmental: limits emissions and waste within the planet’s ability to absorb them, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise.

There are some authors that propose other dimensions of sustainability (Holden et al., 2013) according to different approaches of the Brundtland Report (WCED, 1987). In this paper we have chosen the above mentioned definition that has been used in many studies in the field of urban passenger transport (Miranda and Rodrigues da Silva, 2012; Haghsheenas and Vaziri, 2012). However most of the aspects included in any of the approaches are common although they are structured in different way.

2.1. Literature review

In order to select which indicators were more appropriate to assess sustainability of urban passenger transport systems, a literature review of several initiatives with similar scope was carried out. This section summarises this literature review in regard to the indicators used. The indicators selected should as far as possible incorporate all the aspects mentioned in the chosen definition of sustainable transport systems.

Some authors consider sustainable transportation indicators as decision-making tools which should reflect economic, social and environmental impacts (Litman, 2009), while others (Nicolas et al., 2003) focus their indicators on the issues raised by urban resident mobility and consider surveys of household trips as a highly valuable data source. Here it is worth noting the study carried out by Jeon and Amekudzi (2005), who characterised the emergent thinking on what constitutes urban transportation sustainability

and how to measure it in their collection and classification of indicators used by 16 international institutions – mainly relating to planning and infrastructure provision. Finally, other approaches have focused their analysis on the assessment of policies, in terms of efficiency and equitable functioning (Savelson et al., 2006; Zito and Salvo, 2011).

As a result of this literature review, Table 1 shows the most commonly used indicators directly related to urban transport sustainability, we have classified them into three dimensions – economic, social and environmental. There is a greater range of indicators in the social and environmental than in the economic category. The most frequently applied indicator for measuring social sustainability is the number of transport fatalities; for environmental sustainability it is land consumption of transport infrastructures; and for the economic aspect user transport costs and public expenditure.

The aim of this review was to identify significant indicators for measuring sustainability in order to choose appropriate and available indicators from our sources which are described below.

2.2. Data collection

The research to develop a group of indicators in and to analyse the different dimensions of sustainability regarding urban passenger transport, was initially focused in Spanish cities, due to the existence of a homogeneous database with a sufficient number of cities. In order to achieve a wider scope for comparison, and to avoid an overly biased analysis – referring only to cities in southern Europe – we decided to include other cities from central and northern Europe.

2.2.1. Main data sources

At the European level there are two associations that collect and publish urban transport information from a representative group of cities¹ and promote the exchange of information and good practices in the field of public transport organisation, planning and funding. The Metropolitan Mobility Observatory (MMO, 2014) is a platform comprising 24 public transport authorities (PTA) in the main Spanish cities. The European Metropolitan Transport Authorities (EMTA, 2014) is an association whose members are the bodies responsible for public transport in 28 European cities. Both publish reports analysing the mobility patterns of the participating cities, using indicators. These reports were the main sources for our research; the year of reference for the analysis was 2010 (Monzón et al., 2012; EMTA, 2012a,b).

For the analysis, we selected 18 of the 24 cities in the MMO – those that had sufficient information available for the scope of the study. As the MMO is a national observatory, all of them were Spanish. For a wider scope, the cities to include from central and northern Europe needed to be from different countries and to have enough information on them available. Four cities with these criteria were selected from the EMTA report: Paris, London, Stockholm and Amsterdam. The rest were discarded, mainly due to lack of key data.

While Paris and London were notable for being the most populated cities (>7 mill. inhab.) in the EMTA association, Amsterdam (1.4 mill. inhab.) was characterized by having the highest modal share of non-motorised modes (56%), and Stockholm (2 mill. inhab.) for having the highest ticket prices. All these differences could through up interesting conclusions in the

¹ In this context, the term “city” refers to the urban geographical area in which there is a high degree of interaction between its urban centres in terms of trips, relationships and economic activity. This concept is often called the Metropolitan Area (MMO, 2014; EMTA, 2014).

Table 1
Review of indicators for measuring transport sustainability.

Sustainability dimension	Indicators	Authors	Sustainability aspects according to the definition										
			Newman and Kenworthy (1999)	Nicolas et al. (2003)	Jeon and Amekudzi (2005)	Zegras (2006)	Savelson et al. (2006)	Zhang and Guindon (2006)	Litman (2009)	Tanguay et al. (2010)	Zito and Salvo (2011)	Haghshenas and Vaziri (2012)	Santos and Ribeiro (2013)
Economic	Coverage ratio of public transport	X		X			X	X			X		
	Public expenditure on transit		X	X		X	X			X		X	
	Time spent		X	X	X								
	Congestion		X	X									
Social	Costs of transport for users		X	X		X		X			X	X	
	Transport fatalities per inhabitant	X		X	X	X	X	X	X	X	X	X	
	Accidents			X	X	X	X		X			X	
	Distance travelled		X			X	X		X				
	Motorisation rate/% of car-owning households		X			X	X		X				
	Density of public transport network							X					
	Quality of public transport		X	X	X								
	Affordability of public transport by lower income residents			X	X	X		X	X				
	% of residents with public transit service within 500 metres			X		X				X		X	
	Quality of accessibility for people with disabilities		X	X				X					
	Vehicle-km per capita	X				X							
	Environmental	Non-motorised modal share	X				X	X	X				X
Parking spaces in city centre		X	X										
Land consumption of transport infrastructures			X	X	X	X	X	X		X	X	X	
Length of cycleway		X				X				X			
Length of pedestrian streets		X				X	X	X					
Energy consumption			X	X		X							
Emissions			X	X		X		X			X	X	
Levels of CO, NOx, hydrocarbons and particles			X	X	X					X	X	X	
Noise intensity levels			X	X	X								
			X	X	X		X						

Table 2

Cities included in the analysis.

Population	City	Country
>5 mill. inhab.	1	Paris
	2	London
	3	Madrid
	4	Barcelona
5–1.5 mill. inhab.	5	Stockholm
	6	Valencia
	7	Murcia
	8	Seville
	9	Amsterdam
1.5–1 mill. inhab.	10	Bilbao
	11	Asturias
	12	Malaga
	13	Majorca
1–0.5 mill. inhab.	14	Gran Canaria
	15	Cadiz
	16	Saragossa
	17	Gipuzkoa
	18	Tarragona
	19	Granada
	20	Pamplona
	21	Girona
	22	Corunna
	23	Leon

Map 1. Geographical location of the Spanish cities included in the analysis

comparative analysis. Table 2 shows all the cities analysed in this research. The final sample was therefore composed of 23 cities. Although this sample is rather small from a statistical point of view, it is fairly homogeneous and comparable, and produced conclusions that were very logical and adapted to the context. It also allowed us to check the consistency of the data sets and calculate several specific indicators that were unavailable from common sources for all the cases, for example by consulting the websites of certain Public Transport Authorities.

2.2.2. Other required data and their sources

Not all the necessary information was collected from the OMM and EMTA reports. Data on accidents in cities was supplied by official reports, in most cases by government institutions in charge of road safety.² Information on fare discounts for students on public transport had to be checked and supplemented with

information on PTA webpages.³ The most recent data on length of urban roads per area for Spanish and European cities, dating from 1998 to 1999, was collected from other sources.⁴ It was assumed that the length of urban streets and roads has not changed significantly since then. This approach is considered admissible, given the fact that the length of the road network in established urban areas appears to be relatively constant (Farahani et al., 2013).

The data from all the above sources were compared with the information used to build the indicators collected originally. The last column in Tables 3–5 shows the availability of data for each indicator, and therefore the indicators that could be used in the study.

2.3. Indicators selection

The first step of the research was to summarise each sustainability dimension in one single indicator. But sustainability

² Ministerio del Interior-Dirección General de Tráfico (2010); TfL (2010a); Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer (2010); Stockholm Stad-trafikkontoret (2009); Reurings et al. (2012); Bizkaiko Foru Aldundia (2010).

³ TUZSA (2010); TFG (2010); Empresa Municipal de Transportes Públicos de Tarragona S.A (2010); Ayuntamiento de A Coruña (2010); TfL (2010b); RATP (2010).

⁴ For Spanish case studies: Ministerio de Fomento (1998); for the rest: Newman and Kenworthy (1999).

is a multidisciplinary concept: economic sustainability may refer to productivity, public expenditures or affordability for users; social sustainability may involve safety, accessibility or equity; and environmental sustainability may refer to energy, pollution or land occupation. The indicator for each sustainability dimension must therefore be composed of several indicators in order to reflect all possible aspects of the sustainability dimensions.

However, if the indicators are also intended to be used for management, they must be able to support decision making geared to sustainability objectives, and be capable of measuring policy impacts (Newman and Kenworthy, 1999; Gudmundsson, 2003). Several studies have analysed the requirements that indicators must fulfil to meet this challenge. May et al. (2008) defined these requirements based on surveys of decision makers and other stakeholders in the transport planning sector; according to the results, indicators must be easy to understand and sensitive enough to reveal changes affecting sustainability targets. Jourmard and Gudmundsson (2010) added more criteria for assessing indicator selection:

- Target relevance: each indicator must be related to one aspect of sustainable transportation.
- Validity: indicators must measure the aspect they are supposed to measure.
- Values for calculations should be unambiguous and should not depend on interpretations.
- Data should be available and measurable, and the source must be reliable.

Subsequently, Haghshenas and Vaziri (2012) added that indicators should be able to be standardised by city size.

The most suitable indicators were selected following these guidelines, which can be summarised in seven basic requirements. Tables 3–5 show how far the indicators collected in the literature review meet these requirements. The indicators finally selected (Tables 3–5, first column) fulfil the seven requirements.

For the economic dimension (Table 3), the selected indicators were coverage ratio of public transport, average time spent travelling per user and cost of transport to users, reflecting costs to public authorities per user, productivity losses and user costs. Although the overall public expenditures on transit was also available, it is strongly dependent on city size, and may vary depending on interpretations.

The most appropriate social related indicators (Table 4) were number of transport fatalities per inhabitant, density of the public transport network and discounts on public transport fares for seniors and students, for the purpose of measuring safety, accessibility and equity. In the safety indicators, the number of accidents was also available, but is more ambiguous than the number of fatalities, as it depends on the reporting rate and the definition of an accident, which may vary from country to country. The indicator measuring accessibility to public services for the disabled was discarded as it depended on interpretation, in some cases it referred to stations or stops, and in others to vehicles.

The only suitable indicators for the environmental dimension (Table 5) were land consumption of transport infrastructures, energy consumption, and emissions produced by public transport modes per user. The share of non-motorised transport modes was not considered a suitable indicator as it is not a direct measure of the quantity of emissions, energy or noise, although the increase in the use of soft modes point to a reduction in them. Finally, air and noise pollution levels are not solely the result of urban mobility (Nicolas et al., 2003; Smith et al., 2013), and are therefore

unsuitable for measuring environmental urban transport sustainability (Nicolas et al., 2003).

The indicators finally selected are listed and formulated in Table 6.

In summary, the selection process was methodical and involved several steps. First, we carried out a review of the literature on urban transport indicators for measuring sustainability; this produced a list of indicators that are generally accepted by the scientific community and could be used for our objective. Secondly, the suitability of the indicators for management purposes was evaluated. Three indicators were available in the sources for each sustainability dimension and considered to be appropriate. These indicators were therefore selected to be compiled into a single indicator for each dimension.

3. Methodological procedure for the analysis

After describing the indicators to measure urban transport sustainability, in this section we present the methodology followed to analyse and compare urban transport sustainability in the selected cities. First, we compiled the selected indicators in one single index for each sustainability dimension and each city. These indexes are called composite indicators (CI), and are based on a benchmark approach, namely on the comparison between cases; values for each city therefore depend on the average performance of the rest. Second, we identified which characteristics contribute most to achieving a sustainable urban transport system. In this step, existing correlations between sustainability scores (CI-values) for all cities and other variables such as size, wealth or modal share, were explored by analysing Pearson correlation coefficients. Finally, we cluster the cities according to how close their transport systems are to being economically, socially and environmentally sustainable, using the CIs as classification variables.

3.1. Sustainable composite indicators

Composite indicators (CIs) can be used to summarise complex or multi-dimensional issues in order to support decision makers as they provide a big picture, and can be easier to interpret than trying to find a trend in many separate indicators (Saisana and Tarantola, 2002). CIs are increasingly being recognised as a useful tool in policy analysis, as they can provide simple comparisons of cities that can be used to illustrate complex and sometimes elusive issues in wide-ranging fields, e.g. environment, economy, society or technological development. CIs are easier to interpret and have proven useful in benchmarking different performances (Nardo et al., 2005).

A report by the EC-Joint Research Centre (Saisana and Tarantola, 2002) recommends appropriate treatments and normalisations for obtaining composite indicators. Before computing a composite indicator, the sub-indicators must be normalised (all transformed into the same unit). Five methods are proposed in the report. Three of them are based on rankings, this has the advantage of simplicity, but we discarded them because they imply a loss of absolute level information. The other two are explained below.

The standardised values method has been very widely used (Saisana and Tarantola, 2002; World Economic Forum, 2001; Haghshenas and Vaziri, 2012). The CI is based on the standardised scores for each indicator which equals the difference in the indicator for each city and the mean for the whole sample, divided by the standard error. This method is sensitive to outliers, as the range between the minimum and maximum observed standardised scores will vary for each indicator. In this context, this sensitiveness is desirable: the method gives greater weight to an

Table 3

Indicator requirements for measuring the efficiency of transport management. Economy.

Economic dimension- Indicators								
Selected indicators	Requirements Indicators (most common unit of measure)	Target relevance Each indicator must show one aspect of sustainability (Journard and Gudmundsson ,2010) (Haghsheenas and Vaziri , 2012)	Standardized Indicators should be standardized by city size for comparison (Haghsheenas and Vaziri , 2012)	Validity Indicators must actually measure the issue it is supposed to measure (Journard and Gudmundsson ,2010) (Haghsheenas and Vaziri , 2012)	Transparency Easy to understand (Journard and Gudmundsson ,2010) (Haghsheenas and Vaziri , 2012) (May et al., 2008).	Sensitivity Able to reveal cities sustainable transport changes (Journard and Gudmundsson ,2010) (May et al., 2008)	Unambiguous Do not depend on interpretations (Journard and Gudmundsson ,2010)	Data available, measurable and reliable in the data base (May et al., 2008). (Journard and Gudmundsson ,2010)
X	Coverage ratio of public transport (%)	Public costs per user	YES	YES	YES	YES	YES	YES
	Public expenditure on transit (currency units)	Overall public spending	NO	YES	YES	YES	NO	YES
X	Time spent (min per person per day)	Productivity losses	YES	YES	YES	YES	YES	YES
	Congestion (overall hours lost)		NO	YES	YES	YES	NO	NO
X	Costs of transport for users (currency units per person per day)	User costs	YES	YES	YES	YES	YES	YES

Table 4

Indicator requirements for measuring the efficiency of transport management. Society.

Social dimension- Indicators								
Selected Ind.	Requirements Indicators (most common unit of measure)	Target relevance	Standardized	Validity	Transparency	Sensitivity	Unambiguous	Data available, measurable and reliable
X	Transport fatalities per inhabitant (fatalities per inhabitant)	Safety	YES	YES	YES	YES	YES	YES
	Accidents (accidents per inhabitant)		YES	YES	YES	YES	YES (but it is more ambiguous than no of fatalities)	YES
	Distance travelled (km per person per day)	Facility for users to reach their needs	YES	YES	YES	NO (it is more likely to reveal sustainable land use changes)	NO (usually estimated by users)	NO
	Motorisation rate (no of cars per 1.000 inhabitants)	Car availability	YES	YES	YES	NO (sustainability is more related to car use than car availability)	YES	YES
X	Density of public transport network (km of PT network per area)	Accessibility of PT and supply range	YES	YES	YES	YES	YES	YES
	Quality of public transport (users scores)	Quality of PT	YES	YES	NO	YES	NO	NO
X	Affordability of public transport by lower income residents (costs of transport for users divided by lower incomes or % of discounts for lower income users)	Equity	YES	YES	YES	YES	YES	YES
	Residents with public transit service within 500 metres (%)	Physical accessibility to PT	YES	YES	YES	YES	YES	NO
	Quality of accessibility for people with disabilities (% of services accessible to the disabled)	Physical accessibility to PT for disabled	YES	YES	YES	YES	NO (services include vehicles, stations, stops...)	YES

Table 5

Indicator requirements for measuring the efficiency of transport management. Environment.

Environmental dimension- Indicators								
Selected Ind.	Requirements Indicators (most common unit of measure)	Target relevance	Standardized	Validity	Transparency	Sensitivity	Unambiguous	Data available, measurable and reliable
	Vehicle-km per capita (vehicle-km per inhabitant)	Emissions, energy and noise due to motorised transport	YES	YES	YES	YES	YES	NO
	Non-motorised modal share (% of total trips)		YES	NO (although increasing the use of soft modes is assumed to cause a reduction in these impacts, it is not a direct measure)	YES	YES	YES	YES
	Parking spaces in city centre (number)	Land distribution	NO	YES	YES	YES	YES	YES
X	Land consumption of transport infrastructures (km ² of road network per area)		YES	YES	YES	YES	YES	YES
	Length of cycleway (km)		NO	YES	YES	YES	YES	YES
	Length of pedestrian streets (km)		NO	YES	YES	YES	YES	NO
X	Energy consumption (energy units per traveller)	Energy efficiency	YES	YES	YES	YES	YES	Only for PT
X	Emissions (mass units per traveller)	Air pollution due to motorised transport	YES	YES	YES	YES	YES	Only for PT
	Levels of CO, NOx, hydrocarbons and particles (air concentration)		YES	NO (air and acoustic pollution are not only due to transportation)	YES	YES	YES	YES
	Noise intensity levels (sound units)	Acoustic pollution due to motorised transport	YES		YES	YES	YES	NO

indicator in cities with extreme values.

$$CI_{D,c} = \frac{\sum_{i=1}^n w_i \times y_{ic}}{\sum_{i=1}^n |w_i|}, \text{ where } y_{ic} = \frac{x_{ic} - \bar{x}_i}{\sigma_i} \quad (1)$$

$CI_{D,c}$ is the composite indicator related to the dimension of sustainability D (economic, social or environmental), for the city c. n is the total number of indicators included in the composite indicator ($n=3$).

w_i is the weight given to indicator in the composite index. x_{ic} is the value of the indicator i for the city c . $\bar{x}_i$ and σ_i are the mean and the standard error of indicator i .

Finally, re-scaled values method, which is also very widespread (Saisana and Tarantola, 2002; World Economic Forum, 2001), is similar to the method above, except that it uses re-scaled values of the constituent indicators ($y_{ic} = (x_{ic} - \min(x_i)) / \text{range}(x_i)$). The result is that the standardised scores for all indicators have an identical range. This makes the method more robust when there are outliers. However, this characteristic introduces the opposite problem, namely that the range is increased for indicators with very little variation. These indicators will therefore contribute more to the composite indicator than they would using the standardised values method. The result is that the method of re-scaled values is more dependent on the value of the weights.

The standardised values method was in the end selected. On the one hand, we did not want indicators with a smaller range of variation (such as coverage ratio) to make a great difference

between the cities; we preferred these differences to be caused by indicators with a larger range of variation (such as number of fatalities per inhabitant or land occupation). On the other hand, we wanted to penalise or reward extreme values; for example, a city with too many accidents would rarely have a good social CI. Moreover, this method has the advantage of being less dependent on the weights of each indicator. In our calculations we assigned weights equal to one ($|w_i| = 1$) to each sub-indicator, measuring different aspects of each sustainability dimension, and none of them should be underestimated. The sign of w_i depends on the meaning of the indicator. If an increase in the value of the indicator makes the transport system less sustainable, $w_i < 0$ (for example the number of fatalities); conversely if an increase in the value of the indicator makes the transport system more sustainable, $w_i > 0$ (Haghshenas and Vaziri, 2012). A considerable number of authors have applied the same formula (standardized values) and the same weights simplification ($|w_i| = 1$) to estimate sustainability indicators (World Economic Forum, 2001; Rassafi and Vaziri, 2007; Haghshenas and Vaziri, 2012).

The composite indicators for each sustainability dimension have the following formulations:

$$CI_{econ} = \frac{x_{Cv.Ra} - x_{Cost.us} - x_{Time}}{3} \quad (2)$$

$$CI_{soc} = \frac{-x_{Fatal} + x_{Ntw.den} + x_{Soc.tar}}{3} \quad (3)$$

Table 6
Description of selected indicators.

	Abbreviation	Indicator	Description	Unit
Economic	$x_{Cv,Ra}$	Coverage ratio for public transport	$\left(\frac{\text{Tariff revenues}}{\text{maintenance and operation costs}} \right) \times 100$	%
	$x_{Cost,us}$	Ratio between cost of transport for user and GDP per capita	$\frac{\text{Single public transport ticket price}}{\text{GDP per capita}} + \frac{\text{Price per litre of petrol}}{\text{GDP per capita}}$	–
	x_{Time}	Time spent travelling per capita	Time spent travelling per day and person	min
Social	x_{Fatal}	Traffic fatalities per capita	$\frac{\text{No. of traffic fatalities in urban area per year}}{\text{million inhabitants}}$	No./mill. inhab.
	$x_{Ntw,den}$	Public transport network density	$\left[\frac{(\text{length of rail modes/service area})}{\text{Max. density of rail network in all cases}} \right] + \left[\frac{(\text{length of bus modes/service area})}{\text{Max. density of bus network in all cases}} \right]$	–
	$x_{Soc,tar}$	Reduction of public transport fares for students and old people	(% PT tariff reduction for students $\times$ % students in MA) + (% PT tariff reduction for old people $\times$ % old people MA)	–
Environmental	$x_{Lnd,con}$	Land consumption for transport infrastructure	Length of urban roads/metropolitan area surface	km/km ²
	$x_{Ener,PT}$	Public transport energy consumption per user	Annual energy consumption (rail modes + buses)/millions of public transport users per year	TEP/ million users
	$x_{Emis,PT}$	Public transport emissions per user	Petrol annual consumption by buses/millions of bus users per year	TEP/ million users

$$CI_{env} = \frac{-x_{Lnd,con} - x_{Ener,PT} - x_{Emis,PT}}{3} \quad (4)$$

Due to the normalization method, each x_{ic} , and therefore each CI, had different ranges. Another consequence is that CIs were slightly more influenced by indicators with greater variability between cities, i.e. CI_{econ} was more influenced by the time spent travelling than by coverage ratio.

Weights assigned to the CIs to obtain global sustainability scores (CI_{sust}) were procured from a study carried out by [Guzman et al. \(2014\)](#). These authors analysed the opinions of public decision makers, company representatives and researchers involved in transport and urban planning in order to obtain appropriate weights for each sustainability dimension. The weights were obtained to calculate a global sustainability indicator which considered the three dimensions, in order to evaluate the implementation of passenger urban transport related policies in the European context. The output weights were 0.289 for the economic dimension, 0.357 for the social dimension and 0.354 for the environmental dimension. In any case their values are quite similar and will not therefore have a big impact on the results.

$$CI_{sust} = 0.289 \times CI_{economic} + 0.357 \times CI_{social} + 0.354 \times CI_{environmental} \quad (5)$$

Following this process we have calculated the values of the CI for each dimension in each city. Then they are aggregated to provide the CI of global sustainability for each city. Those results are presented in [Table 10](#), within the results analysis. They are also used for the correlation and cluster analysis that follow.

3.2. Correlation analysis

The CIs are assumed to be a comparative measure of urban passenger transport sustainability in each city. In order to detect the relationships between certain of a city's characteristics such as population or GDP and the sustainability of their transport systems, we explored the existing correlations between the CIs ([Table 10](#)) and those city's characteristics available in the data sources (see [Section 2.2](#)). The Pearson correlation analysis was chosen for this purpose (similar approaches can be found in

[Haghshenas and Vaziri \(2012\)](#)). For the analysis to be valid, at least one of the variables (in this case the CIs) has to be normally distributed ([Huck, 2000; Breakwell et al., 2005](#)).

A very widespread method to test normality is the Kolmogorov–Smirnov (K–S) and Shapiro–Wilk (S–W) test. If the test is not significant (usually $\text{Sig} > 0.05$ for a level of confidence of 95%), this tells us that the distribution of the sample is not significantly different from a normal distribution (i.e. it is probably normal) ([Breakwell et al., 2005](#)). We chose this method despite its severity, as it has been considered by many authors to be appropriate for testing small samples, and some have applied it to samples $n < 23$ ([Lilliefors, 1967; Conover, 1972](#)).

The CIs were verified by the K–S and S–W test. Social, environmental and global sustainability CIs passed the test showing high significances ($\text{Sig} > 0.05$), and therefore can be considered normally distributed variables. The significance of the economic CI ($\text{Sig} = 0.032$) was slightly below 0.05; however, this value is acceptable using some authors' criteria ([Eckel and Grossman, 1998; Öztuna et al., 2006; Lorenz, 2009; Yap and Sim, 2011](#)), who argue that the K–S and S–W test is the most powerful and the strictest. We also contrasted these results with alternative graphical and numerical tests, following the recommendations of [Hair et al. \(2010\)](#). Regarding numerical test, [Table 7](#) shows the skewness values, and the z-values of skewness and kurtosis. None of these contrast tests revealed significant differences from normal distribution,⁵ and we therefore considered economic CI as normally distributed.

Finally, once the Pearson correlation coefficients were calculated, they were tested with a two-tailed test, since there was no specific direction to the hypothesis being tested ([Breakwell et al., 2005](#)). The significance analysis depends on the sample size; the smaller the sample, the higher the Pearson coefficient will have to be in order to prove the correlation between variables. This study therefore only shows characteristics with a high impact on transport sustainability.

⁵ Values inside the range ± 1 for skewness and ± 1.96 for both z-values tells us that the distribution of the sample is not significantly different from a normal distribution. Z-values of skewness and kurtosis outside the range ± 1.96 indicate a not normal distribution for a 0.05 significance level.

Table 7

Normality test results for composite indicators.

	Kolmogorov–Smirnov ^a			Shapiro–Wilk			Skewness and Kurtosis		
	Statistic	df	Sig. (>0.05)	Statistic	df	Sig. (>0.05)	Skewness (>–1)(<1)	Z-Skewness (>–1.96)(<1.96)	Z-Kurtosis (>–1.96)(<1.96)
CI _{econ}	0.189	23	0.032	0.931	23	0.115	0.897	1.865	1.073
CI _{soc}	0.105	23	0.200 ^b	0.976	23	0.837	–0.192	–0.399	–0.745
CI _{env}	0.120	23	0.200 ^b	0.954	23	0.354	–0.463	–0.963	–0.491
CI _{sust}	0.157	23	0.145	0.922	23	0.073	–0.943	–1.960	0.941

^a Lilliefors significance correction.^b This is a lower bound of the true significance.

3.3. Cluster analysis

The last step of the process was to classify the 23 cities according to the sustainability of their passenger transport systems in the three dimensions, measured by the CIs (Table 10). The method used for the classification was the cluster analysis, which aims to reduce the dimensionality of a data set by exploiting the similarities/dissimilarities between the cases (the cities). The techniques can be hierarchical if the classification has an increasing number of nested classes, and non-hierarchical when the number of clusters is decided ex ante (Nardo et al., 2005).

In order to cluster the cities and taking the CI_{econ}, CI_{soc}, CI_{env} and CI_{sust} of each city as the classification variables, we first set the appropriate number of clusters, using a hierarchical method: the Ward method with squared Euclidean distance measurement. This means that membership of the cluster is determined by calculating the sum of the squared deviations of elements from the mean of the cluster (Nardo et al., 2005). The squared distances were selected for being suitable when there are negative values – which is the case of the CIs. The method is an agglomerative procedure where a pair of clusters merge at each step. As the process continues fusing clusters, the similarity between cities belonging to the same cluster decreases and the linkage distances increase.

Economic, social, and environmental CIs have different ranges within the sample of cities, and as the cluster classification measures distances, some sustainability dimension could be

omitted. To avoid this, the CIs were again normalized using Z-scores formulation, the most commonly used for this purpose in cluster analysis (Hair et al., 2010).

The decision to take the optimum number of clusters is largely subjective, although looking at the plots of agglomeration coefficients, and linkage distance across fusion steps may help (Milligan and Cooper, 1985). By looking at the agglomeration schedule and the dendrogram, we decided to classify the cities into four clusters. In the agglomeration schedule (Fig. 1) the optimal step could be said to be number 19, from this point forward, agglomeration coefficient values start to grow rapidly. In step 19, the cities aggregated with Paris (city no. 1) were fused with the cities aggregated with Amsterdam (city no. 9) (Table 8). The dendrogram plot (Fig. 2) illustrates the arrangement of the clusters; the linkage distances for the four clusters appear to be acceptable, and they grow significantly in the next step of the aggregation, where the method forms three clusters.

Unlike the previous method, the *k*-means method of clustering is not hierarchical, and therefore starts from a previously stated number of clusters (=k) and centroids. It is used when the aim is to divide the sample in *k* clusters with the greatest possible differentiation. The algorithm departs from the initial situation moving the objects in and out of the clusters in order to minimise the variance of the elements within the clusters, and maximise the variance of the elements outside the clusters (Nardo et al., 2005).

Fig. 1. Coefficient values in each step of agglomeration.

Fig. 2. Cluster arrangement.

The *k*-means method is used here to test the stability of the resulting clusters. We set $k=4$, and iterations were started from centroids obtained with the Ward method, again using squared Euclidean distance measurement. SPSS made only two iterations and the final results differed only in the assignment of one city (Valencia). Although this could not be interpreted as a confirmatory analysis (we entered the starting centroids), the low number of iterations and the similarities between final clusters show some stability in the results (Hair et al., 2010). The *k*-means method changes the cities from one cluster to another in order to obtain the best solution; while in the Ward method, once the elements have been fused, they remain in the same cluster. Therefore *k*-means could correct some aggregation done in Ward method stages.

The ANOVA analysis (Table 9) shows high *F* values, which means that all the variables contribute to the cluster classification (Breakwell et al., 2005; Hair et al., 2010), especially the social and global sustainability indicators. This could prove that the classification makes sense, because the cities contained in each cluster show high similarities among them considering their CIs values (sustainability scores), and high differences with the rest.

As a result, all cities were classified according to the CI scores obtained in the different sustainability dimensions. Firstly, we identified the optimal number of clusters, which was set at four by a hierarchical method. Secondly, the stability of the result was tested by *k*-means, entering the number of clusters and centroids obtained in the first step. We selected this second agglomeration (*k*-means can rectify results obtained by hierarchical method), presented in Section 4.3. Finally, an ANOVA analysis confirms the consistency of the clusters (all variables contributed to the classification).

4. Results and discussion

This section contains an analysis of the composite indicators obtained for the 23 cities, and a study of the correlations between the variables related to urban transport systems' sustainability and the general characteristics of the cities. Finally, the cities are classified into four groups based on their sustainability scores; each group is characterised by an average profile: the cluster centroid.

4.1. Composite indicator results

The evaluation was based on the average performance of the sample. On this occasion, the sample included European cities which some authors consider to be among the most sustainable in the world (Haghshenas and Vaziri, 2012; Newman and Kenworthy, 1999).

Due to the normalization method, each CI was slightly more influenced by factors with wider ranges, and more variability between cities. For example, CI_{econ} was more influenced by total travel time than by coverage ratio as there is greater variability in travel time between the cities.

The economic CI was substantially influenced by total time spent travelling, which was higher for big cities. Big cities were also characterized by a lower coverage ratio (they normally had a more comprehensive offer of public transport, including metro and rail modes with high operational costs). The most populated cities were therefore more penalised by economic indicators. In fact, almost all cities analysed with more than 1.5 mill. inhab., namely Paris, London, Stockholm, Madrid, Barcelona, Valencia and Seville achieved negative scores for CI_{econ} .

Table 8

Fusion of clusters and coefficient values in each step of the agglomeration process.

Agglomeration schedule-coefficients				
Stage Fig. 1 – horizontal axis	Combination of clusters in each stage Fig. 2		Values Fig. 1 – vertical axis	
	Group	Group		
1		8	12	0.020
2		1	10	0.182
3		3	4	0.427
4		8, 12	16	0.815
5		11	19	1.215
6		9	22	1.678
7		5	6	2.242
8		21	23	2.870
9		1, 10	2	3.633
10		7	14	4.497
11		11, 19	13	5.849
12		3, 4	17	7.205
13		7, 14	18	8.860
14		3, 4, 17	8, 12, 16	10.540
15		15	21, 23	12.730
16		9, 22	20	14.929
17		1, 10, 2	5, 6	18.806
18		3, 4, 17, 8, 12, 16	11, 19, 13	23.020
19		1, 10, 2, 5, 6	9, 22, 20	28.249
20		1, 10, 2, 5, 6, 9, 22, 20	3, 4, 17, 8, 12, 16, 11, 19, 13	40.626
21		7, 14, 18	15, 21, 23	56.749
22		1, 10, 2, 5, 6, 9, 22, 20, 3, 4, 17, 8, 12, 16, 11, 19, 13	7, 14, 18, 15, 21, 23	88.000

Table 10 shows the CI scores obtained; cities are ordered by population size. Negative scores indicate they are less sustainable than the average of the sample, while positive results indicate they are more sustainable than the average. Spanish cities had a poorer assessment within the social dimension than the four European non-Spanish ones. Although the number of urban fatalities was the factor with the greatest impact in this particular CI, the higher scores of foreign cities could be attributed more to the joint effect of a denser public transport network, and higher discounts in social fares.

Environmental scores were more affected by land consumption and public transport emissions per user. Cadiz, Tarragona and Gran Canaria had the worst evaluation; all three cities are fairly disperse, with few public transport users, and their public transport systems consumed a high quantity of resources per passenger compared to the rest. In contrast, cities with greater use of public transport were very efficient with regard to consumption and emissions per passenger; these included cities like Paris, London, Madrid, Barcelona, Bilbao and Saragossa, although London did not receive a very good CI_{env} due to land occupation. The best scores for global sustainability were obtained by Bilbao, Pamplona, Paris, London and Bilbao.

4.2. City and mobility characteristics

Sustainability indicators must be able to determine the characteristics that enhance sustainability in urban transport (Haghshenas and Vaziri, 2012). In this stage of the process, we determined which global variables facilitate or hinder the implementation of a sustainable transport system in cities.

We therefore analysed the correlations between some characteristics (modal share, urban density, GDP per capita, population ...) and the CIs. Haghshenas and Vaziri (2012) also applied this method with cities all over the world using different indicators. Their coefficients were lower, probably because the sample was more heterogeneous, while cities in this study had more similarities.

Table 11 shows the results of the Pearson correlations. We tested correlations with variables contained in MMO and EMTA reports, but only the variables listed in the table were significant. According to the results, and the indicators selected, economic sustainability CI is negatively correlated with public transport share. Generally, cities with high-quality public transport networks and a wide range of services have lower coverage ratios, such as Stockholm, Gipuzcoa or Madrid. These networks tend to capture a large part of the travel demand in spite of having higher ticket prices, a fact that also penalised these public transport systems in terms of economic sustainability. Finally, in the most populated cities, people spent more time travelling per day. These larger cities were typically characterised by better public transport networks, higher ticket prices and a more generalised use of public transport, and therefore worse CI_{econ} scores. It is worth noting that the selected and available indicators are partial, and the analysis omits some important factors such as road investment, which affects both private and public transport. What can be inferred from the results, is that to achieve high quality in PT networks implies a cost for public authorities and users, and this cost affects certain aspects of economic sustainability, as has been reflected here. On the other hand, high quality PT networks with high PT modal shares give very good results for the aspects relating to social and environmental sustainability.

Social sustainability is positively correlated with public transport share, urban density and GDP per capita. The number of fatalities per inhabitant did not show any correlation with these

Table 9ANOVA analysis results from *k*-means procedure.

	Cluster		Error		F	Sig.
	Mean square	df	Mean square	df		
ScoreZ(CI_{econ})	3.679	3	0.577	19	6.374	0.004
ScoreZ(CI_{soc})	6.034	3	0.205	19	29.413	0.000
ScoreZ(CI_{env})	4.406	3	0.462	19	9.533	0.000
ScoreZ(CI_{sust})	5.973	3	0.215	19	27.814	0.000

Table 10

Composite indicators (CI) obtained for each city.

Population	City		CI _{econ}	CI _{soc}	CI _{env}	Aggregated CI _{sust}
>5 mill. inhab.	1	Paris	−0.18	0.49	0.61	0.34
	2	London	−0.16	0.85	0.18	0.32
	3	Madrid	−0.24	0.14	0.83	0.27
	4	Barcelona	−0.15	0.07	0.52	0.17
5–1.5 mill. inhab.	5	Stockholm	−0.44	0.61	−0.20	0.02
	6	Valencia	−0.21	0.18	−0.10	−0.03
	7	Murcia	0.44	−0.12	−0.51	−0.10
	8	Seville	−0.12	−0.39	0.45	−0.01
	9	Amsterdam	0.06	0.57	−0.26	0.13
1.5–1 mill. inhab.	10	Bilbao	−0.23	0.61	0.83	0.45
	11	Asturias	0.14	−0.61	0.12	−0.13
	12	Malaga	−0.10	−0.30	0.40	0.01
1–0.5 mill. inhab.	13	Majorca	−0.12	−0.31	−0.27	−0.24
	14	Gran Canaria	0.39	0.55	−0.72	0.05
	15	Cadiz	0.14	−0.84	−1.34	−0.73
	16	Saragossa	−0.14	−0.56	0.81	0.04
	17	Gipuzkoa	−0.53	−0.12	0.48	−0.03
	18	Tarragona	0.85	0.10	−1.05	−0.09
<0.5 mill. inhab.	19	Granada	0.21	−0.32	0.31	0.06
	20	Pamplona	0.47	0.37	0.29	0.37
	21	Girona	−0.22	−1.20	−0.40	−0.63
	22	Corunna	0.19	0.99	−0.48	0.24
	23	Leon	−0.03	−0.77	−0.51	−0.46
Minimum value			−0.53	−1.20	−1.34	−0.73
Maximum value			0.85	0.99	0.83	0.45
Range of variation			1.38	2.18	2.17	1.18

variables, although it penalised cities with extreme negative values such as Leon and Girona, and favoured those with extreme positive values such as Stockholm. Accessibility, measured by km of public network per service area, was higher in wealthier and denser cities: those with greater GDP tend to invest more in their networks; and high accessibility is obviously more easily achieved in less dispersed areas. Equity, measured by discounts for young and old people on public transport fares, was also addressed in CI_{soc}; GDP was clearly correlated with this aspect: wealthier cities offered more social discounts than poorer ones. Lastly, as expected, transport systems with good accessibility and greater social discounts had higher public transport shares.

Environmental sustainability is negatively correlated with private motorised share and positively correlated with public transport share. Cities with extended car use and lower public transport shares had more inefficient public transport services in terms of energy and emissions per passenger. In addition, cities with a longer length of road per area tend to have higher private motorised shares.

Global sustainability is positively correlated with public transport share and negatively correlated with private transport share. Newman and Kenworthy (1999) have already highlighted the barriers to attaining sustainability imposed by automobile dependence: it drives cities to increase their use of land, energy, water, and other materials, and their rates of transport-related emissions, traffic noise and storm-water pollution. The solutions for improving this situation include favouring transit and non-motorised modes, and constraints on urban sprawl.

Urban density also appears to contribute to urban transport sustainability. This is generally accepted by a number of authors (Nicolas et al., 2003; Jeon and Amekudzi, 2005; Savelson et al., 2006; Zhang and Guindon, 2006; Litman, 2009; Haghsheenas and Vaziri, 2012 etc), who state that urban sprawl has a significant effect on travel distances and hinders public transport supply.

In this study, rich and highly-populated cities generally tend to be more sustainable. Large cities were usually characterised by economies of scale and density, a broader job offer, and a higher GDP. They therefore invest more capital in their public transport

Table 11

CI correlations with cities' characteristics.

		Public transport share	Private motorised share	Urban density	GDP per capita	Population
CI _{econ}	Pearson correlation	−0.502 ^a	0.333	0.000	−0.349	−0.296
	Sig. (2-tailed)	0.015	0.121	0.999	0.103	0.170
CI _{soc}	Pearson correlation	0.473 ^a	−0.215	0.461 ^a	0.509 ^a	0.375
	Sig. (2-tailed)	0.022	0.324	0.027	0.013	0.078
CI _{env}	Pearson correlation	0.517 ^a	−0.575 ^b	0.260	0.358	0.401
	Sig. (2-tailed)	0.012	0.004	0.230	0.094	0.058
CI _{sust}	Pearson correlation	0.540 ^b	−0.455 ^a	0.502 ^a	0.498 ^a	0.453 ^a
	Sig. (2-tailed)	0.008	0.029	0.015	0.016	0.030

^a Correlation is significant at the 0.05 level (2-tailed).

^b Correlation is significant at the 0.01 level (2-tailed).

Fig. 3. Clusters with environmental and social CI scores.

networks, sometimes inhibiting some aspects of economic sustainability but clearly contributing to social, environmental and global sustainability.

4.3. Cluster analysis

This section, includes a characterization of the clusters formed⁶. The cities contained in each cluster are shown in Fig. 3, a two-dimensional plot where each city is represented by its environmental CI score on the horizontal axis and its social CI score on the vertical axis.⁷ Cluster 1 – comprising ten cities – is clearly the largest and most homogeneous, cities in it are more similar to each other,⁸ and most have very good environmental CI scores, as they are located in the positive part of the horizontal axis. Cluster 2, which contains the four non-Spanish cities plus three Spanish ones, is characterised by very good social sustainability scores; which places the cluster in the upper part of the plot. Clusters 3 and 4, are formed by only three cities. Cluster 4 is the least homogenous; its cities are all characterised by negative economic and environmental CI scores. Finally, in Fig. 4, the cities are represented in a three-dimensional plot, which also considers the economic dimension. It can be seen that Cluster 3 is located in the positive part of economic CI axis, contrary to what occurs in almost all cities in Clusters 1 and 2. This figure also shows that Cluster 2 is the most sustainable, as it is located in the front part of the plot, thus performs quite well in the three dimensions.

Table 12 shows the average profiles of the cities assigned to each cluster – with regard to sustainability CI scores and

characteristics correlated with them (according to Table 11). The main features of each cluster are explained below.

Cluster 1 – Environmentally Efficient – characterised by cities with environmentally sustainable transport systems. It includes cities that are very efficient in public transport management, with a high public transport share (14%). The most populated Spanish cities belong to this group, namely Madrid, Barcelona, Valencia, Sevilla and Asturias, plus Saragossa; they have an average population of 2 mill. inhab. Their average global sustainability CI score is positive, but lower than the second cluster, although some cities in this cluster such as Madrid obtained high global sustainability evaluations.

Cluster 2 – Socially Friendly – comprises cities whose transport systems were the most socially sustainable; they usually also achieved high global sustainability scores. According to the results obtained in the correlations analysis, these cities were generally the most populated – with an average of 3.5 mill. inhab. –, the wealthiest – with a GDP of 33,563 per capita – and the densest – 1,693 inhab/km² on average. This cluster is characterized by the highest public transport share and the lowest car share, with average values of 18 and 41%, respectively. The cities included in this group were Paris, London, Stockholm and Amsterdam, plus Corunna, Pamplona and Bilbao. According to their global sustainability scores and general characteristics, Madrid and Barcelona could have been placed in this group, but their social indicators were too low to belong to this cluster.

Cluster 3 – Economically Competitive – formed by cities which achieved economic sustainability, namely Murcia, Gran Canaria and Tarragona with an average of 1 mill. inhab., none of which have rail or metro services.

Cluster 4 – Least Sustainable – contains the smallest populations (400,000 inhabitants). These cities were the least sustainable, taking into account the three dimensions. They presented some barriers to achieving sustainable urban transport systems; i.e. they had the lowest GDP per capita (20,584 per capita on average), and rather dispersed populations (137 inhab/km²). The cities included in this cluster were Girona, Leon and Cadiz.

On average, global sustainability scores decrease in parallel with public transport use. Clusters 3 and 4 – which have the lowest

⁶ We present the clusters done by the *k*-means method; the only difference in the results with the Ward method was the assignment of Valencia to cluster number 1 instead of number 2.

⁷ The variables represented allow a clear identification of the clusters, as the *F* value (Table 9) for the social and economic CI were very high, and therefore had a high contribution in the formation of clusters.

⁸ Most cities in Cluster 1 aggregate in the first stages of the hierarchical clustering process (see Fig. 2).

Fig. 4. Clusters with economic, social and environmental CI scores.

Table 12

Average profiles of cities in each cluster (centroid values).

	Clusters (K-means method)			
	1	2	3	4
	Environmentally efficient	Socially friendly	Economically competitive	Least sustainable
Cl _{econ}	−0.13	−0.04	0.56	−0.04
Cl _{socio}	−0.22	0.64	0.18	−0.94
Cl _{env}	0.36	0.14	−0.76	−0.75
Cl _{sust}	0.01	0.27	−0.04	−0.61
Public transport share (%)	14.45	18.07	8.20	4.33
Private motorised share (%)	41.82	40.56	53.67	50.27
Urban density (inhab./km ²)	624	1,693	292	137
GDP per capita (€)	23,595	33,563	22,401	20,584
Population (inhabitants)	1,968,850	3,519,601	974,836	392,938

global CI (−0.04 and −0.61) – also have low public transport patronage (8 and 4%).

5. Conclusions

Since concern for sustainable development started to permeate through societies in the United Nations (1972) Stockholm Conference on the Human Environment, cities around the world have been pursuing sustainability goals in their agendas. This in turn has led to a need to define indicators to measure how far these targets have been met (Newman and Kenworthy, 1999).

This study defines indicators for measuring the economic, social and environmental sustainability of passenger transport systems in a group of cities. The intrinsic features of the concept of

sustainable transport required the indicators to be multidisciplinary, and this informed our decision to use composite indicators (CI) based on a benchmarking approach; that is, the scores obtained for each city depend on the performance of the whole sample. The scores were therefore not global, but the methodology could be useful for stakeholders and decision makers to assess their progress compared to other real cases and detect their weaknesses and strengths. All the cities analysed were European, considered by certain authors to be among the most sustainable in the world (Haghshenas and Vaziri, 2012; Newman and Kenworthy, 1999).

The method allowed us to analyse the three sustainability dimensions, and to use the results to compare and classify various cities from an economic, social and environmental viewpoint. CIs can highlight the factors that contribute most to achieving

sustainability in transport; the richest and largest cities usually have more sustainable transport systems. CIs also point to certain transport policies that could improve shortcomings, such as increasing the share of public transport, and avoiding urban sprawl. CIs also allow similar cities to be aggregated based on the sustainability of their urban transport systems. It was found that cities with highest social CIs were also the most globally sustainable. This was the case of all non-Spanish European cities plus some Spanish ones. Mid-sized cities (1 mill. inhab.) without metro, rail or tram modes were the most economically sustainable. Finally, small, disperse and non-wealthy cities were the least sustainable.

References

- Ayuntamiento de A Coruña, 2010. www.coruna.es/#panel1-1 (accessed September 2014).
- Bizkaiko Foru Aldundia, 2010. http://www.bizkaia.net/home2/ca_index.asp (accessed September 2014).
- Breakwell, G., Leeux, J., O'Muircheartaigh, C., Saris, W., Schuman, H., Meter, K., 2005. Discovering Statistics Using SPSS. Andy Field, Great Britain.
- Conover, W.J., 1972. A Kolmogorov goodness-of-fit test for discontinuous distributions. *J. Am. Stat. Assoc.* 67, 591–596.
- Council of the European Union, 2001. Council Resolution on the Integration of Environment and Sustainable Development into the Transport Policy. Report from the Committee of Permanent Representatives to the Council 7329/01. Council of the European Union, Göteborg.
- Eckel, C.C., Grossman, P.J., 1998. Are women less selfish than men?: evidence from dictator experiments. *Econ. J.* 108, 726–735.
- Empresa Municipal de Transportes Públicos de Tarragona S.A., 2010. <http://emtanemambtu.cat/> (accessed September 2014).
- EMTA, 2012. Barometer 2011 of public transport in the European metropolitan areas. http://www.emta.com/IMG/pdf/emta_barometre_2011_final_dec_2012.pdf (accessed September 2014).
- EMTA, 2012. Barometer 2009 of public transport in the European metropolitan areas. http://www.emta.com/IMG/pdf/barometer_report_2012_data_2009.pdf (accessed September 2014).
- EMTA, 2014. European Metropolitan Transport Authorities. <http://www.emta.com/?lang=en> (accessed September 2014).
- European Commission, 1996. European sustainable cities. EU Expert Group on the Urban Environment. Directorate General XI Environment, Nuclear Safety and Civil Protection, Brussels.
- European Commission, 2007. Green Paper – Towards a new culture for urban mobility (SEC(2007) 1209)/COM(2007/0551 final), Brussels.
- European Commission, 2011. White Paper – Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system/COM(2011/0144 final), Brussels.
- Farahani, R.Z., Miandoabchi, E., Szeto, W.Y., Rashidi, H., 2013. A review of urban transportation network design problems. *Eur. J. Oper. Res.* 229, 281–302.
- Gudmundsson, H., 2003. Making concepts matter: sustainable mobility and indicator systems in transport policy. *Int. Soc. Sci. J.* 199–217.
- Guzman, L.A., de la Hoz, D., Monzón, A., 2014. Optimal and long-term dynamic transport policy design: seeking maximum social welfare through a pricing scheme. *Int. J. Sustainable Transp.* 8, 297–316.
- Haghshenas, H., Vaziri, M., 2012. Urban sustainable transportation indicators for global comparison. *Ecol. Ind.* 15, 115–121.
- Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E., 2010. *Multivariate Data Analysis*. Pearson Prentice Hall, New Jersey.
- Holden, E., Linnerud, K., Banister, D., 2013. Sustainable passenger transport: back to Brundtland. *Transp. Res. Part A: Policy Pract.* 54, 67–77.
- Huck, S.W., 2000. *Reading Statistics and Research*. Pearson, Boston.
- Jeon, C., Amekudzi, A., 2005. Addressing sustainability in transportation systems: definitions. *Indic. Metrics* 11, 31–50.
- Jourard, R., Gudmundsson, H., 2010. Indicators of Environmental Sustainability in Transport. I'INRETSed Bronce, France.
- Lilliefors, H.W., 1967. On the Kolmogorov–Smirnov test for normality with mean and variance unknown. *J. Am. Stat. Assoc.* 62, 399–402.
- Litman, T., 2009. Sustainable Transportation Indicators: A Recommended Research Program for Developing Sustainable Transportation Indicators and Data. Indicators Subcommittee of the Transportation Research Board.
- Lorenz, J., 2009. Universality in movie rating distributions. *Eur. Phys. J. B* 71, 251–258.
- May, A.D., Page, M., Hull, A., 2008. Developing a set of decision-support tools for sustainable urban transport in the UK. *Transp. Policy* 15, 328–340.
- Milligan, G.W., Cooper, M.C., 1985. An examination of procedures for determining the number of clusters in a data set. *Psychometrika* 50, 159–179.
- Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer 2010. Sécurité Routière. Bulletin mensuel d'information. Ile-de-France. Direction régionale et interdépartementale de l'Équipement et de l'Aménagement d'Ile-de-France. http://www.driea.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/Bilan-SR-IdF-210297_BD_cle0dfb61.pdf (accessed September 2014).
- Ministerio de Fomento, 1998. Vías de Dependencia Municipal. Subdirección General de Estadísticas y Estudios. http://www.fomento.es/NR/rdonlyres/168E494B-083B-42F7-B459-3B523F78A04C/3697/vias_municipales.pdf (accessed September 2014).
- Ministerio del Interior-Dirección General de Tráfico, 2010. Anuario Estadístico de Accidentes- DGT. http://www.dgt.es/Galerias/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-de-accidentes/anuario_estadistico014.pdf (accessed September 2014).
- Miranda, H.D.F., Rodrigues da Silva, A.N., 2012. Benchmarking sustainable urban mobility: the case of Curitiba, Brazil. *Transp. Policy* 21, 141–151.
- MMO, 2014. Metropolitan Mobility Observatory. <http://www.observatoriomobilidad.es/> (accessed September 2014).
- Monzón, A., Cascajo, R., Muñoz, B., Alonso, A., 2012. Informe 2010 Del Observatorio De La Movilidad Metropolitana. Ministerio de Agricultura, Alimentación y Medio Ambiente, Madrid. http://www.observatoriomobilidad.es/images/stories/05_informes/Informe_OMM2010.pdf (accessed September 2014).
- Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., Giovannini, E., 2005. Handbook on Constructing Composite Indicators Methodology and User Guide. OECD Statistics Working Paper, Paris.
- Newman, P., Kenworthy, J., 1999. *Sustainability and Cities. Overcoming Automobile Dependence*. Island Press, Washington.
- Nicolas, J., Pochet, P., Poimboeuf, H., 2003. Towards sustainable mobility indicators: application to the Lyons conurbation. *Transp. Policy* 10, 197–208.
- OECD, 2013. <http://www.oecd.org/governance/regional-policy/urbandevelopment.htm> (accessed September 2014).
- OECD, 2001. Policy instruments for Achieving Project Environmentally Sustainable Transport. Paris.
- Öztuna, D., Atilla, H.E., Tüccar, E., 2006. Investigation of four different normality tests in terms of type 1 error rate and power under different distributions. *Turkish J. Med. Sci.* 36, 171–176.
- Rassafi, A., Vaziri, M., 2007. Assessment of modal transportation sustainability: application of data envelopment and concordance analyses. *Iranian J. Sci. Technol. Trans. B, Eng.* 31, 179–193.
- RATP, 2010. <http://www.ratp.fr/fr/> (accessed September 2014).
- Reurings, M.C.B., Aarts, L.T., Schermers, G., 2012. Analyse van het aantal verkeersdoden in 2011 in Amsterdam, Leidschendam. <http://www.swov.nl/rapport/R-2012-06.pdf> (accessed September 2014).
- Saisana, M., Tarantola, S., 2002. State-of-the-Art Report on Current Methodologies and Practices for Composite Indicator Development, EUR 20408 EN. European Commission-Joint Research Centre, Italy.
- Santos, A.S., Ribeiro, S.K., 2013. The use of sustainability indicators in urban passenger transport during the decision-making process: the case of Rio de Janeiro, Brazil. *Curr. Opin. Environ. Sustainability* 5, 251–260.
- Savelson, A., Colman, R., Litman, T., Walker, S., Parmenter, R., 2006. The GPI transportation accounts: sustainable transportation in Nova Scotia. GPI Atlantic. <http://www.gpiatlantic.org/publications/summaries/transportationsumm.pdf> (accessed September 2014).
- Smith, T.W., Axon, C.J., Darton, R.C., 2013. The impact on human health of car-related air pollution in the UK, 1995–2005. *Atmos. Environ.* 77, 260–266.
- Stockholm Stad-traffikkontoret, 2009. Analysis of traffic in Stockholm. Trafikkontoret. Stockholm. <http://www.stockholm.se/-/Kontakt/Kontakta-oss/?term=216522> (accessed September 2014).
- Tanguay, G.A., Rajaonson, J., Lefebvre, J., Lanoie, P., 2010. Measuring the sustainability of cities: an analysis of the use of local indicators. *Ecol. Ind.* 10, 407–418.
- TERM, 2000. Are we moving in the right direction? Indicators on transport and environment Integration in the EU. European Environment Agency. <http://www.eea.europa.eu/publications/ENVISUENo12> (accessed September 2014).
- TfL, 2010. Casualties in Greater London. Transport for London. <http://www.tfl.gov.uk/cdn/static/cms/documents/casualties-greater-london-2010.pdf> (accessed September 2014).
- TfL, 2010. Transport for London. <http://www.tfl.gov.uk/> (accessed September 2014).
- TTG, 2010. Autoridad Territorial del transporte de Guipúzcoa. <http://atgipuzkoa.com/> (accessed September 2014).
- TUZA, 2010. Transportes Urbanos de Zaragoza. <http://www.urbanosdezaragoza.es/> (accessed September 2014).
- UNECE, 2011. Climate Neutral Cities. How to make Cities Less Energy and Carbon Intensive and More Resilient to Climatic Challenges. United Nations, New York and Geneva.
- United Nations, 1972. Declaration of the United Nations Conference on the Human Environment. Stockholm. <http://www.unep.org/Documents/Multilingual/Default.asp?documentid=97&articleid=1503> (accessed September 2014).
- WCED, 1987. Our common future. World Commission on Environment and Development. Oxford University Press, Oxford.
- World Economic Forum, 2001. Environmental Sustainability Index. Global Leaders for Tomorrow Environment Task Force, World Economic Forum, Davos, Switzerland.
- Yap, B.W., Sim, C.H., 2011. Comparisons of various types of normality tests. *J. Stat. Comput. Simul.* 81, 2141–2155.
- Zegras, C., 2006. Sustainable Transport Indicators and Assessment Methodologies. Biannual Conference and Exhibit of the Clean Air Initiative for Latin American Cities, Sao Paulo, Brazil.
- Zhang, Y., Guindon, B., 2006. Using satellite remote sensing to survey transport-related urban sustainability: Part 1: methodologies for indicator quantification. *Int. J. Appl. Earth Observ. Geoinform.* 8, 149–164.
- Zito, P., Salvo, G., 2011. Toward an urban transport sustainability index: an European comparison. *Eur. Transp. Res. Rev.* 3, 179–195.

5.2. Policy priority objectives: Comparative assessment in four European cities

The literature on urban development highlights some general threats over sustainability in European cities: demographic decline, social segregation, environmental depletion, urban sprawl and economic decline. However, each city faces specific problems and trends, and should establish policy priorities according to them. In Section 5.2, the main threats over sustainability were determined through indicators to measure the evolution of the current and potential problems in four European cities: London, Madrid, Barcelona and Rotterdam.

The research study was presented in the international Transport Conference XII Congreso de Ingeniería del Transporte (CIT 2016), held on 7,8 and 9 June 2016 in Valence (Spain).

5.3. Assessing the progress towards sustainability in and the role of urban transport- city of Madrid

Section 5.3 is focused in the threats and policy priorities for the case of Madrid, which is the main case study of the thesis.

The research work was presented in the international Conference 6th Transport Research Arena (TRA 2016), held on 18, 20 and 21 April 2016 in Warsaw (Poland).

Figure 5.3 shows the role of both analyses (Section 5.2 and 5.3) in the structure of the thesis and the policy cycle.

Figure 5.3. Policy issues analysed in Sections 5.2 and 5.3 within the structure of the thesis

CIT 2016

Universitat Politècnica de València
XII Congreso de
Ingeniería del Transporte
Valencia

Policy priority objectives: comparative assessment in four European cities

Andrea Alonso

TRANSyT Transport Research Centre- Universidad Politécnica de Madrid

Andrés Monzón

Civil Engineer Department- Universidad Politécnica de Madrid

ABSTRACT

Sustainability must be an urban issue. Cities should be managed so as to minimize their impacts on environment, but providing an appropriate framework for economic and social development. However, European cities are facing some trends that threaten sustainable development. The aim of the EC research project INSIGHT-7FP (2013/16) is to develop appropriate management tools that can help to achieve sustainability in the context of European cities. In the project, a set of policy objectives have been designed for the management of urban areas, in order to face the main threats existing over cities. The paper presents a methodology based on indicators for analysing the progress towards these ten policy objectives in the four EU cities participating in the project: London (12.3 mill. inhab.), Madrid (6.4 mill. inhab.), Barcelona (5.4 mill. inhab.) and Rotterdam (1.4 mill. inhab.). All the indicators used in the analysis have been validated by ten policy makers of European cities. These policy makers participated on the stakeholders consultation carried out in the project, where the importance of the policy objectives proposed was also assessed. The paper concludes determining the policy priority objectives in each city, in order to contain the main threats existing over them: London should especially address the threats of social exclusion and transport inefficiency; Madrid the threats of economic decline and urban sprawl; Barcelona the economic decline and Rotterdam the contribution to climate change and the urban sprawl. Finally, the role played by the land use and transport system in these policy objectives is analysed. To this end, the assessment allows for the comparability of the results in a horizontal manner, in the basis of common indicators. Nearly half of these indicators are related to the land use and transport system of the cities.

GLOSSARY OF TERMS

GGE: Greenhouse Gases Emissions (CO₂ equivalent)

Metropolitan Area: geographical area where there is a high degree of interaction between its urban centres in terms of trips, relationships or economic activity

Central City: core city in the metropolitan area

Metropolitan Ring: Metropolitan area excluding Central City

Fig. 1. Scheme of the components of a city. MA includes CC and MR

1. INTRODUCTION AND BACKGROUND

Sustainability must be an urban issue (Newman and Kenworthy, 1999). Cities should be managed so as to minimize their impacts on environment, but providing an appropriate framework for economic and social development (United Nations, 1972). In Europe, over 60% of the population lives in cities, where a bit less than 85% of the EU's GDP is generated (European Commission, 2007). Urban areas play a key role in the development of European territories. However, European cities are nowadays facing some trends that threaten sustainable development (European Union, 2011). "The aim of the research project INSIGHT-7 FP (2015) is to develop appropriate management tools that can help to achieve sustainability in the context of European cities". In the project, ten sustainability objectives have been designed for the management of urban areas, in order to face the main threats over cities (Romanillos et al., 2014). This paper presents a methodology based on indicators for analysing the progress towards the objectives designed. Indicators are considered to be appropriated tools to analyse the many overlapping areas of sustainability (Newman and Kenworthy, 1999), and many authors have already applied them to cities for this very purpose (Tanguay, 2010; Haghshenas and Vaziri., 2012; Alonso et al., 2015). All the indicators used in the analysis have been validated by ten policy makers of European cities. These policy makers participated on the stakeholders consultation carried out in the project (García et al., 2014). The methodology developed is applied to the cities of London, Madrid, Barcelona and Rotterdam, which are the four case studies of the project. The progress towards the objectives in each case is comparatively analysed. Finally, the role played by urban transport management in the progress or deviation from the objectives is showed.

The paper aims to develop a methodology to analyse if we are achieving the objectives in

city management, specifically the sustainability objectives proposed. This will allow prioritizing the objectives and the policies to be implemented, including transport management policies. The paper is structured in five sections. Section 2 details framework and methods used for the analysis. Section 3 presents the results. Section 5 then concludes, summarising the key findings that can be useful for future policy and research.

2. FRAMEWORK AND METHODOLOGY

This section explains the theoretical framework developed in INSIGHT, which has set the basis of the analysis, and introduces the case study application. Finally, the section details the methods used to get the results.

2.1 Theoretical framework for urban planning in European cities- setting the objectives

The first step of INSIGHT project was to study the main trends that threaten sustainability in European cities, in order to design appropriate objectives and policies for city management. For this, we recurred to the main reference document on urban problems at European level, which comes from the initiative Cities of Tomorrow (European Union, 2011). Considering sustainable development as a concept divided into three dimensions: society, environment and economy (OECD, 2002; Tanguay et al., 2010; Haghshenas and Vaziri, 2012), the main trends existing in European cities and threatening each dimension are described below:

Society: the weight of working-age population is decreasing due to the low birth rate, the increase in life expectancy and the migration of active population due to the lack of job opportunities. In addition, the socio-spatial segregation is growing, associated to socio-economic inequalities. Urban transport systems are related to this trend, since they affect the livability of cities and provide accessibility (a concept linked to equity).

Environment: the endless consumption of natural resources during urban growth and sprawl continues to pose a threat to the environment. This negative impact of urban development must be addressed to contain the resulting environmental damage.

Economy: a lot of problems associated with economic sustainability started appearing with the Eurozone crisis. The recent recession has been putting pressure over economic development and competitiveness.

Finally, urban sprawl witnessed by Europe in the latest decades has adversely impacted society, environment and economic efficiency (European Environment Agency, 2006). Therefore, sprawling can be considered as a horizontal threat to sustainability, based on the aforementioned dimensions. Despite the classification, the threats described under each dimension are interrelated.

Fig. 2 – Main trends existing in European cities and threatening sustainability
Romanillos et al. (2014)

At the initial stage of the project, we designed ten sustainability objectives in order to face these threats, and we proposed several indicators for measuring the achievement of each objective (Romanillos et al., 2014). All these outcomes were evaluated in the stakeholder's consultation that was held in the project (García et al., 2014). In the consultation process, ten policy makers of European cities had to select the most important objectives from the list. The stakeholders also assessed the indicators proposed. All the indicators used in this analysis were considered to be relevant for their correspondent objectives by the majority of the stakeholders consulted. Table 1 summarises the sustainability objectives designed in the project and the main results of the stakeholder's consultation process. The detailed list of validated and available indicators in the four cities is showed later on in Table 4, with the correspondent values in each city. All this theoretical background has served to stablish the policy priorities in each city and the role played by the transport system.

Sustainability objective <i>Designed after a literature review about the main problems existing in cities</i>	Importance according to policy makers <i>Asked to select 2-3 objectives</i>	No. validated indicators <i>Considered relevant for the objective by the majority of stakeholders (at least by 5 of 10 stakeholders)</i>
Economic growth	Essential <i>(selected by 6 of 10 stakeholders)</i>	5
Economic efficiency	Little importance <i>(selected by 2 of 10 stakeholders)</i>	3
Liveable streets and neighbourhoods	Very important <i>(selected by 5 of 10 stakeholders)</i>	5
Equal, safe and secure society	Neutral <i>(selected by 3 of 10 stakeholders)</i>	11
Stop demographic decline	Unimportant <i>(selected by 0 of 10 stakeholders)</i>	4
Reduce contribution to climate change	Important <i>(selected by 4 of 10 stakeholders)</i>	3
Reduce pollution	Very important <i>(selected by 5 of 10 stakeholders)</i>	6
Reduce urban sprawl	Important <i>(selected by 4 of 10 stakeholders)</i>	3

Table 1 – Sustainability objectives for EU cities. Summary of the policy makers’ assessment

Compiled by authors from Romanillos et al. (2014) and García et al. (2014)

Table 1 shows the importance attached to the objectives by policy makers. The main objective for most of them resulted to be the economic growth. This concern was especially influenced by the economic crisis, which began to hit the global economy in the summer of 2007 (Directorate- General for Economic and Financial Affairs of the European Commission, 2009). It is noted that more than two thirds of the European Union’s workforce live in cities (European Union, 2011). Many of these cities are now exhibiting a dual personality of economic strength co-existing with weak demand and unemployment (Campbell et al. 2013). Unemployment reduction is a top priority across European cities, since the beginning of the European recession which has caused a large drop in economic activity in the EU, with millions of jobs lost (European Commission, 2012).

Environmental objectives were also considered of high importance. The concern about damages of urban development to natural resources is not new. Environmental sustainability objectives such as stop contribution to climate change or reduce pollution are probably the most classical policy objectives in this comparative (European Union, 2011). In fact, most stakeholders declared their commitment with these problems.

The objective of economic efficiency as well as other social objectives such as equity and to stop demographic decline were of lower priority.

2.1 Case studies

The four European cities involved in INSIGHT project are from three different countries, presenting heterogeneous characteristics and sizes (Fig. 3 and Table 2). There are two capital cities, London (England) and Madrid (Spain), both accounting for a significant percentage of their countries (19 and 14 % respectively) (EUROSTAT- General Statistics).

However, their sizes are very different; the population of London (12 million inhab.) nearly doubles the population of Madrid (6 million inhab.). The city of Barcelona (Spain) is very similar to Madrid in size and relevance for the country. Rotterdam with 1.4 million inhabitants is the smallest in this comparative, accounting for a 8 % of the population in Netherlands. Geographically, we have two cities from Southern Europe and two from Northern Europe. This will make differences in the results since the recent economic crisis has especially impacted Southern cities (European Union, 2011).

Fig. 3 – INSIGHT case studies represented in a map of EU cities illustrated by population

By authors from EUROSTAT Geographical information

VALIDATED INDICATORS	Unit	London		Madrid		Barcelona		Rotterdam	
		Central City	Metrop . Area	Central City	Metrop . Area	Central City	Metrop . Area	Central City	Metrop . Area
Population	M. Inhab.	8.4	12.3	3.2	6.4	1.6	5.4	0.6	1.4
Administrative Area	Km ²	1,595	12,091	606	7,961	98	7,716	208	1,243
Population density (Theoretical)	Inhab. / km ²	5,243	1,021	5,292	825	700	634	2,963	1,124

Table 2 – General characteristics of INSIGHT case studies. Reference year: 2013

3. METHODOLOGY AND RESULTS

In this section we present the methodology used to determine the priority policy objectives in each city, followed by the results, which are summarized in tables. The set of indicators allow analysing the present state of the objectives on a comparative basis, by looking at their actual values (2013) in the four cities. Moreover, by looking at the annual growths of the indicators along the years, we can measure the evolution (2007-2013) of the objectives

in each city. This paper considers these concepts and establishes the priorities having also into account the stakeholders' assessment. Finally, we analyse the role played by the land use and transport system in these policy objectives. The stages followed for this analysis have been:

- Set the theoretical framework, and support it by stakeholders' assessment (Table 1). This framework consists on a series of sustainability objectives to address the threats over cities, and indicators to measure them.
- Collection of the indicators from European and other international databases¹, where the data for the four cities was available. The year of reference for the comparison among cities was the 2013. The period of reference for analysing the evolution in each city was 2007-2013 (Table 3)
- Comparison of the values of the indicators in the four cities for the year 2013 (Table 4). This comparison leads to analyse the most negative values considering their related objectives and some practical considerations (Table 4, indicators in red). The practical considerations are necessary since some indicators have resulted unappropriated for measuring their related objectives.
- Calculation of the annual growth rates of the indicators (Table 5). In order to prioritize the objectives, we need to measure the importance of the correspondent threat, and this means measuring evolution. This rates lead to analyse again the most negative values on a comparative basis, this time regarding evolution (Table 5, indicators in red)
- Qualitative analysis to establish the policy priorities (Table 6). This analysis considers the values of the indicators for the year 2013 as well as the evolution of the indicators during the period 2007-2013 and the policy makers' assessment.
- Policy priorities: the most important policy sustainability objectives in each city (Table 7). These priorities have been established on a comparative basis and have considered the magnitude of the trends threatening the cities. In this stage we analyse from a theoretical point of view the possible land use and transport strategies that could help to achieve the policy priorities.

Sustainability objective	No. validated indicators	No. indicators available for the four cities <i>Reference year: 2013</i>	No. of indicators available for analysing evolution in the four cities <i>Reference period: 2007-2013</i>
Economic growth	5	3	3
Economic efficiency	3	3	2
Liveable streets and neighbourhoods	5	3	3
Equal, safe and secure society	11	3	1
Stop demographic decline	4	1	1
Reduce contribution to climate change	3	3	1
Reduce pollution	6	2	2
Reduce urban sprawl	3	3	1

Table 3 – Collection of indicators for the year 2013 and for the hole period 2007-2013

¹ OECD- Metropolitan Areas Aatabase, EUROSTAT- Regional Statistics, EUROSTAT- Urban Audit, EMTA Barometer, INRIX

Obj.	Indicators (Sign)	Unit	London		Madrid		Barcelona		Rotterdam	
			Cent. City	Met.. Area	Cent. City	Met.. Area	Cent. City	Met.. Area	Cent. City	Met.. Area
Economic Growth	GDP per capita (+)	€/inhab.	55,598		31,004		29,671		36,500	
	Employment rates of the working population (+)	%	70.6		59.0		57.3		71.8	
	Land price (+)	€/m ²	10.700	5.600	2.200		2.400		1,600	
Economic Efficiency	Unoccupied dwellings (-)	%	2.0	2.3	11.6	9.3	12.9	10.2	9.3	6.1
	Average time lost in congestion per driver (-)	Hours/driver	101		22		28		46	
	Labour productivity (added value per worker) (+)	€/employ- yed	78,366		69,401		67,048		63,079	
Liveable and secure streets	Green space per capita (+)	m ² / inhab.	37.9		27.4		2.5		72.4	
	No fatalities per 10,000 inhab. (-)	Ratio	0.183		0.159		0.317		0.178	
	Exposure of the population to air pollutants (-)	µg/m ³	10.3		10.9		11.1		17.1	
Equity	PT supply : (+) Bus	Veh-km / inhab.	58.3		41.4		25.8		13.3	
	Metro		9.0		2.0		4.0		7.5	
	Tram		0.3		4.9		0.5		5.6	
	Train		-		5.4		6.9		-	
	TOT		67.6		53.7		37.2		26.4	
	Income inequality GINI index (-)	Ratio	0.555		0.439		0.462		0.414	
Demog. Decline	People at risk of social exclusion(-)	%	24.8		19.2		21.8		14.2	
	Share of population over 65 years(-)	%	11.5	13.5	20.2	16.1	21.4	17.9	14.5	16.4
Stop Climate Change	GGE emissions per capita (-)	Tonnes/inhab.	7.9		7.1		5.7		16.4	
	GGE emissions by sector: Transport	%	31.2		43.6		39.4		43.1	
	Industry		10.8		1.9		7.4		11.4	
Reduce Pollut.	Air pollutants concentration(-): NO ₂	µg/m ³	36.7		30.3		31.8		30.6	
	PM ₁₀		18.5		17.7		21.6		21.0	
Reduce Sprawl	Urbanised surface (-)	Km ²	1,042		1,043		607		440	
	Population density (in urbanised surface) (-)	Inhab/km ²	8,077		6,228		8,305		5,114	
	Share of the metropolitan area population living in the city	%	60.3		50.0		29.6		42.8	

Table 4 – Values of the indicators associated to the objectives. Year 2013

(Sign) (+) if a higher value of the indicator is positive for the achievement of the objective and (-) is the opposite

Red colour: Indicators with the most negative values for their related objectives on a comparative basis

Grey cells: Transport and land use indicators

Annual growth rates 2007-2013 (%)										
Obj.	Indicators (Sign)	Unit	London		Madrid		Barcelona		Rotterdam	
			Cent. City	Met.. Area	Cent. City	Met.. Area	Cent. City	Met.. Area	Cent. City	Met.. Area
	Population	%	1.5	1.3	-0.7	0.2	-0.2	0.1	0.0	0.7
Economic Growth	GDP per capita (+)		0.0		-1.6		-2.1		-2.3	
	Employment rates of the working population (+)		0.0		-3.2		-3.5		-0.8	
	Land price (+)		8.8	0.9	-10.4		-11.1		-3.7	
Economic Efficiency	Average time lost in congestion per driver (-)		17.4		-11.2		-9.0		-3.6	
	Labour productivity (added value per worker) (+)		-0.1		2.0		3.2		-2.3	
Liveable and secure streets	Green space per capita		-1.2		-1.9		-1.1		0.4	
	No fatalities per 10,000 inhab. (-)		-10.5		-9.3		2.5		-10.0	
	Exposure of the population to air pollutants (-)		-3.8		-1.4		-1.9		-1.2	
Equity	People at risk of social exclusion (-)		1.4		2.9		4.1		-1.0	
Demog. Decline	Share of population over 65 years (-)		1.2	1.8	2.5	3.7	1.3	2.0	1.2	2.9
Stop Climate Change	GGE emissions per capita (-)		-2.0		-2.6		-2.7		-1.0	
Reduce Pollution	Air pollutants concentration: (-) NO ₂		-2.0		-4.5		-4.4		-3.0	
	PM ₁₀		-5.2		-5.6		-6.9		-6.3	
Reduce Sprawl	Share of the metropolitan area population living in the city (-)		0.2		-0.9		-0.2		-0.4	

Table 5 – Annual growth rates of the indicators associated to the objectives. Period 2007-2013

Sign (+) if a growth in the value of the indicator is positive for the achievement of the objective and (-) is the opposite

Red colour: Indicators whose evolution very negative for their related objectives on a comparative basis

Grey cells: Transport and land use indicators

	London	Madrid	Barcelona	Rotterdam
Economic Growth	London presents the highest GDP per capita in 2013 and especially the highest land prices. Is the only city in this comparative that does not present a negative evolution of economic indicators during the EU economic recession (2007-2013). The land prices have even grown in this period (this may indicate economic growth, but it is probably negative for the objective of equity since affects the costs of living).	Both Spanish cities present the lowest GDP per capita and employment rates. Moreover, all their economic indicators have deteriorated significantly during the crisis period. The land prices have dropped an average of 10-11 % per year. Employment rates have declined by a 3 % per year. This negative evolution is of especial concern since it is related to other threats such as demographic decline and social exclusion and polarisation.		Rotterdam presents the highest employment rate. The land prices are the lowest in this comparative, but this is not significant since the land prices decrease with city sizes (Quigley, 1998). The economic indicators present deterioration during the generalised EU recession but much less marked than in Madrid and Barcelona.
Economic Efficiency	Only congestion seems to be a great and growing problem for efficiency in London. However, congestion affects to the energy use, noise, pollution and emissions. Therefore we are going to consider the congestion reduction as priority for the case of London.	Madrid and Barcelona behave very similarly in economic terms. Regarding economic efficiency indicators: - The rate of empty dwellings is high, especially in the central cities. This is an effect associated to the gentrification (unaffordable prices in city centres) that make the population move to the periphery (Cameron, 2003), and is a reflection of the urban sprawl. - The labour productivity has increased in the recession period (less workers but more productive) - The congestion levels are quite good compared to London and Rotterdam and the evolution is positive. Probably associated to the slowdown of activities that leads to a reduction of transport demand and traffic levels (Preston and Rajé, 2007)		Rotterdam presents the highest labour productivity loses in this comparative. Unlike in the Spanish case studies, the GDP of Rotterdam has fallen below the employment rates, reducing the added value created per worker. Congestion in Rotterdam is high for the size of the city.
Liveab	The green space, exposure to pollution ad accident rates in London present quite good values for being such a big city. In addition, the evolution is in general positive.	Madrid presents the lowest rate of fatalities per capita in this comparative	Barcelona presents the lowest green space per capita and the highest number of fatalities per capita. Moreover, these last are growing.	Rotterdam accounts for a lot of green space per capita, although its population is highly exposed to pollution.
Equity	The inequality index and the level of social exclusion are very high in London compared to the rest of the cases. Therefore we are going to consider Equity as a priority for this case. Improving PT services helps to improve equity and inclusion by improving accessibility. The PT supply of London results to be the highest one, but this is not necessarily significant since the indicator is too dependent on the city size (Alonso et al., 2014)	The percentage of people at risk of social exclusion has grown in both Spanish cities in the period 2007-2008, although more in Barcelona than in Madrid. This is related to the economic decline and job losses.		Unlike in the case of London, the equity and social inclusion levels in Rotterdam are the best in this comparative. The PT supply is relatively small, this is not surprising, since this indicator is very dependent on the city size (Alonso et al., 2014).
Dem	The ageing of the population is a trend happening in the four case studies, while it is not a priority for policy makers. We can observe that in all cities except for London, the average age in the periphery is lower than in central cities. This is associated to the gentrification, which makes young families look for affordable houses in the periphery, and is one of the causes of urban sprawl (European Environment Agency, 2006). The percentage of people over 65 years is higher in Madrid and Barcelona and London has the youngest population.			
GGE poll.	The GGE per capita and the pollution levels have reduced in the four cities, probably helped by the slowdown in activities but also due to the stakeholders commitment with environmental problems in general (Alonso and Monzón, 2016). However, Rotterdam has an especially high level of GGE emissions per capita and as this is considered to be an important issue for policy makers we are going to consider it as a policy priority.			
Reduce Sprawl	The urban sprawl in London does not seem to be a great concern compared to the other case studies. The land occupation (urbanised surface) is not big for the size of the city, and the density is high. Moreover, it is the only city where the percentage of population living in the central city has not decreased.	Madrid has a widely dispersed urban population, and presents the biggest land occupation in this comparative. In addition, the population movements to the metropolitan ring are very significant. During the period 2007-2013 the central city has been constantly losing population weight. Therefore this is a priority concern in the city of Madrid.	Barcelona presents most dense urban population in this comparative. The percentage of people living in the central city is low, but this is due to the administrative organization of the city. However, this percentage has not decreased as much as in Rotterdam or Madrid.	Rotterdam accounts for the most dispersed urban population. Moreover, as has occurred in Madrid, the central city has been constantly losing population weight over the whole metropolitan area. Therefore this is a priority concern in the city of Rotterdam.

Table 6 – Qualitative analysis considering values from Tables 4 and 5 and the policy makers’ assessment (Table 1)

	London	Madrid	Barcelona	Rotterdam
Policy priorities	- Reduce congestion to increase efficiency - Equal society and avoid social exclusion	- Economic growth - Reduce/ Stop urban sprawl	- Economic growth - Increase liveability equity and security	- Reduce GGE emissions, and pollution exposure - Reduce/ Stop urban sprawl
Relation to land use and transport	- The congestion is a problem directly related to the land use and transport system, which creates economic inefficiencies and environmental problems. It is due to excessive car use and it can be solved by improving PT services, enhancing soft modes or pricing measures (European Commission, 2007) -The social exclusion is partially related to the segregation of residential zones according to income, and exacerbates social and economic divisions, enhancing inequality. The process usually leads to a growing degradation of the poorest areas, whose residents may be socially excluded due to the lack of accessibility to basic needs, jobs or activities (Preston and Raje, 2007). Some urban planning strategies can partly address this problem. Examples of these strategies are the promotion of tenure mix in housing or the improvement of accessibility levels - by improving PT or making it more affordable to access to these needs (Coline et al., 2013).	- Economic growth and job creation depend on demand, and cities can stimulate demand in many ways. In this regard, land use and transport management could help in some way to create a business- friendly environment, by providing good accessibility, competent transport networks or even liveable neighbourhoods (Campbell et al., 2013). These conditions can attract both businesses and people. - Urban sprawl is clearly a land use and transport issue, defined as the spread of low-density settlements, and considered as one of the main challenges that cities face (European Union, 2011). This threat can be addressed through higher density developments with good public transport connections, but also by preventing migration to peri-urban areas- improving inner city spaces in order to create more liveable and attractive environments or promoting housing mix to avoid gentrification.	- A liveable, equal and secure city accounts for good physical and social environments (Sclappa and Neil, 2013). Therefore, land use and transport strategies such as the increase of green areas and public spaces, the improvement of public services or the reduction of space dedicated to traffic and the enlargement of areas dedicated to pedestrians and bicycles can help to improve liveability, equity and security	- Urban areas consume more than two thirds of the total energy in EU, mainly due to building and transport sectors (UN-HABITAT, 2009). In addition, most of the energy sources are not renewable, and are responsible for air pollution and GGE. Especially in the transport sector where the strong dependence on cars and therefore on fuel cause also air pollution and noise (Enemark and Kneeshaw, 2013). In the case of Rotterdam a 43% of GGE come from the transport sector. Urban strategies designed to avoid sprawl, would help to reduce the environmental impact, since the density of urban areas allows for more energy efficient forms of housing, transport and service provision (European Union, 2011). On response to car dependence, policies such as integrated land use planning, improvement of public transport networks, car restrictions or expansion of infrastructures for pedestrians and cyclists are recommended (European Commission, 2007).

Table 7 – Policy priorities: the most important policy sustainability objectives in each city. Role of land use and transport strategies

4. CONCLUSIONS

European cities need to be sustainable, since they are the drivers of economic development and deliver many public services, such as education, healthcare and transportation

(European Union, 2011). However, urban areas in Europe are facing some trends that have become real threats to their sustainable development. In this paper we present a set of policy objectives, which have been designed for the management of urban areas, in order to face the main threats existing over cities. The objectives have undergone a stakeholder's assessment: ten policy makers from European cities have evaluated them in terms of importance and have validated a series of indicators related to them. This framework has been used to evaluate the policy priorities of four European cities: London, Madrid, Barcelona and Rotterdam. By comparing the values of the indicators in each city for the year 2013 and measuring the evolution of the indicators during the period 2007-2013, we have determined the most important objectives for each city. The priority objectives will respond to the weakness or main threats of the cities: Madrid and Barcelona should especially address the threat of economic decline, Rotterdam the sprawl and London the social exclusion.

Finally, the role played by the land use and transport system in these policy objectives is analysed. This analysis is partially supported by the indicators used, half of which are related to the land use and transport system of the cities. Land use and transport strategies reducing congestion help to achieve economic efficiency, as well as policies enhancing PT and soft modes help to reduce exclusion, liveability or even sprawl.

5. REFERENCES

ALONSO, A., MONZON, A., CASCAJO, R., 2015. Comparative analysis of passenger transport sustainability in European cities. *Ecological Indicators* 48(0), 578–592

ALONSO, A., MONZON, A., 2016. Assessing the progress towards sustainability and the role of urban transport- city of Madrid. *6th Transport Research Arena*, April 18-21, 2016, Warsaw, Poland

CAMERON, S., 2003. Gentrification, housing redifferentiation and urban regeneration: 'Going for Growth in Newcastle upon Tyne. *Urban Studies* 40(12), 2367-2382.

CAMPBELL, M., PARTRIDGE, A., SOTO, P., 2013. *More jobs: better cities- a framework for a better action on jobs*. Saint- Denis .URBACT

COLINI, L., CZISCHKE, D., GÜNTNER, S., TOSICS, I., & RAMSDEN, P., 2013. *Against divided cities in Europe*. Saint- Denis .URBACT

DIRECTORATE- GENERAL FOR ECONOMIC AND FINANCIAL AFFAIRS OF THE EUROPEAN COMMISSION. 2009. *Economic Crisis in Europe: Causes, Consequences and responses*. Luxembourg. : Office for Official Publications of the European Communities.

ENEMARK, A., KNEESHAW, S. 2013. *How cities can motivate mobility mindsets*. Saint- Denis .URBACT

EUROPEAN ENVIRONMENT AGENCY, 2006. *Urban sprawl in Europe- The ignored challenge*. Copenhagen.

EUROPEAN COMMISSION, 2007. *Green Paper: Towards a new culture for urban mobility*. COM (2007) 511 final. Brussels.

EUROPEAN COMMISSION, 2012. *Green Paper- Restructuring and anticipation of change: what lessons from recent experience?*. COM (2012) 7 final. Brussels: European Commission.

EUROPEAN UNION, 2011. *Cities of Tomorrow- Challenges, visions, ways forward*. Luxembourg.

GARCÍA, O., LUCIO, A., SALAS- OLMEDO, M.H., ROMANILLOS, G., ALONSO, A., FEIJOO, C., 2014. D2.1 Stakeholders consultation. INSIGHT 7FP – EC.

HAGHSHENAS, H., VAZIRI, M., 2012. Urban sustainable transportation indicators for global comparison. *Ecological Indicators* 15, 115-121.

NEWMAN, P., KENWORTHY, J., 1999. *Sustainability and cities: overcoming automobile dependence*. Island Press. Washington DC.

OECD, 2002. *Policy instruments for achieving Environmentally Sustainable Transport*. OECD Publishing, Paris.

PRESTON, J., RAJÉ, F., 2007. Accessibility, mobility and transport-related social exclusion. *Journal of Transport Geography*. 15(3), 151–160.

QUIGLEY, JOHN M.. 1998. “Urban Diversity and Economic Growth”. *The Journal of Economic Perspectives* 12 (2). American Economic Association: 127–38

ROMANILLOS, G., ALONSO, A., WANG, Y., 2014. D2.2 *Urban planning and governance: current practices and new challenges*. INSIGHT 7FP – EC

SCHLAPPA, H., NEILL, W. J., 2013. From crisis to choice: re-imagining the future in shrinking cities. URBACT

TANGUAY, G.A., RAJAONSON, J., LEFEBVRE, J., LANOIE, P., 2010. Measuring the

sustainability of cities: An analysis of the use of local indicators. *Ecological Indicators* 10, 407-418.

UN-HABITAT, 2009. *State of the world's cities 2008/2009*. London

UNITED NATIONS, 1992. United Nations Conference on Environment & Development
Rio de Janeiro, Brazil, 3 to 14 June 1992

INSIGHT project webpage:

<http://www.insight-fp7.eu/>

Online databases consulted:

EMTA Barometer

<http://www.emta.com/spip.php?article267&lang=en>

EUROSTAT

Geographical information

<http://ec.europa.eu/eurostat/cache/RSI/#?vis=nuts2.labourmarket&lang=en>

General Statistics

<http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-data/database>

Regional Statistics

<http://ec.europa.eu/eurostat/web/regions/data/database>

Urban Audit

<http://ec.europa.eu/eurostat/web/cities/data/database>

INRIX Traffic Score Card

<http://inrix.com/scorecard/>

OCDE- Metropolitan Areas Database

<http://stats.oecd.org/Index.aspx?Datasetcode=CITIES>

Proceedings of 6th Transport Research Arena, April 18-21, 2016, Warsaw, Poland

Assessing the progress towards sustainability and the role of urban transport- city of Madrid

Andrea Alonso^{a*}, Andrés Monzón^b

^aTRANSyT – Transport research Centre- Universidad Politécnica de Madrid, Calle Profesor Aranguren s/n, Madrid 28040, Spain

^bTransport Civil Engineering Department, Universidad Politécnica de Madrid, Calle Profesor Aranguren s/n, Madrid 28040, Spain

---

Abstract

Most European urban areas are facing some trends that have become real threats to their sustainable development: demographic decline and socio-spatial segregation; depletion of natural resources and environmental damages; pressures over economic development or competitiveness associated to the economic crisis; and finally urban sprawl, which contributes to segregation, inefficient service delivery, land occupation and degradation. The theoretical framework developed in the European project INSIGHT-7FP has set the basis to address these threats in city management: ten sustainability objectives have been designed together with 53 indicators to measure the progress towards the objectives. In this paper, we develop a methodology to analyse if we are achieving the objectives- especially those objectives related to transport. The methodology analyses the indicators by a statistical exploratory technique, and it is applied to the city of Madrid. Results show that the city of Madrid has recently progress towards many environmental objectives, and deviated from the economic ones. Considering the evolution of the city during the whole period analysed (2004/13), the problem of urban sprawl should especially be addressed. Out of the 53 indicators, 15 are directly related to the transport system, these indicators are analysed separately to assess the role played by urban transport.

Keywords: urban threats, sustainability objectives, city management, urban transport

---

1. Introduction and background

Sustainability must be an urban issue (Newman and Kenworthy, 1999). Cities should be managed so as to minimize their impacts on environment, but providing an appropriate framework for economic and social development (United Nations, 1972). In Europe, over 60% of the population lives in cities, where a bit less than 85% of the EU's GDP is generated (European Commission, 2007). Urban areas play a key role in the development of European territories. However, European cities are nowadays facing some trends that threaten sustainable development (European Union, 2011). *“The aim of the research project INSIGHT-7 FP (2015) is to develop appropriate management tools that can help to achieve sustainability in the context of European cities”*. In the project, ten sustainability objectives have been designed for the management of urban areas, in order to face the

Proceedings of 6th Transport Research Arena, April 18-21, 2016, Warsaw, Poland

main threats over cities (Romanillos et al., 2014). This paper presents a methodology based on indicators for analysing the progress towards the objectives designed. Indicators are considered to be appropriated tools to analyse the many overlapping areas of sustainability (Newman and Kenworthy, 1999), and many authors have already applied them to cities for this very purpose (Tanguay, 2010; Haghshenas and Vaziri., 2012; Alonso et al., 2014). All the indicators used in the analysis have been validated by ten policy makers of European cities. These policy makers participated on the stakeholders consultation carried out in the project (García et al., 2014), where the importance of the ten sustainability objectives proposed was also assessed. The methodology developed is applied to the city of Madrid, which is one of the four case studies of the project. The progress towards the objectives in the case of Madrid is analysed in this paper, together with the importance given to each objective by stakeholders. Finally, the role played by urban transport management in the progress or deviation from the objectives is showed.

The paper aims to develop a methodology to analyse if we are achieving the objectives in city management, specifically the sustainability objectives proposed. Also it aims to understand how the policy makers value the importance of the objectives. All together will allow to prioritize the objectives and the policies to be implemented, including transport management policies. The paper is structured in five sections. Section 2 details framework and methods used for the analysis. Section 3 presents the results for the case study application. Section 5 then concludes, summarising the key findings that can be useful for future policy and research.

2. Framework and methodology

This section explains the theoretical framework developed in INSIGHT, which has set the basis of the analysis, and introduces the case study application. Finally, the section details the methods used to get the results.

2.1. Theoretical framework for urban planning in European cities- setting the objectives

The first step of INSIGHT project was to study the main trends that threaten sustainability in European cities, in order to design appropriate objectives and policies for city management. For this, we recurred to the main reference document on urban problems at European level, which comes from the initiative Cities of Tomorrow (European Union, 2011). Considering sustainable development as a concept divided into three dimensions: society, environment and economy (OECD, 2002; Tanguay et al., 2010; Haghshenas and Vaziri, 2012), the main trends existing in European cities and threatening each dimension are described below:

Society: the weight of working-age population is decreasing due to the low birth rate, the increase in life expectancy and the migration of active population due to the lack of job opportunities. In addition, the socio-spatial segregation is growing, associated to socio-economic inequalities. Urban transport systems are related to this trend, since they affect the livability of cities and provide accessibility (a concept linked to equity).

Environment: the endless consumption of natural resources during urban growth and sprawl continues to pose a threat to the environment. This negative impact of urban development must be addressed to contain the resulting environmental damage.

Economy: a lot of problems associated with economic sustainability started appearing with the Eurozone crisis. The recent recession has been putting pressure over economic development and competitiveness.

Finally, urban sprawl witnessed by Europe in the latest decades has adversely impacted society, environment and economic efficiency (European Environment Agency, 2006). Therefore, sprawling can be considered as a horizontal threat to sustainability, based on the aforementioned dimensions. Despite the classification, the threats described under each dimension are interrelated.

At the initial stage of the project, we designed ten sustainability objectives in order to face these threats, and we proposed several indicators for measuring the achievement of each objective (Romanillos et al., 2014). All these outcomes were evaluated in the stakeholder's consultation that was held in the project (García et al., 2014). In the consultation process, ten policy makers of European cities had to select the most important objectives from the list. The stakeholders also assessed the indicators proposed. All the indicators used in this analysis were considered to be relevant for their correspondent objectives by the majority of the stakeholders consulted. Table 1 summarises the sustainability objectives designed in the project and the main results of the stakeholder's consultation process. The detailed list of validated indicators is showed later on in Table 2, together with some results for the city of Madrid.

Table 1. Sustainability objectives and indicators assessed by stakeholders

No.	Sustainability objectives	Importance according to stakeholders <i>Asked to select 3-4 objectives</i>	No. validated indicators <i>considered relevant for the obj. by the majority of stakeholders</i>
1	Economic growth	Essential <i>(selected by 6 of 10 stakeholders)</i>	5 indicators
2	Economic efficiency	Little importance <i>(selected by 2 of 10 stakeholders)</i>	3 indicators
3	Liveable streets and neighbourhoods	Very important <i>(selected by 5 of 10 stakeholders)</i>	5 indicators
4	Equal, safe and secure society	Neutral <i>(selected by 3 of 10 stakeholders)</i>	11 indicators
5	Stop demographic decline	Unimportant <i>(selected by 0 of 10 stakeholders)</i>	4 indicators
6	Human capital improvement	Little importance <i>(selected by 1 of 10 stakeholders)</i>	2 indicators
7	Reduce energy consumption, especially from non-renewable sources	Very important <i>(selected by 5 of 10 stakeholders)</i>	9 indicators
8	Reduce contribution to climate change	Important <i>(selected by 4 of 10 stakeholders)</i>	3 indicators
9	Reduce pollution: air pollution	Very important <i>(selected by 5 of 10 stakeholders)</i>	6 indicators
	noise pollution	Unimportant <i>(selected by 0 of 10 stakeholders)</i>	2 indicators
10	Reduce urban sprawl	Important <i>(selected by 4 of 10 stakeholders)</i>	3 indicators
			TOT: 53 indicators

Compiled by authors from Romanillos et al. (2014) and García et al. (2014)

2.2. Case study application- the city of Madrid

Four European cities are involved in INSIGHT project as case studies to analyse and model: London, Madrid, Barcelona and Rotterdam. This paper is focused in the city of Madrid, which is the capital of Spain and the country's most populated city. Approximately half of its **6.4 million inhabitants** live in the Central City, while the rest live in the suburbs (ALMUDENA, 2013). The whole city spreads on a **8,080 km²-area**. A **12%** of this area is **urban surface**, half of which is built-up land (DESVAN, 2013). In order to analyse the evolution of Madrid in relation to the objectives proposed in the project, first we have collected the 53 indicators validated by policy makers for each year of the period 2004-2013. In the middle of this period (2007) the financial crisis began to hit the European economy (European Commission, 2009). The economic crisis has changed many trends in relation to the objectives and threats exposed (European Union, 2011). For this reason, in the analysis we always distinguish between the period 2004/07 of economic growth and the period 2008/13 of economic recession. The results and conclusions presented especially underline the last period of analysis (2008/13), in which the threats over economic sustainability have become more important. Table 2 shows part of the information collected, containing the 53 indicators and its values for the years 2004, 2008 and 2013. The indicators for the rest of the years of the period have also been collected and used in the calculations, although not shown in the Table.

2.3. Treatment of validated indicators for each objective

The aim of the paper is to measure the progress of a city towards the sustainability objectives and against the threats. For this reason, we focus the analysis on measuring the evolution of the indicators. In order to evaluate their trends, we propose to treat the indicators with a formula to be applied to time-series data. The formula is recommended by the EC-Joint Research Centre (Saisana and Tarantola, 2002) for analysing trends over the years:

$$\text{Annual progress towards the objective (I): } API (\%) = \text{Sign} * \frac{\sum_{t=1}^n \frac{I^t - I^{t-1}}{I^{t-1}}}{n-1} * 100 \quad (1) \quad \text{Where,}$$

API measures the progress (if it is >0) or the deviation (if it is <0) of the indicator *I* towards the related sustainability objective. *Sign* is (+1) if the growth of the indicator is positive for the achievement of the objective and (-1) if the growth of the indicator is negative for the achievement of the objective. *I^t* and *I^{t-1}* are the values of the indicator *I* in year *t* and the previous year (*t-1*). *n* is the number of years in the period analysed (2004/07 *n*=3, 2008/13 *n*=4, 2004, *n*=9)

Therefore, the *API* is the average annual growth or decrease of the indicator *I* over a period of *n-1* years. This measure considers simultaneously the values of the indicator *I* in all the years of the period analysed. Hence, it has the advantage of not depending on spot values of one particular year.

Table 2. Indicators related to sustainability objectives 1- 10 in Madrid (transport indicators coloured in green). Years 2004, 2008 and 2013

Ob.	Indicators	Unit	2004	2008	2013
1	Household budget	€ per household	29,806	37,548	31,456
	GDP per capita	€ per inhabitant	26,064	31,227	28,915
	Unemployed	No. of unemployed	253,804	221,732	532,063
	Job creation	No. of job places	2,664,966	2,949,640	2,672,138
	Land prices	€ per m ²	2,298	3,005	1,998
2	Unoccupied flats or buildings	No.	366,075	410,000	443,986
	Congestion- traffic density: Big streets	ADT	159,025	165,512	122,675
	Medium streets	ADT	106,049	110,332	107,029
	Small streets	ADT	67,813	69,423	53,242
	Time spent travelling	min	47.3	41.0	31.2
3	Pedestrians and cyclists injured in traffic accidents	No.	39	37	35
	Space for pedestrian use	Km ²	94	98	103
	Length of bicycle lanes	Km	108	190	290
	Road land occupation	Km ²	88	91	90
	Green areas	Km ²	130	148	163
4	Public Transport (PT) supply (all modes)	M. Seats-km	54,951	64,334	61,503
	PT supply Central City	M. Seats-km	34,840	41,608	39,941
	PT supply Suburbs	M. Seats-km	20,111	22,726	21,562
	Income inequality- S80/S20 ratio	Ratio (no unit)	5.5	5.7	6.1
	Share of the budget devoted to main needs	%	65.3	59.9	64.9
	Essential services provision in each zone (space devoted to health, educational and social services)	Km ²	65	84	86
	Central City	Km ²	20	25	25
	Suburbs	Km ²	45	59	61
	Traffic accidents with casualties	No.	9,142	10,261	11,160
	Fatalities occurred in traffic accidents	No.	97	85	64
	Crime according to surveys (share of persons that report delinquency and vandalism problems)	%	51.0	52.2	54.0
5	Share of active population	%	51.1	54.6	52.2
	Share of population over 60 years	%	18.9	19.2	20.9
	Share of population under 25 years	%	27.4	25.7	25.2
	Share of skilled workers	%	45.7	52.2	51.8
6	Drop-out rates from secondary education	%	25.6	27.1	19.7
	Cultural offer (no. of cinemas and cultural offer)	No.	203	213	228
7	Energy consumption	Ktoe.	10,619	11,614	9,716
	Energy cons. main sectors: Transport	Ktoe.	5,233	5,814	4,936
	Housing	Ktoe.	2,636	2,668	2,312
	Industry	Ktoe.	1,282	1,378	763
	Fuel dependence (energy coming from petrol and carbon sources)	%	60.1	57.6	55.8
	Fuel dependence in relevant sectors: Transport	%	98.0	97.0	96.6
	Industry	%	22.5	18.0	18.1
	Services	%	4.1	2.4	2.0
	Share of energy cons. from renewable sources	%	1.4	1.4	1.9
8	Greenhouse Gases Emissions (GGE)	KT CO ₂ eq	22,767	23,228	17,325
	GGE by main sectors: Transport	KT CO ₂ eq	9,740	10,369	7,758
	Industry	KT CO ₂ eq	4,521	4,323	2,424
9	Deaths from diseases potentially related to pollution	%	47.0	48.3	45.9
	Avrg. air concentration of: NO _x	µg/m ³	120	96	66
	Particles	µg/m ³	34	27	18
	Total emissions of : NO _x	Tons	91,916	75,798	48,577
	Particles	Tons	111,369	97,635	87,284
	Emissions in relevant sectors: Transport NO _x	Tons	61,958	59,166	39,159
	Transport particles	Tons	12,764	7,273	4,907
	Industry NO _x	Tons	13,833	10,800	4,084
	Industry particles	Tons	1,654	1,662	1,119
	Noise intensity levels	LAeq dBA	65.4	65.29	63.10
	Population declaring noise problems	%	30.1	26.9	14.2
10	Urban density (inhabitants per urban surface)	Inhab/ Km ²	6,321	6,263	6,045
	Land occupied – built up land	Km ²	50	52	56
	Share of the population living in the Central City	%	53.4	51.2	49.4

Sources: ALMUDENA (2013), BACO (2013), DESVAN (2013), DGT (2013), INE (2013), OMM (2013)

2.4. Correspondence Analysis for analyzing the progress towards the objectives

Correspondence Analysis (CA) is an exploratory technique for analysing the association between pairs of objects and/or descriptive characteristics/attributes (Hair et al., 2010). Most applications of this technique involve the correspondence of characteristics of variables measured on nominal scales. Here, the variables are the *indicators*. Each indicator is characterized by a related *objective* (acting as an object), a related *importance* (acting as an attribute), and a degree of *progress towards the objective* (acting as descriptive characteristic). The results of the paper are based in the associations between these elements. Fig. 1 summarises the procedure followed to obtain the nominal and descriptive characteristics of each indicator, showed in Table 3, which are the inputs for the CA.

Fig 1. Methodology followed to get the input for the CA

The perceptual map is the main output of the CA. The perceptual map is a multi-dimensional map that allows visualising the associations among elements spatially on dimensional axes; in other words, which elements are close to other elements on empirically derived dimensions. To carry out the CA we have followed the process suggested by Hair et al. (2010):

- **Research design of CA inputs:** rectangular data matrix (i.e. Table 3 in the following section), containing the variables (indicators), with its elements: objects (i.e. objectives), attributes (i.e. importance) or descriptive characteristics (i.e. progress)
- **Set the objectives of the CA:** the associations to be explored (between pairs of elements: objects and/or descriptive characteristics/attributes)
- **Assess the relative importance of the dimensions** and identify the appropriate number of dimensions to **include** in the **perceptual map**: dimensions are characterized by their inertia (relative contribution of each dimension in explaining the variance in the elements). Each dimension added to the solution contributes to explain the association or variance between elements but at a decreasing amount (i.e. the first dimension explains the most variance, the second dimension the second greatest...). The maximum number of dimensions that can be estimated is one less than the smaller of the number of categories of the elements (i.e. the element *importance* has six categories). However, adding dimensions increases the complexity of interpreting the perceptual map. The more accepted rule is that if the dimensions derived have an inertia > 0.2 significant associations exist between the pair of elements being analysed (Bendixen, 1996). At the same time all dimensions with inertia > 0.2 should be included in the analysis (Hair et al., 2010).
- **Interpretation of the perceptual map** and logic of results

3. Results

Table 3 shows the first relevant results for this paper. It characterises the 53 indicators for the city of Madrid, the indicators appear ordered by their progress towards the objectives during the last period 2008/13 of economic crisis.

Table 3. Inputs for the CA. Indicators characterised for the city of Madrid.

	Indicators (I) (ordered by annual progress in the last 5 years: 2008/2013)	Sustainability objective (no.)	Importance	Sign: Growth is (+) or (-) for objective?	Annual progress tow. the objective (I) (%) formula (1)			Summary (progress 2004/13)
					2004/07 E.Growth	2008/13 E. Crisis	2004/2013	
Significant progress (1-11)	1. Pop. suffering noise	Red. pollution (9)	Unimportant	(-1)	2.3	14.9	9.3	Recent progress
	2. Industry emissions	Red. pollution (9)	V. important	(-1)	2.5	12.3	7.9	Recent progress
	3. Industry enrgy cons.	Energy saving (7)	V. important	(-1)	-1.8	11.0	5.3	Recent progress
	4. Industry GGE	Stp Cl. Change (8)	Important	(+1)	0.6	10.4	6.0	Recent progress
	5. Time travelling	Ec. efficiency (2)	Lit. imprtnc	(-1)	3.5	9.6	6.9	Recent progress
	6. Bicycle lanes	Livble streets (3)	V. important	(+1)	24.5	9.5	16.2	General progress
	7. Transport emissions	Red. pollution (9)	V. important	(-1)	6.9	7.7	7.3	Recent progress
	8. Particles air conc.	Red. pollution (9)	V. important	(-1)	5.0	7.5	6.4	Recent progress
	9. Educ. Drop-out	Human capital (6)	Lit. imprtnc	(-1)	-1.5	5.8	2.6	Recent progress
	10. GGE emissions	Stp Cl. Change (8)	Important	(-1)	-0.6	5.7	2.9	Recent progress
	11. NO _x air conc.	Red. pollution (9)	V.important	(-1)	5.3	5.6	5.5	General progress
Progress (12-22)	12. Transport GGE	Stp Cl. Change (8)	Important	(-1)	-1.7	5.5	2.4	Recent progress
	13. Renewable energy	Energy saving(7)	V. important	(+1)	0.5	5.5	3.3	General progress
	14. Emissions	Red. pollution (9)	V. important	(-1)	2.4	5.3	4.0	Recent progress
	15. Congestion	Ec. efficiency (2)	Lit. imprtnc	(-1)	-0.4	5.2	2.7	Recent progress
	16. Traffic fatalities	Equity & safty (4)	Neutral	(-1)	-0.7	4.6	2.2	Recent progress
	17. Energy cons.	Energy saving (7)	V. important	(-1)	-2.3	3.5	0.9	Recent progress
	18. Transp. enrgy cons.	Energy saving (7)	V. important	(-1)	-2.7	3.2	0.6	Recent progress
	19. Services petrol dep.	Energy saving (7)	V. important	(-1)	12.4	3.0	7.2	General progress
	20. Hous. energy cons.	Energy saving (7)	V. important	(-1)	-0.3	2.8	1.4	Recent progress
	21. Industry petrol dep.	Energy saving (7)	V. important	(-1)	10.4	2.1	5.8	General progress
	22. Green areas	Livble streets (3)	V. important	(+1)	3.2	2.0	2.5	Recent progress
Stable (23-33)	23. Cultural offer	Human capital (6)	Lit. imprtnc	(+1)	1.2	1.4	1.3	General progress
	24. Space for pedestrians	Livble streets (3)	V. important	(+1)	1.2	1.0	1.1	General progress
	25. Pollution diseases	Red.pollution (9)	V.important	(-1)	-0.7	1.0	0.2	General progress
	26. % skilled workers	Dem. Decline (8)	Unimportant	(+1)	3.5	0.9	2.1	General progress
	27. Subrbs services prov.	Equity & safty (4)	Neutral	(+1)	7.6	0.7	3.8	General progress
	28. Noise intensity levels	Red. pollution (9)	V. important	(-1)	-0.1	0.7	0.3	General progress
	29. Petrol dependence	Energy saving (7)	V. important	(-1)	1.1	0.6	0.8	General progress
	30. Services supply	Equity & safty (4)	Neutral	(+1)	7.0	0.5	3.4	General progress
	31. Transp. petrol dep.	Energy saving (7)	V. important	(-1)	0.3	0.1	0.2	General progress
	32. Main city serv. prov.	Equity & safty (4)	Neutral	(+1)	6.1	0.0	2.7	General progress
	33. Pdest. & cycl. injurd	Livble streets (3)	Neutral	(-1)	-2.5	-0.2	-1.2	Constant deviation
Deviation (34-44)	34. % of Pop < 25 years	Dem. Decline (8)	Unimportant	(+1)	-1.1	-0.4	-0.7	Constant deviation
	35. Main city PT supply	Equity & safty (4)	Neutral	(+1)	4.7	-0.7	1.7	Recent dev./global prog.
	36. % Pop. in Cent.City	Stp sprawl (10)	Important	(+1)	-1.0	-0.7	-0.9	Constant deviation
	37. PT supply	Equity & safty (4)	Neutral	(+1)	4.1	-0.8	1.3	Recent dev./global prog
	38. % active population	Dem. Decline (8)	Unimportant	(+1)	1.7	-0.9	0.2	Recent dev./global prog
	39. Suburbs PT supply	Equity & safty (4)	Neutral	(+1)	3.2	-1.0	0.8	Recent dev./global prog
	40. GDP per capita	Econ. growth (1)	Essential	(+1)	4.6	-1.5	1.2	Recent dev./global prog
	41. Income inequality	Equity & safty (4)	Neutral	(-1)	-1.3	-1.6	-1.5	Constant deviation
	42. Unoc. dwellings	Ec. efficiency (2)	Lit. imprtnc	(-1)	-2.9	-1.6	-2.2	Constant deviation
	43. Budget main needs	Equity & safty (4)	Neutral	(-1)	2.0	-1.6	0.0	Recent deviation
	44. % of Pop > 60 years	Dem. Decline (8)	Unimportant	(-1)	-0.3	-1.6	-1.1	Constant deviation
Significant deviation (45-53)	45. Built up land	Stp sprawl (10)	Important	(-1)	-1.0	-1.8	-1.4	Constant deviation
	46. Road occupation	Livble streets (3)	V. important	(-1)	1.4	-1.8	-0.3	Recent deviation
	47. Traffic accidents	Equity & safty (4)	Neutral	(-1)	-4.9	-1.8	-3.2	Constant deviation
	48. Job creation	Ec. growth (1)	Essential	(+1)	2.7	-1.9	0.1	Recent dev./global prog
	49. Crime	Equity & safty (4)	Neutral	(-1)	0.9	-2.0	-0.7	Constant deviation
	50. Urban density	Stp sprawl (10)	Important	(+1)	-0.3	-2.4	-1.3	Recent deviation
	51. Household budget	Ec. growth (1)	Essential	(+1)	6.0	-2.8	1.1	Recent dev./global prog
	52. Land prices	Ec. growth (1)	Essential	(+1)	7.1	-7.8	-1.2	Recent deviation
	53. Unemployment	Ec. growth (1)	Essential	(-1)	3.2	-20.2	-9.8	Recent deviation

The elaboration of Table 3 corresponds to the first stage of the CA: **research design of CA inputs**. In the table, the inputs for the CA are displayed in the form of a rectangular data matrix. The next stage is to **set the objectives** of the analysis. In this paper we aim to explore the associations between the following pairs of elements:

I.a) Sustainability objectives (acting as objects with ten categories: from 1 to 10) - Degree of **Progress 2008/13** (acting as a descriptive characteristic of five categories: significant progress, progress, stable, deviation, significant deviation)

I.b) Sustainability objectives - Summary of progress 2004/13 (acting as a descriptive characteristic of five categories: recent progress, general progress, recent deviation but general progress, recent deviation, constant deviation)

II.a) Importance (acting as an attribute of six categories: essential, v. imp., imp., neutral, lit. imp., unimp.) – **Progress 2008/13**

II.b) Importance– Summary Progress 2004/13

The association between pairs of elements is measured by the Inertia of the dimensions derived by CA. The Inertia values for the pairs explored in this case (Table 4) are used to **assess the dimensions** of the perceptual maps.

Table 4. Inertia values of the CA dimensions for each pair of elements to be explored¹

	Dimension 1	Dimension 2	Dimension 3	Dimension 4	TOT	(*) Main Dim (Inertia >0.2)
Ia) Objectives- Progress	0.675*	0.257*	0.164	0.098	1.194	2
Ib) Objectives- Summary	0.647*	0.309*	0.201*	0.033	1.190	3
IIa) Importance- Progress	0.399*	0.233*	0.132	0.000	0.754	2
IIb) Importance-Summary	0.505*	0.157	0.086	0.003	0.751	1

¹ CA processed with Chi-Square distance measures and symmetrical normalization method, according to standard procedure (Hair et al., 2010)

Fig 2. CA Perceptual maps (a) Ia) Objectives- Progress 2008/13 (2 Dim) (b) Ib) Objectives- Summary Progress 2004/13 (3 Dim)

In the third stage of the CA process, we check that all the pairs of elements explored present at least one dimension (Dim. 1) with Inertia >0.2 . This means that important associations can be found among the elements' categories (Bendixen, 1996). At the same time, the **perceptual maps** are represented **including all dimensions with Inertia >0.2** (Fig 2 and 3), since all these dimensions should be considered in the analysis (Hair et al., 2010).

The **interpretation of the perceptual maps** is the last stage of the CA process. In order to facilitate it, we have grouped the categories that seem to be more associated in the perceptual maps: those categories clearly closer in the multidimensional space appear inside the same red circle. Fig 2a shows that there are two sustainability objectives from which the city of Madrid has significantly deviated during the last period (2008/13): economic growth and stop urban sprawl. The economic indicators reveal a clear economic decline during the last period of economic recession, where for example the number of unemployed inhabitants has grown on average a 20% per year (Table 3). Indicators on urban sprawl demonstrate that this threat is also very relevant for the city. But if we observe both trends from a global perspective (period 2004/13), we can see that they have behaved very differently. The economic outlook has worsened very fast, but very recently, and in fact some economic indicators have globally improved since 2004 (i.e. GDP - Table 3). On the contrary, urban sprawl has been a constant trend, and probably more worrying, since Madrid's population has been steadily dispersing during the global period 2004/13. Other threat that has been constantly growing is the demographic decline (Fig 2b). Madrid has deviated from the objective of stopping this trend, but the deviation is not as significant as in the case of economic growth or stop urban sprawl (Fig 2a). On the other hand, the city has progress towards energy saving, and towards social objectives such as human capital improvement or liveable streets. The most significant progress has been achieved in environmental objectives. Madrid has significantly reduced its pollution and its contribution to climate change during the most recent period (2008/13), probably helped by the general slowdown of activities during the economic crisis.

Fig 3 shows the importance attached to the objectives by policy makers in relation to the progress or deviation towards them. Those objectives from which the city is significantly deviating are considered to be essential (economic growth) (Fig 3a), even when the deviation is very recent and the global evolution is positive (2004/13) (Fig 3b). There are some other objectives whose progress is favourable and are considered of high importance: mainly those related to the environment. The concern about damages of urban development to natural resources is not new, and environmental sustainability objectives such as stop contribution to climate change or reduce pollution are probably the most classical policy objectives in this comparative (European Union, 2011). This relatively old concern has ended up giving good results: environmental indicators show a positive progress towards the objectives (i.e. share of renewable has grown and petrol dependence has decreased since 2004- Table 3). In addition, the slowdown of activities during the economic crisis has also helped to reduce emissions or energy consumption.

Fig 3. CA Perceptual maps (a) Ila) Importance-Progress 2008/13 (2 Dim) (b) Iib) Importance-Summary Progr. 2004/13 (1 Dim)

Finally, in order to analyse the role played by transport management, we conduct other CA just considering the 15 transport related indicators, which are characterized in Table 5.

Table 5. Input for the CA analysis on transport. Indicators characterised for the city of Madrid

Transport Indicators (I) (ordered by progress in 2008/2013)	Transp. policy objective	Summary(progress 2004/13)
Significant progress (1-11)	5. Time travelling	Recent progress
	6. Length of bicycle lanes	General progress
	7. Transport emissions	Recent progress
Progress (12-22)	12. Transport GGE	Recent progress
	15. Congestion levels	Recent progress
	16. Fatalities in traffic accidents	Recent progress
	18. Transport energy consumption	Recent progress
Stable (23-33)	24. Space for pedestrian use	General progress
	31. Transport Petrol dependence	General progress
	33. Vulnerable users injured in traffic accidents	Constant deviation
Deviation (34-44)	35. Main city PT supply	Recent deviation but global progress
	37. PT supply	Recent deviation but global progress
	39. Suburbs PT supply	Recent deviation but global progress
Significant deviation (45-53)	46. Road land occupation	Recent deviation
	47. Traffic accidents	Constant deviation

The elements of Table 5 are the input for the CA displayed in the form of a rectangular data matrix. The objective in this second CA is to explore the associations between the following pairs of elements:

III.a) Progress 2008/13– Transport policy objectives (acting as objects with four categories: transport efficiency, transport liveability, transport environment, transport equity and safety)

III.b) Summary Progress 2008/13– Transport policy objectives (objects)

Table 6 summarises the assessment of the dimensions that have been included in the analysis (Inertia>0.2) and that are represented in the perceptual maps (Fig 4)

Table 6. Inertia values of the CA dimensions for each pair of elements to be explored ¹

	Dimension 1	Dimension 2	Dimension 3	TOT	(*) Main Dim (Inertia >0.2)
IIIa)Prog.- Trans.	1.000*	0.345*	0.058	1.403	2
IIIb)Sum.-Trans.	1.000*	0.531*	0.052	1.583	2

¹ CA processed with Chi- Square distance measures and symmetrical normalization method, according to standard procedure (Hair et al., 2010)

Fig 4. CA Perceptual maps (a) IIIa) Transp. -Progress 2008/13 (2 Dim) (b) IIIb) Transp. -Summary Progr. 2004/13 (2 Dim)

Perceptual maps of Fig 4 show that during the period of economic crisis, Madrid's urban transport system has reduced its environmental damage and has contributed to the objective of economic efficiency. This effect is mainly due to a recent reduction in car traffic levels and therefore of congestion, emissions and energy. On the contrary, the system has deviated from the objective of equity (Fig 4a), but the deviation is very recent (2008/13) and the global evolution (2004/13) is positive (Fig 4b). This is due to the reduction of PT supply during the economic crisis period. The progress towards transport liveability in the city of Madrid is more difficult to classify. From one side the road occupation has grown, a negative effect associated to the suburbanization process. From the other side, the space devoted to pedestrians and cyclist has increased in many zones of the central city, improving its liveability.

4. Conclusions

Results for the last period of economic crisis (2008/13) show that the city of Madrid has recently deviated from economic objectives, and progress towards many environmental ones. Considering the evolution of the city during the whole period analysed (2004/13), the problem of urban sprawl should especially be addressed. Nevertheless policy makers attach more importance to the more recent problem of economic decline. Finally, the transport system has clearly contributed to the progress towards environmental objectives reducing emissions and energy, but has recently deviated from the objectives of equity reducing the PT supply during the last years of economic restrictions.

5. References

- Alonso, A., Monzón, A., Cascajo, R., 2015. Comparative analysis of passenger transport sustainability in European cities. *Ecol. Indic.* 48(0), 578–592.
- Bendixen, M., 1996. A practical guide to the use of correspondence analysis in marketing research. *Marketing Research On-Line*, 1(1), 16-36.
- European Commission, 2007. Green Paper: Towards a new culture for urban mobility. COM (2007) 511 final. Brussels.
- European Commission, 2009. Economic Crisis in Europe: Causes, Consequences and responses. Directorate- General for Economic and Financial Affairs of the European Commission. Luxembourg.
- European Commission, 2011. White Paper: Roadmap to a Single European Transport Area- Towards a competitive and resource efficient transport system. COM(2011) 144 final. Brussels.
- European Environment Agency, 2006. Urban sprawl in Europe- The ignored challenge. Copenhagen.
- European Union, 2011. Cities of Tomorrow- Challenges, visions, ways forward. Luxembourg
- García, O., Lucio, A., Salas- Olmedo, M.H., Romanillos, G., Alonso, A., Feijoo, C., 2014. D2.1 Stakeholders consultation. INSIGHT 7FP – EC
- Haghshenas, H., Vaziri, M., 2012. Urban sustainable transportation indicators for global comparison. *Ecol. Ind.* 15, 115-121.
- Hair, J.F., W.C., B., Babin, B.J., Anderson, R.E., 2010. *Multivariate Data Analysis*. Pearson Prentice Hall, New jersey.
- INSIGHT, 2015. Project INSIGHT (2013/16) - 7FP URL. <http://www.insight-7fp.eu> (accessed 23.09.15).
- Monzón, A., Cascajo, R., Alonso, A., García, A., Tadeo, A., 2014. Informe 2012 del Observatorio de la Movilidad Metropolitana. Ministerio de Agricultura, Alimentación y Medio Ambiente, Madrid
- Newman, P., Kenworthy, J., 1999. *Sustainability and cities: overcoming automobile dependence*. Island Press. Washington DC.
- OECD, 2002. *Policy instruments for achieving Environmentally Sustainable Transport*. OECD Publishing, Paris.
- Romanillos, G., Alonso, A., Wang, Y., 2014. D2.2 Urban planning and governance: current practices and new challenges. INSIGHT 7FP – EC
- Saisana, M., Tarantola, S., 2002. *Report on Current Methodologies and Practices for Composite Indicator Development*. Ispra, Italy.
- Tanguay, G.A., Rajaonson, J., Lefebvre, J., Lanoie, P., 2010. Measuring the sustainability of cities: An analysis of the use of local indicators. *Ecol. Ind.* 10, 407-418.
- United Nations, 1992. United Nations Conference on Environment & Development Rio de Janeiro, Brazil, 3 to 14 June 1992
- Statistical databases consulted*
- ALMUDENA, 2013. Banco de datos municipal y zonal. Instituto de Estadística de la Comunidad de Madrid. Population and socio-demographic data (2004-2013). URL. http://www.madrid.org/desvan/AccionLlamadaArbolDesvan_dwr.icm?tipoArbol=almudena (accessed 23.09.15)
- BACO, 2013. Banco de Datos de Coyuntura. Instituto de Estadística de la Comunidad de Madrid. Data on economic activity (2004-2013). URL. http://www.madrid.org/baco_web/html/web/AccionCargarArbol.icm?acceso=1&annos=5&palabras (accessed 23.09.15)
- DGT, 2013. Anuarios. Dirección General de Tráfico, Ministerio del Interior, Gobierno de España. Data on accidents (2004-2013). URL. <http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-accidentes/> (accessed 23.09.15)
- DESVAN, 2013. Banco de Datos Estructurales. Instituto de Estadística de la Comunidad de Madrid. Environmental and structural data (2004-2013). URL http://www.madrid.org/desvan/AccionLlamadaArbolDesvan_dwr.icm?tipoArbol=desvan (accessed 23.09.15)
- INE, 2013. Instituto Nacional de Estadística. Data coming from surveys: household expenditures, reported noise problems and reported crime problems (2004-2013). URL. <http://www.ine.es/en/welcome.shtml> (accessed 23.09.15).
- MMO, 2013. MMO reports. Metropolitan Mobility Observatory. Data on Public Transport supply (2013-2004). URL <http://www.observatoriomovilidad.es/en/publications/reports.html> (accessed 23.09.15).

5.4. Measuring negative synergies of urban sprawl and economic crisis over public transport efficiency: the case of Spain

Among the general threats in European cities, there are two which have negative effects over the efficiency of urban systems and services: urban sprawl and economic decline. In Section 5.4, the inefficiencies caused by urban sprawl and economic decline over the PT systems were measured through evolution indicators. The analysis was focused in six Spanish cities: Madrid, Barcelona, Valencia, Seville, Malaga and Alicante.

The research work has been published in the scientific journal *International Regional Science Review* (Impact Factor 2015: 0.917), from SAGE.

Figure 5.4. Policy issues analysed in Section 5.4 within the structure of the thesis

Measuring Negative Synergies of Urban Sprawl and Economic Crisis over Public Transport Efficiency: The Case of Spain

International Regional Science Review

1-38

© The Author(s) 2017

Reprints and permission:

sagepub.com/journalsPermissions.nav

DOI: 10.1177/0160017616687361

journals.sagepub.com/home/irx

Andrea Alonso¹, Andrés Monzón² and Rocío Cascajo¹

Abstract

Sustainable urban mobility requires accessible and demand attractive public transport (PT) networks. However, urban sprawl has been the main characterizing growth pattern of European cities since 1950. In these increasingly dispersed cities, PT is facing increasing problems of efficiency to compete with cars. The sprawling cities are dominated by car use, especially in the peripheral areas. Moreover, Europe is still reeling under the financial crisis, which first hit the continent in 2007. In this context of economic crisis, the lack of financing resources and the declining demand for PT have further weakened the PT systems in European cities. This study considered the urban PT systems of six Spanish cities in order to determine their evolution over the last ten years. This evolution is examined in the backdrop of urban sprawl and economic crisis. The analysis is based on several indicators meant to measure PT demand, supply, and efficiency. The study shows how did each city react to the lack of resources and trip reduction during the economic crisis, by adopting different PT management strategies. The differences in reaction produced

---

¹ TRANSyT—Transport Research Centre, Universidad Politécnica de Madrid, Madrid, Spain

² Civil Engineering Department, Universidad Politécnica de Madrid, Madrid, Spain

Corresponding Author:

Andrea Alonso, TRANSyT—Transport Research Centre, Universidad Politécnica de Madrid, Calle Profesor Aranguren s/n, 28040 Madrid, Spain.

Email: andrea.alonso@upm.es

different results, but none of the cities could avoid the loss of PT efficiency. The results indicate that policy strategies need to include land use and transport measures to achieve more sustainable PT systems. Only integrated strategies could improve PT efficiency and quality levels and contribute toward increasing competitiveness of PT, even in adverse contexts.

Keywords

PT efficiency, urban mobility, urban sprawl, economic crisis, cities

Introduction

Scheme of the components of a city. Metropolitan area includes central city and metropolitan ring.¹
 Note: MA = Metropolitan Area; CC = Central City; MR = Metropolitan Ring.

Urban dwellers constitute to the overwhelming majority of the European population (European Environment Agency 2009). Urban environments drive economic development and are the main centers of many public services such as education, health care, and transportation (European Union 2010). Therefore, it is essential for European cities to be sustainable and efficient (European Commission 1996). However, at present, the urban areas in Europe are facing some trends that are really threatening their sustainable development. All these trends are described by the initiative *Cities of Tomorrow* (European Union 2011). Two of them are particularly threatening to the economic development and operational efficiency of the urban systems. The first one is the *urban sprawl*, which has been characterizing the growth of European cities since 1950 (European Environment Agency 2006). The second one is the *economic decline*, linked to the economic crisis that hit European Continent in 2007 (Directorate-General for Economic and Financial Affairs of the European Commission 2009).

- *Urban sprawl*: The low-density expansion of large urban areas is one of the main threats to sustainable territorial development. Public services are more costly and difficult to provide in dispersed cities (European Environment Agency 2006).
- *Economic decline*: Due to the recent economic crisis, many European cities are facing an economic downturn which is hampering their progress. The economic recession, accompanied by job losses and a declining demand, has

severely affected the competitiveness, productivity, and operational efficiency of services (European Commission 2012).

This article analyzes the urban public transport (PT) performance and its evolution, in a context of urban sprawl and economic crisis. The analysis shows how this context has changed the demand–supply balance, adversely affecting the efficiency of the services. The applied methodology is focused on transport services, but it could be extended to other urban services. The specific focus on transport services provides very interesting insights. An efficient urban transport system is a fundamental requirement for the citizens ‘quality of life and economic development’ (European Union 2010). Citizens expect PT to cater for their needs in terms of quality, efficiency, and availability (European Commission 2007, 2011). However, the trends described in the preceding paragraph—urban sprawl and economic crisis—can be particularly unfavorable for the operational efficiency of urban PT systems (Song 2005; European Commission 2007; Haghshenas and Vaziri 2012; Alonso, Monzón, and Cascajo 2015). This analysis was carried out for six Spanish cities with the help of a common national database on urban transport (Metropolitan Mobility Observatory [MMO] 2015). Although the topic of the analysis is of general concern for all European cities, Spain serves as a very relevant case study. The country is severely affected by the economic recession (Campbell, Partridge, and Soto 2013), and some Spanish cities are clearly spreading above the European average (European Environment Agency 2006).

This article is structured into seven sections. The second section presents the background of the study, accompanied by a bibliographic review of other studies. The third section details the methodology, defining and formulating the concepts, specifying the data sources, and detailing the procedures followed in the analysis. The fourth section analyzes the evolution of the economy, the population growth, and its dispersion in the six cities during the period 2002–2012. The performance of the urban PT systems is also analyzed in the fourth section, for the period 2007–2012, in which the adverse effects of the economic crisis were combined with those of urban sprawl. The fifth and sixth sections analyze the evolution of all these factors, discussing their interactions and the effects different policy actions have had over the PT efficiency of the cities. The seventh section finally concludes and summarizes the key findings that can be useful for future policy and research.

Research Background

Ground for and Objective

Historical concerns about demographic dynamics and sustainability were based on the growth of highly populated cities (United Nations 1992). In contrast, the physical expansion of dispersed urban areas is a more recent and worrying phenomenon, known as sprawl (European Environment Agency 2006). The phenomenon is triggered by a variety of factors such as land-use policies and individual housing preferences, influenced by the degradation and gentrification of different parts of the core

cities (European Union 2011). Urban sprawl affects the environmental, economic, and social aspects of the cities. It increases land occupation and energy consumption and complicates the supply of all services and the access to basic needs (Audirac 2005). In sprawling cities, PT has growing problems of efficiency to compete with cars (European Environment Agency 2006; Theodoridou, Papadopoulos, and Hegger 2012). PT networks are insufficient in dispersed cities, which are usually dominated by car use (European Union 2011). Therefore, urban sprawl hampers the accessibility to PT and efficiency in PT management (Preston and Rajé 2007).

In this scenario of urban development, the financial crisis hit the European continent in 2007, causing millions of job losses and a large drop in economic activity (European Commission 2012). More than two-thirds of the European Union's workforce lives in cities, but as an impact of the crisis, many of these cities are exhibiting weak demand and unemployment (Campbell, Partridge, and Soto 2013). The downturn of the economy affects the demand for goods and services, including the demand for transport (Preston and Rajé 2007; Taylor et al. 2009). Economic changes have a great effect on PT performance, since they are linked to transport demand (Hine and Grieco 2003; de Jong and van de Riet 2008; Cordera et al. 2015). In addition, limited public spending in times of austerity may affect the quantity and quality of PT supply, subsequently affecting accessibility levels (Campbell, Partridge, and Soto 2013). Indeed, in the aftermath of the Eurozone crisis, the lack of financing resources and the declining demand for PT have further weakened the PT systems in the European cities (Directorate-General for Economic and Financial Affairs of the European Commission 2009).

Urban sprawl and economic decline introduce difficulties in terms of PT management, thus threatening the sustainability of the system. Both the trends affect PT demand and pose barriers to PT supply management, changing the balance between the supply and demand, which finally affect efficiency. The objective of this article is to measure and analyze these synergies. The methodology is based on indicators, which are considered as appropriate tools for this type of analysis, since they allow objective measurements and comparisons (TERM 2000). Conclusions are drawn on the basis of similarities and particularities observed between the six Spanish cities.

There is an emerging trend related to the topic of the analysis that needs to be mentioned here, even if it goes beyond the scope of this article. In the recent years, the flexible work arrangements have increased exponentially, although the rates vary across different countries (Raffaele and Connell 2016). Flexible work schedules are thought to have appeared in the 1980s, driven in part by the dispersion of jobs and the diffusion of communications technology (Coenen and Kok 2014). At first, the practices appeared in the countries such as Australia and the United States (Brewer 1998), where they are now more widespread than in Europe (Raffaele and Connell 2016). In Spain, the implementation of flexible work arrangements has been slower than in most European countries (Aguila-Obra, Cámara, and Meléndez 2002) and the adoption of such measures by companies is still low (Cegarra-Leiva, Sánchez-Vidal, and Cegarra-Navarro 2012).

Nevertheless, practices such as teleworking or flexible working hours are increasingly gaining importance at a global level and are predicted to grow continuously (Coenen and Kok 2014; Raffaele and Connell 2016). This prediction might also be extended in the case of Spain, where the practices have emerged latter than in other countries, but are showing an upward trend (Cegarra-Leiva, Sánchez-Vidal, and Cegarra-Navarro 2012). Flexible work arrangements are often helpful in transport management solutions, since they are assumed to lessen the number and length of traffic jams at peak hours (Nijland and Dijst 2015). Nevertheless, these measures have some side effects that need to be taken into account. Van Lier, DeWitte, and Macharis (2014) analyzed them in terms of threats, and the discouragement of PT use appeared to be one of them. The reduction in the requirement to travel, especially at peak hours, reduces PT demand and complicates PT management, affecting its efficiency. Moreover, in a long term, the extension of teleworking can encourage urban sprawl, since it reduces the number of commuting days (Vanoutrive et al. 2010). Therefore, the potential effects that flexible work arrangements may have over PT efficiency would be of worth concern in the future studies.

Literature Review

There are several indicator-based studies in the literature, whose objectives overlap with the study presented in this article, especially with regard to the effects of sprawl. Bart (2010) statistically demonstrated that urban sprawl in Europe has increased the transport emissions. The conclusions were drawn from a strong correlation found between two indicators: increase in artificial land per country and total road transport CO₂ emissions per capita. The study analyzed fifteen European countries, and the data were aggregated at the national level. The outcomes of the study were convincing and clear, but the methodology was more appropriate for a global analysis rather than at a city level. Studies at city level are normally carried out very meticulously and focused on a single city (Holden and Norland 2005; Zhao 2010; García-Palomares 2010). Zhao (2010) and García-Palomares (2010) used similar databases and arrived at very similar conclusions for two cities as different as Beijing and Madrid. Both the studies showed how the trip distance and car use for travel to the city fringes have increased greatly due to urban sprawl. In this case, land use and demographic indicators were analyzed for this purpose. The transport indicators were collected from Census and mobility surveys for a given year. The expansion of both cities is characterized by the creation of low-density urban centers far away from the city center. These new settlements are demographically more dynamic, have a larger proportion of commuters, and are more related to other suburban centers. This increased the transversal and radial mobility in both cities, increasing the distances traveled and car use. Both studies are very interesting and present insightful results. However, the methodology can hardly be applied to other cities for comparison, since the data needed are difficult to obtain and homogenize.

Over the past few years, a few researchers have started looking into how the effects of global economic crisis are linked to the changes in transport behavior originated during the recessionary phases. Sobrino and Monzón (2014) analyzed the impact of the economic crisis on road transport in Spain and showed how the reduced demand for activities has decreased the number of cars driven through the network. Ulfarsson et al. (2015) demonstrated through a survey of residents in the Reykjavik capital region of Iceland that the economic crisis influences people's travel behavior. Participants are making fewer trips since the crisis, due to the reduced income or unemployment.

Many studies have examined the effects of sprawl over urban mobility (Zhao 2010), while only few studies have analyzed the more recent effects of the economic crisis over transport systems (Sobrino and Monzón 2014). Nevertheless, the number of studies analyzing the joint impact of both the scenarios for urban development is really low (García 2010), and the available ones are focused on one specific city (Nielsen 2015). On the other hand, some studies have shown that poorer and more dispersed cities are more car dependent, and less transit oriented, at least at the European level (Kenworthy and Laube 1999, Haghshenas and Vaziri 2012; Alonso, Monzón, and Cascajo 2015). These studies were based on the comparison of different cities, analyzing the values of several indicators for a particular year. None of them examined the evolution of the cities along time. The focus of this article is precisely on the evolution of cities, since they are facing unfavorable trends of dispersion and economic decline for their transit systems.

Therefore, the present study is highly relevant in the field. Firstly, it analyzes the combined effects of urban sprawl and economic crisis. Secondly, it can be applied to compare different cities, as the proposed indicators are easy to obtain and standardize. Finally, we consider the evolution of these indicators over the time, rather than taking their instant values for a given year. This allows determination of the relevant trends.

Method

The methodology is based on time-series indicators, which are used to measure the evolution of key explanatory factors that influence urban PT performance. The analysis was carried out with the help of a database with enough information on demography, economy, and urban PT systems of Spanish cities. The database and selection criteria for the indicators and case studies are detailed in this section.

Conceptualizing the Factors to Analyze

The objective of this study was to analyze the effects of urban sprawl and economic crisis on PT efficiency. Prior to selecting the appropriate indicators to measure these factors, it is important to conceptualize them, which allows translating the concepts

into mathematical expressions. In this context, following definitions of the discussed factors were adopted from literature:

Urban sprawl: Spread of low-density urban settlements around the core city, as people decide to live increasingly away from the city center (European Union 2011; European Environment Agency 2006).

Economic crisis: Recession of the economic activity, associated to a generalized fall in demand, gross domestic product (GDP) contraction, and job losses (Directorate-General for Economic and Financial Affairs of the European Commission 2009; Campbell, Partridge, and Soto 2013)

PT efficiency: The term efficiency—usually applied to production business—is related to how effectively input resources in a process are transformed into valuable results for the customers (Grönroos and Katri 2004). When the term refers to transit, efficiency measures should rate the processes by which transport services are produced, through the relationship of inputs to outputs (Fielding, Glauthier, and Lave 1978). An assessment of the efficiency of transport services has been carried out in many studies, the most recent ones distinguish between economic and technical efficiency (Karlaftis and Tsamboulas 2012; Zhang, Juan, and Xiao 2015). In these studies, the economic efficiency is normally expressed by a cost–benefit ratio. Whereas the technical efficiency captures the degree to which system operators attain the maximum output, that is, the satisfied demand for mobility, with given inputs, that is, transport services offered. In this article, we could only analyze the technical efficiency, because of the difficulties on collecting annual data on operating costs and revenues. These difficulties seem to be generalized as data on technical efficiency is usually more reliable (Zhang, Juan, and Xiao 2015). In fact, many studies have focused their analysis on technical efficiency, conceptualizing it as a ratio between satisfied demand and supply implemented (Fielding, Glauthier, and Lave 1978; Karlaftis and Tsamboulas 2012).

Satisfied PT demand: The amount and type of PT travel that people have chosen under specific conditions (Litman 2013).

PT supply: The transport supply is the amount of transport services provided by different modes and made available to meet the mobility demand that arises from the accessibility needs of the population (Preston and Rajé 2007; Tolley and Turton 2014). Accessibility is defined by the “get-at-ability” of a destination (Hillman, Henderson, and Whalley 1976), and the concept involves supply in terms of land use and transport provision (Hine and Grieco 2003; Preston and Rajé 2007). This analysis is particularly focused on the accessibility provided by PT networks. Accordingly, for measuring the PT supply provided, it is recommended to consider the quantity of PT services within an area of service and its spatial distribution (Currie 2010; Bocarejo S and Oviedo H 2012). The spatial dimension has

to be taken into account, as the accessibility provided by transport services is related to the density of the PT supply (Preston and Rajé 2007). Especially, the accessibility levels in spread-out cities depend largely on the allocation of PT resources.

Data Source

The Spanish MMO (MMO 2015) collects and publishes urban transport information from a representative group of metropolitan areas (MAs). The supporting platform, which is expanding, currently comprises twenty-three Public Transport Authorities (PTAs) in the main Spanish MAs. The MMO publishes annual reports analyzing the mobility patterns of the participating MAs, which are the main sources for our research. The first report focuses on eleven MAs and contains information collected in the year 2002 (Aparicio 2004). The last report included in this analysis contains information collected in the year 2012 (Monzón et al. 2014). This time frame (2002–2012) captures the first period of economic growth (2002–2007) and the subsequent financial crisis that began to hit the global economy in the summer of 2007 (Directorate-General for Economic and Financial Affairs of the European Commission 2009). This article analyzes both the tendencies that are different for the two periods (2002–2007 and 2007–2012), determining the effect of external changes on the PT demand. Finally, the study evaluates the evolution of PT supply and efficiency in the second period of the economic decline.

The MMO database is appropriate for characterizing and comparing the urban PT systems of Spanish cities and to contextualize them with the general demographic and economic features. The information is updated annually; therefore, the different trends along time can also be analyzed. However, the data set has some limitations that need to be mentioned. Firstly, the database does not allow detailed analysis, as it is fairly aggregated. The economic data are collected at the MA level and demographic data are disaggregated by central city (CC) and metropolitan ring (MR). The transport data are normally aggregated for each PT mode, that is, for all urban buses or for all metro lines. Secondly, the information on personal mobility is not fully comparable. This is because the information comes from different mobility surveys carried out for each city, in different years and with different procedures. Finally, it provides limited data on private transport, since the PTA are the main information providers.

Indicators for Measuring Factors Related to the Context and PT Performance

The methodology developed is based on indicators, which are carefully selected to measure each factor. Indicators are considered as appropriate tools for the proposed analysis, as there is a common consensus regarding the usefulness of indicators to monitor the progress of transport systems (Fielding, Glauthier, and Lave 1978; Newman and Kenworthy 1999; Haghshenas and Vaziri 2012; Alonso, Monzón, and

Table 1. Selection of Context Related Indicators—Socioeconomic Characteristics.

Factor to be measured	Indicators for each factor that can be collected from MMO reports	Selection of indicators for each factor	Comments selection criteria
Urban sprawl (demography—population growth)	No. of inhabitants in the MA No. of inhabitants in the CC No. of inhabitants in the MR = no. of inhabitants in MA – no. of inhabitants in CC Not directly available but elaborated using other MMO indicators Population density in the MA (no. of inhabitants MA/MA surface) Population density in the CC (no. of inhabitants MA/MA surface) Concentration ratio (no. of inhabitants in CC/ no inhabitants MA)	X X X (elaborated for the purpose)	All indicators are relevant and allow to perceive the differences between the different areas Sprawl is characterized by CC loosing population weight overall MA population. However, as the population is continuously growing in both MA and MR, population densities are getting higher (these indicators are not sensitive to sprawl) The concentration ratio is a very simple indicator, but it completely matches with the definition of urban sprawl that has been adopted To represent value creation It is better to use the employment rate for representing economic activity, as it usually grows positively with GDP
Economic crisis (economic activity)	GDP per capita in MA (annual Euro per inhabitant) Employment rate in MA (percentage of active population employed) Unemployment rate in MA (percentage of labor force unemployed)	X X	The information comes from the household surveys carried out in each city and is not updated annually. Therefore, the indicators are not fully appropriate for comparisons and are not sensitive to changes over time
Satisfied PT demand	No. of trips per person per day (on average in the MA, according to household surveys) PT modal share (%) (in the MA, CC, and MR, according to household surveys) No. of trips per PT mode per year (for suburban modes—operating in MA—and for urban modes—operating in CC—according to PTA registrations)	X	The number of trips is a more homogeneous and reliable data than passengers-km (Fielding, Glauthier, and Lave 1978), and therefore, we prefer it for measuring demand

(continued)

Table 1. (continued)

Factor to be measured	Indicators for each factor that can be collected from MMO reports	Selection of indicators for each factor	Comments selection criteria
PT supply—density of supply	No. of PT trips per inhabitant per year (no. of trips in all PT modes/no. of inhabitants MA, according to PTA registrations)	X	These indicators are related more to the transport network (infrastructure) than to the quantity of transport supply (or amount of services, as we understand it here). In addition, all are very stable indicators and do not reflect evolution of PT offer over the years Ultimately, for a global overview, we are interested in a collective analysis of all modes, and it is not advisable to add up these indicators for railway and bus modes (different characteristics) Both indicators are valid for measuring the quantity of PT supply (amount of PT services; Currie 2010). The indicator seats-km is similar to the indicator vehicles-km, but it considers the capacity of each vehicle to carry passengers. Therefore, we prefer the indicator seats-km to measure the density of supply It allows a collective analysis of railway and bus modes (it is more accurate to add up seats-km than vehicles-km when there are different modes with different carrying capacities)
	No. of passengers-km per PT mode per year (according to PTA registrations and estimations)		
	No. of lines for each PT mode		
	No. of stops for each PT mode		
	Length of the network for each PT mode		
	Vehicles-km per PT mode per year Seats-km per PT mode per year	Used for elaborating other indicators	

(continued)

Table I. (continued)

Factor to be measured	Indicators for each factor that can be collected from MMO reports	Selection of indicators for each factor	Comments selection criteria
PT efficiency—PT offer and demand	Seats-km/ service area (seats-km in all PT modes/ MA surface and seats-km in urban modes/CC surface) Not directly available but elaborated using other MMO indicators	X (elaborated for the purpose)	The adopted definition of PT supply requires measuring the density of PT supply (a concept linked to accessibility). For this, the quantity of PT supply (seats-km in this case) has to be considered within the area of service (Preston and Rajé 2007; Currie 2010; Bocarejo S and Oviedo H 2012) Concerning the area of service, urban modes operate only in the CC, which is contained in the MA, and both suburban and urban modes operate in the MA as a whole This indicator measures the vehicle occupation and does not exactly match the definition of efficiency adopted
	Passengers-km per PT mode /vehicles-km		
	Seats-km/ no. of trips (seats-km in PT modes/no. of trips in PT modes; seats-km in suburban modes/ no. of trips in suburban modes and seats-km in urban modes/no. of trips in urban modes) Not available directly but elaborated using other MMO indicators	X (elaborated for the purpose)	The elaboration of this indicator is coherent with the definition of efficiency adopted (quantity of supply to satisfy each demand unit) and with the indicators selected for measuring demand (no. of trips) and quantifying supply (seats-km)

Note: MMO = Metropolitan Mobility Observatory; MA = metropolitan area; MR = metropolitan ring; CC = central city; GDP = gross domestic product; PT = public transport; PTA = Public Transport Authority.

Cascajo 2015). Table 1 describes the indicators selected and used in this research on the basis of the following parameters (in columns):

- Factors to be analyzed, which have been previously conceptualized;
- List of indicators that could potentially measure each factor and that can be elaborated with the information available in MMO reports;
- Selected indicators for measuring each factor in this research. Some of them are direct indicators, which can be found in their actual form in the MMO reports. Others have been derived by combining various direct indicators; and
- Reasoning for the selection of indicators. Indicators should be, if possible, mathematical expressions of the factors conceptualized. They should also be sensitive to changes over time, since the aim of this article is to analyze the evolution.

All the indicators selected fulfill the seven basic requirements that make an indicator suitable for management purposes (Alonso, Monzón, and Cascajo 2015). They are *unambiguous*, as they are being presented as mathematical expressions. They are *relevant* and *valid* to the topics, since they have been adapted to the definition of the factors that we want to measure. They are *standardized*, *transparent*, and *reliable*, since they come from a common database, which uses reliable and homogenized information. Finally, they are *sensitive* to the changes, as they have been selected because they are valid for measuring the trends and changes over the years. In addition, the indicators are quite simple and it is feasible to obtain their values, so this analysis can be extended to other cities.

Case Studies: Six Spanish Cities

Six Spanish MAs participating in the MMO were included in this analysis (Figure 1 and Table 2), the rest were discarded by the lack of data for the period considered. These MAs account for 32 percent of Spanish population and 37 percent of the national GDP (Organization for Economic Cooperation and Development 2012). The socioeconomic indicators are analyzed for a ten-year period (2002–2012). The transport-related indicators are analyzed only for the last six years of economic decline (2007–2012), due to the limitations of the data series.

Measuring Trends and the Evolution of Indicators

The European Commission (EC)-Joint Research Centre report (Saisana and Tarantola 2002) recommends appropriate formulas and normalization methods for the treatment of indicators in order to summarize complex or multidimensional issues. The report proposes the following formula for the analysis of trends over the years:

Figure 1. Spanish metropolitan area included in the analysis. Represented by their geographical areas.

$$\text{Evolution indicator : } E_{ic}(\%) = \frac{\sum_{t=1}^n \frac{x_{ic}^t - x_{ic}^{t-1}}{x_{ic}^{t-1}}}{n - 1} \times 100, \quad (1)$$

where E_{ic} is the value of the evolution indicator, which measures the trend of the factor i that is being evaluated for the city c (if it is >0 , the analyzed factor has increased positively during the analyzed period); x_{ic}^t and x_{ic}^{t-1} are the values of the indicators measuring the factor in year t and the previous year ($t - 1$; e.g., GDP could be an indicator for measuring economic activity); and n is the number of years in the analysis period.

This formula is applied to the indicators selected to measure all the factors. It enables to analyze mathematically the evolution of each indicator taking into account its year-by-year change. The evolution indicators represent the average annual growth over a period of $n - 1$ years (from year $i = 1$ to year $y = n$). In this article, all the indicators are analyzed from 2007 to 2012, to capture the effects of the economic crisis, and some are also analyzed for the period 2002–2012.

Table 2. Characteristics of the Selected Metropolitan Areas.

Metropolitan Areas	Population 2012 (million inhabitants)	Area (km ²)	Gross domestic product 2012 (€ per capita)
Madrid	6.5	8,030	28,906
Barcelona	5.1	3,239	27,236
Valencia	1.8	1,415	20,678
Seville	1.5	4,221	16,960
Malaga	1.0	1,432	16,900
Alicante	0.5	354	17,064

Source: Report MMO 2012 (Monzón et al. 2014).

Note: MMO = Metropolitan Mobility Observatory.

Clustering the Cities

The cities are clustered according to their PT performance for interpretation and understanding of the results. It is noteworthy that the cluster analysis is applied only as a descriptive and exploratory technique (Hair et al. 2010; Bock and Diday 2012), because of the small size of the sample. Our main motive is not to present a statistically significant classification but to exemplify the similarities and differences among the cities. In this case, we have applied Ward's clustering method with squared Euclidean distances of the classifying variables. This method is considered suitable for a small sample and with a high number of classifying variables (Hair et al. 2010).

Analysis of the Trends in the Indicators

This section describes the notable trends for the previously defined factors. Results are analyzed separately for two periods. The first period (2002–2007) corresponds to a time of steady economic growth of the country and the second one (2007–2012) corresponds to the global economic crisis.

Analysis of the Socioeconomic Context

Demographic changes: Population growth and urban sprawl. This analysis includes the two biggest MAs in Spain, Madrid and Barcelona. Both of them have a population of over five million. In addition, there are three cities with a population between one and two million inhabitants, Valencia, Seville, and Malaga, and one small city with less than half a million residents, Alicante. This heterogeneity does not make any difference in the evolution of their populations—big or small areas do not present similar evolution patterns.

The population in all areas increased during both the analyzed periods (Table 3). However, most of the MA show higher growth rates in the first period (2002–2007) than in the second one (2007–2012), excepting Seville. The MA recorded an average

Table 3. Population in MA, MR, and CC (Million Inhabitants).

Metropolitan Areas	E—average annual growth											
	2002				2007				2012			
	MA	MR	CC	MA	MR	CC	MA	MR	CC	MA	MR	CC
Economic growth 2002/2007												
Economic crisis 2007/2012												
Economic growth 2002/2007												
Economic crisis 2007/2012												
Metropolitan Areas	MA	MR	CC	MA	MR	CC	MA	MR	CC	MA	MR	CC
Madrid	5.42	2.47	2.96	6.08	2.95	3.13	6.50	3.27	3.23	2.3	1.2	1.3
Barcelona	4.48	2.98	1.51	4.86	3.26	1.60	5.05	3.43	1.62	1.6	1.2	0.8
Valencia	1.60	0.86	0.75	1.74	0.95	0.80	1.81	1.01	0.80	1.7	1.3	0.7
Seville	1.12	0.42	0.70	1.25	0.55	0.70	1.48	0.77	0.70	2.2	−0.1	3.5
Malaga	0.72	0.19	0.53	0.94	0.38	0.56	1.02	0.45	0.57	5.7	1.0	1.6
Alicante	0.39	0.11	0.28	0.44	0.12	0.32	0.46	0.13	0.33	2.2	2.7	1.1
Global average										2.8	5.3	1.2
										2.8	5.3	1.2

Note: E—evolution (%). MA = metropolitan area; MR = metropolitan ring; CC = central city.

Table 4. Population Concentration Ratio (Population in Central City/Population in Metropolitan Area).

Metropolitan Areas	2002	2007	2012	E—average annual growth	
				Economic growth 2002/2007 (%)	Economic crisis 2007/2012 (%)
Madrid	0.55	0.52	0.50	−1.1	−0.7
Barcelona	0.34	0.33	0.32	−0.4	−0.5
Valencia	0.47	0.46	0.44	−0.3	−0.7
Seville	0.63	0.56	0.48	−2.2	−3.2
Malaga	0.74	0.59	0.56	−4.2	−1.3
Alicante	0.72	0.74	0.72	0.5	−0.4
Global average				−1.3	−1.1

Note: E—evolution (%).

annual growth rate of 2.8 percent in the first period and 1.5 percent in the second period starting in 2007, when the effects of the economic crisis started to be noticed. A noteworthy fact is the high growth rates of Malaga in the first period and Seville in the second one and the low growth rates of Barcelona and Valencia in the second period.

Table 3 shows the population living in the CCs, and in the MRs. Although population has grown in both CC and MR, big differences can be noticed in both tendencies. The growth rates of MR population are clearly higher than the growth rates of CC for both periods, showing about five times higher values. Therefore, urban sprawl, understood as the spread of low-density settlements around the core cities (European Union 2011), is affecting the analyzed MA; even if the CCs included in the analysis are still not losing population, which is another trend usually associated with urban sprawl (European Environment Agency 2006). These areas are gaining inhabitants but at a much slower rate than their corresponding MA.

As shown in the tables, owing to the demographic evolution, the CCs are steadily losing population weight over their MAs since 2002 (Table 4). Although the cities have different population concentrations, the average percentage of the MA population living in the CC fell down from 58 percent in 2002 to 50 percent in 2012.

Economic decline. The economic indicators reveal considerable differences across the cities. The southern MAs, Seville and Malaga, show more unfavorable economic contexts, with lower GDP and employment rates (Table 5). The evolution of the economic indicators appears different for the two periods. Unlike in the demographic analysis, the economic evolution drastically changes from one period to the other. The first period is characterized by a marked growth in employment rates and a more pronounced growth of GDP. The second period is characterized by

Table 5. Annual GDP per Capita (€ per Year and Inhabitants) and Employment Rate (Percentage of Active Population Employed) in Metropolitan Area.

Metropolitan Areas	E—average annual growth														
	2002			2007			2012			Economic growth 2002/2007			Economic crisis 2007/2012		
	GDP (€)	Employed (%)		GDP (€)	Employed (%)		GDP (€)	Employed (%)		GDP (€; %)	Employed (%)		GDP (€; %)	Employed (%)	
Madrid	23,847	54.0		29,965	60.8		28,906	53.5		4.7	2.4		−0.7	−2.5	
Barcelona	21,246	52.1		29,011	59.0		27,236	50.1		6.5	2.5		−1.2	−3.1	
Valencia	17,277	50.4		22,617	56.8		20,678	45.5		5.5	2.4		−1.7	−4.3	
Seville	13,852	42.8		19,190	50.4		16,960	42.1		6.7	3.3		−2.3	−3.5	
Malaga	13,608	44.0		18,715	50.6		16,900	39.0		6.8	2.9		−2.0	−5.0	
Alicante	16,187	49.0		20,097	50.6		17,064	41.3		4.4	0.7		−3.2	−3.9	
Global average										5.8	2.4		−1.8	−3.7	

Note: E —evolution (%). GDP = gross domestic product.

employment decline and a slight decline in the GDP. The southern MA presents higher economic growth rates in the first period and a sharper decline in the second period. The economic recession, which followed the economic growth period of 2002–2007, affected the wealth (GDP) and activity (employment) of all the analyzed Spanish MA. In addition, the MAs with higher growths in the first period were more sensitive to the crisis in the second period. The GDP per capita seems to be a very sensitive indicator for economic expansion (showing an annual average growth of 5.8 percent in the period 2002–2007). The recorded employment rate appears to be more sensitive to the economic decline (with an annual average decrease of 3.7 percent in the period 2007–2012).

Analysis of PT Performance

This section presents the indicators that were selected for measuring the evolution of the factors related to PT performance and its efficiency. These factors include satisfied PT demand, density of PT supply, and the resulting PT efficiency.

PT demand. The evolution of the PT demand is analyzed together with the economic and demographic trends. The demand is measured for all the PT modes in terms of the number of trips and number of trips per MA inhabitant (Table 6). This indicator presents clear differences based on the size of the MA—larger MA indicates higher PT use (even when the indicator is homogenized by the population).

The demand for transport services is always linked to the economic cycles (Preston and Rajé 2007; Taylor et al. 2009; Moreno and Bazo 2003). This is evident when we analyze the evolution of the number of trips taken by PT during the two periods of analysis (Table 6). The first period of economic growth is characterized by a growth in the number of PT trips (showing an annual average growth of 2.9 percent). In the second period of economic decline, the number of PT trips decreased on an average by 1.7 percent per year.

However, the demand for PT should also be seen in the light of the changes in demography. There was an increase in the population during both periods for all cities. As a consequence, if we analyze the evolution of the demand per inhabitant (Table 6), the outcome is different. The number of trips per inhabitant shows a marginal growth in the first period, whereas a significant decline could be seen in the second period. Therefore, during the first period, which is characterized by economic growth and a general increase in demand, the PT demand per inhabitant remained nearly constant. This is probably because the population growth has concentrated in the suburbs, which are less likely to use massive transport modes (European Environment Agency 2006). In the second period, the effects of the economic crisis are noticeable and the PT demand per capita changes from a stable one to a declining one. Therefore, the PT demand per capita shows a mixed trend between the sprawling tendency and the economic evolution. Figure 2 illustrates the graphical representation of these relations.

Table 6. Overall Public Transport Demand (Millions of Trips and Trips/Inhabitants).

Metropolitan Areas	2002						2007						2012						E—average annual growth					
	Trips (million)			Trips per inhabitants			Trips (million)			Trips per inhabitants			Trips (million)			Trips per inhabitants			Economic growth 2002/2007			Economic crisis 2007/2012		
	Trips (million)	Trips per inhabitants	Trips per inhabitants	Trips (million)	Trips per inhabitants	Trips per inhabitants	Trips (million)	Trips per inhabitants	Trips per inhabitants	Trips (million)	Trips per inhabitants	Trips per inhabitants	Trips (million)	Trips per inhabitants	Trips per inhabitants	Trips (million)	Trips per inhabitants	Trips per inhabitants	Economic growth 2002/2007	Trips per inhabitants (%)	Trips per inhabitants (%)	Economic crisis 2007/2012	Trips per inhabitants (%)	Trips per inhabitants (%)
Madrid	1,514.5	279.3	276.1	1,679.0	276.1	227.7	1,479.9	227.7	2.2	—0.1	—2.5	—3.7	2.2	—0.1	—2.5	—3.7	—0.1	—2.5	—3.7	—0.1	—2.5	—3.7	—0.1	—2.5
Barcelona	800.1	178.5	192.4	934.7	192.4	178.1	899.9	178.1	3.2	1.5	—0.7	—1.5	3.2	1.5	—0.7	—1.5	1.5	—0.7	—1.5	1.5	—0.7	—1.5	1.5	—0.7
Valencia	175.7	109.6	119.7	208.2	119.7	99.7	179.9	99.7	3.5%	1.9%	—2.9	—3.6	3.5%	1.9%	—2.9	—3.6	1.9%	—2.9	—3.6	1.9%	—2.9	—3.6	1.9%	—2.9
Seville	105.9	94.5	85.6	106.7	85.6	75.6	111.6	75.6	0.2	—1.9	0.9	—2.4	0.2	—1.9	0.9	—2.4	—1.9	0.9	—2.4	—1.9	0.9	—2.4	—1.9	0.9
Malaga	52.2	72.3	73.6	69.5	73.6	66.4	67.8	66.4	6.7	1.5	—0.5	—2.0	6.7	1.5	—0.5	—2.0	1.5	—0.5	—2.0	1.5	—0.5	—2.0	1.5	—0.5
Alicante	30.6	77.8	75.0	32.9	75.0	56.2	26.1	56.2	1.5	—0.7	—4.5	—5.6	1.5	—0.7	—4.5	—5.6	—0.7	—4.5	—5.6	—0.7	—4.5	—5.6	—0.7	—4.5
Global average									2.9	0.4	—1.7	—3.1	2.9	0.4	—1.7	—3.1	0.4	—1.7	—3.1	0.4	—1.7	—3.1	0.4	—1.7

Note: E—evolution (%).

Figure 2. Evolution of economy, population, and public transport demand (base year = 2002). Average for the six cities.

Table 7. Public Transport Demand (Millions of Trips).

Metropolitan Areas	2007		2012		E—average annual growth	
					Economic crisis (2007/2012)	
	Suburban modes	Urban modes	Suburban modes	Urban modes	Suburban modes (%)	Urban modes (%)
Madrid	479	1,200	411	1,069	−3.0	−2.3
Barcelona	224	710	211	689	−1.2	−0.6
Valencia	39	169	29	151	−5.8	−2.2
Seville	21	86	20	92	−0.8	1.4
Malaga	20	49	18	50	−2.0	0.2
Alicante	12	20	11	16	−3.7	−5.0
Global average					−2.7	−1.4

Note: E—evolution (%).

From this point onward, we will focus our analysis on the second period of economic crisis. Available data since 2007 allow to carry out more detailed analysis as well as to differentiate the urban and suburban modes. With regard to the PT demand, Table 7 shows that the urban trips are far more numerous than the suburban trips. From one hand, the urban modes are normally used by all the MA inhabitants

and the suburban mode is usually more restricted to the MR inhabitants. From the other hand, trips to and from the suburbs are more car based (European Union 2011). The analysis of the evolution shows that almost all MAs present a more important reduction in the demand for the suburban modes than the urban ones, even though the population in the MRs has grown more than in the CCs. This proves once again that the farther people live from the city center, the less they use PT (European Environment Agency 2006).

Density of PT supply. The indicator proposed to analyze the evolution of the density of PT supply is the amount of PT services within the area of service, as it is related to the PT accessibility. The values of indicator for the selected cities are presented in Table 8 for MA and CC. The first clear finding is that PT accessibility levels in CC are much higher than in MA. As has been expressed in most revised documentation, it is more difficult and less economically viable to provide PT services to segregated zones (European Union 2011; European Environment Agency 2006). This is a factor that contributes toward higher car modal shares in MR (Monzón et al. 2014). Secondly, bigger MA usually presents higher accessibility levels, for both MA and CC. Barcelona is shown to have the most accessible MA and CC (Madrid has a wider amount of PT services but also a larger service area). Thirdly, and in contrast to the forecasts, the PT accessibility globally improved during the years of economic recession and declining PT demand (2007–2012); even these conditions were detrimental to PT service provision and offer (Campbell, Partridge, and Soto 2013; Preston and Rajé 2007). Besides, the accessibility growth rates in CC (3.5 percent annual growth on average) are higher than the growth rates in MA. These growth rates are not concordant with the population growth, and this might have also influenced the demand evolution shown in Table 7.

Demand–supply balance: Efficiency. The PT efficiency indicator is the measure of resources allocated (seats-km offered) to generate one unit of demand (trip made). The corresponding results are presented in Table 9 for all PT modes: suburban and urban modes. The results show that the PT efficiency has decreased in all cases during the analyzed period, although at different paces. This finding implies that more PT services are now made available to perform each trip. This is the result of a declined PT demand, in spite of the efforts made to increase the supply.

With regard to the differences between the discussed modes, the urban modes have higher efficiency ratios than the suburban modes. Therefore, as expected, urban PT modes are more efficient than suburban PT modes. This is consistent with the shorter distances of urban trips (less seats-km are needed for one demand unit). Secondly, it should be clarified that these efficiency indicators penalize metro and in general rail modes, as they are massive modes and provide a high number of seats-km per vehicle-km. This factor contributes toward lower efficiency ratios of big MAs, which have dense rail modes supply, such as Madrid, Barcelona, and Valencia. Therefore, in this case, comparisons between different MA and CC cannot be based

Table 8. Density of Supply: Overall PT Supply within the MA Surface and Supply of Urban PT Modes within the CC Surface (Millions of Seats-km/km²).

	2007		2008		2009		2010		2011		2012		E-average annual growth 2007/2012	
	MA	CC	MA	CC	MA	CC	MA	CC	MA	CC	MA	CC	MA (%)	CC (%)
Madrid	7.6	67.3	8.0	71.7	8.3	74.0	8.2	73.6	8.4	75.8	8.4	72.0	1.1	1.4
Barcelona	10.7	200.7	11.4	211.5	11.4	213.4	12.0	233.1	12.3	239.7	12.3	225.4	2.2	2.5
Valencia	6.2	46.0	6.1	45.7	6.0	46.0	6.0	45.8	6.0	45.9	6.0	42.8	-1.9	-1.4
Seville	0.7	10.4	0.7	11.2	0.8 ^a	14.5 ^a	0.8	12.7	0.9	13.85	0.9	14.1	5.4a	7.1a
Malaga	1.4	2.4	1.5	2.7	1.5	2.9	1.3	2.6	1.4	2.7	1.4	2.7	0.3	2.1
Alicante	2.5	2.6	2.6	2.8	2.8 ^b	3.1 ^b	2.8 ^b	3.1 ^b	2.9 ^b	3.4 ^b	2.9 ^b	3.7 ^b	4.6b	7.7b
Global average													1.9	3,5

Note: E—evolution (%). MA = metropolitan area; PT = public transport; CC = central city.

^aIn 2009, new metro services were inaugurated in Seville (with higher impacts in accessibility levels in CC than in MA).

^bImportant increases in urban tramway services in Alicante (with higher impacts in accessibility levels in CC than in MA).

Table 9. Efficiency of PT Modes (No. Trips/100 Seats-km Offered).

Metropolitan Areas	2007			2008			2009			2010			2011			2012			E-average annual growth 2007/2012		
	2007			2008			2009			2010			2011			2012			E-average annual growth 2007/2012		
	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes	Over all PT modes	Suburban PT modes	Urban PT modes
Madrid	2.7	2.3	2.9	2.6	2.2	2.7	2.4	1.9	2.5	2.3	1.9	2.4	2.3	1.9	2.4	2.3	1.9	2.4	-3.5	-3.4	-3.5
Barcelona	2.6	1.6	3.5	2.5	1.5	3.3	2.5	1.5	3.2	2.4	1.4	3.0	2.3	1.4	2.9	2.3	1.4	3.0	-2.8	-2.9	-2.8
Valencia	2.4	1.6	2.7	2.3	1.5	2.7	2.2	1.4	2.5	2.2	1.4	2.5	2.2	1.4	2.4	2.2	1.3	2.5	-1.0	-2.9	-0.8
Seville	3.7	1.5	5.9	3.7	1.5	5.6	3.2	1.3	4.6	3.4	1.2	5.3	3.1	1.2	4.8	3.0	1.1	4.6	-3.7	-4.3	-4.0 ^a
Malaga	3.9	2.5	5.1	3.6	2.3	4.6	3.2	1.8	4.4	3.5	2.0	5.0	3.5	2.0	4.7	3.3	1.9	4.7	-2.8 ^b	-5.2	-1.3
Alicante	1.8	3.5	3.9	1.7	3.4	3.5	1.6	3.3	2.9	1.5	3.2	2.8	1.5	3.1	2.5	1.4	2.9	2.1	-4.1	-3.2	-11.6 ^b
Global average																			-3.8	-3.5	-4.0 ^c

Note: E—evolution (%). PT = public transport.

^aIn 2009, a new metro service was inaugurated in Seville

^bIncreases in urban tramway services in Alicante impacted on efficiency rates

^cThese values should be interpreted with caution: Seville and Alicante implemented rail services in the middle of the period. The indicator penalizes rail modes as they are massive modes and provide a high number of seats-km per vehicle-km.

on the PT efficiency indicator. The elaborated efficiency indicators are used to analyze the evolution of efficiency in each city, and the comparisons in each case should be made among consecutive years. The cross-site analysis should take into account the different mix of transport modes in each city, which have very different carrying capacities.

Our results show that during the period of economic crisis, PT efficiency decreased in all the cities for suburban and urban modes. Facts such as decline in PT demand linked to the evolution of economic activity and the generalized improvement of PT accessibility due to the expansion of PT supply have contributed toward increasing the number of seats-km devoted to provide each trip. While these facts have led to less efficient use of resources, decreasing PT supply levels would have probably led to even higher demand reductions and lower PT efficiency rates (Hine and Grieco 2003; Preston and Rajé 2007). Compared to urban modes, this cycle seems to be affecting more the suburban modes in Valencia, Seville, and Malaga. In these areas, the expansion of mainly urban PT services has been asymmetric with the population growth, which is concentrated in the MR. This factor may have caused a significant decline in demand and efficiency of suburban modes, which have always been inherently more inefficient than urban modes.

Analyzing the Effects of Described Trends on Efficiency

The final analysis compares the trends followed by the context indicators with the trends followed by the indicators related to PT management for all the cities. These trends are measured by the evolution indicators (E —average annual growth of the context and PT management indicators) and presented in Table 10. For a better understanding of the results, the evolution of the most relevant factors along time is graphically represented in Figure 3. The results show a clear deterioration of the socioeconomic context during the period 2007–2012. The population, although at a slower rate than in the previous years, increased in this period, and this growth was mainly absorbed by the suburbs. Consequently, the CCs lost population weight over their MAs, supporting the ongoing process of urban sprawl. At the same time, the decline in the economic activity led to a sharp decline in jobs and wealth.

The combined effect of urban sprawl and economic decline resulted in a clear drop in the PT trips in most cities. This effect on PT demand cannot justifiably be attributed to a lower quality offered, since there had been a notable growth in the density of supply during the analyzed period. This growth attempted to maintain the demand, by rising or maintaining the levels of service, in spite of the financial constraints that are usually faced in times of recession. This increase or maintenance of supply led fewer passengers to increase the utilization of resources for a trip, thereby reducing the efficiency of PT services.

Table 10. Evolution of the Indicators Related to the Context and PT Performance.

Metropolitan Areas	Context					PT performance					PT supply–demand balance		
	Urban sprawl					Satisfied PT demand					Density of PT supply		
	Population growth					Overall PT					Overall PT		
	MA	MR	CC	Population concentration	Gross domestic product	Employed	Suburb modes	Urban modes	MA (overall PT modes)	CC (urban modes)	Overall PT modes	Suburb modes	Urban modes
Madrid	1.3	2.1	0.6	−0.7	−0.7	−2.5	−3.0	−2.3	1.1	1.4	−3.5	−3.4	−3.5
Barcelona	0.8	1.0	0.3	−0.5	−1.2	−3.1	−1.2	−0.6	2.2	2.5	−2.8	−2.9	−2.8
Valencia	0.7	1.4	0.0	−0.7	−1.7	−4.3	−5.8	−2.2	−1.9	−1.4	−1.0	−2.9	−0.8
Seville	3.5	7.5	0.1	−3.2	−2.3	−3.5	−0.8	1.4	5.4 ^a	7.1 ^a	−3.7	−4.3	−4.0 ^b
Malaga	1.6	3.5	0.2	−1.3	−2.0	−5.0	−2.0	0.2	0.4	2.1	−2.8	−5.2	−1.3
Alicante	1.1	2.3	0.7	−0.4	−3.2	−3.9	−3.7	−5.0	4.6 ^a	7.7 ^a	−8.6	−3.2	−11.6 ^b

Note: E (%) average annual growths (2007/2012). PT = public transport; MA = metropolitan area; MR = metropolitan ring; CC = central city.

^aA further explanation of these extreme values is presented in Table 8.

^bA further explanation of these extreme values is presented in Table 9.

Figure 3. The evolution of gross domestic product, population, and public transport performance (base year = 2007). Average for the six cities.

The solution is to combine mobility policies with spatial planning (De Vos and Witlox 2013). Reducing the quality of PT services would probably have made things worse as it would have led to a greater decline in demand and therefore in efficiency (Hine and Grieco 2003; Preston and Rajé 2007).

Comparative Analysis of the Evolution in Each Case Study

Although this scenario gives a general description of the evolution of the analyzed cities, several differences can be identified among them (see Table 10). We made clusters of the cities according to their PT performance to analyze the similarities and differences. It is important to emphasize that due to the size of the sample, the cluster analysis was carried out to facilitate the description of the results, and not to obtain a statistically consistent classification. Herein, the PT performance is related to demand, density of supply, and efficiency and measured by the evolution indicators. The Ward's clustering method with squared Euclidean distances of the classifying variables, previously standardized, is considered suitable for the following reasons (Hair et al. 2010):

- small sample of the six cities;
- high number of classifying variables: Evolution indicators of PT performance; and
- different ranges and dispersed values of the classifying variables.

Figure 4. Cluster arrangement. Grouping of cities according to their public transport performance in 2007–2012.

The above method is applied using the following evolution indicators as classifying variables (Table 10):

- overall PT demand,
- PT demand of suburban modes,
- PT demand of urban modes,
- density of PT supply in MA,
- density of PT supply in CC,
- overall efficiency of PT modes,
- PT efficiency of suburban modes, and
- PT efficiency of urban modes.

The results show that the PT systems of Madrid and Barcelona, which are combined in a single cluster in the first stage, had a similar performance for the period 2007–2012. The PT systems of Seville and Malaga also seem to have performed similarly, as they are combined in the second stage. We decided to stop the clustering process at the second stage (red line in Figure 4), wherein the city of Valencia is still independent from Madrid and Barcelona. The former clusters in stage 2 facilitate the analysis and presentation of the results, since Valencia and Alicante showed more heterogeneous behavior with respect to the whole sample. Given these associations, the overall results are presented and analyzed first for the cities of Madrid

Figure 5. Economic decline and comparative evolution of the density of public transport (PT) supply and the satisfied PT demand (2007/2012). The degree of economic decline is indicated by the size of the bubbles: the bigger is the bubble, the more decrease occurred in gross domestic product per capita in the metropolitan area.

and Barcelona and then for the cities of Seville and Malaga, followed for Valencia, and finally Alicante.

Figures 5 and 6 show some relations between the clusters arranged. Figure 5 shows two explanatory factors for the evolution of PT trips: economic decline and PT supply. The cities more affected by the economic crisis experienced higher drops in PT demand; this is the case of Alicante and Valencia, as compared to cities of cluster 1. On the other hand, cities of cluster 2 have escaped the strong impacts of the economic crisis in PT demand by increasing the PT supply, especially in the CC (Table 10). Figure 6 shows that the efficiency losses in suburban modes were considerably higher in those cities where the population has dispersed more; this is the case of cities in cluster 2.

Cluster 1

The two largest cities of Spain, Madrid and Barcelona, have many common aspects such as population size and wealth. The results indicate that PT systems of both these cities have also evolved along similar lines, during 2007–2012 (Figure 4). In these years of economic downturn, which was moderate in Madrid and Barcelona as

Figure 6. Sprawl and comparative evolution of the efficiency losses for all public transport modes and for suburban modes (2007/2012). The degree of the sprawl is indicated by the size of the bubbles: the bigger is the bubble, the more has decreased the population concentration in the metropolitan area.

compared to the rest of the cities, both cities improved their PT supply by increasing the density of services in both MA and CC (Figure 5). Despite this effort, demand for PT fell down in both the cities and caused a decline in the PT efficiency. PT efficiency ratios reduced in an equilibrated manner between urban and suburban modes (Figure 6).

While these similarities are evident, it is important to note the differences. The economy of Madrid was slightly less affected than Barcelona, and its population presented a comparatively higher growth rate than Barcelona. Still, Madrid has lost more PT demand and efficiency (Table 10); there were, besides others, two main factors responsible for this. Firstly, Madrid witnessed a more decentralized growth in population than Barcelona during the period 2007–2012. Secondly, Barcelona extended its PT supply more than Madrid during the same period. As mentioned earlier, both sprawl and PT accessibility influence PT demand; in this case, evolution of both these conditions adversely affected Madrid than Barcelona, resulting in significant decline in PT demand and consequently sharper decline in PT efficiency for Madrid. This scenario, as predicted by some theories, has made the situation worse in Madrid as compared to Barcelona (Hine and Grieco 2003; Preston and Rajé 2007).

Cluster 2

The southern cities of Malaga and Seville also present similar features, with a population between 1 and 1.5 million inhabitants and a GDP below the Spanish average. The evolution of these cities during the period 2007–2012 showed a similar pattern in terms of the aspects analyzed (Figure 4). The population living in the suburbs of both cities grew at very high pace, although Seville was more affected by urban sprawl than Malaga. The economic crisis has also severely affected these two cities, reducing their GDP and employment rates. However, both the cities attempted to improve the situation by enhancing the quality of PT supply. The quality was improved by significantly increasing the urban PT services in the CC. This endeavor enabled both the cities to reduce the negative impacts of the crisis over PT demand, which even grew for urban modes, in spite of their especially unfavorable economic contexts (Table 10 and Figure 5). However, the demand did not sufficiently responded to the resources that were made available during this period. This factor led to a sharp decline in the efficiency ratios in both cities during this period, especially in suburban modes (Figure 6).

In Seville, new metro services were inaugurated in 2009, which significantly improved the PT accessibility in the city. This expansion resulted in Seville becoming the only city to achieve a growth of aggregated PT demand, although at the expense of a fall in the efficiency (see “Density of PT supply” and “Demand–supply balance: Efficiency” subsections for further clarifications).

During the period 2007–2012, the population living in the MR of Malaga increased more than ten times faster than the population living in the CC. While the expansion of PT services in Malaga mainly considered urban modes, the PT accessibility, therefore, was improved in the CC rather than in the MR, which was already less accessible by PT and more linked to car use. Consequently, the demand for suburban modes evolved poorly than the demand for urban modes. As a result, suburban modes presented more pronounced efficiency losses than urban modes, and this increased the gap that was already existing between them.

Clusters 3 and 4

Valence and Alicante are very different cities in terms of size and structure. However, their context has evolved very similarly in terms of a moderate population growth, a moderate suburbanization, and a severe economic decline. During the analyzed period, both cities registered significant declines in wealth and employment, comparable to those registered by Seville and Malaga. However, in contrast to the scenario in Seville and Malaga, the PT demand significantly decreased in Valence and Alicante (Table 10, Figure 5). The results point that both Valence and Alicante recorded the most significant declines in PT demand, out of the six analyzed cities. Given this framework, the cities of Valence and Alicante adopted opposite political positions.

Cluster 3

Valence was the only city that reduced the supply of PT services under adverse economic conditions (Figure 5). Its suburban modes were affected more than the urban modes by this reduction, which particularly contributed to the drop of PT demand for the suburban modes. However, the drop of PT demand was not strong enough to adversely impact PT efficiency. In fact, Valence is the city that lost less efficiency. Nevertheless, this alleviation was achieved at the expense of a decrease in PT services, decline of PT demand, and possible social and environmental consequences. The continuous and rapid decline in demand might push Valence into the vicious circle, as noted earlier. Recording a sharper decline in the demand and efficiency in comparison to the urban modes, the suburban modes have more likelihood of being stuck in the vicious cycle (Figure 6, Table 10).

Cluster 4

Alicante is the smallest city and the most atypical case in this comparison. Together with Seville, Alicante is the one with the largest PT supply expansion. During the crisis period, Alicante introduced new tramway services that were concentrated in a few lines. However, this expansion of urban services was not effective. The demand for PT services decreased considerably, in spite of the efforts carried out by the PTA to improve the offer (Figure 5). The allocation of resources on a large scale (seats-km) to serve a shrinking number of passengers resulted in bringing down the efficiency of PT services in Alicante, which is the city where the PT services had a greater loss of efficiency (Figure 6).

Figure 7 presents a description and a graphical representation of the different scenarios in the six cities, in terms of the evolution of the context and the PT performance.

Conclusions

Over the past fifty years, many cities have experienced low-density suburban development in their peripheries (European Environment Agency 2006). This phenomenon, known as sprawl, is accompanied by increasing car use and decreasing efficiency of PT systems (De Vos and Witlox 2013). This adverse scenario for urban PT performance has been worsened by the recent economic crisis. The financial crisis that hit the European continent in 2007 weakened demand for transport services (European Commission 2009), threatening the efficiency of PT systems (Taylor et al. 2009). This study developed a set of simple and easily available indicators to manage trends in economy, demography and PT performance, and the relationships among them. The indicators proposed are sensitive to changes over time, and the PT efficiency indicator shows its validity for monitoring PT competitiveness.

Figure 7. Summary of results and graphical representation.

In the light of the literature reviewed, we noted another potentially threatening trend for the efficient management of PT systems. Work arrangements are predicted to become increasingly flexible (Coenen and Kok 2014; Raffaele and Connell 2016). Practices such as teleworking or flexible working hours may discourage PT use and complicate its performance (Van Lier, DeWitte, and Macharis 2014; Vanoutrive et al. 2010). This trend has not been addressed in this article but is much related to the topic of analysis and might be of interest for future research.

The outcomes of the article are based on the comparative analysis of the evolution of the PT performance in six Spanish cities, all affected by sprawl and economic crisis at differing degrees. The results show that the combination of both the trends resulted in significant decline in PT demand and less efficient PT services. In most cases, PT modes operating in the suburbs have suffered more from the crisis and the sprawl, losing their efficiency levels. The cities analyzed were not able to reverse suburbanization processes in any of the two periods analyzed. Therefore, urban sprawl continued its way during the last ten years (2002–2012). The cities witnessed a period of economic decline after 2007, the transport demand fell and consequently disrupted the PT performance. At the expense of reducing PT efficiency, the PTA made several efforts to maintain the quality of the services. This policy increased costs by carrying fewer passengers, in a context of low investment capacity. However, reduction in supply would have probably worsened this cycle and further reduced demand and efficiency levels. This factor may explain some differences that were identified between different cities. It might also explain some differences identified between the evolution of urban and suburban modes in some cities.

Policy strategies need to include long-term land use and transport measures to achieve more sustainable PT systems. Strategies that limit measures to PT management are not enough in adverse scenarios. While the cities have reacted to these circumstances adopting different PT management strategies, none of them was able to avoid PT efficiency losses. It is necessary to establish the basis of a sustainable transport system that can tackle urban sprawl and encourage investments for improving PT quality, especially when the economic context is favorable. If an economic crisis has to be faced, then the achieved sustainable transport system will play its role in facilitating economic sustainability.

Acknowledgments

The authors would like to thank the three anonymous reviewers for their constructive suggestions, which have been very helpful to improve the work.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Note

1. Abbreviations. PT: Public Transport; MMO: Metropolitan Mobility Observatory; MA: Metropolitan Area (a geographical area where there is a high degree of interaction between its urban centres in terms of trips, relationships or economic activity); CC: Central City (core city in the metropolitan area); MR: Metropolitan Ring (Metropolitan area excluding Central City); PTA: Public Transport Authority.

References

- Aguila-Obra, Ana R., Sebastián B. Cámara, and Antonio P. Meléndez. 2002. "The Economic and Organizational Aspects of Telecentres: The Spanish Case." *Technovation* 22:785–98. doi:10.1016/S0166-4972(02)00032-9.
- Alonso, Andrea, Andrés Monzón, and Rocío Cascajo. 2015. "Comparative Analysis of Passenger Transport Sustainability in European Cities." *Ecological Indicators* 48: 578–92. doi:10.1016/j.ecolind.2014.09.022.
- Aparicio, Angel. 2004. *Informe 2002 del Observatorio de la Movilidad Metropolitana*. Ministerio de Medio Ambiente. Madrid, Spain: Ministerio de Medio Ambiente; Ministerio de Fomento.
- Audirac, Ivonne. 2005. "Information Technology and Urban Form: Challenges to Smart Growth." *International Regional Science Review* 28:119–45. doi:10.1177/0160017604273624.
- Bart, István L. 2010. "Urban Sprawl and Climate Change: A Statistical Exploration of Cause and Effect, with Policy Options for the EU." *Land Use Policy* 27:283–92. doi:10.1016/j.landusepol.2009.03.003.
- Bocarejo S, Juan P., and Daniel R. Oviedo H. 2012. "Transport Accessibility and Social Inequities: A Tool for Identification of Mobility Needs and Evaluation of Transport Investments." *Journal of Transport and Geography* 24:142–54. doi:10.1016/j.jtrangeo.2011.12.004.
- Bock, Hans H., and Edwin Diday. 2012. *Analysis of Symbolic Data: Exploratory Methods for Extracting Statistical Information from Complex Data*. Berlin, Germany: Springer.
- Brewer, Ann M. 1998. "Work Design, Flexible Work Arrangements and Travel Behaviour: Policy Implications." *Transport Policy* 5:93–101. doi:10.1016/S0967-070X(98)00003-1.
- Campbell, Mike, Alison Partridge, and Paul Soto. 2013. *Cities of Tomorrow—Action Today. URBACT II Capitalisation. More Jobs: Better Cities—A Framework for a Better Action on Jobs*. Saint-Denis, France. URBACT.
- Cegarra-Leiva, David., M. Eugenia Sánchez-Vidal, and Juan G. Cegarra-Navarro. 2012. "Work Life Balance and the Retention of Managers in Spanish SMEs." *International Journal of Human Resource Management* 23: 91–108. doi:10.1080/09585192.2011.610955.
- Coenen, Marja, and Robert A. W. Kok. 2014. "Workplace Flexibility and New Product Development Performance: The Role of Telework and Flexible Work Schedules." *European Management Journal* 32:564–76. doi:10.1016/j.emj.2013.12.003.

- Cordera, Ruben, Cesar Canales, Luigi dell'Olio, and Angel Ibeas. 2015. "Public Transport Demand Elasticities during the Recessionary Phases of Economic Cycles." *Transport Policy* 42:173–79. doi:10.1016/j.tranpol.2015.05.022.
- Currie, Graham. 2010. "Quantifying Spatial Gaps in Public Transport Supply Based on Social Needs." *Journal of Transport and Geography* 18:31–41. doi:10.1016/j.jtrangeo.2008.12.002.
- de Jong, Gerard C., and Odette van de Riet. 2008. "The Driving Factors of Passenger Transport." *The European Journal of Transport and Infrastructure Research* 8:227–50.
- De Vos, Jonas, and Frank Witlox. 2013. "Transportation Policy as Spatial Planning Tool; Reducing Urban Sprawl by Increasing Travel Costs and Clustering Infrastructure and Public Transportation." *Journal of Transport and Geography* 33:117–25. doi:10.1016/j.jtrangeo.2013.09.014
- Directorate-General for Economic and Financial Affairs of the European Commission. 2009. *Economic Crisis in Europe: Causes, Consequences and responses*. Luxembourg: Office for Official Publications of the European Communities.
- European Commission. 1996. *European Sustainable Cities—Report of the Expert Group on the Urban Environment*. Brussels, Belgium: European Commission, DGXI Environment, Nuclear Safety and Civil Protection.
- European Commission. 2007. *Green Paper: Towards a New Culture for Urban Mobility (COM (2007) 511 final)*. Brussels, Belgium: Commission of the European Communities.
- European Commission. 2011. *White Paper: Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System (COM (2011) 144 final)*. Brussels, Belgium: European Commission.
- European Commission. 2012. *Green Paper—Restructuring and Anticipation of Change: What Lessons from Recent Experience? (COM (2012) 7 final)*. Brussels, Belgium: European Commission.
- European Environment Agency. 2006. *Urban Sprawl in Europe—The Ignored Challenge*. Luxembourg: Office for Official Publications of the European Communities.
- European Environment Agency. 2009. *Ensuring Quality of Live in Europe's Cities and Towns. Tackling the Environmental Challenges Driven by European and Global Change*. Luxembourg: Office for Official Publications of the European Communities.
- European Union. 2010. *Making Our Cities Attractive and Sustainable*. Luxembourg: Publications office of the European Union.
- European Union. 2011. *Cities of Tomorrow—Challenges, Visions, Ways Forward*. Brussels, Belgium: European Commission, Directorate-General for Regional Policy.
- Fielding, Gordon J., Roy E. Glauthier, and Charles A. Lave. 1978. "Performance Indicators for Transit Management." *Transportation* 7:365–79. doi:10.1007/BF00168037.
- García-Palomares, Juan C. 2010. "Urban Sprawl and Travel to Work: The Case of the Metropolitan Area of Madrid." *Journal of Transport and Geography* 18:197–213. doi:10.1016/j.jtrangeo.2009.05.012.
- García, Marisol. 2010. "The Breakdown of the Spanish Urban Growth Model: Social and Territorial Effects of the Global Crisis." *International Journal of Urban and Regional Research* 34:967–80. doi:10.1111/j.1468-2427.2010.01015.x.

- Grönroos, Cristian, and Katri Ojasalo. 2004. "Service Productivity." *Journal of Business Research* 57:414–23. doi:10.1016/S0148-2963(02)00275-8.
- Haghshenas, Hossein, and Manouchehr Vaziri. 2012. "Urban Sustainable Transportation Indicators for Global Comparison." *Ecological Indicators* 15:115–21. doi:10.1016/S0967-070X(03)00055-6.
- Hair, Joseph F., William C. Black, Barry J. Babin, and Rolph E. Anderson. 2010. *Multivariate Data Analysis*. Upper Saddle River, NJ: Pearson Prentice Hall.
- Hillman, Mayer, Irwin Henderson, and Anne Whalley. 1976. "Transport Realities and Planning Policy." *Political and Economic Planning* 42:196.
- Hine, Julien, and Margaret Grieco. 2003. "Scatters and Clusters in Time and Space: Implications for Delivering Integrated and Inclusive Transport." *Transport Policy. Transport and Social Exclusion* 10:299–306. doi:10.1016/S0967-070X(03)00055-6.
- Holden, Erling, and Ingrid Norland. 2005. "Three Challenges for the Compact City as a Sustainable Urban Form: Household Consumption of Energy and Transport in Eight Residential Areas in the Greater Oslo Region." *Urban Studies* 42:2145–66. doi:10.1080/00420980500332064.
- Karlaftis, Matthew G., and Dimitros Tsamboulas. 2012. "Efficiency Measurement in Public Transport: Are Findings Specification Sensitive?" *Transportation Research Part A Policy and Practice* 46:392–402. doi:10.1016/j.tra.2011.10.005.
- Kenworthy, Jeffrey R., and Felix B. Laube. 1999. "Patterns of Automobile Dependence in Cities: An International Overview of Key Physical and Economic Dimensions with Some Implications for Urban Policy." *Transportation Research Part A: Policy and Practice* 33: 691–723. doi:10.1016/S0965-8564(99)00006-3.
- Litman, Todd. 2013. *Understanding Transport Demands and Elasticities—How Prices and Other Factors Affect Travel Behavior*. Victoria, Canada: Victoria Transport Policy Institute.
- MMO (Metropolitan Mobility Observatory). 2015. Metropolitan Mobility Observatory. Accessed December 30, 2016. <http://www.observatoriomovilidad.es/>.
- Monzón, Andrés, Rocío Cascajo, Andrea Alonso, Andrés García, and Aldara Tadeo. 2014. *Informe 2012 del Observatorio de la Movilidad Metropolitana*. Madrid, Spain: Ministerio de Agricultura, Alimentación y Medio Ambiente.
- Moreno, Rosina, and Enrique López Bazo. 2003. "Returns to Local and Transport Infrastructure under Regional Spillovers." *International Regional Science Review* 30:47–71. doi:10.1177/0160017606296728.
- Newman, Peter, and Jeffrey Kenworthy. 1999. *Sustainability and Cities: Overcoming Automobile Dependence*. Washington, DC: Island Press.
- Nielsen, Thomas A. S. 2015. "Changes in Transport Behavior during the Financial Crisis. An Analysis of Urban Form, Location and Transport Behavior in the Greater Copenhagen Area 2006–2011." *Research in Transportation Economics* 51:10–19. doi:10.1016/j.retrec.2015.07.003.
- Nijland, Linda, and Martin Dijst. 2015. "Commuting-related Fringe Benefits in the Netherlands: Interrelationships and Company, Employee and Location Characteristics." *Transportation Research Part A: Policy and Practice* 77:358–71. doi:10.1016/j.tra.2015.04.026.

- Organization for Economic Cooperation and Development. 2012. "Regional Statistics and Indicators—OECD Metropolitan Database." Accessed December 30, 2016. <http://stats.oecd.org/Index.aspx?Datasetcode=CITIES>.
- Preston, John, and Fiona Rajé. 2007. "Accessibility, Mobility and Transport-related Social Exclusion." *Journal of Transport and Geography* 15:151–60. doi:10.1016/j.jtrangeo.2006.05.002
- Raffaele, Catherine, and Julia Connell. 2016. *Telecommuting and Co-working Communities: What Are the Implications for Individual and Organizational Flexibility?* (pp. 21–35). New Delhi, India: Springer.
- Saisana, Michaela, and Stefano Tarantola. 2002. *State-of-the-art Report on Current Methodologies and Practices for Composite Indicator Development*. Ispra, Italy: European Commission—Joint Research Centre.
- Sobrino, Natalia, and Andrés Monzon. 2014. "The Impact of the Economic Crisis and Policy Actions on GHG Emissions from Road Transport in Spain." *Energy Policy* 74:486–98. doi:10.1016/j.enpol.2014.07.020.
- Song, Yan. 2005. "Smart Growth and Urban Development Pattern: A Comparative Study." *International Regional Science Review* 28:239–65. doi:10.1177/0160017604273854.
- Taylor, Brian D., Douglas Miller, Hiroyuki Iseki, and Camille Fink. 2009. "Nature and/or Nurture? Analyzing the Determinants of Transit Ridership across US Urbanized Areas." *Transportation Research Part A Policy and Practice* 43:60–77. doi:10.1016/j.tra.2008.06.007.
- Transport and Environment Reporting Mechanism (TERM). 2000. *Are We Moving in the Right Direction? Indicators on Transport Environment Integration in the UE*. Copenhagen, Denmark: European Environment Agency.
- Theodoridou, Ifigeneia, Agis M. Papadopoulos, and . Manfred Hegger. 2012. "A Feasibility Evaluation Tool for Sustainable Cities—A Case Study for Greece." *Energy Policy* 44: 207–16. doi:10.1016/j.enpol.2012.01.042.
- Tolley, Rodney, and Brian J. Turton. 2014. *Transport Systems, Policy and Planning: A Geographical Approach*. New York: Routledge.
- Ulfarsson, Gudmundur F., Anne Steinbrenner, Trausti Valsson, and Sungyop Kimb. 2015. "Urban Household Travel Behavior in a Time of Economic Crisis: Changes in Trip Making and Transit Importance." *Journal of Transport Geography* 49:68–75. doi:10.1016/j.jtrangeo.2015.10.012.
- United Nations. 1992. United Nations Conference on Environment & Development Rio de Janeiro, Brazil, 3 to 14 June 1992. Accessed December 30, 2016. <https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf>.
- Van Lier, Tom, Astrid de Witte, and Caty Macharis. 2014. "How Worthwhile Is Teleworking from a Sustainable Mobility Perspective? The Case of Brussels Capital Region." *European Journal of Transport and Infrastructure Research* 14:244–67.
- Vanoutrive, Thomas, Laurent V. Malderen, Bart Jourquin, Isabelle Thomas, Ann Verhetsel, and Frank Witlox. 2010. "Mobility Management Measures by Employers: Overview and Exploratory Analysis for Belgium." *European Journal of Transport and Infrastructure Research* 10:121–41.

- Zhang, Chunqin, Zhicai Juan, and Guangnian Xiao. 2015. "Do Contractual Practices Affect Technical Efficiency? Evidence from Public Transport Operators in China." *Transportation Research Part E: Logistics and Transportation Review* 80:39–55. doi:10.1016/j.tre.2015.05.001.
- Zhao, Pengjun. 2010. "Sustainable Urban Expansion and Transportation in a Growing Megacity: Consequences of Urban Sprawl for Mobility on the Urban Fringe of Beijing." *Habitat International* 34:236–43. doi:10.1016/j.habitatint.2009.09.008.

5.5. Modelling land use and transport policies to measure their contribution to urban challenges in the case of Madrid

Given that urban mobility and development are essential to achieve sustainable cities, transport and land use policies can help to face the sustainability city challenges in cities. In this regard, Section 5.5 presents an analysis of the contribution of three land use and transport policies—cordon toll, teleworking and re-densification—to address the city challenges in the Region of Madrid. The policies were simulated with a LUTI model, and the impacts measured through assessment indicators.

The research work was published in the scientific journal *Sustainability* (Impact Factor 2015: 1.343), from MDPI.

Figure 5.5. Policy issues analysed in Section 5.5 within the structure of the thesis

The model MARS used in Section 5.5 was firstly updated and improved. **All this previous work was published in the scientific journal *Computers, Environment and Urban Systems* (Impact Factor 2015: 2.092).** The article is presented in Annex B. The content is not part of the main body of the thesis but validates the MARS model as an appropriate tool to simulate policy measures in the case of Madrid

Article

Modelling Land Use and Transport Policies to Measure Their Contribution to Urban Challenges: The Case of Madrid

Andrea Alonso ^{1,*}, Andrés Monzón ² and Yang Wang ¹

¹ TRANSyT—Transport Research Centre, Universidad Politécnica de Madrid, 28040 Madrid, Spain; yang.wang@upm.es

² Civil Engineering Department, Universidad Politécnica de Madrid, 28040 Madrid, Spain; andres.monzon@upm.es

* Correspondence: andrea.alonso@upm.es; Tel.: +34-91-336-5234

Academic Editor: Tan Yigitcanlar

Received: 30 December 2016; Accepted: 24 February 2017; Published: 7 March 2017

Abstract: Urban areas play a key role in the development of European territories, and it is essential for them to be sustainable and efficient. However, the European cities are facing some challenges related to certain trends that are threatening their sustainable development and operational efficiency. In this paper, we compare the contribution of three policy measures—cordon toll accompanied by public transport improvements, teleworking and re-densification—to address different city challenges. The policy assessment requires a long term simulation tool, i.e., the MARS (Metropolitan Activity Relocation Simulator) model, which is able to consider interactions between land use and transport systems. The simulations of the different policy scenarios were carried out for the case of Madrid in the period 2012–2031. The contribution of the policy measures to address the city challenges was measured through different indicators. The results indicated that the three policy measures contributed to the time efficiency challenge, by saving time for the commute, reducing congestion and improving the traffic flows at peak hours. The most effective policy in this regard is the teleworking measure. Another challenge addressed by the three policies was the accessibility to PT. The three policy scenarios, when simulated, showed higher PT use, especially the cordon toll scenario. However, the only policy that really contributed to the energy, emissions and pollution city challenges was the re-densification measure, which reduced travel distances and encouraged a mobility that relies more on PT and slow modes.

Keywords: land use and transport model; policy assessment; city challenges; teleworking; cordon toll; re-densification

1. Introduction

Seventy per cent of the European population lives in cities, which is the main driving force of the respective national economies [1]. However, to drive a sustainable development, these urban areas need to face some problems such as unemployment, inefficiency, segregation, pollution and urban sprawl [1,2]. Both threats and opportunities emerge in urban areas, raising the city challenges [2]. The analysis of the challenges faced by the cities in their efforts to achieve a more sustainable development, gives a high priority to integrated transport and land use planning [3–7]. In this context, the land use and transport interaction models are key tools to analyse the impacts that may arise from urban planning decisions [8–10].

In this framework, the European research project INSIGHT-7 FP was proposed with an objective to develop management tools that could help European cities to formulate and evaluate policies to achieve

a sustainable urban development [11]. In the first stage of the project, the main challenges existing in the European cities were identified, linked to some indicators to measure the progress towards each challenge. In the subsequent stages, four urban models were developed for four European cities. These models are expected to address some of the challenges identified. In the final stage, three land use and transport policies were selected for their potential to overcome the city challenges. Each policy was simulated and tested by one or two of the four urban models. The simulations allowed evaluating the contribution of the policies to meet the urban challenges. The evaluation framework, based on urban challenges, indicators and policies, was validated by some ten external advisors. These external advisors were selected by the project consortium for their expertise in urban planning and policy making in European cities, to assess all the outcomes of the project. The modelling tools were also assessed by these experts. The data presented in this paper resulted from the work carried out by the authors during the project in collaboration with the rest of the consortium.

In this paper, we compared the contribution of the three transport and land use policies selected in INSIGHT project—cordon toll, teleworking and re-densification—to address different city challenges in the case of the Madrid Region. The contribution was measured in terms of the indicators identified at the beginning of the project. The policy assessment was carried out by simulating the policies with a Land Use and Transport Interaction (LUTI) model, which considered the assessment indicators for the period 2012–2031. The literature review on these topics showed that other studies have used LUTI models to analyse the effects of pricing schemes [12,13], and teleworking policies [14]. Very few studies have used LUTI models to analyse anti-sprawl policies, and these few studies are more related to TOD developments [15], than to re-densification processes. However there are no studies comparing policies of such different nature using the same tool.

2. Materials and Methods

2.1. Determining the European Urban Challenges

Urban areas play a key role in the development of European territories, thus it becomes indispensable for them to be sustainable and efficient [16]. However, European cities are facing some trends which are threatening their sustainable development and operational efficiency [17]. The first step of the project INSIGHT was to determine the main urban challenges in European cities [18], through an extensive review of some documents from the European and international institutions [1,2,4,19–23].

2.1.1. Challenges of Cities as Living Environments

The urban areas constitute to the **living environment** of a large fraction of the European Population, so the quality of life in these areas should be as high as possible [1,21]. This concern is globally widespread. Meeting the urban health challenge was one of the objectives set by the United Nations in Agenda 21, where the poor living conditions in urban areas around the world were reported [24]. The main causes of the degradation of the European cities are **pollution**, noise and the lack of **safety and security** [19]. These problems have a strong relation with an excessive traffic volume—a growing problem throughout Europe [21,22]. Most of the road accidents (69%) occur in cities [25]. Traffic also contributes to many gaseous air pollutants and suspended particulate matter: road transport accounts for a 30% of the fine Particulate Matter (PM) in urban areas [26]. The human environment should be preserved not only for the present but also for the future generations [27]. Cities are responsible for a significant part of GHG emissions, and therefore should be considered as key players in the **climate change** mitigation [4].

Another challenge related to the society is the **demographic decline**. The ratio of a working-age population is decreasing due to the low birth rate, the increase in life expectancy and the migration of active population due to the lack of job opportunities [2].

Finally, all citizens expect cities to satisfy their needs in terms of **education**, health care and transportation in an equitable manner [3]. This is getting more complicated due to the growing polarisation and socio-spatial segregation [2,23]. Urban transport systems are related to this trend, as they are expected to provide access for different needs [22,28].

2.1.2. Challenges Related to the Efficiency of Urban Systems

Urban environments drive economic development and are the main centres of many public services [3]. Almost 85% of the EU's GDP is generated in urban areas [21]. Cities can contribute to **economic growth and job creation**, by creating a competitive framework and enhancing productivity [2]. However, the recent economic crisis has made this challenge more difficult to achieve. Cities have been especially exposed to the economic recession, which has severely affected the competitiveness, productivity and operational efficiency of services [29].

Another important barrier to overcome the economic competitiveness is the **inefficient consumption patterns**, where European cities have a great scope for improvement, especially regarding **energy consumption** in housing and transport sectors [20]. Moreover, the transport sector is characterised by a predominance of non-renewable energy source, mainly oil, due to the car dependence [4]. This excessive car usage gives rise to another problem related to efficiency and competitiveness. The increased traffic in European cities results in chronic congestion, with the adverse consequences, which are expressed in terms of delays and consequent economic losses [21,22].

Finally, the spatial dispersion of urban areas is one of the biggest barriers to achieve efficient cities [19]. **Urban sprawl**, understood as the spread of low-density urban settlements around the core city, has been the main characterising growth pattern of European cities in the last few decades [2]. Urban sprawl contributes to the fragmentation of living and working spaces and segregates commercial activities and residents far away from city centres, adversely affecting economic dynamics [23]. The dispersion of urban areas is typically accompanied by an increase in the housing and transport spending, growing congestion levels, the extension of urban infrastructures and a more costly provision of public services [19].

At the initial stage of INSIGHT project, ten city challenges aligned with these topics were determined, together with some indicators to measure the progress in addressing the challenges [18]. All these outcomes were validated by some experts and policy makers with the consultation of stakeholder that was a part of the project [30]. All these outcomes are summarised in Table 1.

Table 1. City challenges and indicators assessed by stakeholders.

City Challenges		Validated Indicators ¹
Cities as living environments	Enable social development, in an equitable, healthy and safe manner; and minimise the impacts on environment	Liveable at human level
		5 indicators related to the quantity and quality of the areas in the city devoted to people.
		Equal, safe and secure society
		11 indicators related to the provision and access to main needs and services, accidents, crime and inequalities
		Pollution
		8 indicators for measuring air and noise pollution
Cities as efficient urban systems	Constitute appropriate frameworks for economic growth and efficiency; and minimise the consumption of resources	Climate Change
		3 indicators for measuring GHG emissions
		Demographic decline
		4 indicators for measuring the ageing of the population, and the shrinking of the active population
		Education and culture
		2 indicators related to education in school and cultural services
		Economic activity
		5 indicators related to the job creation, and economic growth
		Efficient use of resources (i.e., time)
		3 indicators related to the time spent in travelling to work or studies, wasted time in congestion or unused space in the city
		Energy efficiency
		9 indicators measuring the energy consumption from different sources
		Urban sprawl
		3 indicators for measuring the dispersion of the population

¹ Considered relevant and related to the challenge. Source: [18,31].

2.2. MARS: A LUTI Model for the Case of Madrid

2.2.1. The Case Study of Madrid: Main Features of the Region and Regulatory Framework

Four European cities, London, Madrid, Barcelona and Rotterdam, were considered in the INSIGHT project as the case studies to be analysed. One of the main objectives of the project was to develop urban models for each specific case study. These urban models should serve as simulation tools for policy implementation. This paper is based in the case of Madrid, where the developed and improved simulation tool is the MARS model. The MARS (Metropolitan Activity Relocation Simulator) model was created by Pfaffenbichler [32], who developed it for the first time for the city of Vienna. This model is a macro strategic LUTI model, which works on the basis of causal loop diagrams (CLD) and represents the cause and effect relations between transport and land use. This model is appropriate for a long term policy making, since it has the predictability up to 30 years.

Madrid Region has a population of 6.4 million inhabitants. The region is organised into administrative units, called municipalities. One of these municipalities is the city of Madrid, where a 50 percent of the region's population live [33]. However, this percentage is gradually decreasing due to the urban sprawl [7]. The whole city covers an area of 8026 km² area, of that, 12% is urbanised [34]. Previous studies on the challenges that Madrid is facing [31,35] give high priority to the problem of urban sprawl and to the economic downturn in the period of economic crisis. During this period of economic crisis, energy consumption and emission levels have decreased together with the activity levels. However, the environmental challenges should not be overlooked, especially if economic growth is expected.

There are three plans especially dealing with the mobility and urban development in Madrid Region. The first one is the Sustainable Mobility Strategic Plan 2013–2025, which was elaborated by the public transport authority in Madrid Region [36]. The objectives of this plan include coordination between land use and urban transport, improving transport efficiency and accessibility, and a shift towards soft modes. Some of the policy actions proposed include the restriction and regulation of cars, the establishment of workplace mobility plans and the implementation of safety features to reduce traffic accidents. Another strategic plan related to urban mobility is the air quality plan 2013–2020 [37], which proposes several measures related to urban transport, e.g., the promotion of cleaner fuels, the establishment of low emissions zones, improvement of infrastructures for pedestrians and bicycles and expansion of the public transport network. As regards to urban planning, the prevalent land law no. 9/2001 [38] contains some general principles such as the need to coordinate urban development with the development of the transport network, duty to provide accessibility to all and responsibility to preserve the environment. There is no document dealing with an integral strategic plan for the transport network and urban land development [39].

In this paper, we present the results of implementing three different policy measures, by the simulation of the MARS model. These policies are cordon toll together with public transport expansion; promotion of teleworking and re-densification measures. The two transport measures are closely related to some action lines proposed by the strategic plans being implemented in Madrid Region, such as restriction of cars, improvement of the public transport network and the establishment of workplace mobility plans. The land use policy measure, re-densification, would be appropriate in the context of Madrid, since the city is facing a clear trend towards urban dispersion [7].

2.2.2. Main Features of MARS Model for Madrid

The fundamental principle of mobility analysis and forecast is the spatial separation of activities and people, which requires them to travel [40]. Transport and land use systems have a mutual influence, and the interaction between them has certain implications that can only be perceived in the long term [41]. One of the complex processes in the modelling of large urban areas for planning purposes is to adequately model the interaction between the transport system and the spatial distribution of residents and activities [42]. LUTI modelling has been investigated since the 1960s as a tool to

support strategic urban planning [8]. Lowry Model of Metropolis [43] was the first attempt to quantify the land use transport feedback cycle in a single integrated model. After the Lowry Model, many spatial interaction location tools have been developed, aiming at modelling the location of human activities as origins and destinations of trips, e.g., METPLAN [44] and PECAS [45]. Other LUTI models do not predict actual spatial interactions but the opportunity for spatial interactions are expressed as accessibility. Compared to the first urban models, which were static equilibrium models, accessibility-based location models, such as INPUT [46], MUSSA [47], DELTA [48] and MARS, tend to be more dynamic, attempting to capture the dynamics of urban processes. Sheperd [10] suggested applying the dynamic approaches in LUTI models. He argued that the land use and transport systems interact at different time scales. The land use changes are much slower than transport changes. These time lags and the complex interactions between them offer an ideal situation for the implication of the system dynamic approaches. Shepherd [10] highlighted the MARS model among others, due to its validation and transferability between cities. The model has already been applied to more than 20 cities around the world [49].

The MARS model is implemented in Vensim®, a System Dynamics programming environment. The model includes a transport sub-model that simulates the travel behaviour of the population, a housing location sub-model and a workplace location sub-model. The sub-models are executed iteratively over a period of up to 30 years, being linked by two factors, namely the accessibility and the location of households and workplaces [50]. Figure 1 shows the basic components of the Model. The **external scenarios and policy instruments** are inputs for the MARS model. The external scenarios include a number of variables in relation to demographic and economic growth, transport data and land use development. The policy instruments are policy interventions which modify the conditions of the land use sub model or the transport sub-model. The **transport sub-model** generates and distributes the trips of residents between the different zones and for different modes. The **land use sub-model** allocates workplaces and residents in the different zones. The accessibility to workplaces acts as an output in the transport model, while as an input in the location sub-models. The distribution of residents and workplaces acts as an output in the land use model. The results from this iterative process are used for assessing the policy instruments.

Figure 1. The basic structure of the MARS model for the case of Madrid. Source: [50], the figure is adapted to the case study of Madrid.

The MARS model for the case of Madrid was developed and calibrated first time by Guzmán [51], who applied it to maximise the welfare of pricing policies [12]. Later, Wang [52] made some developments in the model, which improved the sensitivity of the model to capture the changes in the accessibility-to-jobs levels produced by transport policies (i.e., [13,53]). Finally, in the framework of the INSIGHT project, the MARS model for the case of Madrid was updated and re-developed. Further explanations on the concepts, specifications and improvements of the model are provided in Appendix A.

MARS model divides the whole Region of Madrid into 90 zones (Figure 2). These zones, classified by Guzmán [51], are homogeneous territories in the terms of socioeconomic characteristics and mobility patterns. In the city of Madrid, where 50% of the Region's population lives, the zone aggregation is served at a district level. In the metropolitan ring, where 42% of the population lives, the zones correspond to different municipalities. The zones in the regional ring, which only account for 8% of the population, comprise various municipalities.

Figure 2. The zones of the MARS model for the city of Madrid. Red lines indicate the aggregated regions.

The reliability of the MARS model largely depends on the quality of the input data, which is implemented by the disaggregation of zones. The data needed for the exogenous variables and for the calibration process can be divided into three types [53]:

- **Socio economic data**, i.e., population per zone and population growth per aggregated region (city, metropolitan north, east, south or west and regional ring), household budget per zone, motorisation rate per zone, etc., were mainly obtained from the official statistical sources, provided by institutions at the city, regional and national levels [33,54,55].

- **Basic data on land use development and economic growth**, i.e., the functional proportion of land use (resident, production and service), land prices, expected growth of economic activity etc., were mainly obtained from the structural statistic databases at the regional level [56], and from international databases containing economic projections [57].
- **Basic data of transport mobility**, i.e., trip distance, speeds and time between the zones in different modes, car operating costs, the value of time, car occupation rate, etc., since the MARS model is an aggregated model and does not have a transport network, were partly obtained from VISUM transport model, which was executed through road network of the model (e.g., [58]). Some other transport data were obtained directly from the CRTM [36]. Besides that, the Madrid MARS model was calibrated by using three household mobility surveys conducted in Madrid in 1996, 2004 and 2014. The calibration process involved adjusting the values for the MARS model as external variables.

The main features of the model are summarised in Table 2.

Table 2. Main features of the MARS model ¹.

Model Features	MARS for Madrid
No of zones	90
Demographics	Average household budget, household size, motorisation, etc.
Land use changes	Simulates land use changes depending on changes in accessibility and population growth rates
Allowed time period for predictions	30 years
Modes of travel	Car, public transport (bus, metro, urban train), slow mode (walking and cycling)
Congestion effect	Depends on the origin-destination speed-flow curves for commute trips
Friction factor (Generalised costs)	In-vehicle time, monetary costs, access/egress, parking search time, waiting time, transfer time
Journey purpose	Commute, other
Time periods	Peak hour and off-peak hours
Transport choice	Simultaneous mode and destination choice (not route, the model does not have a transport network)
Transport demand	Inelastic commuting trips and time budget essentially constant

¹ Source: [51].

2.2.3. Model Outputs for Policy Assessment

The purpose of this paper was to measure the contribution of different policy measures to meet city challenges. For this, we simulated the implementation of three policy measures in Madrid, using the MARS model. The effects of the policies should be measured in terms of the indicators validated in the first stage of the project (Table 1). However, the MARS model is focused on territorial and transport dynamics, while the city challenges and indicators were designed following a more open approach. Tables 3 and 4 show the role, if any, of each indicator in the MARS model. Only the indicators given as an output by the MARS model were used for the policy assessment.

The results of the model rely on the input data, especially on the growth projections for the economy and population. The growth projections are mostly provided by official statistical sources, which usually consider linear trends [33,54,55]. This is a simplification that may be different from reality [59]. However, we do not expect the modelling results to provide an accurate prediction of the future trends in terms of emissions or accidents, which are highly dependent on external conditions. What we expect from the modelling results is the possibility to determine if, under the same baseline

conditions, certain policy actions could contribute to reduce emissions, accidents, etc. In general, the model should help us to analyse which policies could contribute to address different city challenges.

Table 3. Socio-environmental challenges: Indicators for Madrid and their role in the MARS model.

City Challenges	No of Validated Indicators ¹	Madrid (2012)	Role in the Mars MODEL
Liveability	Pedestrians & cyclists injured in traffic accidents (no./year)	27.9	-
	Space for pedestrian use (km ²)	102	-
	Length of bicycle lanes (km)	290	-
	Road land occupation (km ²)	90	-
	Green areas (km ²)	160	Input
Equal, safe and secure society	Use and coverage of PT (Million Pax-km/year)	11,839	Output
	Use and coverage of PT within the main city	5191	Output
	Use and coverage of PT within the suburbs	1702	Output
	Income inequality: S80/S20 (ratio)	6.6	-
	Cost of main needs, share of the household budget devoted to main needs (housing, nutrition, health, education and transport) (%)	62.1	Only transport costs are the output of the MARS model
	Essential services provision in each zone: space devoted to health, educational and social services (km ²)	86	The provision of essential services in each zone is considered as an input in the MARS model (acting as a factor of attractiveness of each zone for residents & workplaces)
	Essential services provision in the main city	25	
	Essential services provision in the suburbs	60	
	Traffic accidents with casualties	10,625	Output
	Fatalities occurred in traffic accidents (no)	70	-
	Crime according to surveys, share of persons that report delinquency and vandalism problems (%)	54.2	-
Pollution	Average air concentration of: NO _x (µg/m ³)	76	-
	Particles (µg/m ³)	22	-
	Total emissions of: NO _x (t)	50,749	Only emissions of NO _x and PM due to the urban daily mobility of the population are an output of the MARS model
	Particles-PM (t)	88,308	
	Emissions in relevant sectors: Transport NO _x (t)	40,838	
	Transport PM (t)	5146	
	Industry NO _x (t)	4421	-
	Industry PM (t)	1118	-
Climate Change	Noise intensity levels (LAeq dBA)	62.8	-
	Greenhouse gases emissions (GHG) (Thousands of Ton of CO ₂ eq)	18,857	Only GGE emissions due to the urban daily mobility of the population are an output of MARS
	GHG by main sectors: Transport (Thousands of CO ₂ eq)	8477	
	Industry (Thousands of CO ₂ eq)	3085	-
Demographic decline	Share of active population (%)	53.2	Only the initial population per zone and its growth per aggregated region is an input of MARS
	Share of population over 60 years (%)	20.4	
	Share of population under 25 years (%)	25.3	
	Share of skilled workers (%)	51.8	
Education/culture	Drop-out rates from secondary education (%)	21.5	-
	Cultural offer (no. of cinemas and cultural offer)	222	-

Table 4. Efficiency challenges: Indicators for Madrid and their role in the MARS model.

City Challenges	No of Validated Indicators ¹	Madrid (2012)	Role in the Mars MODEL
Economic activity	Household available budget (€ per household/year)	34,770	Input
	GDP per capita (€ per inhabitant (inhab)/year)	30,446	Input
	Employment (% of the active population)	64.2	Input
	Job creation (No. of workplaces)	2,529,262	Output
	Land prices (€/m ²)	2181	Input
Efficient use of resources (i.e., time)	Unoccupied flats or buildings (No.)	436,977	-
	Congestion, increase of travel time at peak hours (%)	11.8	Output
	Total time spent commuting by all inhab (total hours/day)	1,441,325	Output

Table 4. Cont.

City Challenges	No of Validated Indicators ¹	Madrid (2012)	Role in the Mars MODEL
Energy efficient	Energy consumption (ktoe/year)	10,192	Only energy consumption due to the urban daily mobility of the population are an output of the MARS model
	Energy consumption in relevant sectors:	5176	
	Transport (ktoe/year) ¹	2396	
	Housing (ktoe/year)	869	-
	Industry (ktoe/year)	55.8	-
	Fuel dependence (energy coming from petrol and carbon sources) (%)	96.2	Only energy fuel dependence of the urban daily mobility of the population is an output of the MARS model
	Fuel dependence in relevant sectors:	16.2	
	Transport (%)	15.4	
	Housing (%)	1.9	
	Industry (%)		
Urban sprawl	Share of energy consumption from renewable sources (%)		
	Urban density (inhabitants/km ²)	6277	Input (the urban surface and the population growth are part of the external scenarios of the MARS model)
	Urbanised surface (km ²)	1037	
	Share of the population living in the Central City (%)	49.7	Output

¹ toe: Tonnes Oil Equivalent.

2.3. Policies Design and Implementation: Defining the Policy Scenarios

Three policies were assessed in this study: two transport policies, viz. cordon toll and teleworking, and one land use policy, viz. re-densification. These policy measures were selected for the various reasons. Firstly, for their potential to address some city challenges, essentially those that are related to the excessive car use, such as congestion, pollution or climate change. Secondly, for their diverse nature, such as one pricing policy, one behavioural policy and one structural policy, which would broaden the scope of the study and enrich the comparative assessment. Thirdly, because all policies are aligned with some trends, which are really happening in cities, such as car pricing policies [60], flexible working arrangements [61] and regeneration and revitalisation of inner city centres to avoid the migration of the population to the suburbs [62]. Finally, the limitations of the MARS model to simulate policy measures needed to be considered, since it is an aggregated model. Besides, the three policy measures were discussed and agreed by INSIGHT consortium with the assessment of the experts of the project [63]. In order to analyse the effects of the policies, we had to build one scenario for each policy, in addition to the base scenario. This reference scenario is called the do-nothing scenario.

2.3.1. Do Nothing

The Do-nothing scenario is defined and executed in the model in order to compare the effects of implementing the three policy measures with not taking any particular action. However, in this subsection, we present the most important inputs to be implemented in the model for the long term assessment: economic and demographic growths. In order to input the economic growth, we implied the OECD database [57], which provides economic projections (Figure 3). The model considers an economic growth rate for the whole Region, and then redistributes workplaces and residents in the different zones. This economic growth is the same in the four policy scenarios.

Data on demographic growth were provided by Madrid City Council database [54], which gives the population projections until 2023 for Madrid City, and by the National Spanish Statistical database (INE) [55], which gives the population projections for the whole Madrid Region until 2031. There are no official projections of the population in Madrid beyond 2031. For this reason, we have limited the study and the analysis of this paper to 2031. Regarding the demographic growth, the model considers six different population growth rates for the following aggregated regions: Madrid City, Metropolitan North, Metropolitan East, Metropolitan South, Metropolitan West and Regional Crown (Figure 2). For this study, the growth rates of each zone were calculated on the basis of the projections for the city and the whole Madrid Region. The internal distribution of the population between the different aggregated regions was performed by adopting a similar methodology to that adopted by INE [55] for

Madrid Region, which can be consulted in [64], and is based on the socioeconomic features of each zone (Table 5). Logically, the zones where the population is younger and the average birth rate is higher, show higher growth rates, i.e., Metropolitan North or West and Regional Ring. Conversely, the population of Madrid City is expected to decrease [54], being characterised by the highest death rate and a negative migration balance. These social characteristics of the different zones draw part of the urban sprawl picture, e.g., young families move out of the city centres, looking for better environments and more affordable houses [19]. The final growth rates fed in the model are shown in Figure 4, and are the same in the cordon toll + PT and the teleworking scenarios. The re-densification scenario consists of changing the redistribution between the city and the outside rings, and therefore considers a different internal distribution of the population.

Figure 3. Economic growth. Projections for the whole Madrid Region. Data sources: (INE) [55] for real data, and (OECD) [57] for projections.

Table 5. Socioeconomic features influencing population projections (Year 2012) ¹.

Feature	Unit	City	North	East	South	West	Regional
Population	No. inhab	3,233,527	320,307	652,437	1,292,240	472,043	538,454
Average age	Years	42.4	37.2	37.1	38.3	36.7	37.1
Birth rate	No./1000 inhab	9.9	11.2	11.3	11.6	10.3	11.7
Death rate	No./1000 inhab	8.4	4.5	4.2	5.0	4.1	5.6
Emigration rate	No./1000 inhab	30.5	21.6	19.3	21.5	20.4	19.5
Immigrants from other countries or Spanish regions	No.	98,552	6913	12,597	27,799	9613	10,294
Migration balance with other zones of Madrid	No.	−10,950	1638	2166	466	1720	4960

¹ Data sources: [33].

Figure 4. Population growth in the different zones of Madrid Region. The input for the MARS model. Data sources: [33] for real data, [54] for projections in the case of the Madrid city and [55] for projections in the whole Madrid Region.

With regard to the transport sub-model and the data inputs, Table 6 and Figure 5 provide some aggregated data on the daily trips made in Madrid Region. These data were retrieved from the household mobility survey carried out by CRTM [36], and employed to calibrate the model. In Madrid Region, almost 13 million trips are made per day. One-third of these trips are Commuting trips, which are characterised by their dependence on motorised modes and their longer distances. For this reason, many mobility management strategies focus on commuting mobility [65]. On the other hand, we can observe that the trips made in the city are based more on public transport and walking than the trips made in the suburbs, which are more car-dependent. This is one of the reasons why urban sprawl follows an unsustainable growth pattern [19].

Table 6. Daily trips in Madrid Region: The number and distribution by zones and purposes ¹.

Heading	No. of Trips Per Day	Within the City	Between the City and the Metropolitan & Regional Rings	Within the Metropolitan & Regional Trips
Commuting trips	4.3 million	45.4%	28.9%	25.7%
Non-Commuting trips	9.2 million	49.1%	13.2%	37.7%

¹ Data source: The mobility survey carried out by CRTM [36] in 2014.

Figure 5. Modal share of daily trips in Madrid Region by purposes and zones. Data source: [36].

2.3.2. Cordon Toll and Public Transport Improvement

It is well known that optimal road pricing may yield a social and environmental surplus [66]. Furthermore, in some cases, the added value of the measure to the economy and efficiency has been demonstrated through gains in the value of time and reduced congestion [67]. In this case, for the design of the cordon toll, we decided to follow a similar scheme of the cordon toll implemented in Stockholm, which is usually considered as a successful case study [68] (Table 7). The MARS model simulates the cordon toll policies by increasing the cost of making certain trips, in this case, the area proposed for the cordon toll simulation includes zones 1 to 7 (Figures 2 and 6), and all trips entering in these zones are affected. In addition, and following the Stockholm cordon toll scheme, we implemented improvements in PT service frequencies, which were increased by seven per cent. On the other hand, the acceptability of pricing policies potentially increases along the time, and this can change the effectiveness of the policies [69]. To avoid this effect, it is sometimes recommended to increase the price over time. In the case of Stockholm, the initial price in 2006 was 20 SEK at peak hours, and the price increased to 35 SEK in 2016 [70]. We followed a similar approach for a 15-year simulation, from 2016, which is the initial year of the policy implementation, to 2031, which is the end year of the simulation process. Other authors have also carried out analysis of cordon toll policies using the MARS model before [12,13], where more details about the implementation process can be consulted. Some features about the cordon toll implementation are presented in Table 7.

Figure 6. Cordon toll area proposed. Input for the MARS model in the cordon toll policy.

Table 7. Main features of the cordon toll policy. Input for the MARS model in the cordon toll policy ¹.

Heading	Stockholm (2 Million Inhabitants)	Madrid (6.4 Million Inhabitants)
	Real Data	Input Data for the Simulation
Toll area: limitation	CBD, physically separated by channels	CBD, physically separated by the M-30 (ring road)
Share of the population living inside the toll area	15.6%	15.4%
Initial Price peak (KRN)/ GDP per capita (KRN)	20 SEK in 2006 (~€2.12 in 2006) 418,099 SEK in 2006 (~€44,421 in 2006)	€2 in 2016/ €30,446 in 2015 (considering the GDP and the city size)
Initial Price off peak (€)/ GDP per capita (€)	10 SEK in 2006 (~€1.06 in 2006) 418,099 SEK in 2006 (~€44,421 in 2006)	€1 in 2016/ €30,446 in 2015
Public transport services extension	7% increase in PT frequencies	7% increase in PT frequencies
Increase of the peak price	75% in 10 years	112.5% in 15 years (accompanied by an increase of the PT frequencies: up to 14% in 2031)
Increase of the off-peak price	10% in 10 years	15 % in 15 years

¹ Data sources: Information of Stockholm taken from [68,70].

2.3.3. Teleworking

Practices such as teleworking or flexible working hours are increasingly gaining importance at a global level, and are predicted to grow continuously [61]. This prediction might also be extended in the case of Spain, where such practices emerged later than in other countries, but are showing an upward trend [71]. Flexible work arrangements are often helpful in transport management solutions, since they are assumed to lessen the number and length of traffic jams at peak hours [72]. However, teleworking practices have some other side effects that should be considered. They often result in the growth of non-work related trips during the day, and this may negatively affect the global energy and increase emissions [73].

According to Census surveys carried out by the INE [55], in Madrid Region, the number of people working at home has grown from 2.4% in 2001 to 8% in 2011. In view of this growth, and considering feasibility studies on this topic [73–75], we considered that teleworking encouragement policies could achieve a reduction of a 10 per cent in trips to work by 2031. Teleworking practices could be part of the workplace mobility plans that the public authorities of Madrid Region intend to establish [36,37]. For the implementation of teleworking in the model, this reduction is assumed to be linear. It is supposed to increase from 2016, where there is still no reduction, to 2031, where a 10 per cent reduction on the commuting trips will be achieved. Teleworking policy measures have also been assessed earlier with the MARS model by other authors [50].

2.3.4. Re-Densification

In the on-going search for guidelines and strategic intervention, the need for the re-densification and the restoration of degraded zones in the city centres has emerged at various levels [76]. However, very few studies have quantified the potential effects of re-densification policies over emissions, energy or social inclusion [77]. Only a few studies have analysed the benefits of Transit Oriented Developments [78] through transport models [15].

For the design of the re-densification policy, we firstly assumed that the net population growth in the whole Region keeps constant in all scenarios. What changes in the re-densification scenario is the internal distribution of the population between the aggregated regions. In the re-densification scenario, the city of Madrid loses less population than in the previous scenarios, due to the regeneration of some zones. There is a zone in Madrid that has recently gone through a process of improvement and regeneration. In this zone, which is called Arganzuela (zone 2 in the model), the so-called Operación Madrid Río [54] has improved the environment, and expanded green areas, public spaces and sports facilities. In this zone, the population movements to the suburbs are lower than in most of the zones in Madrid City. Considering this case as a successful regeneration process, we assume that similar regeneration processes took place in various zones of the city. Madrid city comprises zones 1–21 (Figure 2). Out of these zones, we have selected those which are considered more degraded and where the population movements to the suburbs have been higher during the last few years: 8 (Fuencarral), 9 (Moncloa), 10 (Latina), 11 (Carabanchel), 12 (Usera), 13 (Vallecas), 14 (Moratalaz), 17 (Villaverde), 20 (San Blas) and 21 (Barajas). For building the re-densification scenario, it is assumed that these zones would behave similarly to zone 2, and would have lower population losses. Under these assumptions, the resulting population growths are represented in Figure 7. These population growth rates were inputted in the model to obtain the re-densification scenario.

Figure 7. Population growth in the different zones of Madrid Region. Input for the MARS model in the re-densification scenario (compared to the population growth applied in the other policy scenarios).

3. Results

The results of the four simulations corresponding to the four scenarios defined are presented in Figures 8–13. The figures show the variables with the greatest influence in the policy assessment results, which are based on the values of the indicators associated with the different city challenges (Tables 3 and 4). The figures cover each year of the simulation period, from 2012 (Year 0) to 2031 (Year 19): time travelling, passenger-km, car speed and CO₂ COs emissions. In addition, Figures A1–A3 in Appendix A show the causal loop diagrams for the calculation of these variables in the MARS model. Figures 8 and 9 show the time travelling per person. The three policies achieved time savings in commuting trips and reduced the traffic at peak hours. In the cordon toll and teleworking scenarios, the car speed increases due to the improved traffic flow. This is translated into an economic value, and is good in terms of efficiency and reduces congestion. However, the time budget per person and day is more or less constant, and in the three scenarios, people travelled more during nonpeak hours and for not for work reasons. In some scenarios, this resulted in an increase in the total vehicles-km travelled, also increasing the total emissions and energy. This is especially the case of the teleworking scenario, where the trips to work keep decreasing over the years. In fact, the only scenario which achieved a reduction in the total km travelled by car was the re-densification scenario, through a reduction of distances and increasing the trips within the city, which are based more on walking and PT. In the first year of the simulation process (2012–2013), the growth of the economy and the population are still negative, due to the economic crisis that hit European Continent in 2007 [79]. This results in a

reduction of trips and emissions from 2012 to 2013. From 2014 to 2015, the economic indicators start to recover and positive growths for the economy and the population are expected in the upcoming years [54,55,57].

Figure 8. Evolution of time travelling at peak hours in the three policy scenarios, MARS output.

Figure 9. Evolution of time travelling at off peak hours in the three policy scenarios, the MARS output.

Figure 10. Evolution of passenger-km travelled by car in the three policy scenarios, the MARS output.

Figure 11. Evolution of passenger-km travelled by public transport in the three policy scenarios, the MARS output.

Figure 12. Evolution of average car speed in the three policy scenarios, the MARS output.

Figure 13. Evolution of CO₂ emissions per person due to urban transport in the three policy scenarios, the MARS output.

The results of the policy assessment are presented in the terms of the indicators related to the city challenges, as shown in Tables 3 and 4. For measuring the contribution of the three policies to meet the city challenges, we have used only those indicators which are given as an output in the MARS model. The simulation results for the four policies are presented in Tables 8 and 9.

Table 8. Contribution of the three policy measures to efficiency challenge ¹.

Challenges	Indicator	2012	Policy Scenario	2020 (Model)	2031 (Model)	Total Savings (2012–2031)
Economic activity	Workplaces (no. of jobs)	2,529,262	Do-nothing	2,665,996	2,854,384	Base scenario
			Toll + PT	2,667,759	2,870,712	n.a. ²
			Telework	2,665,936	2,852,071	n.a.
			Redensific.	2,665,996	2,855,003	n.a.
Time efficiency	Congestion, increase in travel time at peak hours (%)	11.8	Do-nothing	12.0	12.7	Base scenario
			Toll + PT	11.5	12.0	n.a.
			Telework	11.7	11.5	n.a.
			Redensific.	11.9	12.5	n.a.
	Total time spent commuting by all inhab. (hours/day)	1,441,325	Do-nothing	1,459,921	1,544,282	Base scenario
			Toll + PT	1,433,810	1,506,929	114 mill. hrs saved
			Telework	1,413,901	1,358,071	357 mill. hrs saved
			Redensific.	1,455,872	1,533,569	29 mill. hrs saved
Energy efficiency	Energy consumption in daily urban mobility (ktoe/year)	1961	Do-nothing	2038	2222	Base scenario
			Toll + PT	2029	2239	3 ktoe saved
			Telework	2049	2296	498 ktoe extra
			Redensific.	2027	2199	249 ktoe saved
	Fuel energy dependency (%)	94.4	Do-nothing	94.5	95.0	Base scenario
			Toll + PT	94.5	94.9	n.a
			Telework	94.6	95.2	n.a
			Redensific.	94.5	95.0	n.a
Sprawl	Share of the metropolitan population living in the main city (%)	49.7	Do-nothing	47.0	43.4	Base scenario
			Toll + PT	47.2	43.5	n.a
			Telework	47.2	43.4	n.a
			Redensific.	47.7	45.3	n.a

¹ Bold letters highlight the policy with the best results; ² n.a: not applicable.

Table 9. Contribution of the three policy measures to social and environmental challenge.

Challenges	Indicator	2012	Policy Scenario	2020 (Model)	2031 (Model)	Total Savings (2012–2031)
Safety	Traffic accidents (No./year)	10,625	Do-nothing	11,667	12,027	Base scenario
			Cordon toll	11,255	12,052	4504 accid. less
			Telework	11,157	12,445	3483 accid. less
			Redensific.	10,966	11,561	10,076 accid. less
Accessibility	PT use (million Pax-km/year)	11,836	Do-nothing	11,678	11,048	Base scenario
			Cordon toll	12,267	11,881	n.a
			Telework	11,696	11,053	n.a
			Redensific.	11,718	11,173	n.a
	Cost of mobility to work or study per person (€/day)	1.25	Do-nothing	1.31	1.43	Base scenario
			Cordon toll	1.53	1.74	n.a
			Telework	1.27	1.29	n.a
			Redensific.	1.30	1.40	n.a
Climate change	GGE from urban transport (Thousands of Ton CO ₂ eq./year)	5458	Do-nothing	5531	6064	Base scenario
			Cordon toll	5518	6062	177 t of CO ₂ saved
			Telework	5548	6185	776 t of CO ₂ extra
			Redensific.	5509	6022	519 t of CO ₂ saved
Air pollution	NO _x emissions from urban transport (t/year)	14,677	Do-nothing	16,494	18,725	Base scenario
			Cordon toll	16,583	18,925	1879 t extra
			Telework	16,564	19,190	3078 t extra
			Redensific.	16,428	18,598	1540 t less
	PM emissions from urban transport (t/year)	1088	Do-nothing	1569	1926	Base scenario
			Cordon toll	1563	1914	162 t saved
			Telework	1573	1958	195 t extra
			Redensific.	1560	1912	170 t saved

¹ Bold letters highlight the policy with the best results; ² n.a: not applicable.

4. Discussion

The following paragraphs clarify and discuss the results shown in Tables 8 and 9.

Economic activity: In both cordon toll and re-densification scenarios, the number of workplaces increased with regards to the reference scenario. This was due to the different allocation of residents and workplaces. On the one hand, the cordon toll policy measure allocated more workplaces outside the city, balancing the equilibrium between the residents and workplaces outside the city and reducing unsatisfied demand. On the other hand, in the re-densification scenario more workplaces were allocated in the city, balancing the equilibrium between the residents and workplaces inside the city and reducing slightly the unsatisfied demand. Conversely to the cordon toll and re-densification measures, the teleworking policy measure reduced slightly the total number of workplaces, due to the reduction of supply.

Time efficiency: The three policy measures reduced the time spent on commuting, especially teleworking, which reduced the need to travel to work. On the other hand, the total time budget per person tends to be constant. On this basis, the time spent travelling for other reasons increased in the three policy scenarios. However, these time losses do not necessarily affect the economic efficiency. Regarding the congestion, the three policy measures improved the traffic flow, but the most effective was the teleworking.

Energy efficiency: Only the re-densification policy measure really contributed to save energy. In the teleworking scenario, the increased demand for non-commuting mobility led to increase the total energy consumption. In the cordon toll scenario, the increase of PT services caused a moderate increase in the total energy consumed in the last years.

Safety: The three policy measures reduced the total number of traffic accidents along the period, especially the re-densification, due to a mobility based more on slow modes and PT. At the end of the period, the traffic accidents increased in the teleworking and re-densification scenarios, due to the increases in car speed at peak hours (improved traffic flow) and the increase in the number of trips at non-peak hours.

Accessibility: The three policy measures encourage PT use. Especially the cordon toll, due to the improvement in PT services and the higher costs of travelling by car. In the teleworking scenario, the trips done by PT increased (slightly) due to the increased demand at non-peak hours. In the re-densification scenario, the trips within the city gained significance. This increased the PT use since the mobility inside the city is more based on PT. Regarding the cost of commuting mobility, the more effective measure to reduce the costs of the obligatory mobility is the teleworking, which reduces the need to travel. On the other hand, the only policy measure that increases the cost of mobility to work or study is the cordon toll, due to the increased costs of travelling by car.

Climate change: Both cordon toll and re-densification policy measures contribute to reduce GGE, especially the re-densification policy, by reducing travel distances and encouraging mobility more based more on PT and slow modes. The GGE reduction in the cordon toll scenario is due to the reduction in the total number of trips by car. In the teleworking scenario, the GGE increase due to the increased demand for non-commuting mobility.

Air pollution: Regarding emissions, only the re-densification policy measure contributed to reduce both NO_x and PM emissions. In the teleworking scenario, emissions increased due to the growth of traffic at non-peak hours. In the cordon toll scenario, only the PM emissions decreased due to the reduced car traffic, but the emissions of NO_x increased, due to the increased bus services.

5. Conclusions

In this paper, we compared three land use and transport policy measures to determine their contribution in addressing different city challenges. The three policies, cordon toll, teleworking and re-densification, are aligned with some trends which are really happening in cities and have a high potential to address some city challenges, essentially those related to the excessive car use, e.g., congestion, pollution or climate change. The policy assessment required a long-term simulation tool,

able to consider the interactions between the land use and transport systems. For this, we employed the MARS model applied to Madrid Region. This LUTI model, created by Pfaffenbichler [32] for the city of Vienna, was developed by Guzmán [51] for the city of Madrid, and latter improved by Wang [52]. In the framework of INSIGHT project, the model was updated and re-developed [80,81], and this last version of the model was used to simulate and assess the three policy measures. The simulations were executed for the period 2012–2031.

The contribution of the policy measures to address the city challenges in Madrid Region was measured through indicators, validated and assessed by stakeholders during the project. The results indicate that the three policy measures contribute to the time efficiency challenge, and yield commuting time savings, reducing congestion and improving traffic flow at peak hours. The most effective policy in this regard is the teleworking measure. Another positive effect of the three policies is an increase in the PT use, especially in the cordon toll scenario, which includes PT improvements. This effect is positive for the social inclusion and accessibility for all.

On the other hand, commuting time savings have some side effects: people travel more at nonpeak hours and for not working purposes. This results in increasing the total passengers-km at non-peak hours and, in some scenarios, also in the total energy and emissions. This is especially the case of the teleworking measure. The cordon toll measure produces energy and emissions savings at the beginning of the implementation, but loses efficiency over time due to the acceptability. The only policy that really contributes to the city challenges such as energy, emissions and pollution in the long term is the re-densification measure, which reduces travel distances and encourages a mobility based more on PT and slow modes. The containment of urban sprawl in Madrid should be a priority policy objective, especially considering the dispersion of the population that has occurred during the last years in the region [7,31,39].

Policy strategies need to include long-term land-use and urban development measures to achieve more sustainable transport systems. Strategies that limit measures to transport management are not enough to resolve the city challenges [7]. It is necessary to establish the basis of a sustainable transport system that can tackle urban sprawl and encourage investments for improving PT quality, in order to improve accessibility and equity. Regarding flexible working schemes, they are very effective for time efficiency and to reduce congestion, but they could negatively affect the energy and emissions challenges [73].

Future research could focus on the implementation of combined policy actions to design a strategic plan for achieving a sustainable urban development. An effective strategy to address all the city challenges should contain various measures related to land use development and transport management with an objective of bringing together the positive effects of the different measures.

Acknowledgments: The authors gratefully acknowledge funding from the European Union's Seventh Framework Program (Information and Communications Technologies Call 10) to develop INSIGHT (Innovative Policy Modelling and Governance Tools for Sustainable Post-Crisis Urban Development, European Commission Project Number: 611307).

Author Contributions: Andrea Alonso wrote the paper and elaborated tables and figures to compile and present the data and results. Andrés Monzón structured the paper and the presentation of the results and coordinated the whole research process. Yang Wang worked with the tool used (MARS model) in order to improve it and make it able to simulate the policy measures. The three authors decided the type of policies to be implemented. Andrea Alonso elaborated the list of challenges and assessment indicators, designed and implemented the policies in the model, processed and elaborated the results and drawn the main conclusions.

Conflicts of Interest: There is no conflict of interest.

Abbreviations

CBD	Central Business District
CRTM	Consortio Regional de Transportes de Madrid (Public Transport Authority in Madrid Region)
GHG	Green House Gases
HOH	Home–Others–Home

HWH	Home–Work–Home
INE	Instituto Nacional de Estadística (National Statistical Institute in Spain)
LUTI	Land Use and Transport Interaction
MARS	Metropolitan Activity Relocation Simulator
OD	Origin–Destination
PT	Public Transport
PM	Particulate Matter
TOD	Transyt Oriented Developments

Appendix A

The basic concepts and equations behind the MARS model can be found elsewhere [32]. The main specifications for the case of Madrid are detailed by Guzmán [51] and Wang [52] and the improvements carried out during the INSIGHT project can be found in the studies by Wang et al. [80] and Salas-Olmedo et al. [81]. The main issues are summarised below, following the structure shown in Figure 1.

The **external scenarios** are a necessary input for the MARS model. These include a number of variables in relation to demographic growth, transport data and land use development that can be collected via the local statistic census or mobility surveys. Those variables related to the future growth projections are generally obtained from the institutional data sources. It is not the aim of the model to predict the population or the economic growth but to allocate residents and workplaces depending on the growth scenario and the accessibility provided by the transport sub-model.

The **policy instruments** are policy interventions to be evaluated. They are considered as another input for the MARS model, since they modify the conditions of the land use sub-model or the transport sub-model. Each policy measure needs to be defined in the terms of the implementation period, geographical scale and intensity.

The **transport sub-model** in the MARS model needs to be complemented by another specific transport model, as the model is an aggregated LUTI model and does not include a transport network. The complementary model, representing the road and public transport network, provides the necessary data to build the transport sub-model in the MARS: travel times, distances and speeds between the different zones and for different modes at peak and off-peak hours. The transport sub-model in the MARS contains three stages: trip generation, trip distribution and modal split. The fourth stage, route assignment, which is characteristic of traditional transport models, is not present in the MARS model.

- The **trip generation** stage considers two types of trip purposes: work and others. This stage follows the overall principle of constant time budgets, supported by many studies [82–85]. The work-oriented trips, termed Home–Work–Home (HWH), generated in each zone i depend on the number of employed residents in the zone and on the average trip rate per person (Equation (A1)). The trips related to other purposes, termed Home–Other activities–Home (HOH), depend on the travel time available per person, which is calculated after the trips to work have been generated and distributed. The total travel time per capita and day is assumed to be constant.

$$P_i|_{HWH} = r|_{HWH} * E_i \quad (A1)$$

where $P_i|_{HWH}$ is the production of trips at zone i for tours HWH; $r|_{HWH}$ is the average trip rate per person for tours HWH, and E_i is the number of employed residents living in zone i .

- The **trip distribution** and **modal split** take place simultaneously in the transport sub-model, using a combination of the analogy to the law of gravity and Kirchoff's law from electrical engineering [32]. The trip attraction and mode choice is divided into HWH and HOH trips. The attraction of each zone, j , as a destination is given by the land use sub-model and depends on the activity for which the destination is chosen. For the trips HWH, the attraction depends on the number of workplaces in the destination zone. For the trips HOH, the attraction depends on the population living in the destination zone, and the existence of activities such as retail. Travel times and travel costs per mode and Origin–Destination (OD) pair give the different friction factors. Equation (A2) describes these simultaneous stages.

$$T_{ij}^{m,p} = \left[P_i * \frac{A_j / f(t_{ij}^{m,p}, c_{ij}^{m,p})}{\sum_j A_j / f(t_{ij}^{m,p}, c_{ij}^{m,p})} \right]_{HWH} + \left[P_i * \frac{A_j / f(t_{ij}^{m,p}, c_{ij}^{m,p})}{\sum_j A_j / f(t_{ij}^{m,p}, c_{ij}^{m,p})} \right]_{HOH} \quad (A2)$$

where $T_{ij}^{m,p}$ is the number of trips by mode m from zone i to destination j during the p period (peak or off peak hours); P_i is the production of trips at zone i , A_j is the attraction of zone j as a destination; and $f(t_{ij}^{m,p}, c_{ij}^{m,p})$ is the friction factor for a trip by mode m from zone i to destination j during the period p , including travel time $t_{ij}^{m,p}$ and travel costs $c_{ij}^{m,p}$ (which are calculated iteratively for the mode car, depending on the speed and the traffic flow).

The generation, distribution and modal split influence the **accessibility**, which is an input for the land use sub-model (Equation (A3)). One of the most important improvements in the model carried out during INSIGHT

project was the development of the accessibility measure. The accessibility indicator in the current version contemplates not only the accessibility-to-jobs but also the accessibility to schools and shops. These improvements in the MARS model are described in more detail in [80,81].

$$Acc_j(t) = \sum_t \sum_{j,m,p} \left[a_j * W_j^m(t) * F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)_{Work} + b_j * Edu_j^m(t) * F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)_{edu} + c_j * Hea_j^m(t) * F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)_{health} + d_j * Park_j^m(t) * F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)_{Park} + e_j * Shop_j^m(t) * F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)_{Shop} \right] \quad (A3)$$

where $Acc_j(t)$ is the aggregated accessibility to workplaces and services; $W_j^m(t)$ is the number of jobs in the destination zone j by mode m in the year t ; $Edu_j^m(t)$ is the number of schools in the destination zone j by mode m in the year t ; $Hea_j^m(t)$ is the number of hospitals and health centres in the destination zone j by mode m in year t ; $Park_j^m(t)$ is the number of parks in the destination zone j by mode m in year t ; and $F\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right) = \exp\left[-0.0163 * (c_{ij}^{m,p}(t) + t_{ij}^{m,p}(t) * Time\ value^p)\right]$ is the generalised cost to reach jobs or the respective public service from i to j in the mode m and in the period p , calibrating the value of time on the basis of the mobility surveys.

The **land use sub-model** comprises a module for the location of residents and another for the location of workplaces. The sub-model allocates residents and workplaces in the different zones considering the willingness to move in and out of each zone and the supply-demand balance. Equations (A4) and (A5) represent the calculation for the residents moving out and intending to move in.

$$N_j^{mv} = P^{mv}(t) * \frac{a^{mv} * e^{b^{mv} * Acc_j(t) + c^{mv} * ShGr_j(t) + d^{mv} * R_j^D(t)}}{\sum_j a^{mv} * e^{b^{mv} * Acc_j(t) + c^{mv} * ShGr_j(t) + d^{mv} * R_j^D(t)}} \quad (A4)$$

where N_j^{mv} is the number of residents demanding a living place in zone j in the year t ; $P^{mv}(t) = \frac{N^R(t)}{\Delta T^{mv}}$ is the potential number of residents moving out, which depends on the total number of residents in the study area ($N^R(t)$) and the average time living at the same residence (T^{mv}); $Acc_j(t)$ is the aggregated accessibility to different activities in zone j in the year t ; $ShGr(t)$ is the share of Greenland in zone j in the year t ; $R_j^D(t)$ is the monthly rent for a domicile in zone j in the year t ; and a^{mv} , b^{mv} , c^{mv} , and d^{mv} are parameters derived from a regression analysis using observed data and calibration.

$$N_j^{in} = P^{in}(t) * \frac{\frac{A_j^{in}(t)}{f(Z_j^{in}(t))}}{\sum_j \frac{A_j^{in}(t)}{f(Z_j^{in}(t))}} = P^{in}(t) * \frac{a^{in} * e^{b^{in} * Acc_j(t) + ShGr_j(t) * (c^{in} * ShGr_j(t) + d^{in}) + e^{in} * R_j^D(t)}}{\sum_j a^{in} * e^{b^{in} * Acc_j(t) + ShGr_j(t) * (c^{in} * ShGr_j(t) + d^{in}) + e^{in} * R_j^D(t)}} \quad (A5)$$

where $N_j^{in}(t)$ is the number of residents demanding a living place in zone j in the year t ; $P^{in}(t)$ is the total demand for living places which can be satisfied in the year t ; $A_j^{in}(t)$ is the attraction to move into zone j in the year t ; and $f(Z_j^{in}(t))$ is the friction factor, a^{in} , b^{in} , c^{in} , d^{in} , and e^{in} are parameters derived from a regression analysis using observed data and calibration.

The **location of households and workplaces** is an output from the land use sub-model, which affects to the attraction and generation of trips and to the accessibility of each zone.

The different parameters are obtained in the calibration process. The quality of the input data is essential in this stage. A summary of the different data sources used is provided in Section 2.2.2.

The transport and land use sub-models are executed iteratively over a certain period of years. The results of the simulations in terms of variables and indicators are used for the policy assessment. Figures A1–A3 show some simplified causal loops for calculating some of them.

Figure A1. Simplified causal loop diagram of time calculations in MARS model.

Figure A2. Simplified causal loop diagram of speed calculations in MARS model.

Figure A3. Simplified causal loop diagram of cars CO₂ calculations in MARS model.

References

1. United Nations. *Smart Cities and Infrastructure*; United Nations Economic and Social Council: Geneva, Switzerland, 2016.
2. European Union. *Cities of Tomorrow—Challenges, Visions, Ways Forward*; European Commission, Directorate General for Regional Policy: Brussels, Belgium, 2011.
3. European Union. *Making Our Cities Attractive and Sustainable*; Publications office of the European Union: Luxembourg, 2010.
4. United Nations. *Climate Neutral Cities—How to Make Cities Less Energy and Carbon Intensive and More Resilient to Climatic Challenges*; United Nations: Geneva, Switzerland, 2011.
5. Saunders, M.J.; Kuhnimhof, T.; Chlond, B.; Silva, A.N.R. Incorporating Transport Energy into Urban Planning. *Transp. Res. A Policy Pract.* **2008**, *42*, 874–882. [CrossRef]
6. Alonso, A.; Monzón, A.; Cascajo, R. Comparative Analysis of Passenger Transport Sustainability in European Cities. *Ecol. Indic.* **2015**, *48*, 578–592. [CrossRef]
7. Alonso, A.; Monzón, A.; Cascajo, R. Measuring Negative Synergies of Urban Sprawl and Economic Crisis over Public Transport Efficiency. Available online: <http://journals.sagepub.com/doi/abs/10.1177/0160017616687361> (accessed on 24 January 2017).
8. Geurs, K.T.; Wee, B. Land-use/Transport Interaction Models as Tools for Sustainability Impact Assessment of Transport Investments: Review and Research Perspectives. *Eur. J. Transp. Infra. Res.* **2004**, *4*, 333–355.
9. Wegener, M. The Future of Mobility in Cities: Challenges for Urban Modelling. *Transp. Policy* **2013**, *29*, 275–282. [CrossRef]
10. Shepherd, S.P. A Review of System Dynamics Models Applied in Transportation. *Trans. B Trans. Dyn.* **2014**, *2*, 83–105. [CrossRef]
11. INSIGHT-7FP-EC—Innovative Policy Modelling and Governance Tools for Sustainable Post-Crisis Urban Development. Available online: <http://www.insight-fp7.eu/> (accessed on 21 December 2016).
12. Guzman, L.A.; Hoz, D.; Monzón, A. Optimal and Long-Term Dynamic Transport Policy Design: Seeking Maximum Social Welfare through a Pricing Scheme. *Int. J. Sustain. Transp.* **2014**, *8*, 297–316. [CrossRef]
13. Wang, Y.; Monzon, A.; Ciommo, F.D. Assessing the Accessibility Impact of Transport Policy by a Land-use and Transport Interaction Model—The Case of Madrid. *Comput. Environ. Urban Syst.* **2015**, *49*, 126–135. [CrossRef]
14. Pfaffenbichler, P.; Garcia, G.; Angel, L.; Hoz Sánchez, D.D.L.; Shepherd, S. Analysis of the taxes on CO₂ transport emissions as a measure to reach sustainable scenarios. In Proceedings of the VII Conference on Transport Engineering, La Coruña, Spain, 2–4 July 2008. (In Spanish)

15. Lo Feudo, F. How to Build an Alternative to Sprawl and Auto-Centric Development Model through a TOD Scenario for the North-Pas-De-Calais Region? Lessons from an Integrated Transportation-land Use Modelling. *Transp. Res. Proc.* **2014**, *4*, 154–177. [CrossRef]
16. European Commission. *European Sustainable Cities—Report of the Expert Group on the Urban Environment*; European Commission—DGXI Environment, Nuclear Safety and Civil Protection: Brussels, Belgium, 1996.
17. European Union. *Progress towards the Territorial Agenda of the European Union 2020*; European Union: Luxembourg, 2014.
18. Romanillos, G.; Alonso, A.; Wang, Y. *Deliverable 2.2 Urban. Planning and Governance: Current Practices and New Challenges*; INSIGHT 7FP–EC: Madrid, Spain, 2014.
19. European Environment Agency. *Urban. Sprawl in Europe—the Ignored Challenge*; European Environment Agency: Copenhagen, Denmark, 2006.
20. Lewis, J.O.; Hógáin, S.N.; Borghi, A. *Building Energy Efficiency in European Cities*; URBACT: Saint-Denis, France, 2013.
21. European Commission. *Green Paper—Towards a New Culture for Urban Mobility*; European Commission: Brussels, Belgium, 2007.
22. Enemark, A.; Kneeshaw, S. *How Cities Can Motivate Mobility Mindsets*; URBACT: Nancy, France, 2013.
23. Colini, L.; Czischke, D.; Günter, S.; Tosics, I.; Ramsden, P. *URBACT II Capitalisation against Divided Cities in Europe*; URBACT: Nancy, France, 2013.
24. United Nations. United Nations Conference on Human Environment. Available online: <https://sustainabledevelopment.un.org/milestones/humanenvironment> (accessed on 21 December 2016).
25. European Commission. *White Paper: Roadmap to a Single European Transport Area—Towards a Competitive and Resource Efficient Transport System*; European Commission: Brussels, Belgium, 2011.
26. World Health Organization. *Health Effects of Transport-related Air Pollution*; World Health Organization: Copenhagen, Denmark, 2011.
27. United Nations. United Nations Conference on Environment & Development-AGENDA 21. Available online: <https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf> (accessed on 21 December 2016).
28. Preston, J.; Rajé, F. Accessibility, Mobility and Transport-related Social Exclusion. *J. Transp. Geogr.* **2007**, *15*, 151–160. [CrossRef]
29. European Commission. *Green Paper-Restructuring and Anticipation of Change: What Lessons from Recent Experience?* European Commission: Brussels, Belgium, 2012.
30. García, O.; Lucio, A.; Salas-Olmedo, M.H.; Romanillos, G.; Alonso, A.; Feijoo, C. *Deliverable 2.1 Stakeholders Consultation*; INSIGHT 7FP–EC: Madrid, Spain, 2014.
31. Alonso, A.; Monzón, A. Assessing the Progress towards Sustainability and the Role of Urban Transport—City of Madrid. In Proceedings of the 6th Transport Research Arena, Warsaw, Poland, 18–20 April 2016.
32. Pfaffenbichler, P. The Strategic, Dynamic and Integrated Urban Land Use and Transport Model MARS (Metropolitan Activity Relocation Simulator). Ph.D. Thesis, Technical University of Vienna, Wien, Austria, September 2003.
33. ALMUDENA—Statistical Database for Madrid Region. Available online: <http://www.madrid.org/desvan/Inicio.icm?enlace=almudena> (accessed on 21 December 2016).
34. Madrid Transport Consortium. *EMTA—European Metropolitan Transport Authorities*; Consorcio de Transportes de Madrid: Madrid, Spain, 2014.
35. Alonso, A.; Monzón, A. Policy Priority Objectives: Comparative Assessment in Four European Cities. In Proceeding of the XII Congreso de Ingeniería de Transporte-CIT, Valencia, Spain, 7–9 June 2016.
36. CRTM—Consorcio Regional de Transportes de Madrid (Public Transport Authority in Madrid Region). Available online: <http://www.crtm.es/> (accessed on 21 December 2016).
37. Madrid Region. *Air Quality Strategy 2013–2020*. Available online: http://www.madrid.org/cs/Satellite?c=CM_Planes_FA&cid=1354532201832&language=es&pageid=1350931018212&pagename=ComunidadMadrid%2FCM_InfPractica_FA%2FCM_fichaInfPracticaServicios&vest=1350930997092 (accessed on 21 December 2016). (In Spanish)
38. Madrid Region. *Land law for Madrid Region*; Madrid Region: Madrid, Spain, 2001. (In Spanish)
39. Leboeiro, A. Territorial Planning in Global European Cities: The Case of Madrid. Ph.D. Thesis, Polytechnic University of Madrid, Madrid, Spain, 2015. (In Spanish)

40. Wegener, M. Operational Urban Models: State of Art. *J. Am. Plan. Assoc.* **1994**, *60*, 17–29. [[CrossRef](#)]
41. Greiving, S.; Wegener, M. Integration of Transport and Land Use Policies: State of the Art. In Proceeding of the 9th World Conference on Transport Research, Seoul, Korea, 22–27 July 2001.
42. Bravo, M.; Briceño, L.; Cominetti, R.; Cortés, C.E.; Martínez, F. An Integrated Behavioral Model of the Land-use and Transport Systems with Network Congestion and Location Externalities. *Transp. Res. B Methodol* **2010**, *44*, 584–596. [[CrossRef](#)]
43. Lowry, I.S. *A Model of Metropolis*; Rand Corporation: Santa Monica, CA, USA, 1964.
44. Echenique, M.H.; Flowerdew, A.D.J.; Hunt, J.D.; Mayo, T.R.; Skidmore, I.J.; Simmonds, D.C. The MEPLAN Models of Bilbao, Leeds and Dortmund. *Transp. Rev.* **1990**, *10*, 309–322. [[CrossRef](#)]
45. Hunt, J.D.; Abraham, J.E. Design and Implementation of PECAS: A Generalised System for Allocating Economic Production, Exchange and Consumption Quantities. In *Integrated Land-Use and Transportation Models*; Lee-Gosselin, M., Doherty, S., Eds.; Elsevier Science: New York, NY, USA, 2005; pp. 253–273.
46. Wegener, M. *The IRPUD Model*; Spiekermann & Wegener Urban and Regional Research(S&W): Dortmund, Germany, 2011.
47. Martínez, F. MUSSA: Land Use Model for Santiago City. *Transp. Res. Rec. J. Transp. Res. Board* **1996**, *1552*, 126–134. [[CrossRef](#)]
48. Simmonds, D.C. The Design of the DELTA Land-use Modelling Package. *Environ. Plan. B Plan. Des.* **1999**, *26*, 665–684. [[CrossRef](#)]
49. TU-Wien. Transport Research Institute in the Technische Universitat Wien. Available online: <http://www.ivv.tuwien.ac.at/forschung/mars-metropolitan-activity-relocation-simulator/overview/> (accessed on 21 December 2016).
50. Pfaffenbichler, P.; Emberger, G.; Shepherd, S. The Integrated Dynamic Land Use and Transport Model MARS. *Netw. Spat. Econ.* **2008**, *8*, 183–200. [[CrossRef](#)]
51. Guzmán, L.A. Dynamic Optimization of Sustainable Mobility Strategies in Metropolitan Areas. Ph.D. Thesis, Technical School of Civil Engineering, Madrid, Spain, July 2011. (In Spanish)
52. Wang, Y. Assessing Urban Mobility through Participatory Scenario Building and Combined Utility Regret Assessment. Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, April 2014.
53. Wang, Y.; Alonso, A.; Monzón, A. Transport Policy Evaluation by a LUTI Model (MARS). In *The TRANSPACE Model*; Dell’Olio, L., Cordera, R., Ibeas, A., Eds.; GIST—Transport Systems Research Group: Santander, Spain, 2016; pp. 34–65.
54. Madrid—Ayuntamiento. (Statistical Database for Madrid City). Available online: <http://www-2.munimadrid.es/CSE6/jsps/menuBancoDatos.jsp> (accessed on 21 December 2016).
55. INE—National Statistical Database for Spain. Available online: <http://www.ine.es/> (accessed on 21 December 2016).
56. DESVAN. Statistical Database for Madrid Region. Available online: <http://www.madrid.org/desvan/Inicio.icm?enlace=desvan> (accessed on 21 December 2016).
57. OECD—Organisation for Economic Co-operation and Development. Projections Database. Available online: <https://data.oecd.org/gdp/gdp-long-term-forecast.htm> (accessed on 21 December 2016).
58. Valdes, C.; Monzon, A.; Benitez, F.G. Sustainable Urban Transportation Strategies: Searching for Synergies. *KSCE J. Civ. Eng.* **2016**, *20*, 1066–1075. [[CrossRef](#)]
59. Ziltener, P. The Economic Effects of the European Single Market Project: Projections, Simulations and the Reality. *Rev. Int. Political Econ.* **2004**, *11*, 953–979. [[CrossRef](#)]
60. Anas, A.; Lindsey, R. Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice. *Rev. Environ. Econ. Policy* **2011**, *5*, 66–88. [[CrossRef](#)]
61. Coenen, M.; Kok, R.A.W. Workplace Flexibility and New Product Development Performance: The Role of Telework and Flexible Work Schedules. *Eur. Manag. J.* **2014**, *32*, 564–576. [[CrossRef](#)]
62. Musterd, S.; Bontje, M.; Ostendorf, W. The Changing Role of Old and New Urban Centers: The Case of the Amsterdam Region. *Urban Geogr.* **2006**, *27*, 360–387. [[CrossRef](#)]
63. Armuña, C.; Arenal, A.; Feijoo, C. *Deliverable 7.5 Comparative Evaluation and Assessment*; INSIGHT 7FP-EC: Madrid, Spain, 2016.
64. Spanish Statistical Office. *Population Projections for Spain 2016–2066—Methodology*; Spanish Statistical Office: Madrid, Spain, 2016; pp. 1–56. (In Spanish)

65. Brewer, A.M. Work Design, Flexible Work Arrangements and Travel Behaviour: Policy Implications. *Transp. Policy* **1995**, *5*, 93–101. [CrossRef]
66. Zhang, W.; Kockelman, K. Urban Sprawl, Job Decentralization, and Congestion: The Welfare Effects of Congestion Tolls and Urban Growth Boundaries. In Proceeding of the Transportation Research Board (TRB) 93rd Annual Meeting, Washington, DC, USA, 12–16 January 2014.
67. Eliasson, J. A Cost–Benefit Analysis of the Stockholm Congestion Charging System. *Transp. Res. A Policy Pract.* **2009**, *43*, 468–480. [CrossRef]
68. Eliasson, J.; Hultkrantz, L.; Nerhagen, L.; Rosqvist, L.S. The Stockholm Congestion-charging Trial 2006: Overview of Effects. *Transp. Res. A Policy Pract.* **2009**, *43*, 240–250. [CrossRef]
69. Parry, I.W.; Walls, M.; Harrington, W. Automobile Externalities and Policies. *J. Econ. Lit.* **2007**, *45*, 373–399. [CrossRef]
70. Transport Styrelsen. Available online: <https://www.transportstyrelsen.se/en/road/Congestion-taxes-in-Stockholm-and-Goteborg/> (accessed on 21 December 2016).
71. Cegarra-Leiva, D.; Sánchez-Vidal, M.E.; Cegarra-Navarro, J.C. Work Life Balance and the Retention of Managers in Spanish Smes. *Int. J. Hum. Res. Manag.* **2012**, *23*, 91–108. [CrossRef]
72. Nijland, L.; Dijst, M. Commuting-related fringe benefits in the Netherlands: Interrelationships and company, employee and location characteristics. *Transp. Res. A Policy Pract.* **2015**, *77*, 358–371. [CrossRef]
73. Lier, T.; Witte, A.; Macharis, C. How Worthwhile is Teleworking from a Sustainable Mobility Perspective? The Case of Brussels Capital Region. *Eur. J. Transp. Infrastruct. Res.* **2004**, *14*, 244–267.
74. Vanoutrive, T.; Malderen, L.; Jourquin, B.; Thomas, I.; Verhetsel, A.; Witlox, F. Mobility Management Measures by Employers: Overview and Exploratory Analysis for Belgium. *Eur. J. Transp. Infrastruct. Res.* **2010**, *10*, 121–141.
75. Horvath, A. Environmental Analysis of Telework: What We Know and What We Do Not Know and Why. In Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST), Arlington, TX, USA, 17–19 May 2010.
76. Cacciaguerra, G.; Gatti, M.P. *Urban Re-densification and Regeneration: 21st Century City Strategies*; WIT Transactions on Ecology and the Environment: London, UK, 2015; pp. 217–226.
77. Salvati, L. Urban Containment in Action? Long-term Dynamics of Self-contained Urban Growth in Compact and Dispersed Regions of Southern Europe. *Land Use Pol.* **2013**, *35*, 213–225. [CrossRef]
78. Erli-Handayani, K.D.M. TOD Best Practice: Lesson Learned for GHG Mitigation on Transportation Sector in Surabaya City, Indonesia. *Proc. Soc. Behav. Sci.* **2014**, *135*, 152–158.
79. European Communities. *Economic Crisis in Europe: Causes, Consequences and Responses*; European Communities: Luxembourg, 2009.
80. Wang, Y.; Salas-Olmedo, M.H.; Alonso, A.; Monzón, A.; García-Palomares, J.C. *Deliverable 5.3 Enhanced Version of the MARS Simulation Model*; INSIGHT 7FP-EC: Madrid, Spain, 2016.
81. Salas-Olmedo, M.H.; Wang, Y.; Alonso, A. When GIS Meets LUTI: Assessing Accessibility with Local Coefficients for the LUTI Model MARS. *Comput. Environ. Urban Syst.*.. Accepted.
82. Hupkes, G. The Law of Constant Travel Time and Trip-rates. *Futures* **1982**, *14*, 38–46. [CrossRef]
83. Daly, H.E.; Ramea, K.; Chiodi, A.; Yeh, S.; Gargiulo, M.; Gallachóir, B.Ó. Incorporating Travel Behaviour and Travel Time into TIMES Energy System Models. *Appl. Energy* **2014**, *135*, 429–439. [CrossRef]
84. Marchetti, C. Anthropological Invariants in Travel Behavior. *Technol. Forecast Soc. Chang.* **1994**, *47*, 75–88. [CrossRef]
85. Schafer, A. Regularities in Travel Demand: An International Perspective. *J. Transp. Stat.* **2000**, *3*, 1–31.

© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

6. Conclusions, main findings and future research

From the literature review on urban planning and research tools (Chapters 2 and 3), and especially from the research studies carried out in Chapter 5, a number of conclusions can be drawn. The most relevant conclusions and findings for urban planning and transport management in European cities are summarised in Section 6.1. Finally, Section 6.2 includes proposals for future research lines that have emerged throughout the thesis.

6.1. Specific conclusions and findings

The main conclusions of the work carried out are presented in two sub-sections: conclusions related to urban development and mobility management in European cities (Section 6.1.1) and findings related to the tools that can be applied for strategic urban planning (Section 6.1.2).

6.1.1 Urban development and mobility management in European cities

The conclusions of this thesis, as well as the research work carried out, are structured following the scheme in Figure 6.1:

- Assuming that cities need to be sustainable, the achievement of a sustainable urban mobility is a key priority. Under this approach, in Section 5.1, 23 European cities were analysed through indicators, and the main factors explaining the sustainability of their urban transport systems are consequently identified in this thesis.
- European cities are among the most sustainable cities in the world, but they face some general and specific problems and trends that threaten their sustainable development. Each city should identify its particular threats, in order to consider them in the planning process and establish policy priorities. In Sections 5.2 and 5.3, the main threats over four European cities are identified on a comparative analysis based on indicators.
- Threats and opportunities emerge in cities, thus raising the city challenges: to become liveable and efficient. The efficiency of urban systems and services is particularly affected by the threats of urban sprawl and economic decline. To analyse more deeply these synergies, in Section 5.4 the impacts of both threats over the efficiency PT services were measured for Spanish cities on a trends analysis through indicators.
- Land use and transport policies were identified as potential contributors to address the city challenges. In Section 5.5, three policy measures were simulated using a LUTI model for the case of Madrid. The contribution of these three policy measures to address the city challenges was assessed through the output indicators of the model.

Figure 6.1. City cycle for urban threats and challenges and the role of transport strategies- main findings

Identification of the factors that explain sustainability of urban transport systems

Measuring the sustainability of transport systems requires considering multiple dimensions and overlapping concepts. In Section 5.1, a methodology based on composite indicators was developed to analyse the sustainability of passenger transport systems in 23 European cities, 19 of which were Spanish cities. The indicators-based analysis considered the following concepts:

- Safety, equity, accessibility and supply of PT services for the **social** dimension of sustainability,
- Time spent travelling and costs for users and for public authorities for the **economic** dimension of sustainability,
- land consumption, energy and emissions per passenger for the **environmental** dimension of sustainability.

The results indicate that the transport systems of the four European non-Spanish cities, London, Paris, Amsterdam and Stockholm, are more sustainable in the social dimension than most Spanish cities. However, Spanish cities such as Madrid, Saragossa or Barcelona have very efficient PT systems, and perform quite well on the environmental dimension of sustainability. Regarding the economic sustainability, small cities without rail modes such as Gran Canaria,

Tarragona and Murcia, obtained the best results. Finally, the most sustainable city from a global perspective is Bilbao.

The results also allow exploring correlations between the cities characteristics and the different dimensions of sustainability, and determining which factors facilitate or hinder the achievement of sustainable urban transport systems. The four influencing factors identified are detailed below:

Factor 1- Modal share

High-quality PT networks in cities attract a higher demand for PT. These networks and the derived services are costly for the public authorities, and this penalises some aspects of economic sustainability. However, from a global perspective, cities with higher use of PT and lower use of cars present more sustainable transport systems. They are generally safer, provide a better and more equal access to main needs and services, and consume fewer resources per passenger.

Factor 2- Urban density

Urban density contributes to achieve more sustainable transport systems. It is easier to provide quality PT services in compact cities. Dispersed cities tend to be more car-dependent, and their transport systems are less efficient. PT services in dispersed cities show higher energy consumption and emissions per passenger.

Factor 3- Wealth

In the European context, cities with higher GDP per capita tend to invest more in their PT networks and services, which attract higher levels of demand. These urban transport systems from wealthier cities generally provide better and more equal accessibility to main needs and services, being more sustainable from a social and global perspective.

Factor 4- Size

Among the cities analysed, highly populated cities are usually benefited by agglomeration economies. Bigger cities are characterised by denser and better PT supply, and lower energy consumption and emissions.

In the context of European cities, these factors highlight, on the one hand, that low values of population size, urban density and wealth that can hinder sustainability objectives. Small, less wealthy and dispersed cities generally have less sustainable transport systems. Among the 23 cities¹ analysed (Section 5.1), the most sustainable cities had an average size of 3.5 million

---

¹ The term city refers to the urban geographical area in which there is a high degree of interaction between its urban centres in terms of trips, relationships and economic activity. This concept is often called the Metropolitan Area (MMO, 2017; EMTA, 2017)

inhabitants, and an average GDP of 33,563 Euros per capita per year. These bigger and wealthier cities resulted to be especially sustainable from a social point of view. On the other hand, the least sustainable cities had an average size of 0.4 million inhabitants and a GDP of 20,584 Euros per capita per year.

On the other hand, it can be concluded that certain actions can contribute to achieve more sustainable mobility in cities. These actions include policies aimed at encouraging the use of PT and discourage the car use, and policies intended to limit the spatial dispersion of the population. The most sustainable cities among the 23 analysed had an average urban density of 1,693 inhabitants per km² and an 18% of the trips were made by PT; while the least sustainable cities had an average urban density of 137 inhabitants per km², and a 4% of the trips were made by PT.

The modal share and the density of urban areas have already been highlighted by other authors as factors that explain sustainability in cities around the world (Newman and Kenworthy, 1999; Banister, 2005; Haghshenas and Vaziri, 2012). Some of these authors also point out the wealth of cities as a positive factor for achieving sustainable mobility (Haghshenas and Vaziri, 2012). However, these studies are focused on worldwide cities from developed and developing countries, and do not consider that bigger cities tend to be more sustainable. In the context of European cities, the size seems to be an explanatory factor of sustainability, due to economies of scale (Nijkamp and Perrels, 2014).

Determining the main threats over sustainability in European cities. Findings for four European cities from three different countries.

The identification of the problems and potential problems that constitute the main threats in each city requires monitoring certain trends over time. In Section 5.2, the main threats existing in four European cities—London, Madrid, Barcelona and Rotterdam—were determined. This was done through a comparative analysis of the values of key indicators for the year 2013 and the evolution of these indicators during the years 2007-2013:

London

Social inequalities and exclusion seem to be the main problems in London. Compared to the other three cities, London shows a high GINI index (0.555) and a high and rising rate of population at risk of social exclusion (24.8%). Therefore, equity should be an important priority objective for London. Other important and growing problem in the city is congestion, which threatens the competitiveness and efficiency of the city. In 2013, 101 hours were lost per driver in London due to congestion.

On the contrary, the economic decline does not seem to be a relevant threat in London. The city presents the highest GDP among the four cities analysed (55,598 Euros per capita in 2013), and its economic indicators have not deteriorated during the generalised European recession (2007-2013).

Madrid and Barcelona

The economic decline is a very important threat in both Spanish cities. They present lower GDP per capita and employment rates than London and Rotterdam. Moreover, all their economic indicators have deteriorated significantly during the crisis period. Employment rates have declined by more than 3% per year during the period 2007-2013.

The city of Madrid has also gone through a clear process of suburbanisation. Sprawl is another important threat for this city. The case of Barcelona presents rather problems of equity and safety.

On the positive side, some problems related to the environmental threats have improved in Barcelona and Madrid during the years 2007-2013. In this period, the concentration of air pollutants in both cities has decreased by a 4-6 % per year, and the GHG emissions by 2-3% per year. This is partly due to the slowdown of economic activities during the economic crisis.

Rotterdam

The comparative analysis highlighted two main problems in Rotterdam. On the one hand, the GHG emissions per capita in the city are very high compared to the other three cities (16.4 Tonnes per capita). On the other hand, the city is facing a clear urban dispersion: the population growth is being absorbed by the suburbs.

Apart from these problems, the city of Rotterdam has very positive indexes of employment (70.8% of the working age population in 2013), equity and social inclusion, with only 14.2% of the population at risk of social exclusion.

In general terms, a diagnosis of European cities points to a number of common threats to the sustainable development model, i.e. demographic decline, social segregation, environmental depletion, low competitiveness and urban sprawl (European Union, 2011). However, cities around Europe face a wide diversity of situations and different trajectories (Campbell, Partridge and Soto, 2013; Colini et al., 2013; Enemark and Kneeshaw, 2013; Lewis, Hógáin and Borghi, 2013; Adams and Arnkil, 2013; Schlappa and Neil, 2013). Many of these trajectories have widened down during the economic crisis, which has severely affected cities in Southern Europe (European Union, 2011).

The analysis carried out in Section 5.2 highlights that different cities are exposed to different threats, e.g. in London the most important threats are the social polarisation and exclusion, in Madrid and Barcelona the economic decline and in Rotterdam the urban sprawl, which is a very important threat also for Madrid. Governance systems and urban strategies should adapt to evolving circumstances and include specific approaches and priorities in each city, which will depend on their specific threats (European Commission, 2011).

There are some general threats that characterize the European framework of urban development, and therefore common strategies could be design and transferred among cities to address those threats. However, each city also faces some particular trends and threats, and needs specific measures.

Impacts of urban sprawl and economic decline on transport efficiency. Findings from the analysis of six Spanish cities.

Within the urban threats over European cities considered in the thesis, there are two that particularly constrain the achievement of efficient and sustainable transport systems: urban sprawl and economic decline. As demonstrated in Section 5.1, both wealth and urban density are important explanatory factors to sustainable mobility. In Section 5.4, the effect of both threats over the efficiency of PT services was measured. The analysis included data on six Spanish cities: Madrid, Barcelona, Seville, Malaga and Alicante. The presented data is divided into two periods: the years preceding the economic crisis (2002-2007) and the years of economic decline (2007-2012).

The analysis was based on measuring the evolution of indicators related to GDP, employment, population concentration, PT demand, PT supply and PT efficiency. Despite the differences among cities, results highlight some common trends:

- The six cities face a more or less marked process of urban sprawl since 2002. The concentration of the population reduced in both periods, by more than 1% per year on average.
- The economic indicators present very different trends in the two periods. There was a clear economic growth during the first period 2002-2007, with an average increase of 5.8% per year in the GDP; and a clear decline during the second period 2007-2012, where the GDP decreased by 1.8% per year.

During the first period of strong economic growth, the PT demand per inhabitant only grew by 0.4% per year, probably due to the suburbanisation process. In the second period (2007-2012), in spite of the increased PT supply (by 1.9% per year), the effects of the economic recession together with the effects of urban sprawl decreased the PT demand per inhabitant by 3.1% per year. As a result, the efficiency of PT services– measured as the amount of PT supply implemented to meet each demand unit–decreased by 4% per year.

The combination of urban sprawl and economic decline results in significant decline of PT demand and less efficient PT services. Increasing PT supply may help, but it is not the solution by itself. Policy strategies need to address urban sprawl to achieve efficient transport systems (Banister, 2005). Strategies that limit measures to encourage PT are not enough, especially in adverse scenarios.

How transport and land use policies contribute to achieve long term city challenges. The case of Madrid Region.

After identifying the main problems and trends in European cities, the research was focused on analysing how to address them with long term policies.

Certain land use and transport policies can help address urban threats over sustainable development in cities, thus contributing at addressing the city challenges. In Section 5.5, the effects of three policy actions are evaluated for the case of Madrid, to assess their contribution to the different city challenges with a 16 year time horizon:

- Implementation of a **cordon toll** in the CBC of the city, compensated with increases in PT frequencies.
- Promotion of **teleworking**. Assuming that the trend grows linearly, and that a promotion of teleworking would achieve a reduction of 10% of the trips to work by 2031.
- Improvement of some inner city areas to smooth the suburbanisation process and encourage a **re-densification** of Madrid Region.

The evaluation of these policies required a long-term approach. For this purpose, the three policy scenarios together with a do-nothing scenario were simulated with the LUTI model MARS. The results of the simulations are presented for the period 2012-2031, although the implementation of policies starts in 2015. The potential of the policies to solve the city challenges was measured by indicators related to the threats (similar to the ones used in Section 5.2 and Section 5.3 to identify urban threats).

Cordon toll and PT improvements

The cordon toll measure reduces car use at the beginning of the implementation, reducing total energy and emissions. However, the measure loses its effectiveness over time due to acceptability. Regarding equity and accessibility for all, this policy measure is positive due to the improvement of PT services, which attract a higher level of demand. In 2031, the cordon toll scenario is forecast to have 11,881 passengers-km for PT, while the do-nothing scenario is forecast to have 11,048 passengers-km.

Teleworking

Overall, the results indicate that the three policy measures contribute to increase efficiency, through commuting time savings, reducing congestion and improving traffic flow at peak hours. However, the most effective policy in this regard is the teleworking measure. Compared to the do-nothing scenario, teleworking is expected to save 357 million hours commuting since its implementation (2015) to 2031.

On the other hand, commuting time savings have some side effects: people travel more at non peak hours and for not-working purposes. This increases the number of trips at non peak hours, especially trips by car. The car is more attractive at non-peak hours, since PT frequencies are less competitive and there is less congestion. As a result, the total km travelled by car rise, increasing the total energy and emissions, and especially at the end of the implementation period. During the years 2015-2031, teleworking is expected to generate 776 Tons of CO₂ emissions extra compared to the do-nothing scenario.

Re-densification

The only policy that really contributes at saving energy, and reduces the emission of CO₂ and pollutants in the long term is re-densification. Re-densification reduces travel distances and encourages a mobility based more on PT and slow modes. During the period 2015-2031, the re-densification policy is supposed to save 249 ktoe, 519 Tons of CO₂ emissions, 1540 Tons of NO_x and 170 Tons of PM emissions.

It can be concluded that urban planning strategies need to include land-use and transport policy measures to address long term city challenges (Wegener, 2013). It is necessary to establish the basis of a sustainable transport system, tackling urban sprawl and encouraging investments for improving PT quality. Regarding flexible working schemes, they are very effective for time efficiency and to reduce congestion, but they could negatively affect the energy and emissions challenges in cities.

6.1.2 Validation of tools for addressing sustainability in urban planning and mobility management

For the different analysis, a number of new tools were developed or enhanced. The added value of these tools is highlighted here, as they are considered a different type of contributions of the thesis.

Composite indicators for measuring the sustainability of transport systems in European cities

Other authors had applied before the composite indicators for measuring sustainability (Haghshenas and Vaziri 2012; Freudenberg, M. 2005). However, they have not been applied before for measuring the sustainability of urban transport systems in European cities. European cities are from the developed world, and they are considered among the most sustainable in the world (Newman and Kenworthy, 1999; Haghshenas and Vaziri, 2012). For this reason, the comparison between them, which is the basis of the composite indicators, is the best approach for establishing improvement goals and concrete sustainability targets in the future.

Sustainability is a highly complex and multidisciplinary concept, and measuring it entails many difficulties. On the one hand, it involves three dimensions—society, environment and economy—and involves a series of concerns which may overlap and even oppose, i.e. Section 5.1 shows that high quality PT networks have negative effects for economic sustainability but are positive for the environment and society. On the other hand, sustainability is not an absolute concept. Cities may be more or less sustainable, but there is not a city absolutely sustainable by definition.

For these reasons, in Section 5.1, composite indicators were applied to measure the sustainability of the transport systems in 23 European cities. Composite indicators make it possible to consider several aspects for each dimension, e.g. for measuring the economic sustainability of urban transport systems the aspects considered were the coverage ratio for PT, the time spent travelling per day and the cost of transport for users (Eq. 6.1).

$$\text{Composite Indicator: } CI_{env,c} = \frac{\frac{x_{Cv.Ra,c} + \bar{x}_{Cv.Ra}}{\sigma_{Cv.Ra}} + \frac{x_{Cost.us,c} + \bar{x}_{Cost.us}}{\sigma_{Cost.us}} + \frac{x_{Time,c} + \bar{x}_{Time.us}}{\sigma_{Time}}}{3} \quad (\text{Eq. 6.1}),$$

where

$CI_{env,c}$ is the Composite Indicator for measuring the environmental sustainability of urban passenger systems in the city c ; $x_{Cv.Ra,c}$, $x_{Cost.us,c}$, $x_{Time, Ra,c}$ are the values of the indicators coverage ratio for PT, time spent travelling per day and person and economic cost of transport for users in the city c ; $\bar{x}_{Cv.Ra}$, $\bar{x}_{Cost.us}$, $\bar{x}_{Time}$ and $\sigma_{Cv.Ra}$, $\sigma_{Cost.us}$, σ_{Time} are the mean and the standard deviation of the three indicators for the sample of 23 cities. A positive CI_{env} result ($CI_{env} > 0$) would indicate that the city c is more sustainable than the average for the 23 cities, and conversely, a negative result would indicate that the city c is less sustainable than the average.

Analyses carried out in Section 5.1 demonstrate that the composite indicators are appropriated tools to measure the sustainability of urban transport systems in European cities, and that they could serve to establish concrete targets and goals. The sustainability scores obtained reflect the multiple dimensions and overlapping concepts that embody sustainability, and they provided realistic results based on a comparative basis. However, when applying these tools, it should be borne in mind that the results will depend on the performance of the whole sample. This poses a critical emphasis to the cities to be included.

Indicators to measure trends towards sustainable urban development

The threats over the European urban model of sustainability result from problems and trends (potential problems) that the cities are facing. For this reason, it is especially important to analyse the evolution of some key factors over time and not only the values of these key factors in a given year. For this purpose, the evolution indicators were developed to measure the urban problems and trends (Sections 5.3 and 5.4):

$$\text{Evolution indicator: } E_{ic}(\%) = \frac{\sum_{t=1}^n \frac{x_{ic}^t - x_{ic}^{t-1}}{x_{ic}^{t-1}}}{n-1} * 100 \quad (\text{Eq. 6.2}), \text{ where}$$

E_{ic} is the value of the evolution indicator which measures the trend of the factor i, which is being evaluated (if it is >0, the analysed factor has increased –positively grown– over the analysed period) for the city c; x_{ic}^t and x_{ic}^{t-1} are the values of the indicators measuring the factor (for example, GDP could be an indicator for measuring economic activity) in year t and the previous year (t-1); n is the number of years in the analysis period

The result of the evolution indicator provides a value of the average annual growth of a determinate indicator in a determinate period. The value considers all the years of the period, and therefore is less susceptible to spot values and errors. In Section 5.3, the formula was applied to measure the main threats and problems over the city of Madrid: urban sprawl and economic decline. In Section 5.4, the effects of the sub-urbanisation process and the economic crisis over the PT systems were also analysed with this equation. Therefore, the formula is suitable to identify and measure problems, trends and potential problems that constitute the urban threats in cities.

Identifying common factors and synergies through cluster analysis to city challenges

The cluster analysis was used in this thesis to reduce the dimensionality of a data set by exploiting the similarities and dissimilarities between the cities. The results of the research studies carried out demonstrate that the cluster analysis is suitable for analysing and comparing cities and understanding urban problems.

The study of cities, urban dynamics and processes is not an easy or exact science. It is not based on absolute values or results but on comparative approaches. The cluster analysis is an exploratory technique, which serves to describe data and explore relations. This makes the cluster analysis a suitable technique to analyse, understand and compare cities.

In this thesis, the cluster analysis was applied in the research studies from Sections 5.1 and 5.4. In Section 5.1, 23 cities were classified according to their sustainability scores. This made it possible to observe some facts which are impossible to observe in a case by case analysis, e.g. the most sustainable cities from an economic point of view had an average size of one million inhabitants, and their PT networks did not include rail modes, while the most efficient cities from an environmental point of view had an average size of two million inhabitants and all had metro or suburban rail modes. In Section 5.4, the cluster analysis helped find similarities between the six cities analysed, and facilitated data interpretation, i.e. the cities of the cluster with severe processes of sprawl and economic decline faced more problems of efficiency in their PT services than the cluster of cities with moderate process of sprawl and economic decline.

Further application of LUTI models to face long term urban challenges

LUTI models were previously applied to test policy measures over long term periods. However, in this thesis, the policy analysis was designed to address general and specific challenges of European cities. This approach has an added value because it covers all the steps in the planning process.

LUTI are useful tools for urban planning, as they are able to capture the long term effects of land use and transport policies on environmental, social and economic issues. However, in order to address urban threats and problems, these models need to consider the city challenges. In Section 5.5, the LUTI model MARS was applied to simulate three land use and transport policies—cordon toll, teleworking and re-densification—and assess their contribution to meet the challenges in the city of Madrid. For this purpose the model was firstly improved and updated, to make it more appropriated to deal with current demographic and economic trends (See Appendix 8.1).

The results show that it is necessary to apply long term assessment models to design policy strategies and measures, e.g. some policies achieve a high car reduction at the beginning of the implementation but they lose effectiveness over time, as is the case of the cordon toll policy. Results also show that models for urban planning need to consider a wide and diverse range of impacts, e.g. the teleworking policy reduces congestion and commuting time but it increases the number of trips at non peak hours, for not working purposes and it ends up increasing the total energy and emissions. Therefore, LUTI models, and particularly the MARS model for the case of Madrid, are appropriated tools for addressing city challenges through land use and transport management.

6.2. General remarks and future research

Cities need to achieve a sustainable urban development. This requires achieving a sustainable mobility. Only measuring the sustainability and efficiency of urban transport systems, cities will be able to analyse their state and progress towards urban challenges.

In this thesis are proposed a series of indicators for measuring sustainability, and analyses of the problems and barriers to achieve it in the context of European cities. The research studies carried out in the thesis are especially focused on Spanish cities, where the recent economic crisis has been very severe. Within the Spanish cities, the city of Madrid is analysed more in depth, as an example to test policy measures and the impact of threats. Madrid Region has gone through a process of urban dispersion during more than ten years. As demonstrated, this sprawling process, together with the recent economic decline, has negatively affected the sustainability and efficiency of the transport system in the Region. Finally, three different land use and transport policies are simulated and evaluated for the case of Madrid. Results show that transport strategies need to include land use policy measures. Transport measures may help to achieve an efficient mobility, but on the basis of a sustainable urban development

model, able to address sprawl. These general remarks and findings open up new research lines that can be investigated in the future:

Application of the research tools and research approach to cities in other parts of the world

The tools developed in the thesis, based on indicators and models, are innovative and useful for urban planning. However, this thesis is focused on European cities, which are from the developed world and are considered to be among the most sustainable in the world. Future research lines could focus on developing cities, to help them to address their own threats and problems, and to achieve a sustainable development, e.g. problems of security or lack of access to water.

Analysing the influence of urban form on the sustainability of transport systems

The factors analysed in this thesis for explaining sustainable transport systems are based in quantitative and aggregated indicators, which are easily available in public data sources, e.g. population size and density. However, other factors related to the urban form have also a great influence on mobility patterns and transport management. Measuring the influence of urban form on the sustainability of transport systems would be an interesting research topic for future analysis.

Combining new and classical data sources to improve the tools and follow up the analysis

The research studies carried out are mostly based on data retrieved from classical sources such as census or mobility surveys. On the one hand, many of this data are only available since 2000. In the future, it would be interesting to do a follow up of the trends, problems and threats identified in this thesis, to analyse them from a wider perspective with long term data series. On the other hand, the information from big data sources and other new sources can provide high quality data that may be useful in the future to monitor urban trends and to identify new threats and problems.

Transferring policy measures to face adverse economic situations

The analysis of trends in Spanish cities during the economic crisis has produced clear insights about what strategies are suitable to face unfavourable economic contexts. Further research could be done to extrapolate those findings to cities in other geographical or social contexts suffering from economic decline.

Urban sprawl and economic decline: impacts on other sectors

Urban sprawl and economic decline cause inefficiencies in all urban systems and services. In this thesis, the inefficiencies caused by both threats on transport services were measured. However, urban sprawl and economic decline have clear impacts over other urban services, e.g. energy or electricity. An analysis of the efficiency losses caused by both trends in other services or systems could bring interesting outcomes.

Disaggregated analysis

The impact analysis of the policy measures was done at an aggregated level, for the whole Madrid Region. Further research is needed to analyse the impacts at more disaggregated levels, i.e. district level. This would allow adapting policies to the requirements of different zones of the city.

Sensitivity analysis: impacts of policies in different growth scenarios

The policy scenarios tested in this thesis were based in statistical projections of economic and demographic growths. The aim of the analysis was to test the effects of policy actions under the same base conditions. However, future research could focus on analysing the effects of different growth scenarios in the assessment of policies.

Combined measures

The LUTI model in this thesis was used to simulate three land use and transport measures independently, but not a combination of various policy measures. It is clear that transport policy measures are not enough to achieve a sustainable mobility. In this respect, land use actions are more effective than transport measures. However, an adequate strategy should combine various land use measures and transport measures. It would be interesting to design this type of strategies by a LUTI model.

7. References

- Abreu e Silva, J. de, and Goulias, K., 2009. Structural Equations Model of Land Use Patterns, Location Choice, and Travel Behavior: Seattle, Washington, Compared with Lisbon, Portugal. *Transportation Research Record: Journal of the Transportation Research Board*, (2135), pp.106-113.
- Acheampong, R.A., and Silva, E., 2015. Land use–transport interaction modeling: A review of the literature and future research directions. *Journal of Transport and Land Use*, 8(3).
- Adams, E., and Arnkil, R., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. Supporting urban youth through social innovation: stronger together* . [pdf] Nancy: URBACT-European Union. Available at: <http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS3_YOUTH_low_Final.pdf> [Accessed 6 April 2017]
- ALMUDENA, 2017. *Statistical Database for Madrid Region* [Buscar series en el Banco de Datos> Por árbol temático] ALMUDENA- Banco de datos municipal y zonal [online] Available at: <<http://www.madrid.org/desvan/Inicio.icm?enlace=almudena>> [Accessed 20 April 2017]
- Anas, A., and Lindsey, R., 2011. Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice. *Review of Environmental Economics and Policy*, 5(1), pp.66-88.
- Alonso, A., and Monzón, A., 2016. Policy priority objectives: comparative assessment in four European cities. *XII Congreso de Ingeniería de Transporte (CIT) 2016*, Valencia, Spain, 7-9 June 2016.
- Alonso, A., and Monzón, A., 2016. Assessing the progress towards Sustainability and the Role of Urban Transport- City of Madrid. *6th Transport Research Arena (TRA) 2016*. Warsaw, Poland, 18-20 April 2016.
- Alonso, A., Monzón, A., and Cascajo, R., 2015. Comparative analysis of passenger transport sustainability in European cities. *Ecological Indicators*, 48, pp.578-592.
- Alonso, A., Monzón, A., and Cascajo, R., 2017. Measuring Negative Synergies of Urban Sprawl and Economic Crisis over Public Transport Efficiency. *International Regional Science Review*, [online]. Available at: <<http://journals.sagepub.com/doi/10.1177/0160017616687361>> [Accessed 20 April 2017]

Alonso, A., Monzón, A., and Wang, Y., 2017. Modelling Land Use and Transport Policies to Measure Their Contribution to Urban Challenges: The Case of Madrid. *Sustainability*, 9(3), p.378.

Aparicio, A., 2004. *Informe 2002 del Observatorio de La Movilidad Metropolitana*. [pdf] Madrid: Ministerio de Medio Ambiente, Ministerio de Fomento. Available at: <http://www.observatoriomovilidad.es/images/stories/05_informes/Informe_OMM2002.pdf> [Accessed 20 April 2017]

Armuña, C., Arenal, A., and Feijoo, C., 2016. *Deliverable 7.5 Models and Tools Comparative Evaluation and Impact Assessment*. [pdf] Madrid: INSIGHT-7FP-EC. Available at: <http://www.nommon-files.es/fp7_project_deliverables/INSIGHT_D7.5-Models_Comparative_Evaluation_and_Impact_Assessment_Iss1-30-Sept-2016.pdf> [Accessed 20 April 2017]

Audirac, I., 2005. Information Technology and Urban Form: Challenges to Smart Growth. *International Regional Science Review*, 28(2), pp.119-145.

Ayuntamiento de a Coruña, 2010. *Database* [Ayuntamiento > Gobierno Abierto >Transparencia] Ayuntamiento de a Coruña [online] Available at: <<http://www.coruna.gal/#&panel1-1>> [Accessed 20 April 2017]

Ayuntamiento de Madrid, 2017. *Statistical database* [El Ayuntamiento > Estadística >Banco de Datos] Ayuntamiento de Madrid [online] Available at: <<http://www.madrid.es/portal/site/munimadrid>> [Accessed 20 April 2017]

Backstrand, K., 2006. Democratizing Global Environmental Governance? Stakeholder Democracy after the World Summit on Sustainable Development. *European Journal of International Relations*, 12(4), pp.467-498.

Banister, D., 2005. *Unsustainable Transport: City Transport in the New Century*. London: Routledge.

Banister, D., 2008. The sustainable mobility paradigm. *Transport Policy*, 15(2), pp.73-80.

Barca, F., 2009. *An Agenda for a Reformed Cohesion Policy*. [pdf] European Communities. Available at: <http://www.europarl.europa.eu/meetdocs/2009_2014/documents/regi/dv/barca_report/_barca_report_en.pdf> [Accessed 6 April 2017]

Bart, I.L., 2010. Urban sprawl and climate change: A statistical exploration of cause and effect, with policy options for the EU. *Land Use Policy*, 27(2), pp.283-292.

- Bendixen, M., 1996. A practical guide to the use of correspondence analysis in marketing research. *Marketing Research On-Line*, 1(1), pp. 16-36.
- Birol, F., 2008. *World Energy Outlook 2008*. [pdf] Paris: International Energy Agency (IEA). Available at: < <http://www.worldenergyoutlook.org/media/weowebiste/2008-1994/weo2008.pdf>> [Accessed 6 April 2017]
- Bivand, R., 1998. *A review of spatial statistical techniques for location studies*. [pdf] Bergen: Norwegian School of Economics and Business Administration. Available at: <<https://brage.bibsys.no/xmlui/bitstream/handle/11250/162352/rober%20bivand221.pdf?sequence=1&isAllowed=y>> [Accessed 27 April 2017]
- Bizkaiko Foru Aldundia, 2010. *Database* [Bizkaia Abierta] Bizkaiko Foru Aldundia [online] Available at: <http://www.bizkaia.net/home2/ca_index.asp> [Accessed 20 April 2017]
- Bocarejo S, J.P., and Oviedo H, D.R., 2012. Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments. *Journal of Transport Geography*, 24, pp.142-154.
- Bock, H., and Diday, E., 2012. *Analysis of Symbolic Data: Exploratory Methods for Extracting Statistical Information from Complex Data*. Springer Science & Business Media, Berlin.
- Bracken, I., 2014. *Urban Planning Methods : Research and Policy Analysis*. Taylor and Francis.
- Bravo, M., Briceño, L., Cominetti, R., Cortés, C. E., and Martínez, F., 2010. An integrated behavioral model of the land-use and transport systems with network congestion and location externalities. *Transportation Research Part B: Methodological*, 44(4), pp. 584-596.
- Breakwell, G., Leeux, J., O'Muircheartaigh, C., Saris, W., Schuman, H., and Meter, K., 2005. *Discovering Statistics Using SPSS*. Andy Field, London.
- Brewer, A.M., 1998. Work design, flexible work arrangements and travel behaviour: policy implications. *Transport Policy*, 5(2), pp.93-101.
- Brown, B.J., Hanson, M.E., Liverman, D.M., and Merideth, R.W., 1987. Global sustainability: Toward definition. *Environmental Management*, 11(6), pp.713-719.
- Butler, R.W., 1999. Sustainable tourism: A state of the art review. *Tourism Geographies*, 1(1), pp.7-25.
- Cacciaguerra, G., and Gatti, M. P., 2015. Urban re-densification and regeneration: 21st century city strategies. In: Ö. Özçevik, C.A. Brebbia, and S.M. Şenereds. eds. 2015. *Sustainable Development and Planning*, Southampton: WIT Press. pp. 217-226.

Cameron, S., 2003. Gentrification, housing redifferentiation and urban regeneration: 'Going for Growth' in Newcastle upon Tyne. *Urban Studies*, 40(12), pp. 2367-2382

Campbell, M., Partridge, A., and Soto, P., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. More jobs: better cities- a framework for a better action on jobs*. [pdf] Nancy: URBACT- European Union. Available at: http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS2_MORE_JOBS_low_FINAL_01.pdf [Accessed 6 April 2017]

Cardozo, O.D., García-Palomares, J.C., and Gutiérrez, J., 2012. Application of geographically weighted regression to the direct forecasting of transit ridership at station-level. *Applied Geography*, 34, pp.548–558.

Cegarra-Leiva, D., Sánchez-Vidal, M.E., and Cegarra-Navarro, J.G., 2012. Work life balance and the retention of managers in Spanish SMEs. *The International Journal of Human Resource Management*, 23(1), pp.91-108.

Coenen, M., and Kok, R.A.W., 2014. Workplace flexibility and new product development performance: The role of telework and flexible work schedules. *European Management Journal*, 32(4), pp.564-576.

Colini, L., Czischke, D., Günter, S., Tosics, I., and Ramsden, P., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. Against divided cities in Europe*. [pdf] Nancy: URBACT- European Union. Available at: http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS4_DIVIDED_low_FINAL.pdf [Accessed 6 April 2017]

Comunidad de Madrid, n.a. *Estrategia de calidad del aire y cambio climático de la Comunidad de Madrid*. [pdf] Madrid: Comunidad de Madrid. Available at: <http://www.madrid.org/bvirtual/BVCM003469.pdf> [Accessed 20 April 2017]

Comunidad de Madrid, 2001. Ley 9/2001, de 17 de julio. *Ley del Suelo de la Comunidad de Madrid*. Madrid, Spain, 17 July 2001.

Conover, W.J., 1972. A Kolmogorov Goodness-of-Fit Test for Discontinuous Distributions. *Journal of the American Statistical Association*, 67(339), pp.591-596.

Consorcio de Transportes de Madrid (CRTM), 2014. *EMTA Barometer 2012*. [pdf] Madrid: Consorcio Regional de Transportes de Madrid (CRTM). Available at: http://www.emta.com/IMG/pdf/emta_barometer_2012.pdf?2442/22a5dce79fc38debfeb19cb0dccc91f35cfa4899 [Accessed 20 April 2017]

- Croft, J., 2003. Gating Communities for Children? The perennial problem of school choice, residential location and their (continuing) relationship with neighbourhood. *Housing Studies*, 19(6).
- Coppola, P., Ibeas, Á., dell'Olio, L., and Cordera, R., 2013. LUTI Model for the Metropolitan Area of Santander. *Journal of Urban Planning and Development*, 139(3), pp.153-165.
- Cordera, R., Canales, C., dell'Olio, L., and Ibeas, A., 2015. Public transport demand elasticities during the recessionary phases of economic cycles. *Transport Policy*, 42, 173-179
- Council of the European Union, 2001. Council Resolution 7329/01 of 28 March 2001 on transport policy. Follow-up to the Cardiff/Helsinki Summit on the integration of environment and sustainable development into the transport policy.
- CRTM, 1998. *EDM'96: Encuesta domiciliaria de movilidad en día laborable 1998*. Available through: Consorcio Regional de Transportes de Madrid.
- CRTM, 2004. *EDM'04: Encuesta domiciliaria de movilidad en día laborable 2004*. Available through: Consorcio Regional de Transportes de Madrid.
- CRTM, 2014. *EDM'04: Encuesta domiciliaria de movilidad en día laborable 2014*. Available through: Consorcio Regional de Transportes de Madrid.
- CRTM, 2017. *Consorcio Regional de Transportes de Madrid* [online] Available at: <<http://www.crtm.es/>> [Accessed 20 April 2017]
- Currie, G., 2010. Quantifying spatial gaps in public transport supply based on social needs. *Journal of Transport Geography*, 18(1), pp.31-41.
- Daly, H. E., Ramea, K., Chiodi, A., Yeh, S., Gargiulo, M., and Gallachóir, B. Ó., 2014. Incorporating travel behaviour and travel time into TIMES energy system models. *Applied Energy*, 135, pp. 429-439.
- De Haan, F.J., Ferguson, B.C., Adamowicz, R.C., Johnstone, P., Brown, R.R., and Wong, T.H.F., 2014. The needs of society: A new understanding of transitions, sustainability and liveability. *Technological Forecasting and Social Change*, 85, pp.121-132.
- De Jong, G., and Riet, O. Van de., 2008. The driving factors of passenger transport. *EJTIR*, 8 (3), pp.227-250.
- Del Aguila Obra, A.R., Cámara, S.B., and Meléndez, A.P., 2002. The economic and organizational aspects of telecentres: the Spanish case. *Technovation*, 22(12), pp.785-798.

de Oña, J., Calvo, F., Garach, L., de Oña, R., and López, G., 2010. How to expand subway and urban railway networks: light rail extensions in Madrid, Spain. *Transportation Research Record: Journal of the Transportation Research Board*, (2146), pp. 10-17

DESVAN, 2017. *Structural Database for Madrid Region* [Buscar series en el Banco de Datos> Por árbol temático] DESVAN- Banco de datos Estructurales [online] Available at: <<http://www.madrid.org/desvan/Inicio.icm?enlace=desvan>> [Accessed 20 April 2017]

De Vos, J., and Witlox, F., 2013. Transportation policy as spatial planning tool; reducing urban sprawl by increasing travel costs and clustering infrastructure and public transportation. *Journal of Transport Geography*, 33, pp.117-125.

DGT (Dirección General de Tráfico), 2013. *Anuario Estadístico de accidentes 2013*. [pdf] Madrid: Dirección General de Tráfico (DGT). Available at: <<http://www.dgt.es/Galerias/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-de-accidentes/anuario-accidentes-2013.pdf>> [Accessed 20 April 2017]

Directorate-General for Economic and Financial Affairs of the European Commission. 2009. *Economic Crisis in Europe: Causes, Consequences and responses*. [pdf] Luxembourg: Office for Official Publications of the European Communities. Available at: <http://ec.europa.eu/economy_finance/publications/pages/publication15887_en.pdf> [Accessed 6 April 2017]

Duque, J.C., Velásquez, H., Agudelo, J., 2011. Public infrastructure and housing prices: An application of geographically weighted regression within the context of hedonic prices. *Ecos de Economía*, 15 (33), pp. 95-122.

EC Delft, INFRAS, and Fraunhofer ISI, 2011. *External Costs of Transport in Europe- Update study for 2008*. [pdf] Delft: CE Delft. Available at: <http://www.cedelft.eu/publicatie/external_costs_of_transport_in_europe/1258> [Accessed 6 April 2017]

Echenique, M.H., Flowerdew, A.D.J., Hunt, J.D., Mayo, T.R., Skidmore, I.J., and Simmonds, D.C., 1990. The MEPLAN models of Bilbao, Leeds and Dortmund. *Transport Review*, 10(4), pp.309-322.

Eckel, C.C., Grossman, P.J., Eckel, C., and Grossman, P., 1998. Are Women Less Selfish Than Men? Evidence from Dictator Experiments. *Economic Journal*, 108(448), pp.726-35.

Efthymiou, D., Farooq, B., Bierlaire, M., and Antoniou, C., 2014. Multidimensional Indicator Analysis for Transport Policy Evaluation. *Journal of the Transportation Research Board*, 2430, pp.83-94.

Eliasson, J., 2009. A cost–benefit analysis of the Stockholm congestion charging system. *Transportation Research Part A: Policy and Practice*, 43(4), pp.468-480.

Eliasson, J, Hultkrantz, L., Nerhagen, L., and Rosqvist, L. S., 2009. The Stockholm congestion–charging trial 2006: Overview of effects. *Transportation Research Part A: Policy and Practice*, 43(3), pp. 240-250.

Empresa Municipal de Tránsports Publics de Tarragona S.A, 2010. *Database* [EMT > Portal de Transparencia] [online] Available at: <<http://emtanemambtu.cat/>> [Accessed 20 April 2017]

EMTA, 2013. *European Metropolitan Transport Authorities*. [online] Available at: <<http://www.emta.com/spip.php?article204&lang=en>> [Accessed 6 April 2017]

EMTA, 2012a. *EMTA Barometer 2011 of public transport in the European metropolitan areas*. [pdf] EMTA. Available at: <http://www.emta.com/IMG/pdf/emta_barometre_2011_final_dec_2012> [Accessed 20 April 2017]

EMTA, 2012b. *EMTA Barometer 2009 of public transport in the European metropolitan areas*. [pdf] EMTA. Available at: <http://www.emta.com/IMG/pdf/barometer_report_2012_data_2009_.pdf?2127/7564091f6db657b007bc69457afc806900b1b043> [Accessed 20 April 2017]

EMTA, 2017. *EMTA Barometer 2015 of public transport in the European metropolitan areas*. [pdf] EMTA. Available at: <http://www.emta.com/IMG/pdf/2015_barometer_brochure-170330.pdf?3419/f03173513024ae75d0146e69a33eabc8f68529a5> [Accessed 27 April 2017]

Enemark, A., and Kneeshaw, S., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. How cities can motivate mobility mindsets*. [pdf] Nancy: URBACT- European Union. Available at: <http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS5_MOBILITY_Iow_FINAL.pdf> [Accessed 6 April 2017]

Engelen, G., White, R., and Nijs, T., 2003. Environment Explorer: Spatial Support System for the Integrated Assessment of Socio-Economic and Environmental Policies in the Netherlands. *Integrated Assessment*, 4(2), pp.97-105.

Epstein, M.J., and Rejc, A., 2014. *Making Sustainability Work: Best Practices in Managing and Measuring Corporate Social, Environmental, and Economic Impacts*. 2nd ed. San Francisco: Berrett-Koehler Publishers

Erli-Handayani, K.D.M., 2014. TOD Best Practice: Lesson Learned for GHG Mitigation on Transportation Sector in Surabaya City, Indonesia. *Procedia - Social and Behavioral Sciences*, 135, pp.152-158

European Commission, 1996. *European Sustainable Cities*. [pdf] Brussels: Expert Group on the Urban Environment- European Commission, Directorate General XI Environment, Nuclear Safety and Civil Protection. Available at: <<http://edz.bib.uni-mannheim.de/www-edz/pdf/sonstige/sustcities.pdf>> [Accessed 6 April 2017]

European Commission, 2005. *Green Paper- Confronting demographic change: a new solidarity between the generations*, COM (2005)94, final

European Commission, 2007. *Green Paper- Towards a new culture for urban mobility*, COM (2007) 551, final.

European Commission, 2011. *White Paper- Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*, COM (2011) 144, final.

European Commission, 2010. *Making our cities attractive and sustainable- How the EU contributes to improving the urban environment*, [pdf] Brussels: European Union (EU). Available at: <<http://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2011/04/Making-our-cities-attractive-and-sustainable.pdf>> [Accessed 6 April 2017]

European Commission, 2012a. *Green Paper- Restructuring and Anticipation of Change: What Lessons from Recent Experience?*, COM (2012) 7, final.

European Commission, 2012b. *White Paper- An Agenda for Adequate, Safe and Sustainable Pensions*, COM (2012)7, final

European Environment Agency. 2006. *Urban Sprawl in Europe—The Ignored Challenge*. [pdf] Copenhagen: European Environment Agency (EEA). Available at: <http://www.eea.europa.eu/publications/eea_report_2006_10> [Accessed 6 April 2017]

European Environment Agency. 2009. *Ensuring Quality of Life in Europe's Cities and Towns. Tackling the Environmental Challenges Driven by European and Global Change*. Copenhagen: European Environment Agency (EEA). Available at: <http://www.eea.europa.eu/publications/quality-of-life-in-Europes-cities-and-towns/at_download/file> [Accessed 20 April 2017]

European Environment Agency, 2013. *Understanding pollutant emissions from Europe's cities- Highlights from the EU Air Implementation Pilot project*. [pdf] Copenhagen: European Environment Agency (EEA). Available at:

<<http://www.eea.europa.eu/publications/understanding-pollutants-emissions-from-europes>>
[Accessed 6 April 2017]

European Union, 2010. *Making Our Cities Attractive and Sustainable*. [pdf] Luxembourg: Publications office of the European Union. Available at:
<<http://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2011/04/Making-our-cities-attractive-and-sustainable.pdf>> [Accessed 6 April 2017]

European Union, 2011. *Cities of Tomorrow- Challenges, visions, ways forward*. [pdf] European Commission, Directorate General for Regional Policy. Available at:
<http://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/citiesoftomorrow/citiesoftomorrow_final.pdf> [Accessed 6 April 2017]

European Union, 2014. *Progress towards the Territorial Agenda of the European Union 2020*. . [pdf] Luxembourg: ESPON 2013 programme. Available at:
<https://www.espon.eu/export/sites/default/Documents/Publications/Monitoring/TerritorialMonitoringReport/ESPON_MONITORING_REPORT.pdf> [Accessed 20 April 2017]

Farahani, R.Z., Miandoabchi, E., Szeto, W.Y., and Rashidi, H., 2013. A review of urban transportation network design problems. *European Journal of Operational Research*, 229(2), pp.281-302.

Feudo, F., 2014. How to Build an alternative to sprawl and auto-centric development model through a TOD scenario for the North-Pas-de-Calais region? Lessons from an Integrated Transportation-land Use Modelling. *Transportation Research Procedia*, 4, pp. 154-177.

Fielding, G.J., Glauthier, R.E., and Lave, C.A., 1978. Performance indicators for transit management. *Transportation*, 7(4), pp.365-379.

Fotheringham, A.S., Brunsdon, C., and Charlton, M., 2002. *Geographically weighted regression: the analysis of spatially varying relationships*. Wiley & Sons.

Freudenberg, M., 2005. *Composite Indicators of Country performance- A critical assessment* [pdf] Paris: OECD publishing. Available at: < http://www.oecd-ilibrary.org/science-and-technology/composite-indicators-of-country-performance_405566708255> [Accessed 6 April 2017]

García, M., 2010. The Breakdown of the Spanish Urban Growth Model: Social and Territorial Effects of the Global Crisis. *International Journal of Urban and Regional Research*, 34(4), pp.967-980.

García, O., Lucio, A., Salas-Olmedo, M.H., Romanillos, G., Alonso, A., and Feijoo, C., 2014. *Deliverable 2.1 Stakeholder Consultation Report*. [pdf] Madrid: INSIGHT-7FP-EC. Available at: <[http://www.nommon-files.es/fp7_project_deliverables/INSIGHT-D2.1 Stakeholder Consultation Iss1 19-08-2014.pdf](http://www.nommon-files.es/fp7_project_deliverables/INSIGHT-D2.1_Stakeholder_Consultation_Iss1_19-08-2014.pdf)> [Accessed 20 April 2017]

García-Palomares, J.C., 2010. Urban sprawl and travel to work: the case of the metropolitan area of Madrid. *Journal of Transport Geography*, 18(2), pp.197-213.

Geurs, K.T., and van Wee, B., 2004a. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2), pp.127-140

Geurs, K., and Wee, B. Van., 2004b. Land-use/transport interaction models as tools for sustainability impact assessment of transport investments: review and research perspectives. *European Journal of Transport and Infrastructure Research*, 4(3), pp.333-355.

Geurs, K., Zondag, B., de Jong, G., and de Bok, M., 2010. Accessibility appraisal of land-use/transport policy strategies: More than just adding up travel-time savings. *Transportation Research Part D: Transport and Environment*, 15(7), pp.382-393.

Golinska, P., and Hajdul, M., 2012. *European Union Policy for Sustainable Transport System: Challenges and Limitations*. In: Sustainable Transport. Berlin, Heidelberg: Springer

Golubchikov, O., 2011. *Climate neutral cities: how to make cities less energy and carbon intensive and more resilient to climatic challenges*. [pdf] Geneva: United Nations Economic Commission for Europe (UNECE). Available at: <https://www.unece.org/fileadmin/DAM/hlm/documents/Publications/climate.neutral.cities_e.pdf> [Accessed 6 April 2017]

Greiving, S. and Wegener, M., 2001. Integration of transport and land use policies: state of the art. *9th World Conference on Transport Research (WCTR) 2001*, Seoul, Korea, 22-27 July 2001.

Griffith, D.A., 1992. What is spatial autocorrelation? Reflections on the past 25 years of spatial statistics. *Espace géographique*, 21(3), pp.265-280.

Grönroos, C., and Ojasalo, K., 2004. Service productivity. *Journal of Business Research*, 57(4), pp.414-423.

Gudmundsson, H., 2003. Making concepts matter: sustainable mobility and indicator systems in transport policy. *International Social Science Journal*, 55(176), pp.199-217.

Güell, J. M. F., 2006. *Planificación estratégica de ciudades: nuevos instrumentos y procesos*. Barcelona: Reverté.

- Guerreiro, C., de Leeuw, F., and Foltescu, V., 2013. *Air quality in Europe - 2013 report*. [pdf] Copenhagen: European Environment Agency (EEA). Available at: <<http://www.eea.europa.eu/publications/air-quality-in-europe-2013>> [Accessed 6 April 2017]
- Guerreiro, C., González, A., de Leeuw, F., Viana, M., and Horálek, J., 2016. *Air quality in Europe - 2016 report*. [pdf] Copenhagen: European Environment Agency (EEA). Available at: <<http://www.eea.europa.eu/publications/air-quality-in-europe-2016>> [Accessed 6 April 2017]
- Guzmán, L.A., 2011. *Optimización dinámica de estrategias de movilidad sostenible en áreas metropolitanas*. Universidad Politécnica de Madrid.
- Guzmán, L.A., de la Hoz, D., and Monzón, A., 2014. Optimal and Long-Term Dynamic Transport Policy Design: Seeking Maximum Social Welfare through a Pricing Scheme. *International Journal of Sustainable Transportation*, 8(4), pp.297-316
- Haghshenas, H., and Vaziri, M., 2012. Urban sustainable transportation indicators for global comparison. *Ecological Indicators*, 15(1), pp.115-121.
- Hair, J.F., Black, W.C. Babin, B.J, and Anderson, R.E., 2010. *Multivariate Data Analysis*. Pearson Prentice Hall, New Jersey.
- Haken, H., 1983. *Advanced synergetics instability hierarchies of self-organizing systems and devices*. Berlin: Springer
- Hansen, W.G., 1959. How Accessibility Shapes Land Use. *Journal of the American Institute of Planners*, 25(2), pp.73-76.
- Hillman, M., Henderson, I., and Whalley, A., 1976. Transport realities and planning policy. *Publication of: Political and Economic Planning*, 42(567).
- Hine, J., and Grieco, M., 2003. Scatters and clusters in time and space: implications for delivering integrated and inclusive transport. *Transport and Social Exclusion*, 10(4), pp.299-306.
- Holden, E., Linnerud, K., and Banister, D., 2013. Sustainable passenger transport: Back to Brundtland. *Transportation Research Part A: Policy and Practice*, 54, pp.67-77.
- Horvath, A., 2010. Environmental Analysis of Telework: What We Know and What We Do Not Know and Why. *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, Arlington, TX, USA, 17-19 May 2010.
- Huck, S.W., 2000. *Reading Statistics and Research*. Pearson, Boston.

Hunt, J.D., and Abraham, J.E., 2005. Design and Implementation of PECAS: A Generalised System for Allocating Economic Production, Exchange and Consumption Quantities. In: M.E.H Lee-Gosselin, and S.T. Doherty, eds. 2005. *Integrated Land-Use and Transportation Models*. Elsevier Science. pp.253 - 273

Hunt, J.D., and Simmonds, D.C., 1993. Theory and application of an integrated land-use and transport modelling framework. *Environment and planning B: Planning and Design*, 20(2), pp.221-224.

Hupkes, G., 1982. The law of constant travel time and trip-rates. *Futures*, 14(1), pp. 38-46.

INE, 2016. *Proyecciones de la Población de España 2016-2066- Metodología* [pdf] Madrid: Instituto Nacional de Estadística (INE). Available at: <http://www.ine.es/inebaseDYN/propob30278/docs/meto_propob_2016_2066.pdf> [Accessed 20 April 2017]

INE, 2017. *Instituto Nacional de Estadística (Spanish Statistical Office)*. [online] Available at: <<http://www.ine.es/>> [Accessed 20 April 2017]

INSIGHT, 2017. *INSIGHT- 7FP project webpage. Innovative Policy Modelling and Governance Tools for Sustainable Post Crisis Urban Development* [online] Available at: <<http://www.insight-fp7.eu/>> [Accessed 20 April 2017]

Jackson, S.E., and Dutton, J.E., 1988. Discerning Threats and Opportunities. *Administrative Science Quarterly*, 33(3), pp.370-387.

Jeon, C., and Amekudzi, A., 2005. Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics. *Journal of Infrastructure Systems*, 11(1), pp.31-50.

Jones, B.D., and Baumgartner, F.R., 2005. *The politics of attention : how government prioritizes problems*. University of Chicago Press.

Jourard, R., and Gudmundsson, H., 2010. *Indicators of environmental sustainability in transport*. INRETS.

Karlaftis, M.G., and Tsamboulas, D., 2012. Efficiency measurement in public transport: Are findings specification sensitive? *Transportation Research Part A: Policy and Practice*, 46(2), pp.392-402.

Kendall, M.G., 1939. The Geographical Distribution of Crop Productivity in England. *Journal of the Royal Statistical Society*, 102(1), pp.21-62

- Kenworthy, J.R., and Laube, F.B., 1999. Patterns of automobile dependence in cities: an international overview of key physical and economic dimensions with some implications for urban policy. *Transportation Research Part A: Policy and Practice*, 33(7), pp.691-723.
- Khan, M.E., 2014. *Sustainable and Smart Cities*. [pdf] Washington: World Bank. Available at: <<https://openknowledge.worldbank.org/bitstream/handle/10986/18748/WPS6878.pdf?sequence=1&isAllowed=y>> [Accessed 6 April 2017]
- Kim, J., Pagliara, F., and Preston, J., 2005. The intention to move and residential location choice behaviour. *Urban Studies*, 42(9), pp.1621-1636.
- Kletting, P., and Glatting, G., 2009. Model selection for time-activity curves: The corrected Akaike information criterion and the F-test. *Zeitschrift für Medizinische Physik*, 19(3), pp.200-206.
- Kwan, M.P., 2010. Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. *Geographical Analysis*, 30(3), pp.191-216.
- Leboreiro, A., 2015. *La Ordenación del Territorio en las Ciudades Globales Europeas: El caso de Madrid*. Universidad Politécnica de Madrid
- Lewis, J.O., Hógáin, S.N., and Borghi, A., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. Building energy efficiency in European cities*. [pdf] Nancy: URBACT- European Union. Available at: <http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS6_ENERGY_low_FINAL.pdf> [Accessed 6 April 2017]
- Lilliefors, H.W., 1967. On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown. *Journal of the American Statistical Association*, 62(318), pp.399-402.
- Litman, T. A., 2009. Sustainable transportation indicators: a recommended research program for developing sustainable transportation indicators and data. *Transportation Research Board 88th Annual Meeting*. Washington DC, USA, 11-15 January 2009.
- Litman, T.A., 2013. *Understanding Transport Demands and Elasticities- How Prices and Other Factors Affect Travel Behavior*. [pdf] Victoria: Victoria Transport Policy Institute. Available at: <<http://www.vtpi.org/elasticities.pdf>> [Accessed 20 April 2017].
- Loos, J., Abson, D. J., Chappell, M. J., Hanspach, J., Mikulcak, F., Tichit, M., and Fischer, J., 2014. Putting meaning back into “sustainable intensification”. *Frontiers in Ecology and the Environment*, 12(6), pp.356-361.

Lorenz, J., 2009. Universality in movie rating distributions. *The European Physical Journal B*, 71(2), pp.251–258.

Loucks, D.P., 2000. Sustainable Water Resources Management. *Water International*, 25(1), pp.3-10.

Lowry, I. S., 1964. *A model of metropolis*. Santa Monica, USA: Rand Corporation.

Lu, B., Harris, P., Charlton, M., and Brunsdon, C., 2014. The GW model R package: further topics for exploring spatial heterogeneity using geographically weighted models. *Geo-spatial Information Science*, 17(2), pp.85-101.

Lu, B., Harris, P., Charlton, M., Brunsdon, C., Nakaya, T. and Gollini, I., 2015. *GWmodel: Geographically-weighted models*. [online] Available at: < <https://CRAN.R-project.org/package=GWmodel> > [Accessed 27 April 2017]

Manganelli, B., Pontrandolfi, P., Azzato, A., and Murgante, B., 2014. Using geographically weighted regression for housing market segmentation. *International Journal of Business Intelligence and Data Mining*, 9(2), pp. 161-177.

Marchetti, C., 1994. Anthropological invariants in travel behavior. Technological forecasting and social change. *Technological forecasting and social change*, 47(1), pp. 75-88.

Martínez, F., 1996. MUSSA Land Use Model for Santiago City. *Journal of the Transport Research Board*. 1552, pp.126-134.

Martínez, F.J., 1996. Analysis of Urban Environmental Policies Assisted by Behavioural Modelling. In: Y. Hayashi, and J. Roy, eds. 1996. *Transport, Land-Use and the Environment*, Springer Science & Business Media, pp.233-257.

May, A.D., Jopson, A.F., and Matthews, B., 2003. Research challenges in urban transport policy. *Transport Policy*, 10(3), pp.157-164.

May, A. D., Karlstrom, A., Marler, N., Matthews, B., Minken, H., Monzón, A and Shepherd, S., 2003. *Developing Sustainable Urban Land Use and Transport Strategies-A Decision Makers' Guidebook*. Leeds: Institute for Transport Studies-University of Leeds.

May, A.D., Page, M., and Hull, A., 2008. Developing a set of decision-support tools for sustainable urban transport in the UK. *Transport Policy*, 15 (6), pp.328-340.

Mebratu, D., 1998. Sustainability and sustainable development. *Environmental Impact Assessment Review*. 18(6), pp.493–520.

Milligan, G.W., and Cooper, M.C., 1985. An examination of procedures for determining the number of clusters in a data set. *Psychometrika*, 50(2), pp.159-179.

Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer 2010. *Sécurité Routière. Bulletin mensuel d'information. Ile-de-France. Direction régionale et interdépartementale de l'Équipement et de l'Aménagement d'Ile-de-France*. [pdf] Paris: Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer. Available at: <http://www.driea.ile-de-france.developpement-durable.gouv.fr/IMG/pdf/Bilan-SR-IdF-210297_BD_cle0dfb61.pdf> [Accessed 11 September 2014]

Ministerio de Fomento, 1998. *Vías de Dependencia Municipal*. [pdf] Ministerio de Fomento-Subdirección General de Estadísticas y Estudios. Available at: <http://www.fomento.es/NR/rdonlyres/168E494B-083B-42F7-B459-3B523F78A04C/3697/vias_municipales.pdf> [Accessed 20 April 2017]

Ministerio del Interior- Dirección General de Tráfico, 2010. *Anuario Estadístico de accidentes 2010*. [pdf] Madrid: Dirección General de Tráfico (DGT). Available at: <<http://www.dgt.es/Galerias/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-de-accidentes/Anuario-estadistico-de-accidentes-2010.pdf>> [Accessed 20 April 2017]

Miranda, H.d.F., and Rodrigues da Silva, A.N., 2012. Benchmarking sustainable urban mobility: The case of Curitiba, Brazil. *Transport Policy*. 21, pp.141-151.

MMO, 2017. *Metropolitan Mobility Observatory*. [online] Available at: <<http://www.observatoriomovilidad.es/>> [Accessed 6 April 2017]

Monzón, A., Cascajo, R., Alonso, A., García, A., and Tadeo, A., 2014. *Informe 2012 del Observatorio de La Movilidad Metropolitana*. [pdf] Madrid: Ministerio de Agricultura, Alimentación y Medio Ambiente. Available at: <http://www.observatoriomovilidad.es/images/stories/05_informes/Informe_OMM_2012.pdf> [Accessed 20 April 2017]

Monzón, A., Cascajo, R., Díaz, M.A., and Barberán, A., 2016. *Informe 2014 del Observatorio de La Movilidad Metropolitana*. [pdf] Madrid: Ministerio de Agricultura, Alimentación y Medio Ambiente. Available at: <http://www.observatoriomovilidad.es/images/stories/05_informes/informe_OMM2014.pdf> [Accessed 20 April 2017]

Monzón, A., Cascajo, R., Muñoz, B., and Alonso, A., 2012. *Informe 2010 del Observatorio de La Movilidad Metropolitana*. [pdf] Madrid: Ministerio de Agricultura, Alimentación y Medio Ambiente. Available at:

<http://www.observatoriomovilidad.es/images/stories/05_informes/Informe_OMM2010.pdf>
[Accessed 20 April 2017]

Moreno, R., and López-Bazo, E., 2007. Returns to local and transport infrastructure under regional spillovers. *International Regional Science*, 30(1), 47-71.

Musterd, S., 2005. Social and ethnic segregation in Europe: Levels, causes, and effects. *Journal of urban affairs*, 27(3), pp 331-348.

Musterd, S., Bontje, M., and Ostendorf, W., 2006. The Changing Role of Old and New Urban Centers: the Case of the Amsterdam Region. *Urban Geography*, 27(4), pp.360-387.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., and Giovannini, E., 2005. *Handbook on Constructing Composite Indicators: Methodology and User Guide* [pdf] Paris: OECD publishing. Available at: < http://www.oecd-ilibrary.org/economics/handbook-on-constructing-composite-indicators_533411815016> [Accessed 6 April 2017]

Newman, P.W., 1999. Sustainability and cities: extending the metabolism model. *Landscape and Urban Planning*. 44(4), pp.219-226.

Newman, P., and Kenworthy, J., 1999. *Sustainability and cities: overcoming automobile dependence*. Island Press.

Nicolas, J.P., Pochet, P., and Poimboeuf, H., 2003. Towards sustainable mobility indicators: application to the Lyons conurbation. *Transport Policy*, 10(3), pp.197-208.

Nielsen, T., 2015. Changes in transport behavior during the financial crisis. An analysis of urban form, location and transport behavior in the greater Copenhagen area 2006–2011. *Research in Transportation Economics*, 2011, pp. 1-10

Nijkamp, P., and Perrels, A., 2014. *Sustainable Cities in Europe*. Taylor and Francis.

Nijland, L., and Dijst, M., 2015. Commuting-related fringe benefits in the Netherlands: Interrelationships and company, employee and location characteristics. *Transportation Research Part A: Policy and Practice*, 77, pp.358-371.

Nilsson, M., Jordan, A., Turnpenny, J., Hertin, J., Nykvist, B., and Russel, D., 2008. The use and non-use of policy appraisal tools in public policy making: an analysis of three European countries and the European Union. *Policy Sciences*, 41(4), pp. 335-355.

Nugent, C., Blanes, N., Fons, J., Sáinz de la Maza, M., Ramos, M.J., Domingues, F., van Beek, A., and Houthuijs, D., 2014. *Noise in Europe 2014*. [pdf] Copenhagen: European Environment

Agency (EEA). Available at: < <http://www.eea.europa.eu/publications/noise-in-europe-2014>> [Accessed 6 April 2017]

OECD, 2002. *Policy Instruments for Achieving Environmentally Sustainable Transport* [pdf] Paris. Available at: < http://www.oecd-ilibrary.org/environment/policy-instruments-for-achieving-environmentally-sustainable-transport_9789264176249-en> [Accessed 6 April 2017]

OECD, 2008. *Statistical database*. [Statistics > Regions and Cities > Metropolitan areas > Environment] OECD [online] Available at: <<http://stats.oecd.org/Index.aspx?Datasetcode=CITIES>> [Accessed 6 April 2017]

OECD, 2011. *Towards Green Growth: Monitoring Progress: OECD Indicators*. Paris: OECD Publishing.

OECD, 2013. *Green Growth in cities*. Paris: OECD Publishing.

OECD, 2013. *Urban policies for an increasingly urban world*. OECD [online] Available at: <<http://www.oecd.org/governance/regional-policy/urbandevelopment>> [Accessed 20 April 2017]

OECD, 2017. *Projections database* [GDP long term forecast > Countries] OECD [online] Available at: <<https://data.oecd.org/gdp/gdp-long-term-forecast.htm>> [Accessed 20 April 2017]

Organization for Economic Cooperation and Development (OECD), 2012. *Statistical database*. [Statistics > Regions and Cities > Metropolitan areas > Population in Cities] OECD [online] Available at: <<http://stats.oecd.org/Index.aspx?Datasetcode=CITIES>> [Accessed 20 April 2017]

Öztuna, D., Elhan, A. H., and Tüccar, E., 2006. Investigation of four different normality tests in terms of type 1 error rate and power under different distributions. *Turkish Journal of Medical Sciences*, 36(3), 171-176.

Parry, I. W., Walls, M., and Harrington, W., 2007. Automobile externalities and policies. *Journal of Economic Literature*, 45(2), pp. 373-399

Pfaffenbichler, P., 2003. *The strategic, dynamic and integrated urban land use and transport model MARS (metropolitan activity relocation simulator)*. PhD. Technischen Universität Wien.

Pfaffenbichler, P., 2011. Modelling with Systems Dynamics as a Method to Bridge the Gap between Politics, Planning and Science? Lessons Learnt from the Development of the Land Use and Transport Model MARS. *Transport Reviews*, 31(2), pp.267-289.

Pfaffenbichler, P., Emberger, G., and Shepherd, S., 2008. The Integrated Dynamic Land Use and Transport Model MARS. *Networks and Spatial Economics*, 8(2–3), pp.183-200.

Pfaffenbichler, P., Emberger, G., and Shepherd, S., 2010. A system dynamics approach to land use transport interaction modelling: the strategic model MARS and its application. *System Dynamics Review*, 26(3), pp.262-282.

Pfaffenbichler, P., Garcia, G., Angel, L., Hoz Sánchez, D. D. L., and Shepherd, S., 2008. Análisis de las tasas sobre emisiones de CO₂ en el sector del transporte como medida de alcanzar escenarios sostenibles. *VIII Congreso de Ingeniería de Transporte (CIT) 2008*, A Coruña, Spain, 2-4 July 2008.

Pfaffenbichler, P. C., and Shepherd, S. P., 2002. A Dynamic Model to Appraise Strategic Land-Use and Transport Policies. *European Journal of Transport and Infrastructure Research*, 2(3/4), 255-283.

Preston, J., and Rajé, F., 2007. Accessibility, mobility and transport-related social exclusion. *Journal of Transport Geography*, 15(3), pp.151–160.

Quigley, J. M., 1998. Urban diversity and economic growth. *The Journal of Economic Perspectives*, 12(2), pp. 127-138.

Raffaele, C., and Connell, J., 2016. Telecommuting and Co-Working Communities: What Are the Implications for Individual and Organizational Flexibility?. In: J. Connell, and J. Burgess, eds. 2016. *Flexible Work Organizations*. New Delhi: Springer India, pp. 21-35

Ramasco, G., Lenormand, M., Lamanna, F., Galloso, I., Piovano, L., Luque, L., Silva, R., Garrido, D., Salas-Olmedo, H., Romanillos, A., García-Palomares, J.C., and Gutiérrez, J., 2015. *Deliverable 3.2 Analysis of Urban Location Patterns*. [pdf] Madrid: INSIGHT-7FP-EC. Available at: <http://www.nommon-files.es/fp7_project_deliverables/INSIGHT-D2.2_Urban_Planning_And_Governance_Iss_1_01-10-2014.pdf> [Accessed 27 April 2017]

RATP, 2010. *Database [Il Gruppo> Rapport Annuel]*. RAP [online] Available at: <<http://www.ratp.fr/fr/>> [Accessed 20 April 2017]

Rassafi, A. A., and Vaziri, M., 2007. Assessment of modal transportation sustainability: application of data envelopment and concordance analyses. *Iranian Journal of Science and Technology*, 31(B2), 179.

Reurings, M.C.B., Aarts, L.T., and Schermers, G., 2012. *Analyse van het aantal verkeersdoden in 2011 in Amsterdam*. [pdf] Leidschendam: Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (SWOV). Available at: <<http://www.swov.nl/rapport/R-2012-06.pdf>> [Accessed 20 April 2017]

- Romanillos, G., Alonso, A., and Wang, Y., 2014. *Deliverable 2.2 Urban planning and governance: current practices and new challenges*. [pdf] Madrid: INSIGHT-7FP-EC. Available at: <http://www.nommon-files.es/fp7_project_deliverables/INSIGHT-D2.2_Urban_Planning_And_Governance_Iss_1_01-10-2014.pdf> [Accessed 6 April 2017]
- Russo, F., and Musolino, G., 2007. Urban Land-Use Transport Interaction modelling: state of the art and applications. In: *Urban Transport XIII: Urban Transport and the Environment in the 21st Century*. Southampton: WIT Press, 96, pp. 525-534.
- Saisana, M., and Tarantola, S., 2002. *State-of-the-Art Report on Current Methodologies and Practices for Composite Indicator Development*. . [online] Ispra: Joint Research Centre-European Commission. Available at: <<http://www.eea.europa.eu/data-and-maps/indicators/economic-water-productivity-of-irrigated/state-of-the-art-report>> [Accessed 6 April 2017]
- Salas-Olmedo, M. H., Wang, Y., and Alonso, A., 2017. Assessing accessibility with local coefficients for the LUTI model MARS. *Computers, Environment and Urban Systems*, 64, pp. 194-203.
- Salvati, L., 2013. Urban containment in action? Long-term dynamics of self-contained urban growth in compact and dispersed regions of southern Europe. *Land Use Policy*, 35, pp.213-225.
- Santos, A.S., 2013. The use of sustainability indicators in urban passenger transport during the decision-making process: the case of Rio de Janeiro, Brazil. *Current Opinion in Environmental Sustainability*, 5(2), pp.251–260.
- Saunders, M.J., Kuhnimhof, T., Chlond, B., and da Silva, A.N.R., 2008. Incorporating transport energy into urban planning. *Transportation Research Part A: Policy and Practice*, 42(6), pp.874-882.
- Savelson, A., Colman, R., Litman, T., Walker, S., and Parmenter, R., 2006. *The GPI transportation accounts: sustainable transportation in Nova Scotia*. [pdf] Nova Scotia: GPI Atlantic. Available at: <<http://www.gpiatlantic.org/publications/summaries/transportationsumm.pdf>> [Accessed 20 April 2017]
- Schafer, A., 2000. Regularities in travel demand: an international perspective. *Journal of transportation and statistics*, 3(3), pp. 1-31
- Schlappa, H., Neil, W.J.V., 2013. *Cities of Tomorrow- Action Today. URBACT II capitalisation. From crisis to choice: re-imagining the future in shrinking cities*. [pdf] Nancy: URBACT-European Union. Available at:

<http://urbact.eu/sites/default/files/import/general_library/19765_Urbact_WS1_SHRINKING_low_FINAL.pdf> [Accessed 6 April 2017]

Shepherd, S.P., 2014. A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics*, 2(2), pp.83-105

Shepherd, S.P., Zhang, X., Emberger, G., Hudson, M., May, A.D., and Paulley, N., 2006. Designing optimal urban transport strategies: The role of individual policy instruments and the impact of financial constraints. *Transport Policy*, 13(1), pp.49-65.

Shiftan, Y., Kaplan, S., and Hakkert, S., 2003. Scenario building as a tool for planning a sustainable transportation system. *Transportation Research Part D: Transport and Environment*, 8(5), pp.323-342.

Smith, T.W., Axon, C.J., and Darton, R.C., 2013. The impact on human health of car-related air pollution in the UK, 1995–2005. *Atmospheric Environment*, 77, pp.260-266.

Simmonds, D.C., 1999. The design of the DELTA land-use modelling package. *Environment and Planning B: Urban Analytics and City Science*, 26, pp.665-684.

Sobrino, N., and Monzon, A., 2014. The impact of the economic crisis and policy actions on GHG emissions from road transport in Spain. *Energy Policy*, 74, pp.486–498.

Song, Y., 2005. Smart growth and urban development pattern: A comparative study. *International Regional Science Review*, 28(2), pp. 239-265.

Soria-Lara, J.A., and Banister, D., 2017. Dynamic participation processes for policy packaging in transport backcasting studies. *Transport Policy*, 58, pp.19-30

Sterman, J. D., 2000. *Business dynamics: Systems thinking and modelling for a complex world* New York: Irwin/McGraw-Hill.

Stockholm Stad-trafikkontoret, 2009. *Analysis of traffic in Stockholm*. [pdf] Stockholm: Trafikkontoret. Available at: <<http://www.stockholm.se/-/Kontakt/Kontakta-oss/?term=216522>> [Accessed 11 September 2014]

Swain, A., 2013. *Understanding emerging security challenges: threats and opportunities*. Routledge.

Tanguay, G.A., Rajaonson, J., Lefebvre, J., and Lanoie, P., 2010. Measuring the sustainability of cities: An analysis of the use of local indicators. *Ecological Indicators*. 10 (2), pp. 407-418.

Taylor, B.D., Miller, D., Iseki, H., and Fink, C., 2009. Nature and/or nurture? Analyzing the determinants of transit ridership across US urbanized areas. *Transportation Research Part A: Policy and Practice*, 43(1), pp.60-77.

TERM (Transport and Environment Reporting Mechanism), 2000. *Are we moving in the right direction?- Indicators on transport and environment integration in the EU*. [pdf] Copenhagen: European Environment Agency (EEA). Available at: <<http://www.eea.europa.eu/publications/ENVISSUENo12>> [Accessed 6 April 2017]

TfL, 2010. *Casualties in Greater London*. [pdf] London: Transport for London (TfL). <<http://www.tfl.gov.uk/cdn/static/cms/documents/casualties-greater-london-2010.pdf>> [Accessed 20 April 2017]

TfL, 2017. *Transport for London- Information*. TfL [online] Available at: <http://www.tfl.gov.uk/> [Accessed 20 April 2017]

Theodoridou, I., Papadopoulos, A., and Hegger, M., 2012. A feasibility evaluation tool for sustainable cities—A case study for Greece. *Energy Policy*.

Thill, J.C., and Kim, M., 2005. Trip making, induced travel demand, and accessibility. *Journal of Geographical Systems*, 7(2), pp.229-248.

Tolley, R., and Turton, B.J., 2014. *Transport Systems, Policy and Planning: A Geographical Approach*. New York: Routledge.

Torrens, P.M., 2000. *How land-use-transportation models work*. London: Centre for Advanced Spatial Analysis (UCL)

TRANSPORT STYRELSEN, 2017. *Information on Transport in Sweeden*. [online] Available at: <<https://www.transportstyrelsen.se/en/road/Congestion-taxes-in-Stockholm-and-Goteborg/>> [Accessed 20 April 2017]

TTG, 2010. *Database* [ATTG > Somos Transparentes] Autoridad Territorial del transporte de Guipúzcoa (TTG) [online] Available at: < <http://www.atgipuzkoa.eus/es/>> [Accessed 20 April 2017]

TU-Wien, 2017. *Transport Research Institute in the Technische Universität Wien*. [online] Available at: <<http://www.ivv.tuwien.ac.at/forschung/mars-metropolitan-activity-relocation-simulator/overview/>> [Accessed 20 April 2017]

TUZSA, 2010. *Transportes Urbanos de Zaragoza- Información*. TUZSA [online] Available at: < <http://www.atgipuzkoa.eus/es/>> [Accessed 11 September 2014]

Uhel, R., 2006. *Urban sprawl in Europe- The ignored challenge*. [pdf] Copenhagen: European Environment Agency (EEA). Available at:

<http://www.eea.europa.eu/publications/eea_report_2006_10> [Accessed 6 April 2017]

Ulfarsson, G., Steinbrenner, A., and Valsson, T., 2015. Urban household travel behaviour in a time of economic crisis: Changes in trip making and transit importance. *Journal of Transport Geography*, 49, pp. 68-75.

UN (United Nations), 1972. *The United Nations Conference on the Human Environment*. Stockholm, Sweden, 5-16 June 1972. United Nations.

UN (United Nations), 1992. *United Nations Conference on Environment & Development- AGENDA 21*. Rio de Janeiro, Brazil, 3-14 June 1992. United Nations Sustainable Development.

UN-HABITAT, n.d. *UN- HABITAT- History, mandate and role in the UN system*. [online] Available at: <<https://unhabitat.org/about-us/history-mandate-role-in-the-un-system/>> [Accessed 6 April 2017]

UN-HABITAT, 2009. *State of the world's cities 2008/2009*. [pdf] Nairobi: United Nations Human Settlements Programme (UN-Habitat). Available at:

<<http://mirror.unhabitat.org/pmss/listItemDetails.aspx?publicationID=2562>> [Accessed 6 April 2017]

UN-HABITAT, 2016. *World Cities Report 2016: Urbanization and Development – Emerging Futures*. [pdf] Nairobi: United Nations Human Settlements Programme (UN-Habitat). Available at:

<<http://wcr.unhabitat.org/wp-content/uploads/2017/02/WCR-2016-Full-Report.pdf>> [Accessed 6 April 2017]

United Nations, 2011. *Climate neutral cities: how to make cities less energy and carbon intensive and more resilient to climatic challenges*. [pdf] Geneva: United Nations Economic Commission for Europe (UNECE). Available at:

<https://www.unece.org/fileadmin/DAM/hlm/documents/Publications/climate.neutral.cities_e.pdf> [Accessed 6 April 2017]

United Nations, 2016. *Smart cities and Infrastructure*. [pdf] Geneva: Economic and Social Council from the United Nations (UN). Available at:

<http://unctad.org/meetings/en/SessionalDocuments/ecn162016d2_en.pdf> [Accessed 20 April 2017]

URBACT, 2016. *URBACT at a glance*. [online] Available at: < <http://urbact.eu/urbact-glance#>> [Accessed 6 April 2017]

- Urban Audit, 2017. *Statistical database*. [Eurostat > Cities (Urban Audit) >Data > Database] EUROSTAT [online] Available at: <<http://ec.europa.eu/eurostat/web/cities/data/database>> [Accessed 27 April 2017]
- Valdes, C., Monzon, A., and Benitez, F.G., 2016. Sustainable urban transportation strategies: Searching for synergies. *KSCE Journal of Civil Engineer*. 20(3), pp. 1066-1075
- Van Lier, T., De Witte, A., and Macharis, C., 2014. How worthwhile is teleworking from a sustainable mobility perspective? The case of Brussels Capital region. *EJTIR*, 14(3), pp. 244-267.
- Vanoutrive, T., Malderen, L. Van, Jourquin, B., Thomas, I., Verhetsel, A., and Witlox, F., 2010. Mobility Management Measures by Employers: Overview and Exploratory Analysis for Belgium. *EJTIR*, 10(2), pp.121–141.
- Waas, T., Hugé, J., Block, T., Wright, T., Benitez-Capistros, F., and Verbruggen, A., 2014. Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development. *Sustainability*, 6(9), pp.5512-5534.
- Waddell, P., 2011. Integrated Land Use and Transportation Planning and Modelling: Addressing Challenges in Research and Practice. *Transport Reviews*, 31(2), pp.209-229.
- Wang, Y., 2014. *Assessing urban mobility through participatory scenario building and combined utility regret assessment*. Universidad Politécnica de Madrid.
- Wang, Y., Alonso, A., and Monzón, A., 2016. Transport policy evaluation by a LUTI model (MARS). In: L. Dell’ Olio, R. Cordera, and A. Ibeas, eds. 2016. *The TRANSPACE model*. Santander: GIST- Transport Systems Research Group, 2016, pp. 34-65
- Wang, Y., Monzon, A., and Ciommo, F. Di., 2015. Assessing the accessibility impact of transport policy by a land-use and transport interaction model – The case of Madrid. *Computers, Environment and Urban Systems*, 49, pp.126-135.
- Wang, Y., Monzon, A., Ciommo, F., and Kaplan, S., 2014. Integrated transport planning framework involving combined utility regret approach. *Journal of the Transportation Research Board*, (2429), pp. 59-66.
- Wang, Y., Salas-Olmedo, H., Alonso, A., Monzón, A., and García-Palomares, J.C., 2016. *Deliverable 5.3 Enhanced Version of the MARS Simulation Model*. [pdf] Madrid: INSIGHT-7FP-EC. Available at: <http://www.nommon-files.es/fp7_project_deliverables/INSIGHT_D5.3_Enhanced_MARS_Model_Iss_1_26-07-2016.pdf> [Accessed 20 April 2017]

WCED (World Commission on Environment and Development), 1987. *Report of the World Commission on Environment and Development: Our Common Future*. Oslo, Norway, 20 March 1987.

Wee, B. Van., 2015. Toward a new generation of land use transport interaction models: a viewpoint. *Journal of Transport and Land Use*, 8(3).

Wegener, M., 1986. Transport Network Equilibrium and Regional Deconcentration. *Environment and Planning A*, 18(4), pp.437-456.

Wegener, M., 1994. Operational Urban Models: State of Art. *Journal of the American Planning Association*, 60(1), pp. 17-29.

Wegener, M., 2004. Overview of land-use transport models In D.A. Hensher, K.J. Button, ed, 2004. *Handbook of transport geography and spatial systems*. pp. 127-146.

Wegener, M., 2011. *The IRPUD Model*. Dortmund: Spiekermann & Wegener Urban and Regional Research(S&W).

Wegener, M., 2013. The future of mobility in cities: Challenges for urban modelling. *Transport Policy*, 29, pp.275-282.

Węziak-Białowolska, D., 2016. Quality of life in cities – Empirical evidence in comparative European perspective. *Cities*, 58, pp.87–96.

Wilson, A., 2016. New roles for urban models: planning for the long term. *Regional Studies, Regional Science*, 3(1), pp.48-57.

World Economic Forum, 2001. *2001 Environmental Sustainability Index*. [pdf] Davos: World Economic Forum, January 2001. Available at:
<http://sedac.ciesin.columbia.edu/es/esi/ESI_01a.pdf> [Accessed 6 April 2017]

World Health Organization, 2011. *Health Effects of Transport-related Air Pollution*. [pdf] Copenhagen: World Health Organization (WHO). Available at:
<http://www.euro.who.int/_data/assets/pdf_file/0006/74715/E86650.pdf> [Accessed 20 April 2017]

Yap, B. W., and Sim, C. H., 2011. Comparisons of various types of normality tests. *Journal of Statistical Computation and Simulation*, 81(12), 2141-2155

Zegras, C., 2006. Sustainable transport indicators and assessment methodologies. *Biannual Conference and Exhibit of the Clean Air Initiative for Latin American Cities*. Sao Paulo, Brazil, 25-27 July 2006.

- Zhang, C., Juan, Z., and Xiao, G., 2015. Do contractual practices affect technical efficiency? Evidence from public transport operators in China. *Transportation Research Part E: Logistics and Transportation Review*, 80, pp.39-55.
- Zhang, Y., and Guindon, B., 2006. Using satellite remote sensing to survey transport-related urban sustainability: Part 1: Methodologies for indicator quantification. *International Journal of Applied Earth Observation and Geoinformation*, 8(3), 149-164.
- Zhang, W., and Kockelman, K., 2014. Urban Sprawl, Job Decentralization, and Congestion: The Welfare Effects of Congestion Tolls and Urban Growth Boundaries. *Transportation Research Board 93rd Annual Meeting*. Washington DC, USA, 12-16 January 2014.
- Zhao, P., 2010. Sustainable urban expansion and transportation in a growing megacity: Consequences of urban sprawl for mobility on the urban fringe of Beijing. *Habitat International*, 34(2), pp.236-243.
- Ziltener, P., 2004. The economic effects of the European Single Market Project: projections, simulations – and the reality. *Review of International Political Economy*, 11(5), pp.953–979.
- Zito, P., and Salvo, G., 2011. Toward an urban transport sustainability index: an European comparison. *European Transport Research Review*, 3(4), 179-195.
- Zondag, B., 2007. *Joint modeling of land-use, transport and economy*. Delft: Netherlands TRAIL Research School.
- Zondag, B., and de Jong, G., 2011. The development of the TIGRIS XL model: A bottom-up approach to transport, land-use and the economy. *Research in Transportation Economics*, 31(1), pp.55-62.

8. Abbreviations

CBC: Central Business District

CC: Central City (core city in the metropolitan area)

CI: Composite Indicator

CTRM: Consorcio Regional de Transportes de Madrid (Public Transport Authority in Madrid Region)

EMTA: European Metropolitan Transport Authorities

EU: European Union

GDP: Gross Domestic Product

GHG: Greenhouse Gas

HOH: Home- Others- Home

HWH: Home- Work- Home

IC: Indicator Computed

INE: Instituto Nacional de Estadística (National Statistical Institute in Spain)

INSIGHT: Innovative Policy Modelling and Governance Tools for Sustainable Post Crisis Urban Development

LUTI: Land Use and Transport Interaction

MA: Metropolitan Area (geographical area where there is a high integration between its urban centres in terms of trips, relationships or economic activity)

MARS: Metropolitan Activity Relocation Simulator

MMO: Metropolitan Mobility Observatory

MR: Metropolitan Ring (metropolitan area excluding the core city)

OD: Origin- Destination

OECD: Organisation for Economic Co-operation and Development

PM: Particulate Matter

PT: Public transport

PTA: Public transport Authorities

TERM: Transport and Environment Reporting Mechanism

TOD: Transyt Oriented Developments

TOE: Tonnes of Oil Equivalent

UN: United Nations

Annex A) Characterization of cities from Section 5.1

Table A.1. Characteristics of the cities

City	Population (no. inhab)	GDP (€ per capita)	Urban density (inhab/km ²)	Modal share (%)	
				Private Motorised	PT
Paris	11,729,613	46,984	4,910	45.3	20.5
London	7,753,600	35,326	1,402	36.7	41.7
Madrid	6,458,684	29,963	804	34.7	31.6
Barcelona	5,013,000	27,916	1,548	34.3	17.9
Stockholm	2,019,182	41,160	311	42.0	24.0
Valencia	1,805,942	19,780	1,276	38.7	17.3
Murcia	1,461,979	19,541	129	53.5	9.8
Seville	1,457,428	19,405	345	53.9	10.4
Amsterdam	1,406,500	30,600	976	34.0	34.0
Bilbao	1,153,724	30,572	520	31.0	31.0
Asturias	1,084,341	21,882	102	37.0	37.0
Malaga	1,001,287	16,839	699	52.4	52.4
Majorca	869,067	24,672	240	55.2	55.2
Gran Canaria	845,676	19,746	542	57.7	57.7
Cadiz	773,569	26,136	265	26.8	26.8
Saragossa	707,263	31,951	357	41.8	41.8
Gipuzkoa	777,807	17,405	253	47.9	47.9
Tarragona	616,852	27,916	206	49.8	49.8
Granada	517,923	17,405	602	43.4	43.4
Pamplona	328,540	30,246	7,824	42.4	42.4
Girona	753,046	21,373	127	57.5	57.5
Corunna	246,047	20,056	39	52.5	52.5
Leon	134,012	22,974	39	45.4	45.4

Table A.2. Data for the economic CI

City	Coverage ratio (%)	Prices oil (€/l)	Fare for single PT ticket (€)	Time spent travelling per day (min)
Paris	37	1.32	1.70	75.0
London	63	1.39	2.69	73.4
Madrid	43	1.10	1.00	79.1
Barcelona	49	1.10	1.40	72.2
Stockholm	39	1.24	3.51	67.6
Valencia	44	1.10	1.20	58.1
Murcia	63	1.10	1.00	47.8
Seville	48	1.10	1.20	56.4
Amsterdam	54	1.50	1.50	62.0
Bilbao	49	1.10	1.20	81.7
Asturias	55	1.10	1.35	54.0
Malaga	48	1.10	1.25	46.3
Majorca	32	1.10	0.95	58.3
Gran Canaria	69	1.10	1.20	51.5
Cadiz	37	1.10	1.10	63.5
Saragossa	33	1.10	1.35	81.7
Gipuzkoa	77	1.10	1.25	61.3
Tarragona	63	1.10	1.20	41.4
Granada	67	1.10	1.20	51.1
Pamplona	65	1.10	1.15	63.6
Girona	37	1.10	1.30	54.8
Corunna	76	1.10	1.16	68.2
Leon	46	1.10	0.95	62.9

Table A.3. Data for the social CI

City	Traffic fatalities (no.)	Reduction in PT fares for students (%)	Reduction in PT fares for retired (%)	Length bus network (km/km ²)	Length rail network (km/km ²)
Paris	156	49.93%	100.00%	1,784	24,660
London	126	30.00%	100.00%	1,253	3,730
Madrid	67	35.87%	76.30%	703	5,591
Barcelona	87	18.80%	61.73%	714	6,592
Stockholm	8	39.13%	47.22%	418	10,539
Valencia	35	20.16%	74.46%	486	1,125
Murcia	7	33.33%	0.00%	205	851
Seville	13	0.00%	0.00%	175	1,146
Amsterdam	23	34.00%	34.00%	406	4,032
Bilbao	9	47.69%	81.33%	154	3,291
Asturias	12	8.78%	0.00%	118	3,877
Malaga	12	0.00%	0.00%	68	1,378
Majorca	12	33.33%	0.00%	114	3,609
Gran Canaria	7	35.06%	100.00%	0	2,994
Cadiz	23	25.02%	100.00%	17	881
Saragossa	7	14.01%	52.00%	167	181
Gipuzkoa	17	0.00%	0.00%	51	343
Tarragona	11	52.53%	97.89%	0	1,802
Granada	7	0.00%	0.00%	0	1,014
Pamplona	6	40.00%	50.77%	0	236
Girona	16	0.00%	0.00%	0	740
Corunna	9	76.38%	74.02%	7	91
Leon	13	0.00%	0.00%	0	177

Table A.4. Data for the environmental CI

City	Road occupation (km road/km²)	Energy consumption in PT modes (TOE/ million inhab.)	Emissions per passenger (Ton CO₂/ million inhab.)
Paris	4.15	55.41	258.14
London	8.46	60.18	238.26
Madrid	1.67	107.75	262.12
Barcelona	4.53	115.99	379.99
Stockholm	11.68	131.77	390.68
Valencia	6.52	436.45	2047.80
Murcia	0.62	1447.72	5100.82
Seville	1.89	432.78	1441.33
Amsterdam	12.69	69.87	360.01
Bilbao	1.18	121.70	514.84
Asturias	0.64	877.56	2881.79
Malaga	3.88	299.19	963.85
Majorca	1.29	1219.25	3841.22
Gran Canaria	2.72	1588.43	4606.45
Cadiz	2.13	72.47	206.52
Saragossa	1.22	512.44	1418.92
Gipuzkoa	1.63	1839.14	8534.53
Tarragona	1.96	2005.08	5814.74
Granada	6.64	121.34	351.88
Pamplona	2.78	542.24	1572.50
Girona	4.89	1035.36	3002.55
Corunna	5.62	1040.54	3017.57
Leon	6.08	1031.94	2992.63

Annex B) Improvement of MARS model for its application in the research work from Section 5.5

The model MARS used in Section 5.5 was firstly updated and improved. All this previous work **was published in the scientific journal *Computers, Environment and Urban Systems* (Impact Factor 2015: 2.092)**. The article is presented in Annex II. The content is not part of the main body of the thesis but validates the MARS model as an appropriate tool to simulate policy measures in the city of Madrid.

Assessing accessibility with local coefficients for the LUTI model MARS

María Henar Salas-Olmedo ^a, Yang Wang ^{b,*}, Andrea Alonso ^b

^a Department Human Geography, Faculty Geography and History, Universidad Complutense de Madrid, Calle Profesor Aranguren, s/n, 28040 Madrid, Spain

^b Transport Research Centre (TRANSyT), Universidad Politécnica de Madrid, Calle Profesor Aranguren, s/n, 28040 Madrid, Spain

ARTICLE INFO

Article history:

Received 4 November 2016

Received in revised form 20 February 2017

Accepted 21 February 2017

Available online xxxx

Keywords:

Complex accessibility

LUTI model

Geographically weighted regression

GIS

Urban planning

ABSTRACT

Accessibility-based land use and transport interaction (LUTI) models are tools for policy assessments that facilitate coherent implementation of sustainable strategic urban plans. This study aims to improve one of those LUTI models introducing the different impact of factors influencing residential and workplace choice by computing local coefficients. In particular, this research explores the methodology of integrating the public choice model into the MARS (Metropolitan Activity Relocation Simulator) model using a complex accessibility indicator. We established a new approach to input the variation of the influence of each public service across space with the use of Geographically Weighted Regression (GWR). The model update and extension of MARS are all based on the Region of Madrid, Spain. Using the new accessibility indicator yielded better results and corrected some under estimation and overestimations in the number of workplaces. The correlation using the new accessibility indicator is significantly higher than the one using the old one. The prediction using the new indicator achieves better results for the whole area whatever the zone is small or large. The analysis evidences the convenience of GIS and LUTI combination to improve model accuracy and precision. Using the new accessibility indicator based on local coefficients, MARS model fits better with the real data in respect of the distribution of workplaces and residents, which are the key representatives of the land use sub-model.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Land-Use Transport Interaction (LUTI) modelling has been investigated since 1960s (Geurs & Van Wee, 2004b) as the only available tool that can support strategic planning, policy making, public and private investment decisions that arise in land use and transport. Recent literature on the topic expresses the need for LUTI models to adequately answer the policy questions raised by current trends in cities (Wegener, 2013; Van Wee, 2015). One of these outstanding challenges is to adapt the accessibility measures to the real population's needs (Van Wee, 2015 and Acheampong & Silva, 2015). In this paper, this accessibility challenge is addressed. Conceptually, this is a very important challenge. While LUTI models have diverse theoretical foundation and modelling techniques they share the use of an accessibility indicator as one of a critical link between land-use and transport system (Wegener, 2004). The transport system influences land-use development and the re-distribution of residential and jobs, while the land-use system determines the travel demand.

According to previous research on the accessibility-based LUTI models, accessibility can be addressed from four different perspectives: infrastructure-based measure, location based measure, person-based

measure and utility based measure (Geurs & Van Wee, 2004a). Similarly, Thill and Kim (2005) show evidence that accessibility has multiple facets, thus supporting Kwan's (1998) argument that accessibility modelling needs to be flexible to capture different situations. However, accessibility is integrated in most LUTI models with the use of a single function indicator, namely job accessibility, and neglect other impacts like those on public services or on retail (Geurs & Van Wee, 2004b; Wegener, 2004 and Russo & Musolino, 2007), regardless the type of accessibility perspective in use in the model. A single accessibility indicator that only considers people accessibility to workplaces is not sufficient to account for land-use/transport interactions because it leads to a substantial underestimation in policy effects. For example, increasing the public transport fare affects the accessibility to other activities (like shopping or leisure) rather than the accessibility to jobs (Wang, Monzon, & Di Ciommo, 2016). A complex accessibility measure through an up-to-date measure thus is required to combine all types of opportunities in a single indicator.

This paper follows this line of research in which focuses on a complex accessibility measure by incorporating multipurpose activities into one of the LUTI model – MARS, considering the capability to reach workplaces but also involving the ease to access public services (i.e., education, health and parks) and retail. There are two aims associated with this objective. The first one is to generate local coefficients (or say weights) of each modelling zone for different types of trip purposes. In order to estimate the weight of each factor in the complex

* Corresponding author.

E-mail addresses: msalas01@ucm.es (M.H. Salas-Olmedo), yang.wang@upm.es (Y. Wang), andrea.alonso@upm.es (A. Alonso).

Fig. 1. Research outline.

accessibility indicator, we adopt the method often used in GIS science, the Geographically Weighted Regression (GWR) (Duque, Velásquez, & Agudelo, 2011; Cardozo, García-Palomares, & Gutiérrez, 2012; Manganelli, Pontrandolfi, Azzato, & Murgante, 2014). The application of GWR is to provide the coefficient of each trip motive to the MARS model, like job, school, health, shop and park. The methodology is original and the result we obtained from the MARS model indeed improves the model accuracy and precision.

The second aim is to integrate the complex accessibility measure with the local coefficients into one of the widely applied LUTI model (MARS). The MARS model was introduced by Pfaffenbichler, Emberger, and Shepherd (2010) and Pfaffenbichler (2011), representing the cause and effect relations between transport and land-use systems through accessibility for long-term policy making. The single accessibility indicator used in the MARS model is substituted by the complex one from the perspective of location based measure. The Region of Madrid is used for validating the developed methodology. Number of public facilities and shops of Madrid are input to the MARS using the recent survey collected from various sources.

A comparison analysis with the single accessibility and complex accessibility indicator is provided using observed and predicted population and workplace data. The results illustrate how the complex accessibility measure yields a better fit model. The work provides a new viewpoint for transport and urban planners for further cooperation, being one of the first outcomes to integrate the knowledge of geographers and transport planners. A summary of the objectives, methods and results of this paper is shown in Fig. 1.

The paper is articulated in the following sections. After this introduction, Section 2 briefly reviews the accessibility-based LUTI models with the focus on accessibility measures, and the background of the MARS model in respect of the model characteristics and the role of accessibility. Following that, Section 3 defines the methodology of the paper, including the data source, the definition of the complex accessibility indicator, the local coefficients estimation and its results. Section 4 compares the land use indicators using old and new accessibility indicator respectively. The document closes with some conclusions.

2. Background

2.1. Review of accessibility-based LUTI models

Since the first generation of land use and transport interaction model created in the 1960s, it is found that locations with good accessibility shapes land use" (Hansen, 1959, Lowry, 1964; Wegener, 2004; Geurs & Van Wee, 2004a). Accessibility indicator can be simple indicator, such as distance to the nearest school, or complex indicator as the ease of reaching all destinations of interest. There is a number of real-world applications of LUTI models falling under the above definition created by Wegener (1986), Martinez (1996), Simmonds (1999), Engelen, White, and de Nijs (2003), Pfaffenbichler and Shepherd (2003), Zondag (2007) and Waddell (2011).

The review on the previous literatures of accessibility-based LUTI models confirms that accessibility is either the unique interaction between the land-use system and transport system or one of the key factors to co-determine decisions on locating residential or jobs (Geurs & Van Wee, 2004b). In the light of the characteristics of the accessibility LUTI models, accessibility can be expressed in terms of disaggregate trip utility (IRPUD and DELTA models) aggregated location-based measure (EE and MARS models), or a mix of disaggregate local accessibility and aggregate regional accessibility (UrbanSim model) (Wegener, 1986; Simmonds, 1999; Engelen et al., 2003; Pfaffenbichler, 2003; Waddell, 2011).

Among those models, most of their accessibility measure expresses accessibility as the opportunity to achieve a single activity, e.g., job or retail, except the IRPUD and DELTA models, which consider a multipurpose accessibility indicator. Both of these two models calculate a weighted accessibility indicator. The difference is IRPUD model estimates accessibility as mean trip utility according to various activities and travel modes, while DELTA model combines the accessibility value from each zone to alternative destinations using a simple weighted

Fig. 2. Model structure of MARS.

Fig. 3. Simplified CLD of accessibility indicators in the MARS model.

summation. The weights used in the DELTA model are simply the average weekly household trip rates by purpose (Simmonds, 1999). However, Martinez (1996) and Wegener (2013) state that a complex accessibility measure needs further research.

Moreover, a simple accessibility indicator is not sufficient to represent neighborhood quality and attractiveness of housing and working, thereby leading to proper re-location of residents. Croft (2003) reveals schooling as one of the main reasons for family to choose living place particularly in where the public service is less distributed. Kim, Pagliara, and Preston (2005) use a nested logit model to estimate factors of the intention to move and residential location choice based on stated preference data and they conclude that the residential location choice model quantify the trade-offs between transport, public facilities and other factors.

As the key connection of land use and transport sub-model, the accessibility indicator is influenced by a series of factors, like the number of jobs or job centres, schools, health centres, parks or retail. The influence of these factors varies between different population groups. These differences have been neglected when computing land use and transport impacts using the LUTI models. As a consequence, it is imperative to incorporate both job accessibility and other accessibility measures into one of the widely applied LUTI model-MARS, which is introduced in next section.

2.2. MARS model

The MARS model so far has been applied in more than 20 cities world-wide and has been used as a training tool for planners and practitioners in European and Asia, and in optimising strategic transport policies for a range of cities/regions (Shepherd, 2014). It owns a flexible platform to tailor and modify the conditions of analysis as required by planners and model users (Pfaffenbichler, 2011). It is also a Sketch Planning Model (SPM) embedded in an assessment and optimisation framework. In particular, it is developed in an SD (system dynamics) programming environment, based on the concept of Causal Loop Diagrams (CLD) and represents the relation of cause and effect of the variables in the model (Shepherd et al., 2006; Wang, Monzon, Ciommo, & Kaplan, 2014).

Pfaffenbichler et al. (2010) and Pfaffenbichler (2011) provides a more detailed version of this concept and demonstrates that real-world applications follow this pattern. MARS model can simulate the interaction between land use and transport system that works with a significant level of aggregation and makes long-term assessments, see

Fig. 2. It is important to clarify that MARS model does not include transport networks. Instead, it contains the transport data in relation to the road network, such as the number of commuting routes, travel distance and free flow speed of Madrid between the origin and destination zone, which were obtained by a supplementary transport model VISUM. Data from this VISUM model was added to the MARS model by joining by aggregated zone name.

The location based accessibility indicator is the only link between the two sub-models in MARS. The aggregate level of job accessibility was estimated on a rigorous methodological basis (Wang et al., 2016). A complex accessibility indicator substitutes the single indicator which is defined in terms of both trips to work and to public facilities, e.g., schools, health centres, parks and shops. It combines the effects of transport/land use and incorporates assumptions regarding residential choice by using local coefficients. The mathematical definition of the complex accessibility indicator is given in Section 3.2.

3. Methodology

3.1. Data sources

In order to embed the complex accessibility indicator into the MARS model, data related to the number of schools, health centres, green areas and shops are required. The number of job centres as well as the number of health, education and retail activities for each census tract¹ is computed from the geo-localized units available from the Directory of Economic Activities (DUA) of the Regional Statistics Institute of the Community of Madrid with the use of a Geographic Information System (GIS). The number of jobs in each activity is estimated from the number of units in each job range. The location of parks and gardens was obtained from the Nomenclatures database (Regional Statistics Institute of the Community of Madrid). We also obtained the location of education and health centres from Nomenclatures, which is a dataset more accurate than the DUA, but lacking any reference to the number of employees or any other proxy to its size.

¹ Please note that census tracts are of dissimilar size in order to contain approximately the same number of resident population (i.e. 2000 inhabitants). For this reason, highly populated areas like the city centre are divided into a high number of small census tracts, while census tract size increases towards the low-density periphery. This helps minimizing the Modifiable Areal Unit Problem (MAUP), firstly defined by Kendall (1939) and discussed in-depth in the nineties (Griffith, 1992; Bivand, 1998).

Table 1
Correlation matrix.

	Pop.	Work	Jobs	Edu01	Edu02	Edu03	Edu04	Edu05	Edu06	Edu07	Edu08	Edu09	Edu10
Population	1.00												
Workplace	0.18	1.00											
Jobs	0.14	0.85	1.00										
Edu_01	0.36	0.19	0.22	1.00									
Edu_02	0.28	0.08	0.10	0.73	1.00								
Edu_03	0.25	0.20	0.22	0.75	0.09	1.00							
Edu_04	0.18	0.26	0.30	0.58	0.32	0.53	1.00						
Edu_05	0.27	0.12	0.13	0.62	0.42	0.50	0.60	1.00					
Edu_06	0.11	0.22	0.20	0.45	0.22	0.45	0.60	0.18	1.00				
Edu_07	0.00	0.17	0.24	0.13	0.04	0.15	0.72	0.05	0.16	1.00			
Edu_08	0.06	0.11	0.21	0.30	0.17	0.28	0.78	0.19	0.34	0.87	1.00		
Edu_09	0.15	0.10	0.13	0.48	0.37	0.34	0.47	0.68	0.19	0.08	0.27	1.00	
Edu_10	0.11	0.10	0.11	0.42	0.22	0.39	0.42	0.15	0.71	0.08	0.38	0.19	1.00
Edu_11	0.00	0.07	0.17	0.10	0.04	0.11	0.62	0.02	0.10	0.92	0.93	0.04	0.04
Health_01	0.08	0.08	0.09	0.18	0.22	0.05	0.15	0.07	0.04	0.15	0.17	0.07	0.04
Health_02	0.07	0.10	0.18	0.15	0.09	0.13	0.30	0.05	0.12	0.36	0.38	0.09	0.11
Health_03	0.10	0.03	0.02	0.10	0.14	0.02	0.05	0.10	0.02	0.00	0.01	0.07	0.02
Health_04	−0.02	0.03	0.00	0.07	0.14	−0.03	−0.04	−0.02	−0.04	−0.01	−0.02	−0.03	−0.03
Health_05	0.00	0.37	0.25	0.07	−0.03	0.13	0.21	0.05	0.17	0.18	0.13	0.07	0.10
Health_06	0.03	0.24	0.29	0.12	0.04	0.13	0.26	0.06	0.14	0.27	0.27	0.11	0.11
Health_07	0.00	0.36	0.22	0.06	−0.04	0.12	0.18	0.04	0.16	0.15	0.09	0.06	0.08
Health_08	0.05	0.18	0.26	0.14	0.07	0.13	0.33	0.05	0.12	0.41	0.42	0.10	0.09
Health_09	0.05	0.12	0.23	0.14	0.08	0.13	0.34	0.04	0.10	0.45	0.46	0.09	0.09
Health_10	0.01	0.16	0.15	0.05	0.01	0.06	0.08	0.04	0.06	0.06	0.05	0.05	0.03
Retail shop	0.11	0.68	0.46	0.04	0.00	0.06	0.09	0.03	0.10	0.06	0.02	0.01	0.02
Retail job	0.10	0.63	0.65	0.11	0.06	0.10	0.11	0.06	0.10	0.05	0.03	0.05	0.04
Parks	0.05	0.08	0.13	0.10	0.09	0.06	0.16	0.03	0.08	0.18	0.18	0.04	0.05

Key code (data source): Pop.: total population (INE); Work: number of workplaces (DUAE); Jobs: number of jobs (DUAE); Edu01: education centres (Nomenclal); Edu02: public education centres (Nomenclal); Edu03: private education centres (Nomenclal); Edu04: education centres (DUAE); Edu05: primary schools (DUAE); Edu06: secondary schools (DUAE); Edu07: third cycle education centres (DUAE); Edu08: number of employees at education centres (DUAE); Edu09: number of employees at primary schools (DUAE); Edu10: number of employees at secondary schools (DUAE); Edu11: number of employees at education centres third cycle education centres (DUAE); Health01: all health centres (Nomenclal); Health02: hospitals (Nomenclal); Health03: primary health centres (Nomenclal); Health04: rural health centres (Nomenclal); Health05: all health centres (DUAE); Health06: hospitals (DUAE); Health07: health activities (DUAE); Health08: number of employees in health centres (DUAE); Health09: number of employees in hospitals (DUAE); Health10: number of employees in health activities (DUAE); Retail shop: retail shops (DUAE); Retail job: number of employees in retail shops (DUAE); Parks: number of parks and gardens (Nomenclal).

Population data was obtained for estimating the local coefficients from National Statistics Institute of Spain (INE) at the census tract level for the whole study area. An origin-destination cost matrix of minimum travel time between all census tract centroids was computed using TomTom's road network in ArcGIS.

The data was then aggregated based on the MARS spatial units, which aggregates the 199 municipalities of Madrid Region into 90 modelling zones. The zoning was carried out following homogeneity parameters of socioeconomic characteristics and mobility, plus correspondence with transport zones and regional rings (Wang et al., 2014). Data collected at different levels were aggregated to the MARS zoning.

3.2. Complex accessibility indicator

The traditional potential accessibility (also referred to as the single accessibility indicator in the text) is widely used to measure the aggregate level of job accessibility, (Geurs, Zondag, De Jong, & De Bok, 2010), and it is estimated regarding personal perceptions of transport by using a function that decreases with distance or time (Geurs & Van Wee, 2004a). Eq. (1) shows the potential accessibility to workplaces $^{WP}ACC_i(t)$ that uses a negative exponential cost function in MARS model.

$$^{WP}ACC_i(t) = \sum_{jm} Work_{jm}(t) * F(t_{ijm}, c_{ijm}) \quad (1)$$

where $^{WP}ACC_i(t)$ is the potential accessibility to working places in zone i in year t ; $Work_{jm}(t)$ is the number of jobs in the destination zone j by mode m in year t ; $F(t_{ijm}, c_{ijm})$ is a function of the average generalized travel cost associated with travel time and costs between zone i and j by mode m . For this study, the $F(t_{ijm}, c_{ijm})$ is defined in Eq. (2) (Guzmán, 2011):

$$F(t_{ijm}, c_{ijm}) = 0.16 * \exp[-0.0163 * (c_{ijm}(t) + t_{ijm}(t) * VOT)] \quad (2)$$

where $t_{ijm}(t)$ is the total travel time between i and j by mode m in year t ; $c_{ijm}(t)$ is the total travel cost between i and j by mode m in year t ; VOT is the value of time (€10.45/hour during peak hours and €5.7/hour during non-peak hours). The parameters in Eq. (2) were calibrated by Guzmán (2011) on the basis of two household mobility surveys in Madrid (C. T. R. M., 1998, 2006).

The potential accessibility (also called gravity-based accessibility) is based on the principle that the probability to visit an opportunity decreases with the cost of travel from the observation point to that destination (opportunity). In other words, the potential visitors to a particular point of interest (i.e. opportunity) are directly related to the size of that opportunity and to the population volume of the study area, and inversely related to the travel cost (i.e. distance, time, etc.) between where people are located and the location of that opportunity. Those opportunities also called activity sites are not only jobs, but also other sites like schools, hospitals, shops and parks, etc. In the case of an aggregated LUTI model, we develop a complex accessibility indicator considering both the accessibility to jobs as well as to other motives. The combination of the complex accessibility for each zone is different in respect of the characteristics of the area. For example, the accessibility to school is more important than the accessibility to shops for those people who live in a commercial area of the city. This is because they can easily reach a shop close to their home, but not a school. Therefore, the complex accessibility indicator in MARS model is defined in Eq. (3) consisting of all factors varied by different zones.

$$GACC_i(t) = \sum_{jm} [a_j * Work_j(t) * F(t_{ijm}, c_{ijm})_{work} + b_j * Edu_j(t) * F(t_{ijm}, c_{ijm})_{edu} + c_j * Hea_j(t) * F(t_{ijm}, c_{ijm})_{health} + d_j * Park_j(t) * F(t_{ijm}, c_{ijm})_{park} + e_j * Shop_j(t) * F(t_{ijm}, c_{ijm})_{shop}] \quad (3)$$

Edu11	Health01	Health02	Health03	Health04	Health05	Health06	Health07	Health08	Health09	Health10	Retail shop	Retail job	Parks
1.00													
0.16	1.00												
0.37	0.44	1.00											
0.00	0.66	0.00	1.00										
−0.01	0.58	−0.01	−0.04	1.00									
0.09	0.17	0.31	0.08	−0.04	1.00								
0.24	0.26	0.58	0.02	−0.01	0.42	1.00							
0.06	0.14	0.24	0.09	−0.04	0.99	0.30	1.00						
0.41	0.38	0.75	0.08	−0.01	0.38	0.57	0.31	1.00					
0.46	0.35	0.80	−0.01	0.00	0.27	0.61	0.20	0.89	1.00				
0.03	0.18	0.15	0.19	−0.02	0.31	0.12	0.31	0.53	0.08	1.00			
0.01	0.04	0.01	0.05	−0.01	0.25	0.10	0.24	0.07	0.03	0.10	1.00		
0.01	0.03	0.06	0.01	−0.01	0.14	0.17	0.12	0.12	0.08	0.10	0.66	1.00	
0.18	0.04	0.08	0.00	0.00	0.02	0.07	0.02	0.12	0.12	0.05	0.00	0.02	1.00

$GACC_i(t)$ is the complex accessibility to jobs and public services (i.e., education, health, park and shops) in zone i in year t ;

$Work_j(t)$ is the number of jobs in the destination zone j in year t ;

$Edu_j(t)$ is the number of schools in the destination zone j in year t ;

$Hea_j(t)$ is the number of hospitals and health centres in the destination zone j in year t ;

$Park_j(t)$ is the number of parks in the destination zone j in year t ;

$Shop_j(t)$ is the number of shops in the destination zone j in year t ;

$F(t_{ijm}, c_{ijm})_x$ is the generalized cost from origin zone i to destination zone j where jobs or the respective public service x located by mode m .

a_j, b_j, c_j, d_j, e_j : coefficients for zone j , weighting the importance of accessibility to each activity, the sum of them equals to 1.

It is crucial to properly define the weights of each factor of the complex accessibility indicator, since the result identifies different people preferences that can contribute to the manifestation of public services imbalances. This is done with the integration of local coefficients, which calculation method consists on a geographical weighted regression with the use of network based distances, as explained in detail in Section 3.3.

The accessibility indicator acts as an output of the transport sub-model and as an input of the land use sub-model. Thus, the integration of the local coefficients consists of two parts: one is linking the new indicator with the generalized travel costs that were calculated from transport sub-model, and another is to replace the old accessibility indicator both in the residential and workplaces location sub-model. Fig. 3 shows the simplified CLD of the single potential accessibility (the old one) and the complex potential accessibility indicator (the new one) within MARS model, as defined in this study. The old accessibility indicator (Eq. (1)) is decided by the number of jobs and the generalized travel cost. The number of jobs is determined by the input/output flow of jobs in zone j (i.e. the difference between the jobs attracted to zone j and the jobs that migrate from zone j to other zones). There is a mutual influence between job supply and accessibility indicator, as the

job supply in each zone is also influenced by its accessibility, in addition to the variables in land-use submodels (such as land price, land-use development opportunities, and employment sector growth rate). With the job supply, there is a mutual influence between job demand (number of employees) (i.e., the input/output flow of employees) and accessibility, because accessibility is one of the main determinants of job demand and residential growth (Wang et al., 2016).

As seen in Fig. 3, the new accessibility indicator consists of accessibility to jobs and to other public services. By estimating the local coefficients (Section 3.3), hospital and parks are dropped through the coefficients estimation procedure (their weights equal to 0). The number of education centres and shops are defined as variables using the data collected from the local census. The negative exponential cost function to schools and shops considers all four travel modes, e.g., car, bus, rail and slow modes using Eq. (2), but the parameters vary on the basis of the new household mobility surveys in Madrid (C. T. R. M., 2006 and 2014).

The complex accessibility indicator is implemented in the MARS model using the interaction between transport and the different land-use submodels. It improves the accessibility characterization of the MARS model (expand MARS model objective) and brings out a more accurate indicator than the single one for representing the public facility locations among zones.

3.3. Computing the coefficients

3.3.1. Method

The estimation of local coefficients was based on the most disaggregated spatial units that were available (i.e. census tracts). Our aim is to improve the traditional model that estimates the global coefficients by estimating them locally. This way, the spatial variation of the intensity of each explanatory variable across the city is captured. Following Kwan's (1998) argument that different groups of people show

differences in accessibility, the null hypothesis is that people residing in different parts of the city have different preferences, which cannot be captured with a global model.

In order to check this hypothesis, we examined the correlation between the dependent variable (i.e. population) and a collection of potential explanatory variables, and run all the possible combinations of Ordinary Least Squares (OLS) models. Our candidate variables to predict population volume are related to jobs, different types of health care and education, retail and parks (see note in Table 1 for details and data sources). We run local correlation statistics between population data and the highest globally correlated variables for each of these topics in order to reduce the set of potential candidate variables.

Once we had a global explanatory model, we tried to improve it with the estimation of local coefficients for each observation, thus capturing the spatial variations of the sign and intensity of the relationship between the explanatory and dependent variables. To do this, we took into account each observation neighbours' values of the chosen explanatory variables by applying the Geographically Weighted Regression method (GWR, see Section 3.3.3). An essential part of this method is the bandwidth selection in terms of distance (i.e. fixed bandwidth) or number of near neighbours (i.e. adaptive bandwidth). This way the local model will only capture the spatial relationships that are relevant to each observation, with this relevance decreasing with distance using a Gaussian function.

Once we had the best-fit model and according optimal bandwidth, we obtained the corresponding coefficients of each variable at each location, and to compare the local and the general GWR fitting parameters with the corresponding OLS model. Should local coefficients fit better than the global ones, our null hypothesis will be validated and therefore the accessibility indicator in the MARS model will be updated with the transformed local coefficients for the corresponding explanatory

variables (Eq. (3)). This transformation consists in a normalization and aggregation in which, for each local observation, the sum of all its corresponding coefficients equals one, following Eqs. (4) and (5):

$$x_{zi} = \frac{\sum_{m \in i} p_{zm} w_{zm}}{\sum_{m \in i} w_{zm}}, \forall i \in N \quad (4)$$

where x_{zi} is the coefficient of variable z (or 1 for the intercept) of MARS zone i , p_{zm} is the local coefficient of variable z in census tract m within MARS zone i , w_{zm} is the value of variable z in census tract m within MARS zone i , and N is the total number of MARS zones.

$$y_{zi} = \frac{x_{zi} / \sum x_{zi}}{\sum_i \sum_z x_{zi} / \sum x_{zi}} \quad (5)$$

where y_{zi} is the transformed coefficient of variable z of MARS zone i .

3.3.2. Preliminary judgement

The correlation matrix (Table 1) evidences the relationship between the dependent (population) variable and some of the candidate variables, while discarding collinearity issues among the latter. It also allows the reduction of candidate variables (see key code in Table 1 for details and data source) to the most suitable in each topic: number of work places, Nomenclatures' education centres, Nomenclatures' primary health centres, and number of shops are the most suitable variables of each corresponding topic (i.e. jobs, education, health and retail, respectively).

Continuing with the global analysis, Ordinary Least Squares (OLS) yielded poor results, with adjusted r^2 values below 0.2 in any of the 9231 possible models with up to 5 explanatory variables.

In view of these unsatisfactory results, we checked for spatial heterogeneity by computing local Pearson correlations within a 5-km

Fig. 4. Local Pearson correlation statistics between population and the candidate variables.

Table 2
Best-fit models after bandwidth selection.

Model	RSS	AIC	AICc	r ²	Adjusted r ²
1	552,193,804	63,639	64,729	0.611	0.483
5	513,738,740	63,527	65,040	0.638	0.485
6	464,867,520	63,227	65,057	0.672	0.500
7	484,644,807	63,327	64,959	0.658	0.497
8	431,978,657	63,094	65,438	0.695	0.501
9	411,869,765	62,936	65,428	0.710	0.508

bandwidth. Network-based distance and private motor vehicle travel times were tested to build the origin-destination cost matrix in ArcGIS 10.3 Network Analyst extension. Running the local models in subsequent steps evidenced that network-based distance is a better proxy to travel cost in order to estimate population accessibility. The aim is to see whether considering the different intensities of the variables across the city unveils location patterns that got masked in the global model.

Fig. 4 shows the variability of the Pearson correlation between the dependent and the candidate variables. There is a centre-periphery pattern in which the candidate variables have stronger explanation power in areas where these resources are scarce. On the contrary, in the city

centre the ubiquity of most variables downgrades these coefficients. Of them, the presence of education centres seems the strongest variable in all the study area, while the presence of parks and gardens does not follow a logic pattern, which might be due to data being limited to official parks and gardens.

3.3.3. Geographically weighted regression (GWR)

Geographically weighted regression is a technique widely developed in Fotheringham, Brunsdon, and Charlton (2002) to deepen the understanding of the spatial relationships of the variables that explain a particular phenomenon. Similar to gravity-based accessibility models that use the negative exponential function, GWR is based on Tobler's first law of Geography, i.e. close things are more related to each other than distant things. What is new in GWR is that it considers the variation of this relationship across the study area. In order to identify these varying relationships, GWR allows the estimation of local coefficients that capture the varying intensity of the spatial relationships with the use of a moving window centred on one observation at a time. Consequently, the selection of an appropriate bandwidth is essential.

In order to estimate the optimal bandwidth, we introduced the above-mentioned candidate variables into a local pre-selection process with a 5-km bandwidth, following Ramasco et al. (2015)'s results on Madrid metropolitan area. Within this bandwidth, we used the default Gaussian decay function (Fotheringham et al., 2002), which continuous behaviour reducing the value of distant neighbours is similar to the negative exponential function, except at the origin (Lu, Harris, Charlton, & Brunsdon, 2014). This way we obtained the most suitable pre-models according to a bandwidth that deemed reliable for the metropolitan area. We then estimated the best bandwidth for each of them in terms of distance (fixed) and number of neighbours (adaptive), and both for

Fig. 5. Mean standardized local coefficients, total observed and predicted population values and student residuals of Model 9 aggregated by MARS zones.

Fig. 6. Comparison of N° of the estimated and real number of workplaces and resident population using the new and old accessibility indicator.

distance along the road network and for private motor vehicle travel time.

By introducing distance (or travel time) in our calculations, we removed collinearity concerns related to the analysis of absolute values, since for every zone, we consider both its value and the distance from its centroid to its neighbours' centroid. Therefore, large zones are penalized by their large internal distance, while a small zone with high values is not. This means that, should there be some correlation between zone size and variable volume, they are now not directly related to each other.

Geographically weighted Regression was computed on the best-fit models. We obtained specific coefficients for each observation (i.e. spatial unit) and for each significant variable. The calculation of these local coefficients is based on the values of the corresponding independent variables in nearby locations, and giving more weight to close locations, thus establishing an inverse distance relationship with a Gaussian function.

The general formula for GWR (one predictor variable) is set in Eq. (6) and subsequent (Fotheringham et al., 2002):

$$y_i = \beta_0(i) + \sum_k \beta_k(i)x_{ik} + \varepsilon, \quad (6)$$

where $\beta(i) = (\beta_0(i), \beta_1(i), \dots, \beta_k(i))$ is the vector of regression coefficients census tract i , x_{ik} is the k^{th} independent variable value at census tract i , and y_i is the value of the dependent variable at census tract i .

The vector of parameters $\beta(u)$ is estimated by:

$$\beta(i) = (X^T W(i) X)^{-1} X^T W(i) Y, \quad (7)$$

where $W(i)$ is an $n \times n$ diagonal matrix whose diagonal elements denotes the geographical weighting of each of the n observed data for

the regression point at census tract i . X is the matrix of independent variables and Y is the vector of dependent variables.

Our final GWR model after the variable selection process is set in Eq. (8):

$$Pop_i = \beta_0(i) + \beta_{work}(i)Work + \beta_{edu}(i)Edu + \beta_{shop}(i)Shop + \varepsilon \quad (8)$$

where Pop_i is population in zone i , $Work$ is number of workplace centres, Edu is number of education centres, and $Shop$ is the number of retail shops.

Unlike most studies, distance was computed through the street network. The origin-destination travel cost matrix, computing the shortest path between each pair of locations, was computed with ArcGIS Network Analyst extension. This matrix was used as input in GWmodel R package (Lu et al., 2015) in order to consider network travel costs in the computation of the model.

3.3.4. Results

The pre-model selection process based on the spatial relationships of the observations within 5 km resulted in dropping the variable 'parks and gardens' due to reciprocal condition number (not surprisingly in view of the local coefficients). The following table (Table 2) illustrates the main evidence ratios of the most suitable potential geographically weighted models. The diagram at the bottom of the table indicates the variables that are considered in each model.

Of the tenth best-fitted models, we chose models 6th (workplace and education), 8th (workplace, education and health) and 9th (workplace, education and retail) as the ones with higher explanatory power to describe the spatial distribution of population in the study area (lowest delta Corrected Akaike Information Criterion

Fig. 7. Final model comparison, local results.

(AICc)² value, weight and evidence ratio). As explained in Section 3.3.3, we then estimated the best bandwidth in terms of distance (fixed) and number of neighbours (adaptive) for distance along the road network and for private motor vehicle travel time. In all cases, a 5-neighbor adaptive bandwidth provided the best results, with distance along the network performing better than travel time. Therefore, we re-run the model selection tool with the 5-neighbours adaptive bandwidth, and then run the most likely models in order to choose the final one.

The best-fit model in terms of producing the lowest value of Corrected Akaike Information Criterion (AICc) and Residual Sum of Squares (RSS), and highest adjusted r^2 is the one considering the number of workplaces, education centres and retail (model 9). Fig. 5 shows the standardized local coefficients once aggregated at the MARS zones. The intensity and sign of the relationship between each factor and population location have a great variety across space, especially in the case of retail. For this reason, maps have individual (i.e. not comparable) legends, thus the variability of each variable can be better appreciated. Population figures predicted with our model are consistent with real figures, with discrepancies below ± 0.5 Standard Deviation in the most populated areas (student residuals).

4. Comparison analysis with the two accessibility indicators

GWR coefficients were transformed to coefficients a_j , b_j , and e_j , the sum of them equals to 1, following Eqs. (4) and (5), and then introduced in Eq. (3). The old accessibility indicator in the MARS model was

² Corrected Akaike Information Criterion (AICc) is a model selection test based on the calculation of the Kullback-Leibler distance that has been confirmed to be preferred to the F-test (Kletting & Glatting, 2009).

replaced with the new one. Simulation was conducted using the two indicators respectively in the condition of no policy intervention. The comparison was based on two selected variables which are strongly influenced by the accessibility changes, i.e., the number of workplaces and the number of residents. The real data used in the comparison are collected from the Municipal Data Bank in 2015. The simulation by the MARS model starts from 2012, and the outputs on the two variables were obtained from the same year.

In general terms, the model computed with the new accessibility indicator improves the previous results. Although the differences in R^2 are small due to the already high values, the AICc differences between each corresponding model being over the common threshold (over 3) evidence that the improvement provided by the new accessibility indicator is significant (Fig. 6), which is more evident when observing the details.

Fig. 5(a) and (b) illustrates the correlation of the number of predicted workplaces using the old accessibility indicator and the real data, and the (c) and (d) shows the same results but in terms of number of residents. The Ordinary Least Squares (OLS) yielded better results when comparing the number of workplaces by using the two accessibility indicators (R^2 equals 0.9733 comparing with 0.9596). In particular, the old accessibility leads to an under estimation of the workplaces in zones between 60,000 to 100,000 workplaces; and overestimations in the zones which have more than 120,000 workplaces (basically the city centre). This can be better appreciated in Fig. 7 and is corrected with the new accessibility indicator.

Similar results are also found for the number of residents, whose results are shown in Fig. 5(c) and (d), and mapped in the top row of maps in Fig. 7. The correlation using the new accessibility (bottom chart) is higher than the one using the old accessibility indicator. Moreover, the prediction using the new indicator achieves better results for the whole area whatever the zone is small or large.

5. Conclusions

Calculating the weights of different public services in different urban areas is important in order to identify people preferences that can contribute to the manifestation of public services imbalances. This study focuses on the development of a complex accessibility indicator for a LUTI model by using the GWR method with two main innovations. The first is to apply the GWR method to generate local coefficients for different type of trip purpose. The second is to integrate the new accessibility indicator, via transformed coefficients, into the MARS model.

This new accessibility indicator combined three single accessibility indicators by using the estimated weights; and it was integrated into MARS LUTI model. The new indicator includes local coefficients of jobs, schools and shops, while the distance decay calculation is straightforward by using generalized travel costs multiplying the number of the opportunities. By using the new accessibility indicator based on local coefficients, MARS model fits better with the real data both in terms of the number of workplaces and residents, which are the key representatives of the land use sub-model.

The methodology presented has served to improve MARS model for the case of Madrid. This methodology addresses one of the most important challenges for LUTI models- the improvement of accessibility measures (Van Wee, 2015; Acheampong & Silva, 2015). Future developments should address the improvement of its environmental and energy modules and consider different age groups and household types (Pfaffenbichler, Emberger, & Shepherd, 2008). However, to address the accessibility challenge was probably the most important issue in the MARS model for Madrid. On the one hand, accessibility is the only link between the transport and the land use sub-models in the MARS model, and therefore a key concept in the model. On the other hand, this improvement makes the model more suitable to deal with problems such as urban sprawl.

This methodology was originally developed for the case of MARS model. Still, the concept of the method is generic and can be adapted for application to other LUTI model for other cities as well, which constitutes and open line for further research.

References

- Acheampong, R. A., & Silva, E. (2015). Land use–transport interaction modeling: A review of the literature and future research directions. *Journal of Transport and Land Use*, 8(3), 11–13.
- Bivand, R. (1998). *A review of spatial statistical techniques for location studies*. Bergen, Norway: Norwegian School of Economics and Business Administration.
- C. T. R. M. (1998). EDM'96: Encuesta domiciliaria de movilidad en día laborable 1998.
- C. T. R. M. (2006). EDM'04: Encuesta domiciliaria de movilidad en día laborable 2004.
- C. T. R. M. (2014). ESM'14: Encuesta sintética de movilidad en la comunidad de madrid.
- Cardozo, O. D., García-Palomares, J. C., & Gutiérrez, J. (2012). Application of geographically weighted regression to the direct forecasting of transit ridership at station-level. *Journal of Applied Geography*, 34, 548–558.
- Croft, J. (2003). Gating communities for children? The perennial problem of school choice, residential location and their (continuing) relationship with neighbourhood. *Journal of Housing Studies*, 19(6).
- Duque, J. C., Velásquez, H., & Agudelo, J. (2011). Public infrastructure and housing prices: An application of geographically weighted regression within the context of hedonic prices. *Ecos de Economía*, 15(33), 95–122.
- Engelen, G., White, R., & de Nijs, T. (2003). Environment explorer: Spatial support system for the integrated assessment of socio-economic and environmental policies in the Netherlands. *Integrated Assessment*, 4(2), 97–105.
- Fotheringham, A. S., Brunsdon, C., & Charlton, M. (2002). *Geographically weighted regression: The analysis of spatially varying relationships*. John Wiley & Sons.
- Geurs, K. T., & Van Wee, B. (2004a). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, 12(2), 127–140.
- Geurs, K. T., & Van Wee, B. (2004b). Land-use/transport interaction models as tools for sustainability impact assessment of transport investments: Review and research perspectives. *The European Journal of Transport and Infrastructure Research*, 4, 333–355.
- Geurs, K. T., Zondag, B., De Jong, G. C., & De Bok, M. (2010). Accessibility appraisal of land use/transport policy strategies: More than just adding up travel-time savings. *Transportation Research Part D*, 15(7), 382–393.
- Griffith, D. A. (1992). What is spatial autocorrelation? Reflections on the past 25 years of spatial statistics. *Espace géographique*, 21(3), 265–280.
- Guzmán, L. A. (2011). *Optimización dinámica de estrategias de movilidad sostenible en áreas metropolitanas*. (Doctoral dissertation, Caminos).
- Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2), 73–76.
- Kendall, M. G. (1939). The geographical distribution of crop productivity in England. *Journal of the Royal Statistical Society*, 102(1), 21–62.
- Kim, J. H., Pagliara, F., & Preston, J. (2005). The intention to move and residential location choice behaviour. *Urban Studies*, 42(9), 1621–1636.
- Kletting, P., & Glatting, G. (2009). Model selection for time-activity curves: The corrected Akaike information criterion and the F-test. *Zeitschrift für Medizinische Physik*, 19(3), 200–206.
- Kwan, M. P. (1998). Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geographical Analysis*, 30(3), 191–216.
- Lowry, I. (1964). A model of metropolis. *Tachricol Repor RM-4035-RC*. California: Santa Monica: The IRAND CODORation.
- Lu, B., Harris, P., Charlton, M., & Brunsdon, C. (2014). The GWmodel R package: Further topics for exploring spatial heterogeneity using geographically weighted models. *Geo-Spatial Information Science*, 17(2), 85–101.
- Lu, B., Harris, P., Charlton, M., Brunsdon, C., Nakaya, T., & Gollini, I. (2015). GWmodel: Geographically-weighted models. Available at: <https://CRAN.R-project.org/package=GWmodel>
- Manganelli, B., Pontrandolfi, P., Azzato, A., & Murgante, B. (2014). Using geographically weighted regression for housing market segmentation. *International Journal of Business Intelligence and Data Mining*, 9(2), 161–177.
- Martinez, F. J. (1996). Analysis of urban environmental policies assisted by behavioural modelling. *Transport, Land Use and the Environment*, 233–257.
- Pfaffenbichler, P. (2011). Modelling with systems dynamics as a method to bridge the gap between politics, planning and science? Lessons learnt from the development of the land use and transport model MARS. *Transport Reviews: A Transnational Transdisciplinary Journal*, 31(2), 267–289.
- Pfaffenbichler, P. (2003). *The strategic, dynamic and integrated urban land use and transport model MARS (metropolitan activity relocation simulator)* Institut für Verkehrsplanung und Verkehrstechnik der Technischen Universität Wien.
- Pfaffenbichler, P., Emberger, G., & Shepherd, S. (2008). The integrated dynamic land use and transport model MARS. *Networks and Spatial Economics*, 8(2–3), 183–200.
- Pfaffenbichler, P., Emberger, G., & Shepherd, S. (2010). A system dynamics approach to land use transport interaction modelling: The strategic model MARS and its application. *System Dynamics Review*, 26(3), 262–282.
- Pfaffenbichler, P., & Shepherd, S. P. (2003). A dynamic model to appraise strategic land-use and transport policies. *European Journal of Transport and Infrastructure Research*, 2(3/4), 255–283.
- Ramasco, J. J., et al. (2015). D3.2 analysis of urban location patterns. Scientific report available at: <http://www.insight-fp7.eu/deliverables>
- Russo, F., & Musolino, G. (2007). Urban land-use transport interaction modelling: State of the art and applications. *WIT Transactions on the Built Environment*, 96.
- Shepherd, S. P. (2014). A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics*, 2(2), 83–105.
- Shepherd, S. P., Zhan, X., Emberger, G., Huds, M., May, A. D., & Paulley, N. (2006). Designing optimal urban transport strategies: The role of individual policy instruments and the impact of financial constraints. *Transport Policy*, 13(1), 49–65.
- Simmonds, D. C. (1999). The design of the DELTA land-use modelling package. *Environment and Planning B: Planning and Design*, 26, 665–684.
- Thill, J. -C., & Kim, M. (2005). Trip making, induced travel demand, and accessibility. *Journal of Geographical Systems*, 7(2), 229–248.
- Van Wee, B. (2015). Viewpoint: Toward a new generation of land use transport interaction models. *Journal of Transport and Land Use*, 8(3).
- Waddell, P. (2011). Integrated land use and transportation planning and modelling: Addressing challenges in research and practice. *Transport Reviews*, 31(2), 209–229.
- Wang, Y., Monzon, A., Ciommo, F., & Kaplan, S. (2014). Integrated transport planning framework involving combined utility regret approach. *Transportation Research Record: Journal of the Transportation Research Board*, 2429, 59–66.
- Wang, Y., Monzon, A., & Di Ciommo, F. (2016). Assessing the accessibility impact of transport policy by a land-use and transport interaction model—The case of Madrid. *Computers, Environment and Urban Systems*, 49, 126–135.
- Wegener, M. (1986). Transport network equilibrium and regional deconcentration. *Environment & Planning A*, 18, 437–456.
- Wegener, M. (2004). Overview of land-use transport models. *Handbook of transport geography and spatial systems*. 5. (pp. 127–146).
- Wegener, M. (2013). The future of mobility in cities: Challenges for urban modelling. *Transport Policy*, 29, 275–282.
- Zondag, B. (2007). *Joint modeling of land-use, transport and economy*. TU Delft: Delft University of Technology.

Annex C) Characterization of the zones in MARS model for Madrid (Section 5.5)

Figure C.1. Zones of Madrid Region in MARS model

Table C.1. Zones of Madrid Region in MARS model: population and workplaces in 2012.

Zone	Municipality/ies (District)	Population	Workplaces	GDP per capita (€)
1	Madrid (Centro)	140,930	176,350	23,084
2	Madrid (Arganzuela)	154,805	90,716	23,356
3	Madrid (Retiro)	121,815	92,439	26,409
4	Madrid (Salamanca)	146,935	190,237	26,265
5	Madrid (Chamartín)	146,067	204,320	25,815
6	Madrid (Tetuán)	156,798	116,798	22,025
7	Madrid (Chamberí)	142,268	146,761	25,984
8	Madrid (Fuencarral, el_Pardo)	234,019	81,629	23,371
9	Madrid (Moncloa, Aravaca)	117,698	83,360	23,941
10	Madrid (Latina)	247,538	29,350	19,333
11	Madrid (Carabanchel)	251,949	38,424	18,049
12	Madrid (Usera)	138,591	24,685	16,691
13	Madrid (Puente de Vallecas)	238,667	33,462	16,730
14	Madrid (Moratalaz)	100,084	9,617	21,231
15	Madrid (Ciudad Lineal)	223,449	88,530	22,182
16	Madrid (Hortaleza)	175,435	75,975	23,229
17	Madrid (Villaverde)	146,968	50,118	16,970
18	Madrid (Villa de Vallecas)	95,620	18,671	20,402
19	Madrid (Vicálvaro)	70,970	5,679	19,537
20	Madrid (San Blas)	156,706	104,647	21,556
21	Madrid (Barajas)	46,423	46,885	25,297
22	Alcobendas	111,040	99,423	24,203
23	San Sebastián de los Reyes	81,466	41,878	19,052
24	Algete/Cobeña	27,408	8,701	21,538
25	San Agustín del Guadalix	12,770	3,552	22,218
26	Fuente el Saz de Jarama/Molar (EL)/Pedrezuela/Valdeolmos-Alalpardo/Valdetorres de Jarama	27,371	5,119	16,666
27	Ajalvir/Daganzo de Arriba/Paracuellos de Jarama	33,645	11,737	19,553
28	Coslada	91,832	26,944	15,492
29	San Fernando de Henares	41,376	17,655	14,887
30	Torrejón de Ardoz	125,331	27,237	14,588
31	Alcalá de Henares	203,924	51,600	15,840
32	Loeches/Rivas-Vaciamadrid/Velilla de San Antonio	95,471	31,881	18,018
33	Mejorada del Campo	22,902	5,254	13,656
34	Getafe	171,280	58,322	15,732
35	Leganés	187,125	49,882	14,679
36	Fuenlabrada	198,132	41,667	13,396

Table C.1. (cont.) Zones of Madrid Region in MARS model: population and workplaces in 2012.

Zone	Municipality/ies (District)	Population	Workplaces	GDP per capita (€)
36	Fuenlabrada	198,132	41,667	13,396
37	Alcorcón	169,308	40,199	16,053
38	Pozuelo de Alarcón	83,844	67,322	33,113
39	Majadahonda	70,198	27,268	28,116
40	Rozas de Madrid (Las)	90,390	56,522	27,750
41	Torrelorones	22,680	5,822	27,098
42	Hoyo de Manzanares	7,812	1,735	21,871
43	Tres Cantos	41,302	32,031	24,653
44	Colmenar Viejo	46,321	10,616	18,083
45	Arganda del Rey	55,506	19,049	14,180
46	San Martín de la Vega	19,615	4,147	13,621
47	Pinto	46,763	24,454	15,704
48	Parla	124,208	14,057	12,956
49	Móstoles	206,031	40,511	14,404
50	Brunete/Villaviciosa de Odón	36,772	11,666	21,663
51	Boadilla del Monte	47,037	27,077	28,216
52	Villanueva de la Cañada	18,425	6,158	26,428
53	Colmenarejo/Villanueva del Pardillo	25,262	4,284	20,078
54	Galapagar	32,930	5,363	19,728
55	Collado Villalba	61,955	13,004	16,649
56	Becerril de la Sierra/Boalo (El)/Moralzarzal	24,518	4,119	18,916
57	Manzanares el Real/Soto del Real	16,429	3,328	19,662
58	Bustarviejo/Miraflores de la Sierra	8,245	1,425	16,207
59	Cabanillas de la Sierra/Guadalupe de la Sierra/Navalafuente/Valdemanco/Venturada	10,917	1,542	17,250
60	Berrueco (El)/Cabrera (La)/Patones/Redueña/Talamanca de Jarama/Torrelaguna/Torremocha de Jarama/Valdepiélagos/Vellón (El)	15,233	2,263	14,662
61	Camarma de Esteruelas/Fresno de Torote/Meco/Ribatejada/Valdeavero	23,769	6,911	15,528
62	Ciempozuelos	23,716	5,452	13,979
63	Valdemoro	70,315	14,690	15,919
64	Torrejón de la Calzada/Torrejón de Velasco	11,827	5,079	15,355
65	Griñón/Humanes de Madrid	28,622	12,446	14,572
66	Arroyomolinos/Moraleja de En medio	27,460	8,397	17,626
67	Casarrubuelos/Cubas de la Sagra/Serranillos del Valle	12,242	2,533	15,174
68	Álamo (El)/Batres	10,253	1,844	14,681

Table C.1. (cont.) Zones of Madrid Region in MARS model: population and workplaces in 2012.

Zone	Municipality/ies (District)	Population	Workplaces	GDP per capita (€)
68	Álamo (El)/Batres	10,253	1,844	14,681
69	Morata de Tajuña/Perales de Tajuña	10,392	1,512	13,124
70	Quijorna/Valdemorillo	14,892	2,695	18,545
71	Fresnedillas de la Oliva/Navalagamella	3,984	406	14,235
72	Escorial (El)/San Lorenzo de El Escorial	33,706	6,449	18,879
73	Alpedrete/Collado Mediano/Guadarrama	35,711	6,754	18,594
74	Alameda del Valle/Canencia/Garganta de los Montes/Gargantilla del Lozoya y Pinilla de Buitrago/Lozoya/Navarredonda y San Mamés/Pinilla del Valle/Rascafría	4,439	769	14,284
75	Cercedilla/Molinos (Los)/Navacerrada	14,369	2,873	17,560
76	Acebeda (La)/Braojos/Buitrago del Lozoya/Gascones/Horcajo de la Sierra/Madarcos/Piñuécar-Gandullas/Robregordo/Serna del Monte (La)/Somosierra/Villavieja del Lozoya/Lozoyuela-Navas-Sieteiglesias/Puentes Viejas	5,273	1,111	13,939
77	Atazar (El)/Berzosa del Lozoya/Cervera de Buitrago/Hiruela (La)/Horcajuelo de la Sierra/Montejo de la Sierra/Prádena del Rincón/Puebla de la Sierra/Robledillo de la Jara	1,349	311	12,859
78	Anchuelo/Santos de la Humosa (Los)/Torres de la Alameda/Valverde de Alcalá/Villalbilla	22,935	5,446	16,629
79	Ambite/Corpa/Pezuela de las Torres/Santorcaz/Villar del Olmo/Nuevo Baztán/Olmeda de las Fuentes	11,558	1,831	16,464
80	Campo Real/Pozuelo del Rey	6,687	1,445	14,449
81	Brea de Tajo/Carabaña/Estremera/Orusco de Tajuña/Tielmes/Valdaracete/Valdilecha	11,507	2,721	12,180
82	Belmonte de Tajo/Colmenar de Oreja/Fuentidueña de Tajo/Valdelaguna/Villamanrique de Tajo/Villarejo de Salvanés	21,199	3,882	12,303
83	Chinchón	5,404	1,249	13,247
84	Villaconejos	3,484	602	11,390
85	Aranjuez/Titulcia	58,083	11,789	15,797
86	Robledo de Chavela/Santa María de la Alameda/Valdemaqueda/Zarzalejo	7,679	1,343	14,636

Table C.1. (cont.) Zones of Madrid Region in MARS model: population and workplaces in 2012.

Zone	Municipality/ies (District)	Population	Workplaces	GDP per capita (€)
87	Navas del Rey	2,666	481	12,772
88	Cadalso de los Vidrios/Cenicientos/Pelayos de la Presa/Rozas de Puerto Real/San Martín de Valdeiglesias/Villa del Prado	22,955	4,025	12,970
89	Navalcarnero	25,453	5,889	15,309
90	Aldea del Fresno/Colmenar del Arroyo/Chapinería/Sevilla la Nueva/Villamanta/Villamantilla/Villanueva de Perales	20,330	3,653	15,137